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A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios

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Master in Industrial Ecology
Submission date: July 2013
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Abstract: The commercial aviation industry is drawing more and more attention from governments, international organizations and industry stakeholders as calls for improved environmental performance escalate and global concern to mitigate the production of greenhouse gas (GHG) emissions increases. International demand for commercial air transport is projected to steadily grow at a rate of 4.8% through 2036, which raises concern that emissions production will outpace related technological advancement. Additionally, aviation contributions of anthropogenic derived GHGs are already significant at an estimated 2% of global totals. To appropriately manage these issues, decision makers must consider the life cycle inventory of environmental impacts produced from various transport modes to design policies that effectively benchmark technologies and address environmental objectives. Unfortunately, it is often the case that tailpipe emissions act as the only indicators for entire system performance, which neglects necessary requirements of capital goods, supply chain services, infrastructure and vehicle manufacturing. The intention of this thesis is to assess environmental impacts of passenger air transport using a life cycle framework to provide a more comprehensive understanding of total environmental impacts. Using three different aircraft flight scenarios, total passenger, vehicle and vehicle lifetime impacts are modeled on a per kilometer basis. Results show that non-tailpipe GHG impacts are significant and constitute between 16-21% of the total. Findings demonstrate that shorter flights create the largest emissions per passenger kilometer travel due to the energy requirement of the landing and take-off cycle. Vehicle and vehicle lifetime perspectives facilitate an overall understanding of net environmental costs as a result of demand for transport services thus providing a more holistic representation of transport impacts. Individual life cycle phases are examined and results for non-GHG related impacts are also reported.

Acknowledgements:
I would like to thank my thesis advisor Anders Hammer- Strømman whose insight, instruction and support made this thesis a reality. Without his expertise and guidance, this work would not have been possible. In addition, I would like to thank Geoffrey Guest, who also gave invaluable advice with regard to the analytical methods and approaches taken. Drisana Lewis and my family are also due many thanks for their support, encouragement and inspiration throughout my graduate school experience. I would also like to acknowledge and thank my colleagues in the Industrial Ecology program, it has been a pleasure learning and working with all of you and I am grateful for the time and experiences shared.

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List of Acronyms & Abbreviations

AEM: Advanced Emissions Model
BUSD: Billion U.S. dollars
EIOLCA: Economic Input-Output Life Cycle Assessment
EOL: End-of-life
Eq: Equivalent
Fuel Prod: Fuel Production
GHG: Greenhouse Gas
g: Gram
IATA: International Aviation Transportation Association
ICAO: International Civil Aviation Organization
IPCC: Intergovernmental Panel on Climate Change
Inf Cons: Infrastructure Construction
Inf Ops: Infrastructure Operations
Kt: kiloton
kg: kilogram
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LTO: Landing and take-off cycle
Mfg: Manufacturing
mg: milligram
MMT: Million metric tons
Mt: Megatonne
MUSD: Million U.S. Dollars
OPEX: Operation Expenditure
Ops: Operations
PAX: Passenger
PRO: Process
RF: Radiative Forcing
TOG: Total Organic Gas
USD: U.S. dollar
VOC: Volatile Organic Compounds

Introduction

Introduction and Motivation

Aviation is a critical part of the global economy as well as both domestic and international transport systems. ICAO's Environmental Report 2010 concludes the world's airlines transported approximately 2.3 billion passengers and 38 million tons of freight on scheduled services while concurrently forecasting passenger traffic to grow at a rate of 4.8% per year through 2036. Aviation services have enhanced the mobility of goods and people at faster speeds and with connectivity that is unparalleled by other modes of transport. The air transport sector undoubtedly provides services that are integral to the transport and economic systems of modern society however, there are also significant environmental impacts that will likely increase with the expansion of this transport mode.

In its Special Report on Aviation and the Global Atmosphere (1999), the Intergovernmental Panel on Climate Change (IPCC) projected that the global anthropogenic greenhouse gas (GHG) contributions from aviation were 2% of total. Within the transport sector shares of global GHGs, aviation is accountable for 13% of total and constitutes the second largest individual contributor behind automobiles (ICAO, 2010). Perhaps more concerning, total emissions from aviation are anticipated to grow at three to four percent per year (ICAO, 2010), a rate that many believe will outpace environmental technological improvements. Although GHG emissions are often the primary focus when discussing transport related environmental impacts, there are a number of other pollutants and resource impacts that are generated. These can be caused by both the consumption of fuel and by the broader requirements of capital goods, supply chain services, infrastructure and vehicle manufacturing inputs needed by the sector. To date, little is known about these impacts and as such, ICAO has requested that the IPCC include non-CO_2 related emissions in its upcoming Fifth Assessment Report.

The combined importance of aviation in global systems, significance of net GHG related impacts and relative uncertainty associated with non-CO_2 impacts and supply chain contributions, presents an opportunity to provide increased resolution on some of these subjects. Furthermore, as the predominate emphasis in aviation impact assessment has historically been on tailpipe GHG emissions only, research examining other life cycle phases and environmental stressors would prove beneficial. Transportation related work is also extremely important as most product and service related studies depend on transportation emission factors that are out of date or incomplete (Cristiano Facanha, 2006). Therefore any related contributions could potentially improve the emissions reporting on products and services throughout the economic system. These issues all substantiate the need for an assessment methodology that provides system wide analysis of environmental contributions and thus, a need exists for a life cycle assessment examining the impacts of passenger air transport.

State of the Field

Literature Review

Increasingly, aviation emissions are attracting global attention as demand for air transportation climbs and pressures to mitigate climate impacts continue to influence policy. Initiatives such as the European Union Emissions Trading Scheme that incorporate air traffic regulations as part of Europe's obligations under the Kyoto framework (Robert Malina, 2012), provide recent evidence towards this end while underscoring the need for increased clarity on total aircraft emissions. As such, the current paradigm for assessing environmental impacts can be classified into two broad areas, those that focus on the operational phase of air transportation or "tailpipe emissions" and those that focus on one or a combination of all other life cycle phases of an aircraft in conjunction. Within this realm, studies differ on their prioritization and analysis of various stressors produced by air transport with the majority of work predominately highlighting GHG impacts.

Research efforts assessing the GHG impacts of the aircraft operation phase are well documented (A.J. Kolios, 2013; Chester, 2008; Cristiano Facanha, 2006; Kahn Ribeiro, 2007; Lopes, 2010), providing useful frameworks through which policy and continued research can be developed. Intergovernmental organizations, namely the IPCC and the International Civil Aviation Organization (ICAO), have written extensively on both the present emissions production of the global aircraft fleet as well as the long-term outlook under different technology and growth scenarios (ICAO, 2010; Kahn Ribeiro, 2007). Organizations such as the U.S. Federal Aviation Association (FAA) and European Organization for the Safety of Air Navigation have both developed modeling software that enables quantification and collation of emissions data for aircraft and related infrastructure. Finally, there has also been a study examining the life cycle emissions impacts over the operation phase due to the selection of lightweight airframe materials (L. Scelsi, 2010). Collectively, though not exhaustive, this information provides important context and represents some key findings in the current established body of work with a GHG focus.

Full LCA representation of the air transport system including all life cycle components, additional indicator categories as well as GHG's are much less established in terms of published works. Perhaps the most relevant efforts towards completing a full LCA on the given subject have been made by Mikhail Chester and Arpad Horvath using a hybrid approach (Mikhail Chester, 2008, 2011) and by João Lopes (Lopes, 2010) with his process LCA research for an Airbus A330-200 aircraft (Lopes, 2010). These works both consider the entire life cycle distilling their final results into a passenger kilometer of travel. Similar system boundaries were used in each study however; Chester 2008 incorporates a wider view of the transport system by considering three different aircraft in an effort to capture the impacts of the broader U.S. fleet. Lopes' 2010 work relies on the processes available in Ecoinvent and provides a more detailed analysis of a single aircraft type and its respective material inventory. His efforts represent one of the most detailed initiatives to inventory aircraft materials at the time of this report.

An additional study in this category that acknowledges the air emissions throughout the manufacturing, use, maintenance and EOL phases of freight transported via aircraft was conducted by Cristiano Facanha and A. Horvath (Cristiano Facanha, 2006). This study is very similar in structure to Chester 2008's work and utilizes a hybrid process LCA and EIOLCA approach to assess net impacts throughout the life cycle phases under study. Finally, a study conducted by A.J. Kolios 2013, utilizes a process LCA and the Ecoinvent database to calculate impacts for the service lifetime of an A320 aircraft. Customized data was also generated for some of the most important processes and materials. This study was also concerned with doing some comparative work on impacts between certain materials as well as using biofuel to operate the aircraft (A.J. Kolios, 2013).

The common comparative metric from these studies is the share of GHG's attributed to the operation phase in the net life cycle. Interestingly, this value varies quite significantly across these studies. Chester 2008 reports that these emissions can be as high as 81% of total life cycle contributions. Facanha 2006 reports that the vehicle operation phase is accountable for 70% of total life cycle emissions while Lopes 2010 and A.J. Kolios 2013 assign over 99% of net GHG emissions to the operation phase.

Aviation and the Environment

As with most transport modes, aviation primarily produces environmental impacts through the actual operation of the aircraft vehicle. Supporting infrastructure and supply chain requirements also add contributions through their respective resource and energy requirements. To provide context to the overall impacts from direct aircraft operation; aircraft consumed approximately 187 Mt of fuel globally in 2006, which translates to approximately 591 Mt of CO_2-eq (ICAO, 2010).

Internationally, goals such as ICAO's carbon neutral growth by 2020, have been set towards reducing GHG impacts from aviation but no substantive measure has been enacted to date. As such, the European Union has incorporated airlines into its Emissions Trading Scheme (ETS, mentioned above), which is a market based measure system whereby companies buy and sell credits based on their emissions. Recently, ETS has been put on hold as ICAO has signaled it is willing to consider recommended international frameworks at its next general assembly meeting. This recommendation will likely be similar to the ETS system and will come from the High-level Group on International Aviation and Climate Change (HGCC); a consortium of seventeen nations. As the EU implementation of ETS was purportedly viewed to be problematic by some nations, there appears to be added emphasis towards reaching an international accord as the EU has implied it will resume implementation of ETS if not achieved (Thompson, 2013). To date, GHG contributions from aviation represent the primary environmental concern for this sector.

Other environmental issues associated with air transport include the production of NO_x, SO_x, HC, H_2O and soot from engine operations over the aircraft transport cycles, which can contribute to an array of different impacts to air, terrestrial and aquatic systems. Combustion of fossil fuels and related emissions also occur indirectly throughout the air transport system as elements such as airport power requirements, ground support equipment, fuel production, aircraft manufacturing, etc. require primary energy to operate. These same elements also require vast resources and inputs from nature to industry for building, maintaining and operating their respective functional capabilities. This can create significant environmental implications beyond those generated by fuel combustion. To better understand these impacts across all transport systems requires the framing of a system boundary and synthesis of a related environmental inventory.

Research Goals

Goal and Scope of Thesis

The overarching objective of this thesis is to assess the environmental impacts of passenger air transport on selected aircraft and routes. The secondary objective is to understand the relevance of different life cycle stages across selected environmental impacts. In this study, primary emphasis will be given to greenhouse gas emissions although final results will be presented on a number of different environmental categories.

Method

Overview

The method employed in this work to analyze the environmental impacts of commercial air transport is Life Cycle Assessment (LCA). This research will use two different methods of LCA; the first being process-based LCA utilizing the Ecoinvent database, the second being an Economic Input-Output Life Cycle Assessment (EIOLCA) relying on similar mathematics but using U.S. economic input-output data at the sector level. Individually and combined, these methods are useful for holistically and systematically presenting the total environmental impacts of various production and consumption systems. Moreover, using a combined model for LCA that utilizes advantages of both methods is the appropriate approach for the most comprehensive study (Chester, 2008; Sangwon Suh, 2004).

Modeling transport from an LCA perspective is also complex as it incorporates the use of vehicles, infrastructure, services and energy production. This, and the quantity and quality of process information available necessitate a combined approach to modeling transport (Cristiano Facanha, 2006). At the same time, EIOLCA sector aggregation issues limit its use, particularly if the necessary sector is critical to the system under study and incorporates too many commodities with significant technological differences. EIOLCA cannot model the use and end-of-life (EOL) phase of LCA due to its commodity production focus. The culmination of all of this suggests that the most applicable method for modeling air transport from an LCA perspective would then be a combination of both EIOLCA and process LCA. The following sections will provide a more detailed description of each method.

Process-Based Life Cycle Assessment

A traditional or process LCA is best described as a method made up of four different phases, those being: Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation (ISO, 2006). As Figure 1 suggests, there are several potential direct applications of LCA including product development and improvement, strategic planning and public policy making and marketing, among other prospective uses. LCA information can also be used to differentiate the impacts of two comparable products, to assess design options for the same product or to identify where in the life cycle an impact should be targeted for reduction (Carnegie Mellon University Green Design Institute, 2008). The formulation of a goal and scope for a given assessment involves defining the functional unit, the system boundaries, assumptions, allocation methods and impact categories chosen. Inventory analysis represents the most data and time intensive aspect of an LCA as the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) are compiled into a Life Cycle Inventory (LCI) for all processes included in the scope of the project. Next, Impact Assessment where the inventory results are characterized into midpoint indicators (e.g. infra-red forcing or Global Warming Potential) and/or endpoint indicators (e.g. Human Health) to present environmental impacts is completed. Finally, Interpretation aims to systematically evaluate the information and results generated in the previous phases to analyze content, develop conclusions, assess limitations and formulate recommendations.

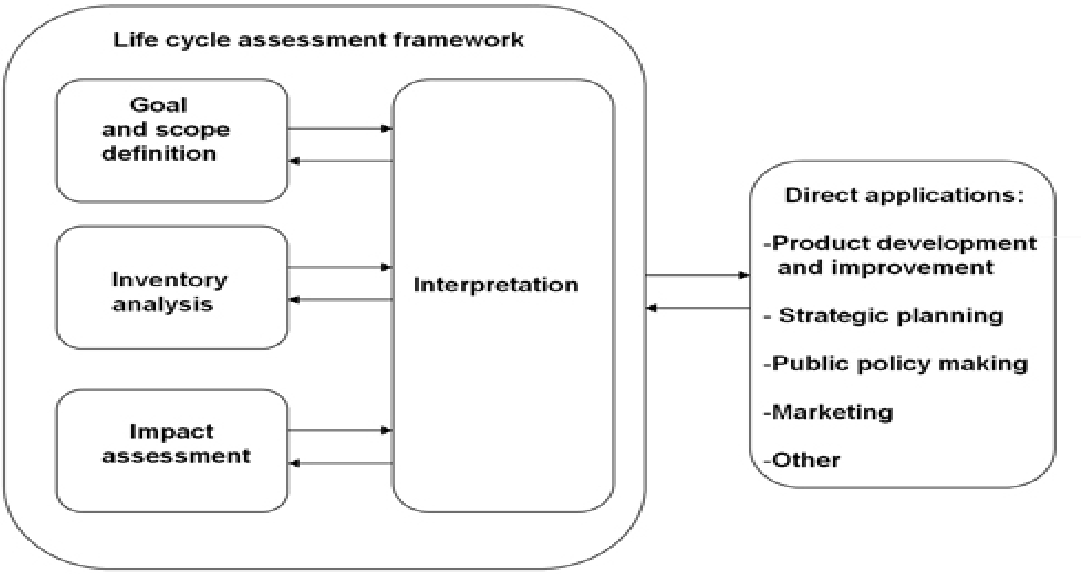


Figure 1 Life Cycle Assessment Framework

LCAs allocate considerable time to the Inventory Analysis and Impact Assessment phases, as this is where the vast majority of data is captured and synthesized into results. Once the LCI is assembled, there are several approaches that can be taken to calculate impacts. In this study, the LCA tools Arda and Simapro were both used to connect the LCI information with relevant processes in the Ecoinvent database[1] and conduct impact assessment. Through the application of a requirements matrix or "A" matrix, one can quantify the material inputs per unit of output between the different production processes. The "A" matrix is further divided into both a foreground A_{ff} and background A_{bb} where the foreground distinguishes those requirements that directly relate to the functional unit while the background matrix represents the requirements of all indirect or upstream elements in the supply chain that can be called upon by foreground processes. These two matrices are interlinked through the background to foreground matrix A_{bf}. This connectivity establishes a model framework where the entire supply chain impacts for a given function or product can be measured based on intermediate requirements.

Once the A matrix is established, it can be used to calculate the total output "x" from all processes for a given final demand "y". This is done through the following equation:

$$Ax + y = x$$

[1] The Ecoinvent database represents a collection of data for the material and energy inputs into a process and the related outflows and emissions.

$$x = (I - A)^{-1}y$$

Where: $L = (I - A)^{-1}$ or the Leontif Inverse[2]

To calculate the environmental impacts of a final demand, a stressor matrix "S" that categorizes the emissions per unit output for each process is defined. The emissions intensities in this matrix can be distinguished as either foreground or background as well and are often a point of improvement as new research and data become available. In addition to the S matrix, a characterization matrix "C" can be implemented to convert emissions of different substances with similar environmental impacts into relative equivalents; for example different GHG's into GWP 100 (measured in CO_2-eq.). With these matrices, one can derive the impact assessment phase where "d" denotes total impact:

$$d = CSLy$$

Total impacts can also be divided into total impacts by process or by stressor:

$$D_{pro} = CS\widehat{Ly}$$

$$D_{str} = C\widehat{SLy}$$

The following Figure represents the nomenclature with descriptions that can be commonly used and may be referred to in this work:

Sets	**pro**		**Processes**
	str		**Stressors**
	imp		**Impact categories**
Matrices and variables	A	*(pro x pro)*	Matrix of inter process requirements
	y	*(pro x 1)*	Vector of external demand of process
	x	*(pro x 1)*	Vector of outputs for a given external demand
	L	*(pro x pro)*	The Leontief inverse. Matrix of outputs per unit of external demand
	F	*(str x pro)*	Matrix of stressor intensities per unit output
	e	*(str x 1)*	Vector of total emissions generated for a given external demand
	E	*(str x pro)*	Matrix of emissions generated from each process for a given external demand
	C	*(imp x str)*	Characterization matrix
	d	*(imp x 1)*	Vector of impacts generated for a given external demand
	D_{pro}	*(imp x pro)*	Matrix of impacts generated from each process for a given external demand
	D_{str}	*(imp x str)*	Matrix of impacts generated from each stressor for a given external demand

Figure 2 LCA Nomenclatures

[2] I in the equation represents the identity matrix. It is symmetric to the A matrix and comprised of all zeros except for the diagonal, where every value is equal to one.

*Note the notation F is replaced by S by this author.

Economic Input-Output Analysis

Economic input-output models provide a framework through which the industry sectors in a given economy can be mathematically modeled to map the flows of goods and services throughout an economy. These models indicate what goods or services are required by other industries and are typically constructed in matrix form where each row and column represents a single industry sector. The intersection of the two provides information about the total requirement or value that the row sector (output) provides to the column sector (input) (Carnegie Mellon University Green Design Institute, 2008). Similar to the "A" matrix for process LCA, this model can be derived into a sector-by-sector requirements matrix that can be used in linear equations. Official statistics bureaus typically compile the initial data requirements. In the U.S. the System of National Accounts (SNA) is managed by the U.S. Bureau of Economic Analysis.

To combine economic input-output models with LCA, environmental emissions can be assigned to sector output, effectively creating an allocation relationship between the economic output of a given sector and the associated environmental impacts (Carnegie Mellon University Green Design Institute, 2008). One of the key elements of EIOLCA is that it provides the complete supply chain of economic activity needed to manufacture any good or service in the economy. As a result, the system boundary is extended to the entire economy thus facilitating broader inclusion of extended supply chain impacts (H. Scott Matthews, 2001). When implemented in LCA form, these models present a more time efficient and less data intensive alternative to process LCA where issues such as detailed process data requirements can demand extensive effort (Chris Hendrickson, 1998). One of the significant downsides to this methodology is the major uncertainty one can encounter when assessing the similarity of a process under study to a representative economic sector, as well as other errors that aggregation at this level can cause (Cristiano Facanha, 2006; H. Scott Matthews, 2001). To model the EIOLCA portions of this thesis, a combination of Simapro, CEDA matrix data and Matlab were utilized to generate an inventory and conduct impact assessment.

Case Description and Data

Overview and System Boundary

Given the inherent complexity and vast material, resource and technology inputs of the global air transport system; this research examines a representative sample of some of the more prevalent elements. This was accomplished by developing three different air transport scenarios with different aircraft vehicles covering common travel distances, infrastructure requirements and aircraft models present in global aviation.

The life cycle components included in the foreground system are the manufacturing phase of the different aircraft, the operation cycle of those aircraft over specific distances, the inputs required for airport construction and operation and the impacts associated with jet fuel production (see Figure 3). The results of the system are then normalized into three different functional units or reportable metrics: passenger kilometer of travel (PKM), vehicle kilometer of travel (VKM) and lifetime vehicle travel (LKM). The system boundary for this LCA includes all of the processes described in Figure 3 however, it excludes EOL scenarios for both aircraft and infrastructure. This section explains the approach taken to structure this research, gather all necessary data and important observations made in establishing the overall life cycle inventory.

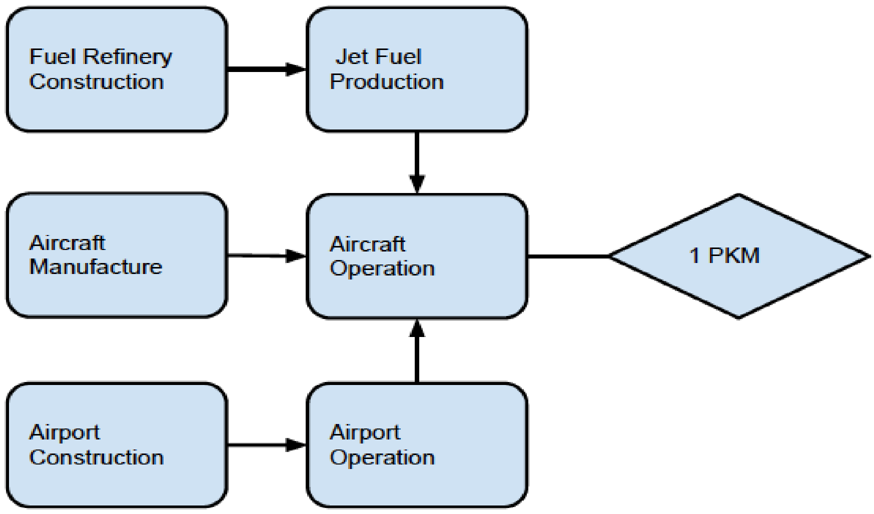


Figure 3 Air Transport System Flow Chart

Selecting Aircraft for Study

The selection of diversified vehicle[3] types is essential to the evaluation of air transport impacts because of to the substantial differences in the direct material and operational requirements that each aircraft exhibits. It is likewise prudent to consider relative passenger capacities, current global market share and projected demand to select aircraft that best represent the most popular vehicles in current and future markets. A review of air transport market dynamics and related literature was undertaken to determine which aircraft models were relevant for study, represented diversity in aircraft transport and provided interesting content for future development in the field. After completing this, the Airbus A320, A330-200 and A380 were selected to model in this thesis.

The global aircraft fleet, estimated at 26,000 aircraft, is primarily represented by two aircraft manufacturers, *to wit*, Boeing and Airbus, representing 39.7% and 28.7% (respectively) of the in-service aircraft operating today (Centre for Aviation, 2013b). Both of these companies manufacture a diversified line of competing commercial jets, ranging from a narrow-body offering of approximately 100 seats to the superjumbo wide-body class with up to 535 plus seats in average seating configurations. The narrow-body jets, particularly the Boeing 757 and Airbus A320, are the most predominant and popular models in commercial aviation (Wilhelm, 2012). These two aircraft lines have also been the two top selling aircraft in aviation history and are projected to continue growing as new markets develop and ageing North American fleets are replaced.

Within the narrow-body class, the 100-149 seat aircraft make up 14% of overall sales while the 150+ seat vehicles capture the remaining 86% share (Wilhelm, 2012). The preeminence of the 737 and A320 in passenger air transport necessitated incorporating this class of aircraft into the study. These models have also been incorporated into other important aviation studies because of their high utility and market share (A.J. Kolios, 2013; Chester, 2008).

[3] "Vehicle" and "aircraft" are used interchangeably throughout this work.

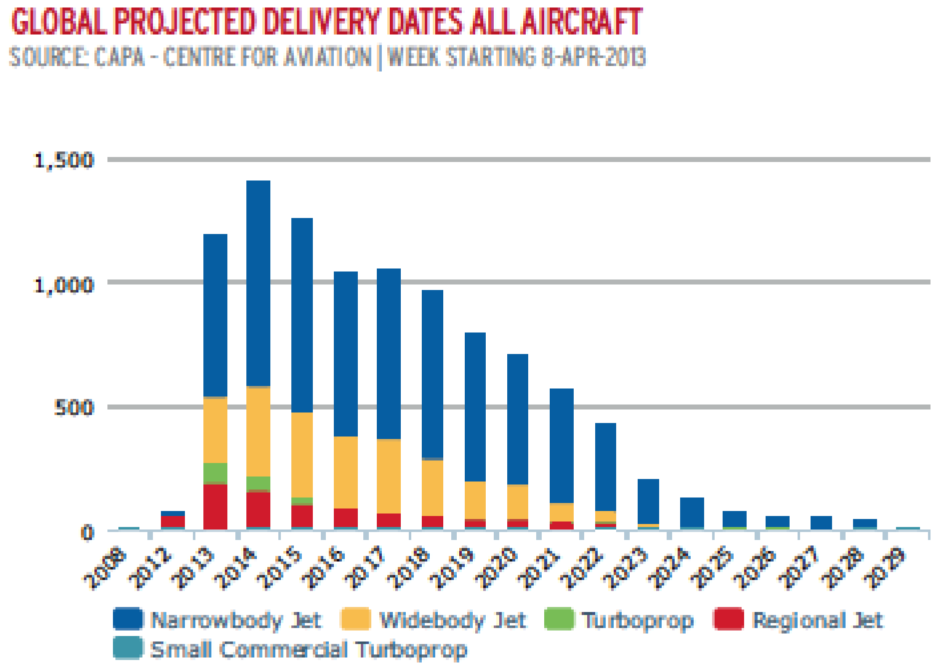


Figure 4 Global Projected Delivery Dates, Aircraft Types

Figure 4 endorses both the selection of the A320 as a critical aircraft to assess as well as the wide-body jet classes adopted, which include two larger Airbus models, the A330 and the A380 by visualizing demand over projected aircraft delivery dates. Airbus aircraft were selected because in addition to holding a sizable global market share, it is presently the fastest growing aircraft manufacturer (Airbus, 2012) and data for their aircraft were more readily available. As can be seen from the graph, the narrow and wide-body jets are the predominate vehicles forecasted to be delivered in the coming years.

This study acknowledges that smaller regional jet classes such as the Embraer 175 and MD DC9 do provide a valuable contribution to many aviation markets; nevertheless they have been omitted. Instead, this work opts to focus on the A320 and larger models given their global significance, higher net energy requirement and increasingly important emissions contributions. In addition, ICAO asserts that international flights are responsible for approximately 62% of global aviation fuel consumption (ICAO, 2010), implicating added emphasis on larger aircraft. Further research also indicates that longer term forecasts project a decline in the use of regional jets serving the 50 PAX market and an increase in newer A320 and 757 models as fleets retire older, less fuel efficient aircraft (FAA, 2012). Moreover, the industry has observed an overall upward trend in the demand for larger aircraft over the last two decades as can be observed in Figure 5.

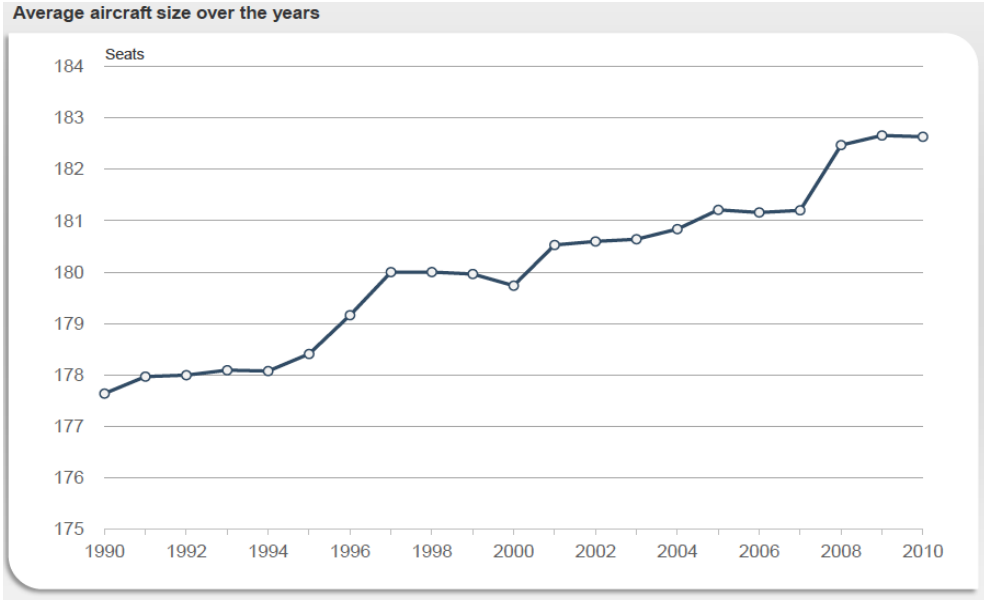


Figure 5 Average Aircraft Size Over Time

From an aircraft diversity perspective, Figure 6 is presented to demonstrate the differences in terms of vehicle technologies, capacity and range between the selected aircraft. An examination of the figure highlights the substantial differences in utility among vehicle types when a narrow-body (A320), wide-body mid to long range (A330-200) and superjumbo (A380) long-range jet are modeled. The unique properties and associated aircraft class of each of these planes, enable this study to assess environmental impacts for some of the most important vehicles in current and future global aircraft fleets.

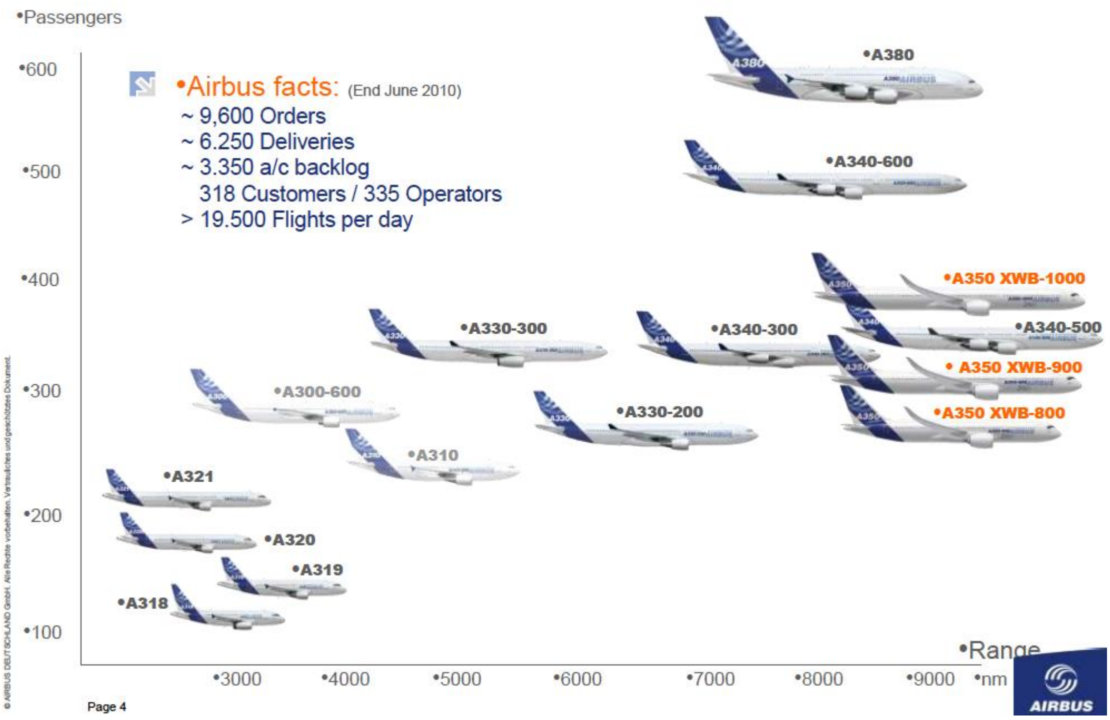


Figure 6 Airbus Aircraft Fleet, PAX versus Range

Selected Aircraft Descriptions

Airbus A320

According to Airbus, the A320 aircraft typically operates on short to medium haul flights with common seating configurations of 150 seats in a two-class cabin or up to 180 seats in a higher density layout for low-cost carriers. The aircraft can be used for everything from short commuter flights up to transcontinental routes in countries like the U.S. As a single aisle passenger aircraft serving these markets, the Airbus A320 competes with the Boeing 737 models. The vehicle has a range of 6,100 km, a 16.6 ton max payload, a 11.76 by 37.57 m height by length and a wingspan of 34.10 m (Airbus, 2013c).

Figure 7 Airbus A320 Description

Airbus A330

The Airbus A330-200 is described as a mid-sized, wide body twin-engine aircraft that can accommodate 253 passengers in a comfortable two-class cabin layout. The aircraft is very versatile and was designed to operate efficiently on everything from short haul to true long distance routes while maintaining the higher passenger capacity. Currently, there are 479 aircraft in operation with orders for an additional 575 currently logged on Airbus' website. The vehicle has a total range of 13,400 km, a max payload of 36.4 tons, is 17.39 by 52.8 meters (height by length) and a wingspan of 60.3 meters (Airbus, 2013a).

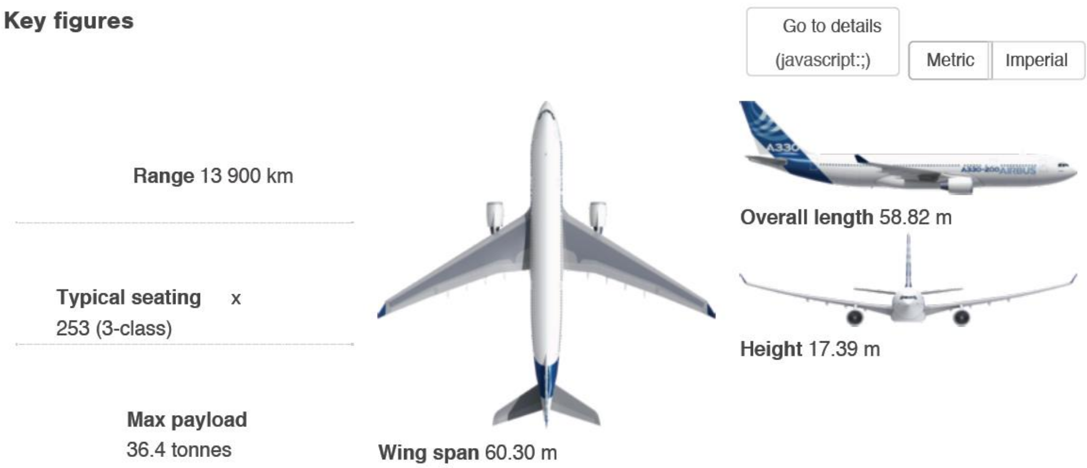


Figure 8 Airbus A330-200 Description

Airbus A380

Although not as commonly sighted in airports as the A330-200 or A320, the A380 is Airbus' superjumbo jet equivalent and was designed to compete with the Boeing 747 on long haul or transcontinental flights carrying larger quantities of passengers and freight. The A380 entered the commercial marketplace in 2007 and is the largest commercial aircraft in operation today.

Its ability to shift large volumes of traffic and influence economic and tourism activity (Reuters, 2013) has made it is a critical part of the passenger and air traffic strategies of several large international airlines such as Emirates and Quantas. The A380 is capable of carrying 525 passengers in a comfortable three-class cabin as well as 853 passengers in a single class configuration. With four engines, a wing span of 79.75 meters, 24 m height and 72.7 m in length, the Airbus A380 has been considered a single flying equivalent of the Boeing 777-200 and the Airbus A340 combined (Air France, 2011). Range is listed at 15,700 km with a maximum take-off weight of 560mt and fuel capacity for up to 320,000 liters. Interestingly, although not confirmed in any known study, some airlines have asserted that the aircraft's size and public allure break with the conventional industry consensus that consumers are predominately not concerned with which vehicle they fly on. Overall, superjumbos are increasingly becoming a significant element in the operating strategies of many airliners and intercontinental travel.

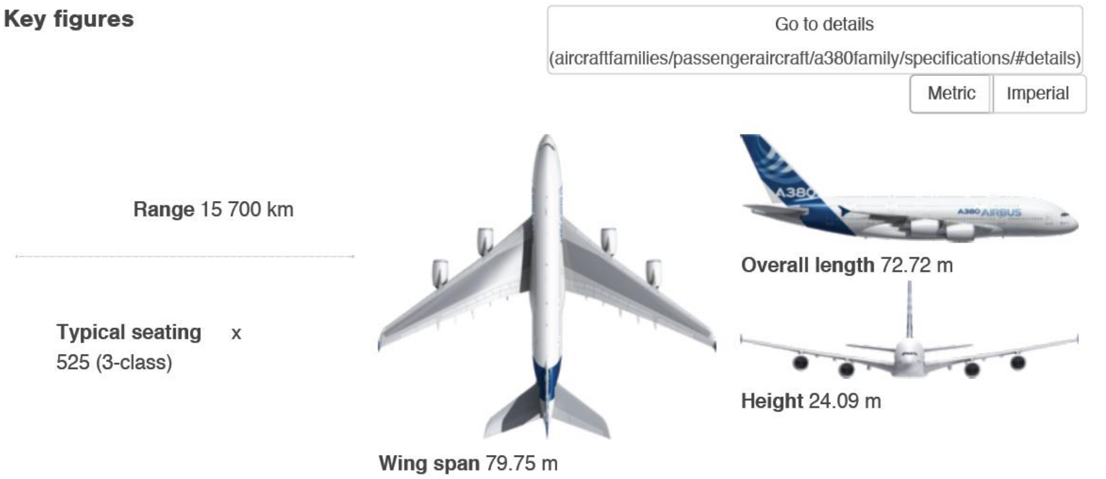
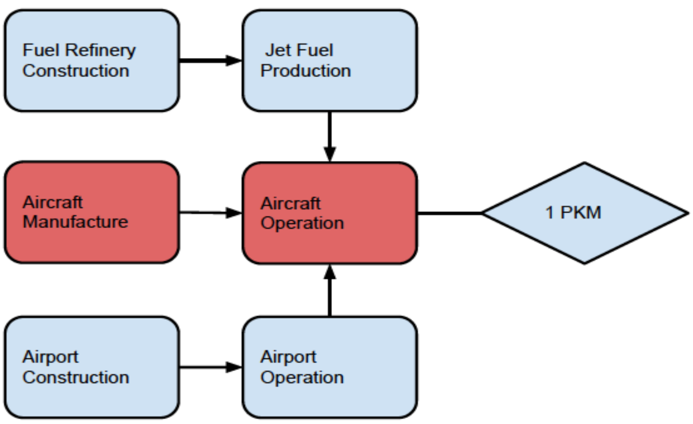


Figure 9 Airbus A380 Description

Aircraft Manufacturing & Operation

Once the aircraft for study were selected, the actual manufacturing and operational requirements for each were examined in detail. The following sub-sections outline the approach used to generate total impacts for both of these phases for all three aircraft types. In addition, all of the challenges and processes used to analyze the manufacturing of these three aircraft are discussed and documented. Given the sophistication of aircraft inputs this phase presented particularly challenging obstacles.



Aircraft Manufacturing LCA Approach

The air transport life cycle begins with the manufacturing phase where infrastructure and vehicle requirements undergo both primary and secondary production and are then assembled into usable products. Determining the environmental impact of manufacturing a given plane was more complicated than originally anticipated. Currently, available literature has taken two approaches with respect to this subject: (i) process-based LCA using the primary structural components of the aircraft (A.J. Kolios, 2013; Lopes, 2010) and (ii) EIOLCA using the price of the aircraft under study and the relevant sector in which it is produced to generate results (Chester, 2008; Cristiano Facanha, 2006). To develop adequate inventories for assessment in this study, a thorough examination of both methods was undertaken to establish the most appropriate LCA path.

Process-Based LCA Overview

Existing research suggested that process-based LCA on commercial aircraft was an exceedingly complex procedure; the collection of necessary information for the different assemblies and subcomponents is difficult and compounded by the lack of openly available aerospace information (A.J. Kolios, 2013; Chester, 2008; Lopes, 2010). During the time this study was undertaken, only two process based LCAs were known to exist (A.J. Kolios, 2013; Lopes, 2010) and, as a result, they became key resources in developing process based LCAs for examination in this study. , Inventories for each of the Airbus model aircraft were created and analyzed using a process-based model in an effort to provide a comparative assessment of both LCA methods considered for the manufacturing phase.

In his 2010 work, João Lopes was motivated to improve upon the Ecoinvent process for aircraft manufacturing as it only considered two materials (aluminum and polyethylene) in the vehicle manufacturing process. He subsequently partnered with the organization 3 Drivers and two TAP engineers João Carrolo and João Martins to compile a materials inventory for an Airbus A330-200. The combined effort facilitated better collation of the necessary data and helped the author identify key material components through use of the Airbus aircraft flight manuals. Mr. Lopes subsequently translated the structural component information found in the aircraft manuals into materials that were available in the Ecoinvent database (Lopes, 2010). A shortcoming delineated by both previous authors (Kolios 2013, Lopes 2010) was that the navigation and communication instrumentation, electronic parts, hydraulic fluids and some interior features were left out of the analysis as only the structural components were evaluated. This was attributable to the inability to collect adequate information and masses for these features. Lopes

2010 however, provided the highest level of detail in his aircraft inventory and thus his work is adopted to form baseline material inputs for this study.

Process LCA Analysis

To understand the aircrafts' structural requirements for vehicle manufacturing, a detailed inventory of materials was established for the three different aircraft types in this study. To accomplish this, the breakdown of material ratios in each structural component (e.g. engines, wing, fuselage, etc.) of Lopes' Airbus A330-200 study were extrapolated and presumed to be similar across the aircraft types (A320 and A380) under the supposition that a manufacturer uses similar component engineering and design economies of scale in its fleet production.

Next, the relative fractions of broader weight distribution (e.g. total percentage of aircraft kg per structure) were allocated[4] to both the A320 and A380 vehicles, using total structural weight and fractions from an Airbus presentation[5] (Rendigs, 2010) and A.J. Kolios 2013. By using the broader materials allocations in conjunction with more specific detail provided by Lopes 2010's A330-200, an inventory (structural components) of the Ecoinvent material requirements for the production of all three aircraft could be established. Environmental impacts from the transport of goods during final assembly were also considered using data from A.J. Kolios 2013.

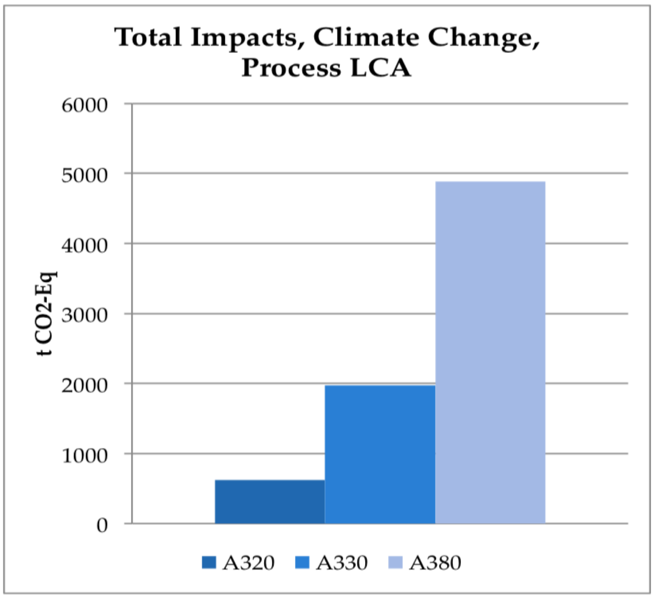


Figure 10 Total Mfg Impacts, Climate Change, Process LCA

At this point, LCA calculations were completed using Arda[6] software and results were categorized into ReCiPe midpoint (H) indicators. Total impacts

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[4] The A330-200 allocation was already detailed by the Lopes 2010 study. Includes 4x engines for A380.

[5] See Appendix 1

[6] Arda is an LCA software developed by the Norwegian University of Science and Technology's Industrial Ecology Department

for GHG's are presented in Figure 10. In addition to total GHG impacts for each aircraft type, Figure 11 presents the advanced contribution analysis of the A330 and provides information on the individual process contributions to total LCA impacts. Additional contribution analysis results for the A320 and A380 can be found in Appendix 1.

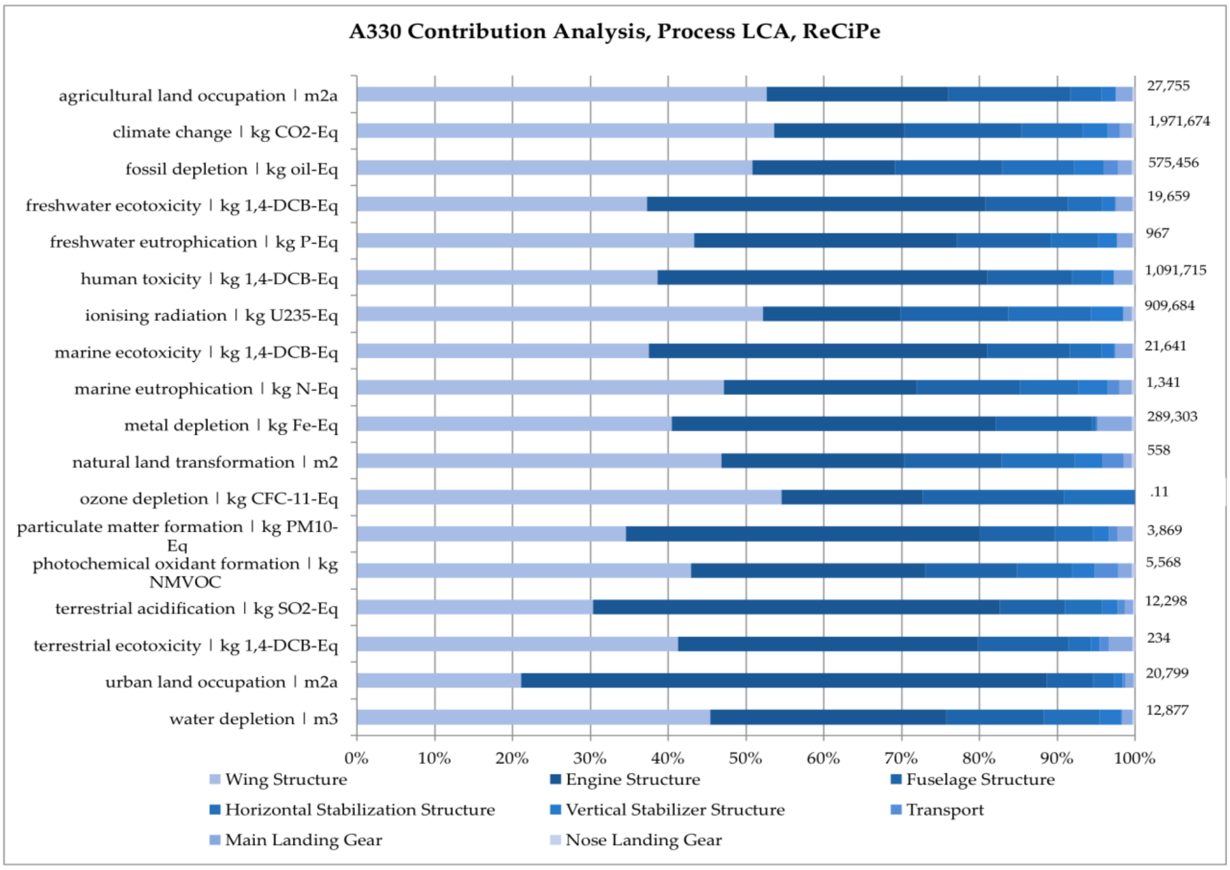


Figure 11 A330 Contribution Analysis, Process LCA

The detailed breakdown of materials by aircraft structural component enabled analysis of the various structures based on their contribution to total impact categories. This analysis allows investigation into how various aircraft elements contribute to a given environmental category of concern. It also provides a clear visual indication of the most environmentally significant structures when there is concern over a particular stressor. For example, in the figure above, the wing structure is accountable for over 50% of the aircraft's 1.97 t CO_2-eq for the climate change indicator.

At least 70% or more of all environmental impacts are attributed solely to the wing and engine structures, with several impact categories even exceeding 80%. From this analysis, a conclusion may be drawn that if the objective were to improve environmental impacts from aircraft manufacturing, the wing and engine structures would be the two most critical and practical places to begin looking for efficiencies.

Analyzing the three aircraft using process LCA provided some interesting insights into the physical direct requirements of the vehicle as well. For example, the relative impacts of the wing and engine structure noticeably change among all three aircraft. Looking at the three most material intensive structures (by weight) in the aircraft (see Table 1) by relative shares of climate change impacts, the A320 exhibits a more balanced contribution among the analyzed structures and perhaps is more influenced by the engine than other aircraft. The A330 is more heavily weighted towards impacts generated from the wing structure and the A380 exhibits a more balanced distribution between the wing and engine structures when looking at all impact categories (ref. to Appendix 1). Considering the airframe size and technical differences between the aircraft, this would make sense. The aircraft wings impact changes significantly as aircraft size increases while the engine and fuselage impacts relative to the total do not.

Table 1: Total Climate Change Shares of Top Contributing Structures

Structure	A320	A330	A380
Wing	27%	54%	44%
Fuselage	20%	15%	17%
Engine	20%	17%	16%

EIOLCA Approach

To conduct an EIOLCA accurate price information (at producer price) is required in the year that the U.S. IO Data is reported. The average 2002[7] price for each aircraft was obtained using Airbus' reported values (Airbus, 2013b; Today, 2004) and production costs are determined by assuming a 10% markup inclusive of overhead, profit, distribution and marketing (Chester, 2008). The A380 was not produced in 2002 so the latest value for the aircraft was scaled back to 2002 dollars using a factor derived from analyzing the A330 price differential between the same periods. The following table outlines presumed production costs:

[7] 2002 is the latest year of IO data available at the time of writing

Table 2: Aircraft Cost in 2002 USD

Aircraft Model	Total 2002 MUSD	Adjusted 2002 MUSD
A320	$57.2	$51.48
A330-200	$138.6	$124.74
A380	$225.84	$203.26

The U.S. sector "Aircraft Manufacturing" (#336411) was then used to calculate total impacts using Simapro software. Simapro was selected because it provided the option to characterize results into ReCiPe midpoint indicators, facilitating a cleaner normalization process and data analysis later on in the study. Through the use of CEDA input-output data in the Simapro program, total impacts for each aircraft model were produced (Simapro, 2011).

EIOLCA and Process LCA Comparison

Given the known constraints, a narrower system boundary, material and services exclusions implicit in most process LCA calculations for aircraft manufacturing (A.J. Kolios, 2013; Lopes, 2010), additional comparative work was conducted to determine whether or not process LCA or EIOLCA would provide the most practical modeling approach towards more accurate life cycle impacts. Upon comparing the total climate change impacts for both methods, it became evident that there was over an order of magnitude difference between the results (see Figure 12). This suggested that there was clearly a need for further research to determine why this differential was so large.

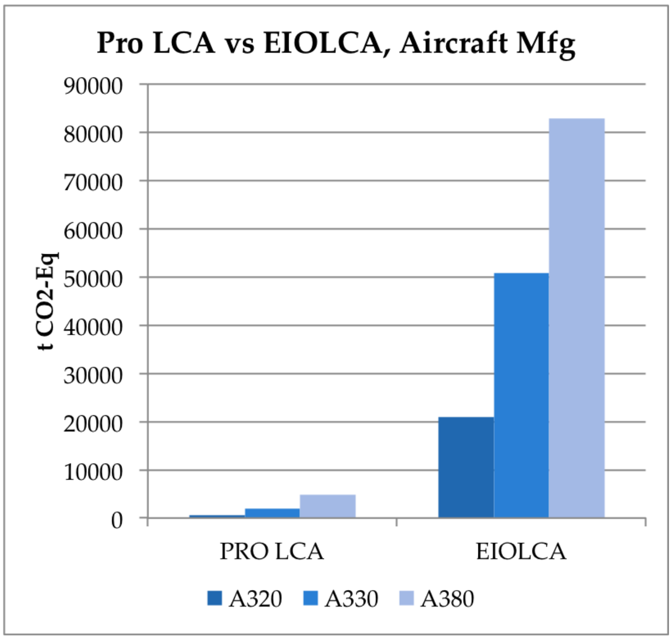


Figure 12 Pro LCA versus EIOLCA, Aircraft Manufacturing

Upon reviewing the EIOLCA impacts derived from the first tier[8] of contributing sectors to the Aircraft Manufacturing sector (using GHG equivalents for the A330) it was observed that

[8] The first tier is the direct input flows from other sectors into the aircraft manufacturing sector. This was derived using Matlab and CEDA matrices.

the there was not one definitive answer. For example, over 8,000 t CO_2-eq are generated from the Iron and Steel Mill sector, approximately 1,200 from the service sector Management of Companies and Enterprises and overall, approximately seventeen sectors contribute over 500 t CO_2-eq individually (ref. Appendix 1 for chart). This is a critical finding considering the total process LCA impacts for the same aircraft model were 1.97 t CO_2-eq. Essentially, there is a wide range of diversity in sectors, both service and production, that have substantial contributions to the final GHG result. This observation indicates that perhaps the economic requirements of aircraft production are too diversified and relevant to omit when assessing aircraft production impacts. Other potential implications would require further investigation into the requirements matrices for the U.S. Input-Output tables, which was considered beyond the scope of this work. As such, another high-level form of analysis to aid in method selection was required.

A comparison of reported CO_2 emissions to revenue was completed for both Boeing and Airbus. By calculating the emissions intensity per revenue dollar, the total direct emissions from the manufacturers could be compared to aircraft output, providing a better sense of scale. For Boeing, the annual 2012 emissions were listed at 1.24 MMT and revenue over the same period was $68,735 MUSD resulting in an emission intensity of 18.14 t CO_2-eq per million U.S. dollar (Boeing, 2013). Using the 737-800 average price of $100.5 MUSD[9] (2012), total direct emissions would amount to 1,823 t CO_2-eq or nearly three times the 635 t CO_2-eq amount produced using process LCA for the comparative Airbus A320 model. The same approach applied to Airbus was used with annual emissions in 2012 reported at 1,040,810 t CO_2-eq and revenues of approximately $76.2 BUSD (EADS, 2012). An average 2012 A320 price, according to Airbus, was $88.3 MUSD (Airbus, 2013b). Using the emission intensity of 14.33 t CO_2-eq /MUSD, total direct GHG impacts are 1,265 t CO_2-eq. This is approximately two times the amount reported using process LCA. Meanwhile the total impacts using EIOLCA were calculated at 20.9 kt CO_2-eq, over thirty-three times the amount reported by process LCA.

Upon examination of the output from process LCA using EIOLCA and direct emissions projections as comparative benchmarks and after conferring with the advisor of this study, the conclusion drawn from this analysis was that the process LCA results are likely much too low when considering the total direct emissions reported by manufacturers per revenue dollar, the magnitude of the extended supply chain, and service sector impacts. At best, the EIOLCA

[9] Reported average price on Boeing's jet price list.

represents a more reasonable solution although at the upper bound of environmental impacts attributable to aircraft manufacturing. As a result, EIOLCA serves as the manufacturing LCA methodology in this study. It should be noted that this method has also been chosen in Mikhail Chester's 2008 transport study as the most practical and justified approach (Chester, 2008).

Aircraft Operation:

The operation phase of air transport consists of the landing and take-off cycle (LTO) and the cruise phase of vehicle operations. The LTO cycle is further segmented into more specific aircraft activities including: taxi-out, take-off, climb-out, approach, landing and taxi-in (see Figure 13). Although these time durations can vary at different airports and when unanticipated conditions arise (ice, traffic delay etc.), ICAO has calculated the average amount of time each of these segments usually requires (see Table 3). The LTO cycle occurs at elevations below 3,000 feet and is best characterized by the use of varying levels of aircraft thrust and fuel to propel the vehicle to the desired speed. It is also increasingly important from an environmental perspective as the LTO phases are conducted at altitudes that more directly influence human and land-based ecosystem health.

The cruise phase is the operating segment following the climb to a targeted elevation and immediately preceding the approach or descent. It is the largest individual time and fuel requirement in the overall flight cycle. It can also be very dynamic as flight trajectories are managed to satisfy weather and traffic constraints, time and fuel economics, which impact variables such as speed, elevation and flight path.

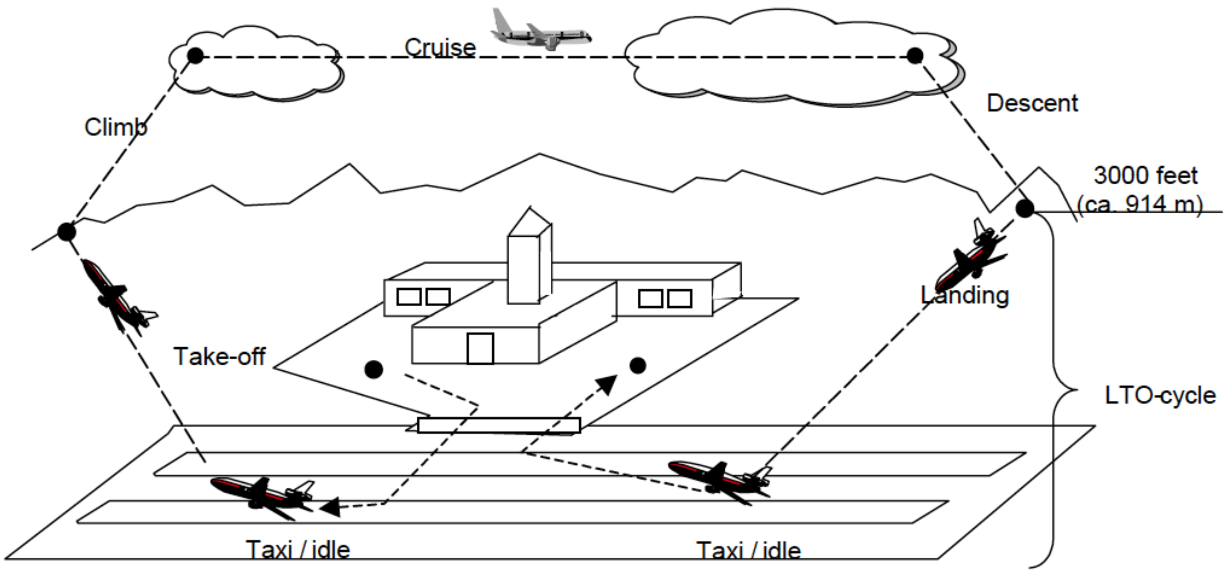


Figure 13 Aircraft Landing and Take-off Cycle

Table 3: LTO Cycle Power Setting and Time in Phase

Operation Phase	Avg. Power Setting	Avg. Time in Phase (min.)
Idle, Taxi-out	7%	19
Take-off	100%	0.7
Climb	85%	2.2
Approach	30%	4
Landing	N/A	0.7
Taxi-in	7%	7

Aircraft Emissions and the Environment

The aircraft operation phase is perhaps the most significant aspect of passenger air transport in terms of environmental impacts because of the direct energy requirement of large commercial aircraft and global demand for air transport. Many variables affect the dispersion of emissions into the environment during an aircraft's operation phase due to the dynamic nature of both the technology used and the environmental conditions observed throughout its use. For example, the engine used, load factor of the vehicle, design of vehicle, weather in route, atmospheric conditions and elevations are all variables that impact the emission dispersion and production on a given flight.

Emissions are produced by the combustion of fuel (jet kerosene and jet gasoline) in the aircraft engine and can exhibit variation depending on the relative performance of the machinery. Given this, commonly observed emissions from petroleum products are obtained and include CO_2, CO, hydrocarbons, H_2O, oxides of nitrogen and SO_2 (dependent on sulfur content) (Morten Winther, 2009, Updated 2010). Other species are also present such as PM and volatile organic compounds (VOC) and will be detailed later in this work. Importantly, the emissions of CO_2, H_2O, and SO_2, have proportional relationships[10] with the fuel use and therefore are independent of engine combustion characteristics.

As can be seen in Figure 14, a complete combustion of jet fuel would yield a cleaner profile of emissions; however this is not the case with current aircraft engine technology. The "Actual Combustion Products" listed in the diagram provide a more realistic picture of the engine performance and can vary as new technology and innovation are introduced by manufacturers. Thus, the overall emissions introduced into the environment are a function of the total energy requirement and the relative technology employed by the aircraft engine.

[10] In this thesis, the factors used for these emissions are based on Eurocontrol standards and are ~3.15, 1 and 1.23 respectively.

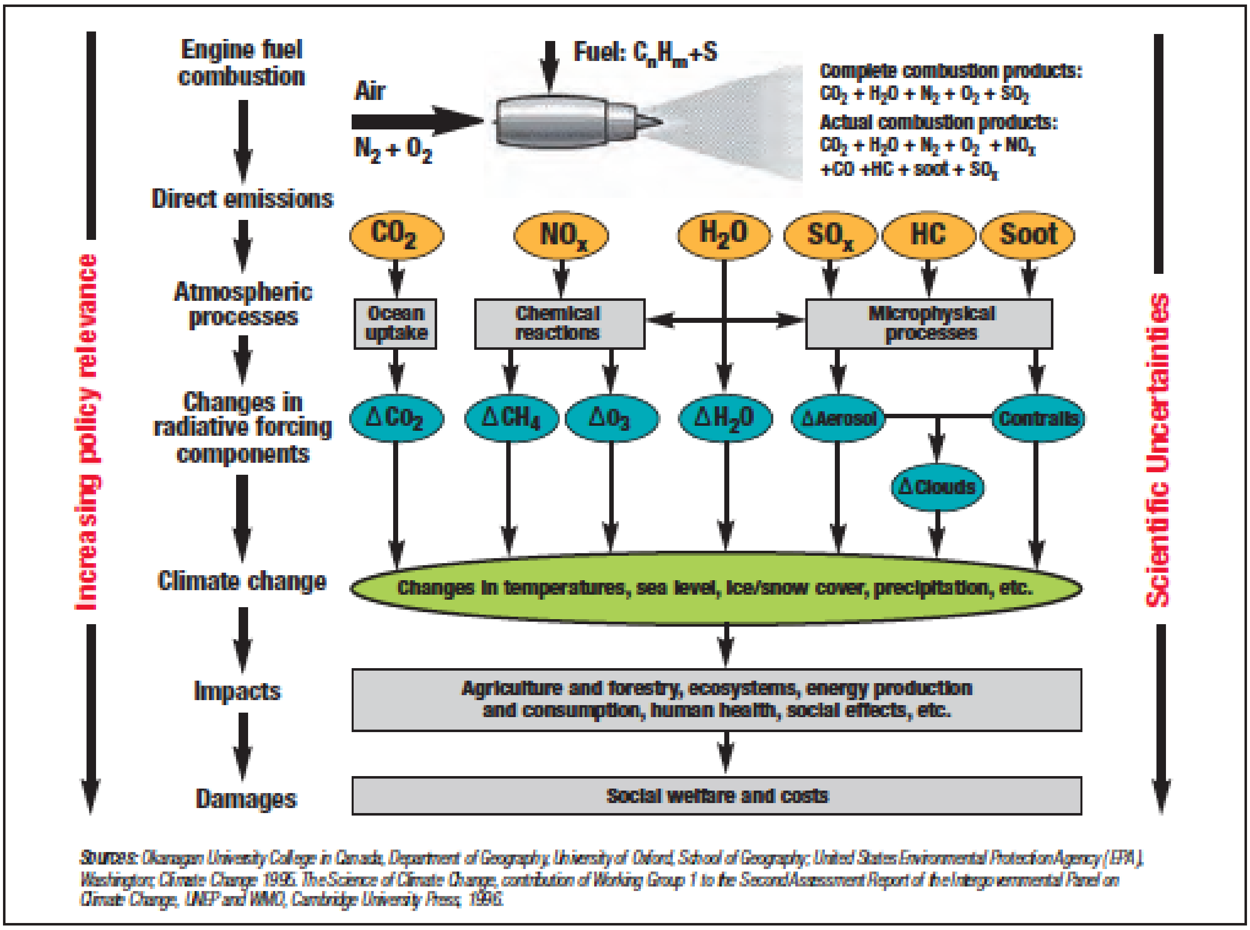


Figure 14 Aircraft Engine Fuel Combustion and Emission Diagram

Of the emissions aircraft engines generate, two are classified as GHG's: CO_2, and H_2O. However, more than just these two species contribute to climate change and are better understood using the concept of radiative forcing (RF). These additional emissions are graphically depicted in Figure 14 (ICAO, 2010). Simply defined, RF is the global, annual mean radiative imbalance caused to the Earth's climate system due to anthropogenic activity and is measured in watts per square meter. Essentially, aviation produces a variety of emissions beyond just CO_2 that alter the chemical composition of the atmosphere and the radiative balance, thus influencing climate. For example, NO_x, H_2O, sulphate and soot particles can contribute to RF through influencing ozone formation and methane destruction (NO_x) and production of contrails leading to increased cirrus cloud formation (H_2O, sulphate and soot particles) (ICAO, 2010).

Aviation can affect climate through the following processes (Heinrich Bofinger, 2013; Lopes, 2010):

1. Emissions of CO_2 resulting in positive RF.

2. NO_x emissions creating tropospheric O_3 through atmospheric chemistry. Increased UV radiation at high altitude facilitates more effective ozone formation and increases RF. This can also lead to indirect destruction of methane through ozone formation. This is done when the creation of ozone results in hydroxyl radicals (-OH) that break down CH_4 into CO_2 and water, which are less potent GHGs and therefore produces a small negative RF (Stockholm Environment Institute, 2011). In the lower stratosphere NO_x emissions destroy ozone.
3. Emissions of H_2O, increasing RF.
4. Formation of contrails that may contribute to cirrus cloud formation and increase RF, depending on weather.
5. Sulphate particle emissions as a result of sulphur content in fuels. Sulphate aerosols can scatter a fraction of solar radiation back into space creating a negative direct RF. The potential positive RF from these same particles is deemed negligible due to the small particle size and longwave radiation (International Panel on Climate Change, 1999).
6. Soot particle emissions causing direct positive RF.
7. Aviation induced cloudiness, potentially positively influencing RF.

Other factors contributing to the dispersion and emission of pollutants are associated with the physical nature of air transport. For instance, the fuel burn ratio is related to the propulsion of the aircraft required to achieve a necessary trajectory and is dependent upon criteria such as intended destinations, aerodynamics and vehicle weight. The trajectory that aircraft take is also important to the dispersion of pollutants; aircraft deploy them both on ground and as they achieve different altitudes. More specifically, aircraft are unique in that they directly emit gases into both the upper troposphere and lower stratosphere as they reach cruising elevations. Though impacts via radiative forcing have been outlined as one of the main concerns caused by emissions at higher elevations, aircraft emit large quantities of pollutants below 3,000 feet in elevation throughout their Landing and Take-off cycle as the vehicle undergoes the pressures of gaining and losing elevation.

The LTO phase is increasingly important as it more directly impacts higher density population centers and human health and represents a significant portion of overall aircraft emissions. For example, NO_x and PM emissions have become more and more important to regulatory agencies as they directly impact human health. Global NO_x emission levels in 2006 were at .25 million metric tons (mt), and forecasted to increase to between 0.52 and 0.72 mt in 2036 (ICAO, 2010). In addition to the focus on human health impacts, emissions are frequently discussed within the context of energy efficiency improvements in traffic control; the reduction of idle times and more efficient movement of airport traffic could present large savings on a global level.

Three other interactions with the environment that are not well studied although occurring over the course of aircraft operations are emissions resulting from engine startup, auxiliary power operations and emergency fuel dumping. Emissions resulting from startup are not included in standard LTO cycle reporting and, as a result, there is little available information to assess what impacts may be directly correlated with this activity. With respect to auxiliary power units (APU) operations, no current allocation methodology is prescribed for the fuel use of these power sources. The APU is utilized when there is no other airport power source available, such as when the aircraft is not next to the terminal building. It is the position of the European Environmental Agency that these emissions should be allocated on the basis of aircraft operations e.g. number of landings and take-offs (Morten Winther, 2009, Updated 2010) however this is not standard in global aviation. Fuel dumping is only practiced when an aircraft (predominately long-range) is going to exceed its maximum landing weight and releases fuel at higher elevations (+1,000m) where no direct ground impacts will be affected. The primary concern with this activity is the potential for elevated non-methane VOCs (NMVOC) becoming significant at larger airports with frequent international flights (Morten Winther, 2009, Updated 2010).

Modeling of Aircraft Emissions

Emissions Modeling Software

To model emissions of the three different aircraft cases described in this study one of four ICAO Committee on Aviation Environmental Protection (CAEP) approved models for fuel and emissions estimates, Eurocontrol's Advanced Emissions Model (AEM), is used (Eurocontrol, 2013). Using flight profile data, this tool calculates the total emissions generated by a specific aircraft and engine type over a defined distance. It relies on several high quality underlying systems databases (aircraft, aircraft engines, fuel burn rates and emissions indices) provided by external agencies and is regarded as a top aviation emissions modeling tool.

The AEM uses these different data sets to derive a fuel burn calculation and subsequent emission calculation as can be seen in Figure 17. Emission factors and fuel flow are aligned with atmospheric conditions at altitudes through the use of a method developed by the Boeing Company and later modified by the Eurocontrol Experimental Centre Business unit Environmental Studies

(EEC-BM2). The additional work by EEC-BM2 enables emissions better estimates for NO_x, HC and CO pollutants through all phases. The remaining emissions directly correlate with other parameters. CO_2 and H_2O result from the oxidation process of the carbon and hydrogen contained in the fuel with atmospheric oxygen. Benzene, VOC, TOG and related pollutants are generated from the HC emissions, while SO_x emissions are proportional to the sulfur content of the fuel used (Eurcontrol, 2012). Using HC emissions, AEM generates a larger emission profile by using a set of calculations to derive a range of VOCs and TOGs. In all, twenty-two different types of emissions are reported in AEM's output, which have been integrated into the results reported in this study.

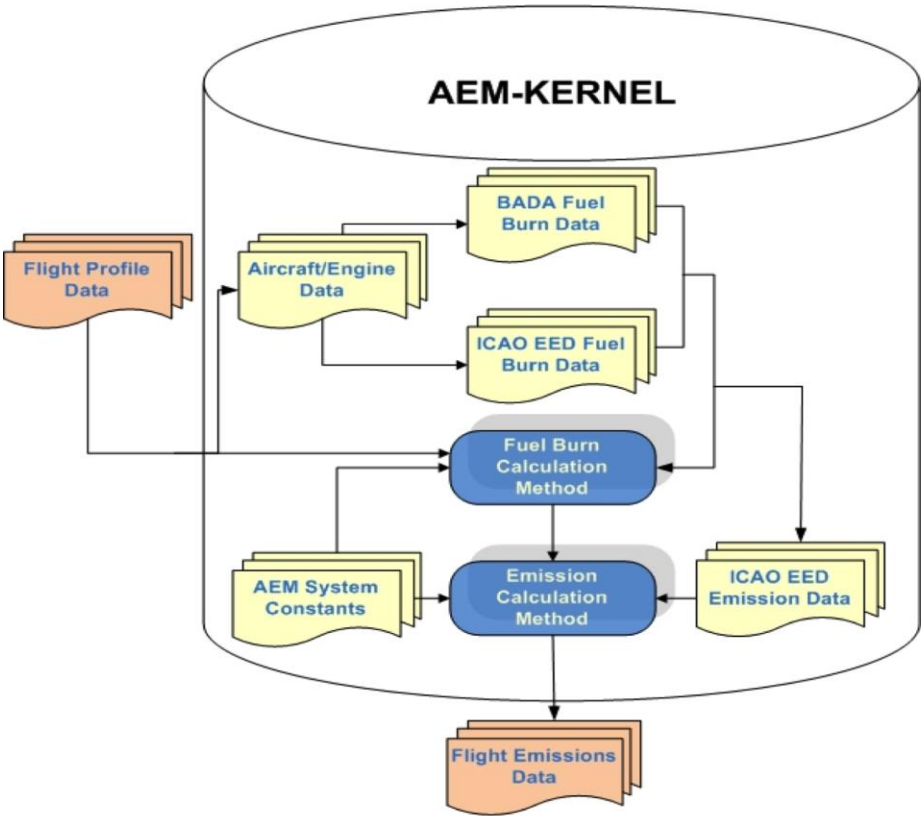


Figure 15 AEM Model Process Diagram

The minimum flight profile data required consists of geographic coordinates, flight times, elevation profiles and aircraft information to calculate emissions over a complete flight trajectory. , The default ICAO LTO times and AEM model data assumptions were adopted to maintain consistency in the analysis between different cases and aircraft in this study. In addition, default engines in the AEM model for each aircraft were used and are listed below.

Table 5: Aircraft Engine Models

Aircraft	**A320 (X2)**	**A330 (X2)**	**A380 (X4)**
Engine Model	IAE V2500-A5	GE CF6-80E1A2	RR Trent 970-84

Scenario Development

The principal task of the operations phase in this study was to capture the total environmental impacts from the operations of all three aircraft over different selected flight scenarios. Having established the software to model direct environmental emissions, the actual geographic assumptions and finer details of the flight paths needed to be determined. As the AEM model enabled the selection of most commercial airports and aircraft as inputs, the decision regarding which airports and what distances to use for each scenario became more dependent on modeling routes that served as good proxies for common distances traveled and high volume airports in today's aviation market. This both improves the utility of the data for future studies as well as provides a better context for analysis and comparative efforts in this work.

As the world's largest airport for long haul international traffic (Airbus, 2012) London's Heathrow Airport (LHR) was chosen as the base departure point for all three flights . LHR serves as a good data point for the A330 and A380, both of which are designed for mid to long range travel. Once this was established, the destination airports were selected based upon proximity to LHR. Aviation data that correlates with distances traveled is frequently reported in round nautical miles at intervals of 500. In trying to align as closely as possible with this (for comparative efforts) and find high traffic routes that better represented common PAX travel, Milan's Malpensa, New York's JFK and Tokyo's Narita airports were chosen. Table 6 provides additional scenario detail.

Table 6: Scenario Flight Detail

Scenarios	Aircraft	Distance from LHR (NM)	Distance from LHR (km)	Assumed Avg. Cruise Elevation (feet)
Scenario 1: Milan Malpensa, MXP	A320	504	935	30,000
Scenario 2: New York, JFK	A330	2,991	5,538	37,000
Scenario 3: Tokyo Narita, NRT	A380	5,178	9,582	35,000

The assignment of aircraft type with final destination was done to best replicate typical flight scenarios considering the aircraft design from both a physical and economic standpoint. Further research also confirmed actual flights by these types of aircraft on these particular routes in the current aviation market. It should be noted that although scenario 1 is short considering the 6,100 km max range of the A320, this type of aircraft is commonly flown on analogous routes. Although elevations throughout the cruise phase may vary over the course of a flight, this analysis assumes a consistent elevation for this phase and adopts AEM model constants for the remaining LTO phases. The values used were obtained by researching common flight altitudes for commercial aircraft and where checked against maximum cruising elevations provided by airline operators (Berlin, 2013). As this value is largely dependent on variables such as weather, operating weight and fuel economy targets, ensuring it was under the maximum cruising altitude for the aircraft specifications was the most prudent quality measure. In addition, all model output for each of the phases was quality checked with reported commercial flight times by reverse calculating the reported fuel flow per second for each phase and comparing the total flight durations.

Despite the primary role of transporting passengers, commercial flights also transport mail and freight in many cases. Data on the weight ratios attributed to passenger, freight and mail by aircraft size and regional routes were tracked through ICAO and have been averaged for 2010 air traffic (ICAO, 2012). As this metric has significant influence on environmental attributions to passengers, it is critical to use the best available information available. Given ICAO's scientific credibility and the assumption that this data provided the best available load factor data, it was adopted in this study's model. Final weight attributions are later incorporated into the passenger values from the operational, manufacturing and fuel production impacts of this life cycle assessment. As can be seen from the table below, the outcome of this analysis shows a decreasing weight attribution to passengers as the size of the aircraft increases.

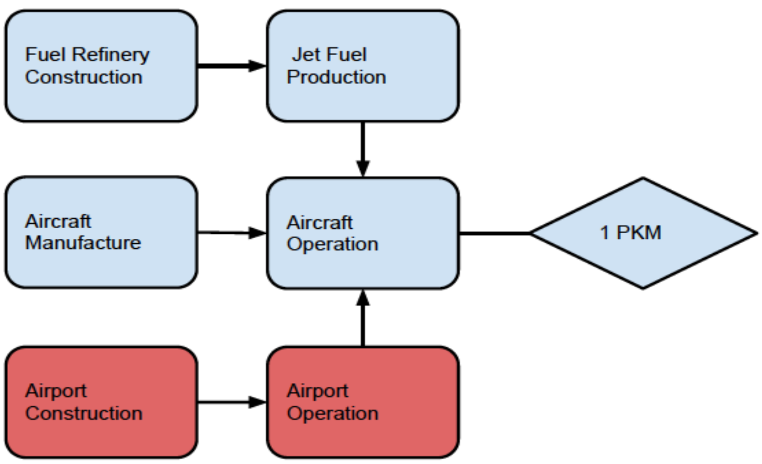
Table 7: Scenario PAX and Freight Allocations

Aircraft	Route Grouping	Weight to PAX	PAX to Freight Ratio
A320	Local Europe | Narrow-body	73.96%	99%
A330	North Atlantic | Wide-body	82.89%	81.32%
A380	Between EUR/Mid East/AFR and Asia | Wide-body	75.91%	76.95%

After the emissions calculations were completed and data was collated for the three flight scenarios, the direct environmental inventory had essentially been created for this phase. In order to characterize the results into ReCiPe midpoint indicators, Arda software was used and total impacts were derived. The use of Arda software for inventory characterization and the careful alignment of AEM output with the stressor database allowed for the selection of some pollutants by geographic proximity; for example, carbon dioxide emissions to the lower stratosphere and upper troposphere could be modeled for the aircraft cruise phase. These were also differentiated using the LTO cycle output and the relative Ecoinvent data for emissions. This process facilitated better overall data presentation and collation as ReCiPe indicators are both reviewed and commonly adopted throughout literature.

Infrastructure: Construction, Operation & End-of-Life

Infrastructure is synonymous with passenger transport in modern economies as most available forms of mechanized transport depend on it for efficient operation. In the case of air transport, a commercial passenger system is simply infeasible without adequate infrastructure to support the requirements of passenger jets and air traffic loads. Despite this, many managers and government officials base transport policy decisions on environmental data derived only from the tailpipe. In order to properly address transportation related energy and emissions issues while also properly attributing impacts, a life cycle approach incorporating infrastructure requirements is essential (Chester, 2008; Lopes, 2010; Mikhail Chester, 2009).



In this study, the infrastructure phase includes both the construction of the airport and the necessary elements to operate it. To model all of the different infrastructure elements of this transport system within the same geographic region was not optimal, particularly while maintaining the objective of using the most accurate data available at the time of writing.

As a result, this study uses infrastructure data from different locations in Europe and the U.S. because the available information was determined to be of better quality. The assumption is that the construction of a new airport at a given capacity is going to have design and construction criteria that must meet the physical and safety requirements of the commercial transport system regardless of its location. The same construction and design criteria for a modern-day airport at a certain capacity level can then be assumed to have a proportional amount of expenditure to meet these requirements. The total expenditure would likely vary depending upon factors such as the region in which the airport was constructed in and material prices. However this variability is determined to be within an acceptable range given that no two airports will ever be constructed at the exact same price when considering the overall complexity, general design differences, price escalation and other regional economic factors. This approach also enabled the use of the U.S. input-output data tables, which gave much better resolution at 500 reported sectors than many other economies. Essentially, the incorporation of infrastructure data into this study is based upon the view that similar inputs and technology will be used across various geographic regions thus permitting the use of data from geographically diverse system elements.

Airport Construction

Airport construction is characteristically a large infrastructure advancement for any urban center or regional district. The planning, material and general resource requirements are obviously substantial. Airports not only provide a mechanism for transport for many regions but also fill an important role in an area's economy; the movement of goods and people facilitates higher economic productivity. Although airports are well understood from the financial and operational perspectives, focused environmental studies have not been well developed (Mikhail Chester, 2008).

Chester 2008's work represents one of the better-documented assessments of airport construction from an environmental impact perspective. Through the use of EIOLCA and a proprietary tool for pavement emissions, he calculates the impacts of Dulles Airport in Washington D.C. This study adopts a similar approach using EIOLCA although the pavement tool is not utilized. To obtain a data point for the construction price of an airport, Berlin's Brandenburg Airport (BER) was selected as it has recently been constructed for a maximum annual passenger capacity of 27 million, and is projected to handle the majority of Berlin's international traffic. BER is being constructed to replace Berlin's two current airports Tegel and Schönefeld, which currently serve approximately 25 million passengers per year (Brandenburg, 2013).

As a result of its relatively recent construction (still underway at time of writing), a price for a complete modern airport with full functionality could be obtained. The construction cost for this airport was estimated at 2.5B

Euros (Centre for Aviation, 2013a). This was subsequently scaled back to 2002 USD using historical average inflationary and exchange rates. Although the price of the airport is projected to double as a result of major construction delays and technical issues, the original estimate for construction will be used in this study. Investigating the direct causes of the price increases is beyond the scope of this work. Instead, this study assumes the original construction estimate would have monetarily met the requirements of the planned infrastructure.

The overall approach to incorporating infrastructure elements from the construction phase are considered conservative in this study. In addition to using a conservative construction estimate, the value of the airport is assigned to the "Nonresidential Commercial and Health Care Structures" sector to calculate the impacts using Simapro. Although this represented the best possible option with a wide range of construction classifications included within it, there are several weaknesses that should be noted. Particularly, airports may be considered to be more technologically sophisticated than most buildings and infrastructure (e.g. control towers, runway lighting, building security etc.) and they incorporate an immense amount of paved surfaces in the form of runways, apron areas and parking structures. Despite this, the Nonresidential Commercial and Health Care Structures sector covers such a wide array of construction types that the stated shortcomings will, in all likelihood, bear minimal influence on final numbers. This sector has also been used in other studies that have selected EIOLCA as the assessment tool for airport construction (Chester, 2008; Cristiano Facanha, 2006; Mikhail Chester, 2009).

Airport Operation

Airport operations represent a significant contribution component to overall infrastructure impacts. Similar to the operation phase of an aircraft, this element in the life cycle represents the use phase of infrastructure and therefore amasses a significant environmental profile over the assets total lifetime. It is estimated that up one third of global GHGs are directly attributable to buildings predominately due to their fossil fuel requirement throughout the use phase (United Nations Environment Programme, 2009). Modern day airports range in size and function however many that serve larger portions of global traffic are comprised of numerous buildings and facilities, requiring vast amounts of resources and energy. It is with this in mind that the operation of airport infrastructure should be considered a valuable part of the total environmental profile for air transport systems.

The selection of airport operation data required additional analysis to determine the best data to use given the use of EIOLCA and the U.S. input-output data. It can be argued that operations are more dependent on geographic parameters then a single construction event as key inputs such as energy expenditure and employee wages can vary greatly from region to region, particularly over the duration of an assets lifetime. The principal concern was that European operational data, which was preferable initially due to the level of detail, may be significantly higher due to factors such as energy and labor economics. This could inadvertently generate higher emissions readings using EIOLCA and U.S. data then what were actually occurring. As such, a basic analysis of different U.S. and European airports was performed. This was achieved through examining a ratio of total operations expenditure (OPEX), less depreciation and amortization, to total PAX for several U.S. and European airports[11]. By using this ratio, the airports could be compared on the basis of their spending relative to capacity, which would help point out any large differences.

Table 8: Airport Expenditure and Capacity Comparison

Airport:	**Denver International Airport (2011)**	**San Francisco International Airport (2012)**	**Detroit Metro Wayne Cty. Airport (2012)**	**London Gatwick Airport (2011)**	**Zurich Airport (2012)**	**Munich Airport (2011)**
Annual Capacity (Million)	52.8	44.4	32.2	31.6	28.4	37.8
OPEX/ PAX	$7.43	$8.31	$5.80	$14.52	$22.67	$27.21

The outcome of this analysis suggested that the European OPEX/PAX ratio resulted in much higher expenditures than U.S. airports. As the underlying economic and systemic details explaining this are out of the scope of this thesis, it can be assumed that some of this difference may be explained by different policies towards energy subsidies and labor practices.

[11] All financial figures are extracted from Airport Annual Reports. Avg. annual currency conversion done via Oanda.com

Although the U.S. airport operational data was not as detailed as some European options, San Francisco International Airport provided an acceptable level of clarity to work with. The approach in using this for EIOLCA was to extrapolate the reported operating expenses and assign them to the best corresponding U.S. sector to build a more accurate account of emissions generated by the annual operation requirements of airports. This approach seemed prudent and has been utilized in other air transport studies (Cristiano Facanha, 2006). Enough detail was provided to allocate $288 MUSD in operating expenditures amongst seven different sectors. Figure 16 provides detail on the breakdown of services required to operate an airport at a capacity of 44.4M passengers in the U.S.

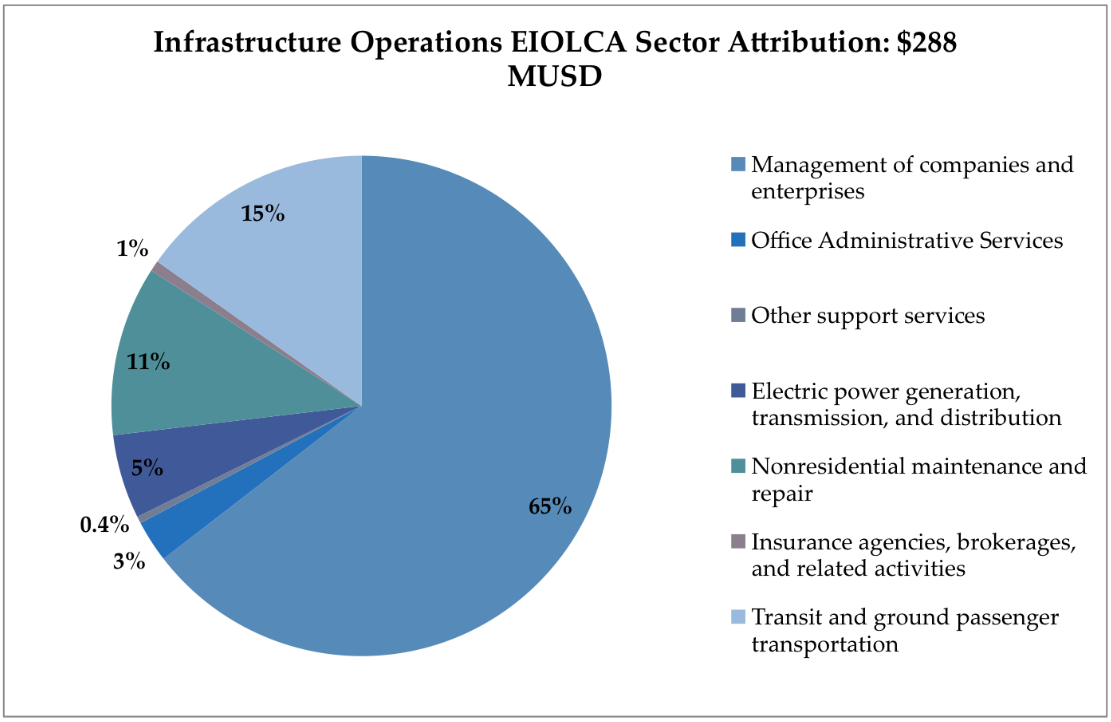
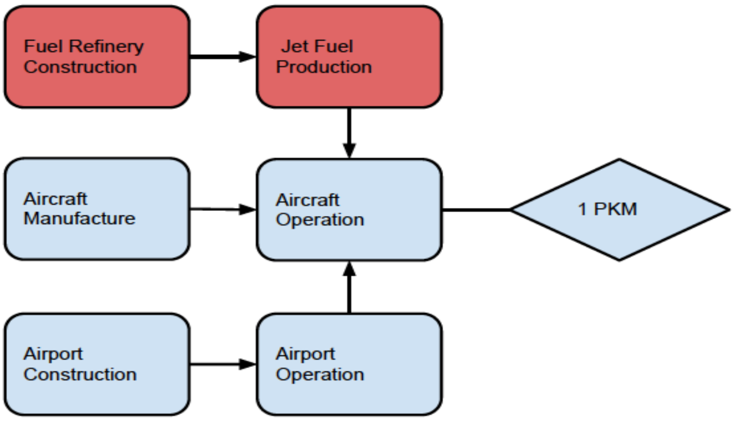


Figure 16 EIOLCA Sector Attribution, Infrastructure Operations

Management of companies and enterprises holds the primary share of expenditure, this is due to staff wages and management comprising approximately 65% of the OPEX for the airport (Airport Commission, 2012). Other important aspects of operation included the ground transportation services, airport maintenance and energy requirement of the airport. Using Simapro software, an environmental inventory was created and results were characterized into ReCiPe midpoint indicators.

Fuel Production



Fuel production inputs are key in any process or system that makes use of fossil fuel products as their extraction and production is resource and energy intensive. Previous studies have shown that fuel production can represent up to 8% of total energy consumption for all aircraft and with respect to GHGs, approximately 10% of life cycle totals are attributable to this element (Chester, 2008). This being the case, the importance of including impacts from this phase was high given the large jet fuel requirement of aircraft operations.

The fuel production phase includes those impacts that are derived from all flows of materials and energy required for the throughput of a given amount of kerosene at a refinery (Ecoinvent, 2012). The assumption of one hundred miles of freight transport by truck are included to account for the impacts of delivering fuel to the airport (Chester, 2008). This study utilizes process LCA for the impact analysis of this portion of the life cycle using the processes published in the Ecoinvent dataset. The Ecoinvent process "kerosene, at refinery" is adopted as the closest representative fuel for jet fuel. It can be assumed that the production processes used to make jet fuel and other fossil fuel products at refineries are fairly similar (Chester, 2008). The kerosene process used includes waste water treatment, process emissions and direct discharges to rivers in production while allocating the impacts of total production amongst the various co-products created from refinery operations (Ecoinvent, 2012).

In calculating the total impacts from this portion of the life cycle assessment, the total fuel use from each of the flight scenarios in this thesis are used as the direct requirement from fuel production facilities. Using Arda software, the total environmental inventory is calculated and afterward characterized into ReCiPe midpoint indicators.

Functional Units

Once the total impacts had been calculated for each phase of the life cycle assessment, a model to normalize these results into a functional unit was developed. This was accomplished through researching key parameter data and applying a set of equations to allocate impacts. Results were normalized into three different functional units for several reasons. Foremost, it provides additional information that may contribute to developing new research or work on the subject. Secondly, normalizing in this way overcomes some of the bias that can occur when only one metric is reported. For instance, reporting passenger car emissions for each kilometer that the vehicle travels versus those attributed to the one to five passengers riding represent different values but provide unique and important information. These three functional units (PKM, VKM and LKM) have been used in other transportation studies (Chester, 2008), although many opt to report on PKM only as it is commonly adopted in many transport studies.

Results

The results section in this thesis will convey overall findings in two sections; Total Life Cycle Impacts of Selected Scenarios and Life Cycle Stages Results and Analysis. The former will cover the complete impacts over all life cycle stages using the three functional units discussed in the next section. Primary emphasis will be on conveying total climate change impacts. The second section will take a more detailed approach in dissecting the individual life cycle phases and discussing both the climate change contributions therein and additional selected environmental impacts. In an effort to present results in a consistent manner and due to the large amount of information produced in this study, results will often focus on those for the A320 scenario under PKM normalization where appropriate. It is also worth noting that the use of the aircraft name, for example "A320" and the scenario ("Scenario 1") will be used interchangeably at times.

Total Life Cycle Impacts of Selected Scenarios

Overview

Results will be primarily presented in total impacts using absolute values and through contribution analysis. Contribution analysis is used to disaggregate the process or phase contributions to a particular environmental stressor. All results have been presented using the ReCiPe midpoint indicators (H) which use a widely accepted method to aggregate total inventories into eighteen different reportable factors (Mark Goedkoop, 2009). Results for climate change for all three functional units and scenarios will be presented graphically. The absolute values for VKM and LKM for each life cycle phase are provided in table format for comparative and reference purposes. The entire impact assessment inventory for all three normalizations and scenarios can be accessed in Appendix 1 for reference. The contribution analysis shares allocated to each life cycle phase (given by PKM) are presented in Table 9 for all normalization factors. Therefore the total inventory results for VKM and LKM can be used in conjunction with the contribution shares provided in the table to obtain additional results by VKM and LKM if desired.

Total Climate Change Impacts, All Scenarios

To provide context and scale for all three scenarios, Figures 17-19 are presented. They illustrate the life cycle results of total climate change impacts derived per PKM, VKM and LKM for each of the selected aircraft and scenarios. Impacts that contribute to climate change are the predominate focus of this thesis, as such these charts provide the main findings.

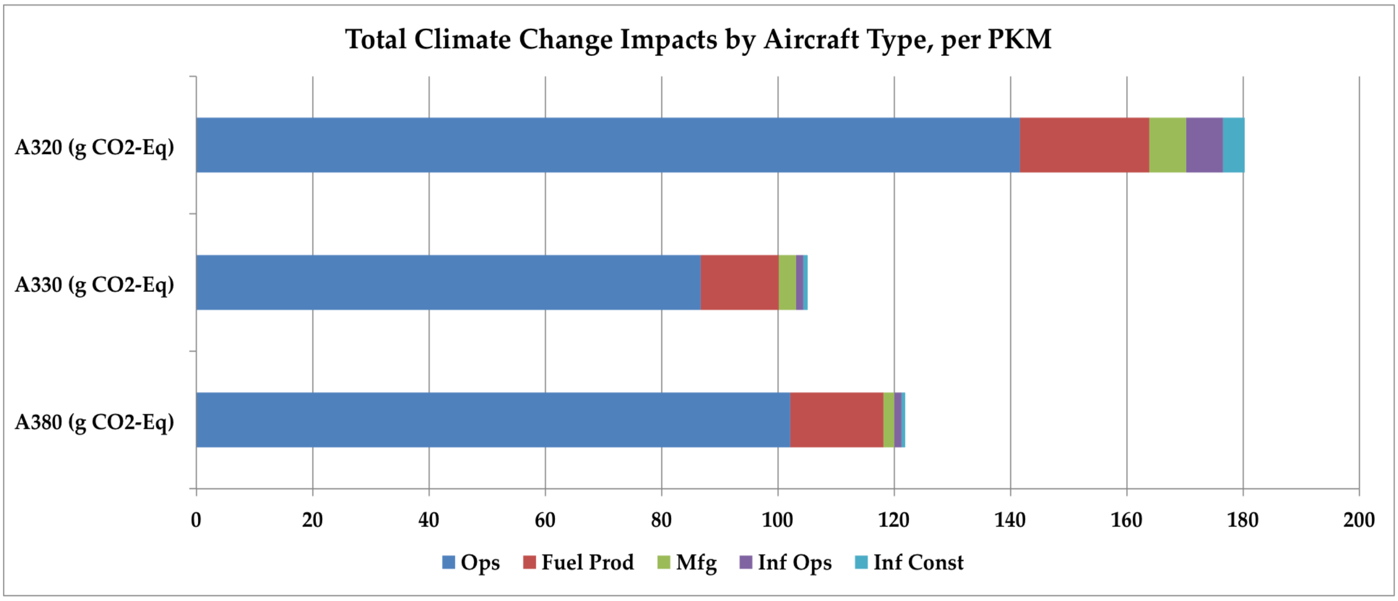


Figure 17 Total Climate Change Impacts, PKM

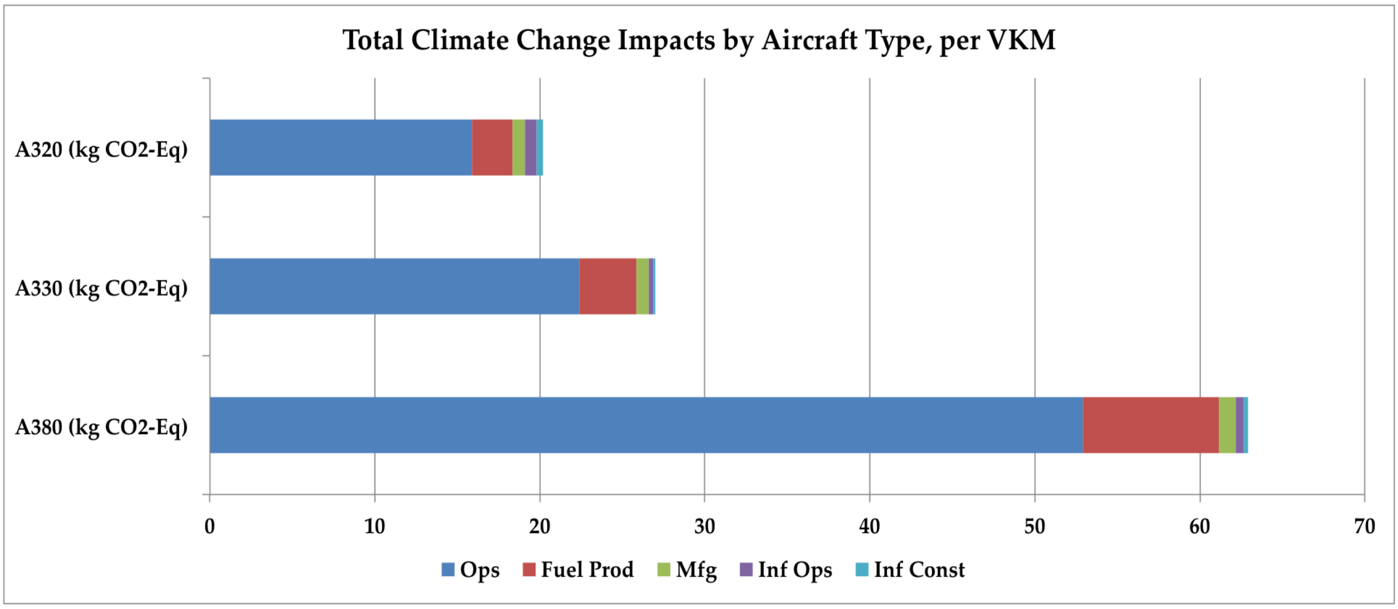


Figure 18 Total Climate Change Impacts, VKM

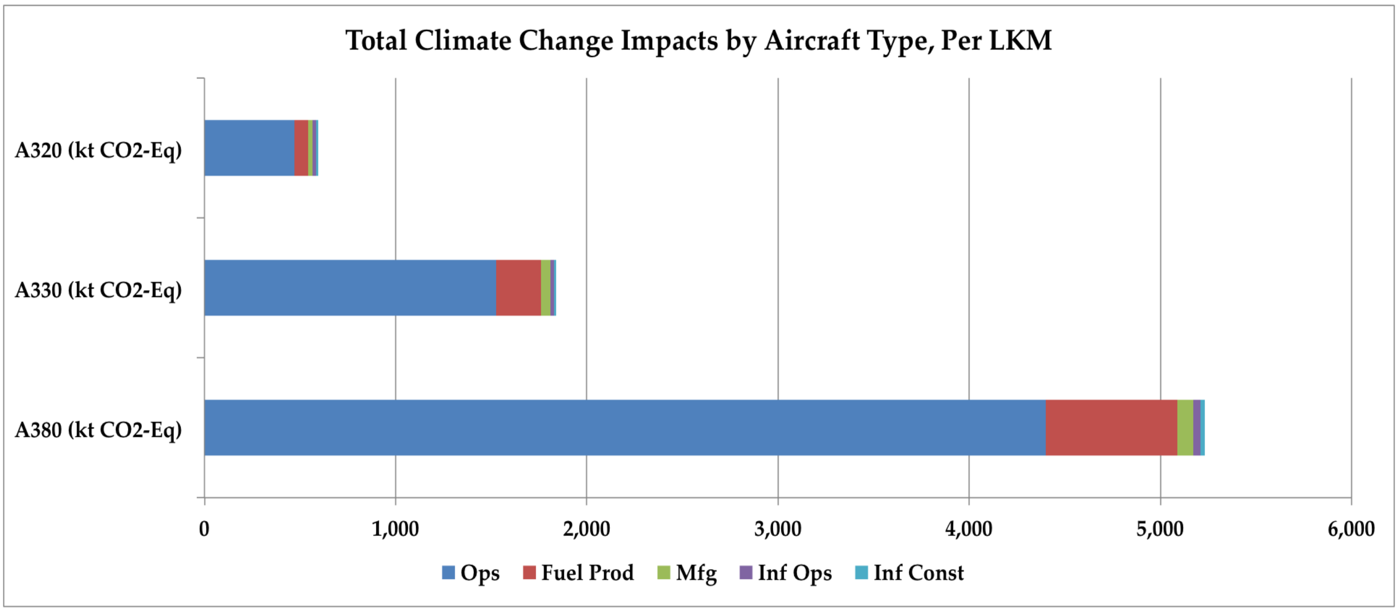


Figure 19 Total Climate Change Impacts, LKM

The results of these graphs indicate both the commonalities and vast differences of analyzing the same LCA output under different normalization factors for transport. The three functional units provide three different viewpoints from which one can analyze transport impacts. It may be challenging to see the distinction between an A380 generating approximately 122 g CO_2-eq on a PKM basis and 5,233 kt CO_2-eq on a LKM basis; however, the difference in these results conveys the unique perspectives and information differences achieved with each functional unit. The charts also indicate that life cycle impacts outside of tailpipe emissions[12] are relevant from a climate change perspective and should be incorporated into total GHG calculations for air transport. Exhibiting anywhere from approximately 16% at the lowest to 21% at the highest, shares of these emissions over all normalized factors and aircraft demonstrate that life cycle impacts are significant in air transport scenarios. These results are also consistent with similar findings in other air transport works (Chester, 2008; Mikhail Chester, 2009).

A key observation to take away from these charts is the fact that each aircraft's relative shares of impacts per life cycle phase do not change much across normalization factors. Rather, the different normalization factors demonstrate the variation in impact results that are achieved when a vehicle

[12] "Tailpipe Emissions" will be used intermittently throughout this section to refer to those emissions coming strictly from the propulsion of the aircraft during operation.

is analyzed from different viewpoints. The same relative contributions from each life cycle phase to total impacts only vary slightly when normalized by PKM (see Table 9). This is largely due to the use of a passenger versus freight weight attribution factor in the normalization formulas. For example, when calculating the impacts using a PKM functional unit for aircraft operations, the share of impacts allocated to passengers versus freight matters. When doing this per vehicle kilometer traveled distinguishing by PAX or cargo is irrelevant as the vehicle travel is independent of these factors. Lastly, the charts provide a wide range of information about both the aircraft vehicle and normalization perspective, which will be discussed in greater detail below.

Table 9: Life Cycle Shares of Total GHG Emissions

		Mfg	Ops	Inf Const	Inf Ops	Fuel Prod
A320	**PKM**	3.52%	78.63%	2.07%	3.50%	12.29%
	VKM	3.52%	78.67%	2.05%	3.47%	12.30%
	LKM	3.52%	78.67%	2.05%	3.47%	12.30%
A330	**PKM**	2.75%	82.60%	0.71%	1.20%	12.74%
	VKM	2.76%	82.90%	0.58%	0.98%	12.79%
	LKM	2.76%	82.90%	0.58%	0.98%	12.79%
A380	**PKM**	1.58%	83.79%	0.57%	0.97%	13.10%
	VKM	1.58%	84.09%	0.44%	0.75%	13.14%
	LKM	1.58%	84.09%	0.44%	0.75%	13.14%

Total Climate Change Impacts per PKM

Examining the scenarios by PKM provides a comparative metric for the transport options selected that can be assessed against other transport modes. As was mentioned previously, PKM results are reported in many different transport studies.

Notably in Figure 17, the A320's total is the highest followed by the A380 then A330. Non-tailpipe emissions hold approximately 21%, 17% and 16% shares of the life cycle emissions, respectively. The scenarios analyzed convey that on a PKM basis, a passenger flying under similar circumstances will generate 180 g-CO_2–eq while flying aboard an A320, 105g on the A330 and 122g on the A380. For each of the selected scenarios, the total attribution of GHGs per individual passenger can be seen in the Table 10 below (tailpipe emissions only in parenthesis).

Table 10: Total Flight GHG/PAX

Scenario:	kg CO_2-eq
Scenario 1: LHR to MPX	169 (132)
Scenario 2: LHR to JFK	582 (481)
Scenario 3: LHR to NRT	1,168 (979)

To better understand the impact per PKM of each scenario with respect to GHGs, the fuel burn per kilometer and passenger was compared between all three. This was done as the fuel burn and CO_2 emissions produced have a linear relationship of 1 to 3.16, fuel burn to CO_2. The findings showed that both the A320 and the A380 burn close to the same amount of fuel per passenger kilometer using the study scenario distances (See Figure 20). The basic implications of this are that the respective scenarios are equally as energy intensive over their operating cycle when compared by

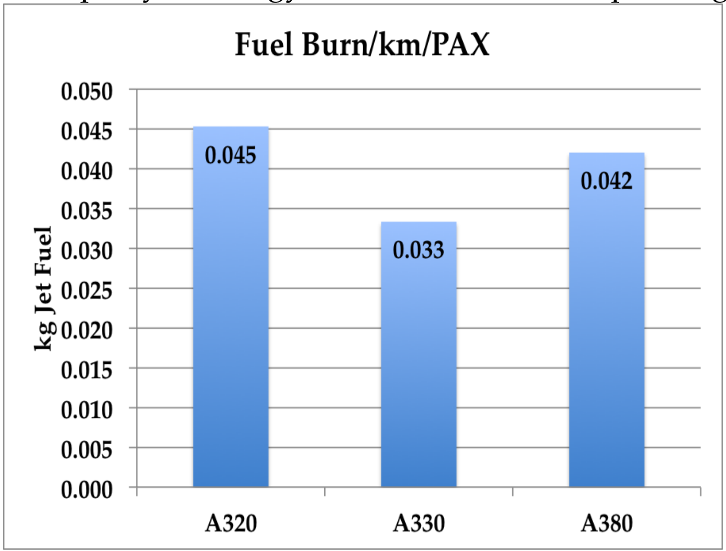


Figure 20 Fuel Burn/km/PAX Comparison

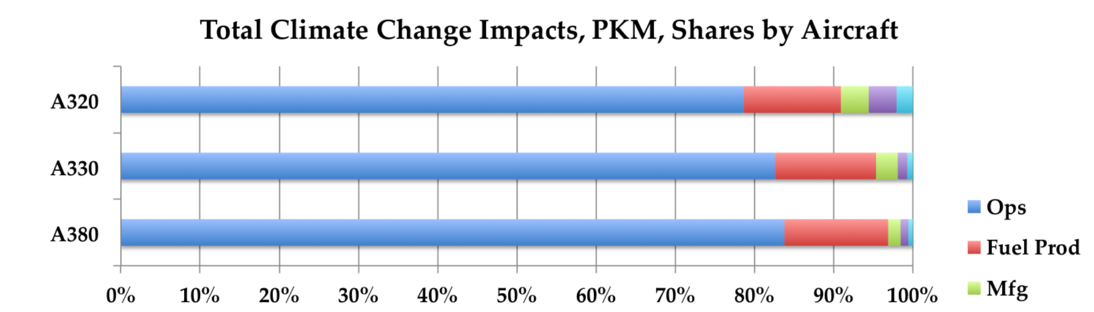
their passenger load and unit of distance flown. This is interesting as it implies that under the assumed model conditions, and PKM normalization, the London to Milan flight on an A320 is more detrimental from a climate change and energy use perspective for the per unit transport economy it provides than one that is just over ten times the distance aboard an A380.

Outside the more intricate inputs to the AEM model and its calculation approach[13], two inputs in the normalization equation also influence the differences observed between the total climate impacts: the load factors assumed in calculating the average passenger load per flight and the weight attributions applied to assign passenger versus freight and mail allocations.

[13] Examples of this could be assumed elevation, trajectory/route assumption by AEM etc.

As the load factor differential between the A320 and A380 is only three percent, the weight attributions are part of the explanation of this difference with a delta of approximately 22% extending throughout several phases of the life cycle impacts. When the same freight weight attribution that is used for the A320 is applied to the A380, the grams of GHG equivalents for the A380 increases 22% to 148g for the life cycle total.

The last element to highlight with regard to the climate impact differences between scenarios is that the A320 is also influenced more by life cycle phases other than operation. Figure 21 illustrates the percent of impact allocated to each life cycle phase. The graphic shows that the manufacturing (Mfg), infrastructure operation (Inf Ops) and infrastructure construction (Inf Const) phases contribute to a higher share of climate impacts than the other scenarios with 3.5%, 3.5% and 2.1% respectively. This is most likely due to the assumption that this aircraft will be used for shorter flights over its lifetime and thus has higher associated impact attributions on a kilometer basis. The emission intensity on a PKM basis for this scenario is higher as the LTO contribution and smaller relative cruise impacts has a greater influence on the total trip at this distance and passenger capacity. As distance increases, the intensity per PKM will go down as the overall emissions value for the flight goes up. Given the larger average distances flown by the A330 and A380, impacts per unit of travel are tempered.



	A380	A330	A320
Ops	83.79%	82.60%	78.63%
Fuel Prod	13.10%	12.74%	12.29%
Mfg	1.58%	2.75%	3.52%
Inf Ops	0.97%	1.20%	3.50%
Inf Const	0.57%	0.71%	2.07%

Figure 21 Climate Change Impact, PKM Shares by Aircraft

The overarching conclusion as to the differences observed between the aircraft PKM impacts is that the combination of passenger capacity, distance traveled, ability to transport shares of non-passenger goods and energy efficiency per VKM strongly influence the life cycle climate impacts observed per PKM. The passenger capacity is relevant throughout the life cycle as it influences the distribution of impacts. The weight attribution between passengers and freight also has a similar effect. The distance flown by the vehicle is critical to the intensity derived per unit of travel as the addition of kilometers in the cruise phase tempers the LTO contributions. Finally, the energy intensity per VKM is reliant on many technological factors such as aircraft material composition and thrust requirements that dictate final emissions output per PKM. The large gap between the A330 and A380 per VKM intensity highlights the energy efficiency relevance between different technologies.

Total Climate Change Impacts per VKM

The information presented in the preceding section provides a good platform from which total climate impacts from a VKM viewpoint can be discussed. The passenger capacity and freight attribution elements played a critical role in assigning impacts per unit of distance traveled on a PKM basis, but they do not in the operation phase per VKM. Impacts by VKM are useful for assessing the value of a particular trip and vehicle. As can be seen in Figure 18, the VKM life cycle impacts for the three scenarios are 20, 27 and 63 kg CO_2-eq for the A320, A330 and A380 respectively. Table 11 outlines the full emissions value for each scenario with the tailpipe contributions in parenthesis.

Table 11: Total GHGs/Flight

Scenario:	t CO_2-eq
Scenario 1: LHR to MPX	18.9 (14.8)
Scenario 2: LHR to JFK	149.5 (124)
Scenario 3: LHR to NRT	602.9 (507)

Contrary to PKM normalization, the A320 now has the lowest emissions level per kilometer. This type of normalization can prove beneficial to those concerned with emissions levels within specific regions or for those comparing competing technologies. For instance, managers of airports in urban environments would have interest in understanding the impacts produced by vehicle traffic for facilitating control measures and meeting environmental standards. VKM emissions could also aid municipalities or regions that may be more inclined to understand air traffic pollutants from a vehicle-based metric.

Perhaps one of the more notable aspects of Figure 18 is the relatively close total emissions per VKM from the A320 and A330. These two aircraft are quite different in both capacity and range characteristics (ref. Case Description section), but the emissions gap between them is not proportional to the PAX capacity and range differences. Upon analyzing the fuel burn per kilometer of each aircraft over the operations phase, it became clear that the A330 and A320 are simply much more efficient consumers of energy than the A380. In addition, considering that the VKM normalization calculation for the operations phase is the total process LCA impacts divided by the kilometers traveled in the case flight, the A330 scenario is a more efficient flight per kilometer given its size, passenger capacity and distance traveled. This can be seen in the AEM model output for fuel burn where the A320, A330 and A380 achieved 5.0, 6.9 and 16.7 kg/km averaged over the study scenarios. It should be emphasized that this analysis is relative to the scenario travel and use assumptions as all the aircraft have wide range capabilities. For example, the A320's use on flights near its 6,100 km range as opposed to 935 km would reduce the VKM output while increasing net emissions.

Total Climate Change Impacts per LKM

The LKM results obtained, shown in Figure 19, convey the expected results: the highest impacts are associated with the long-haul superjumbo jet. The gap between this aircraft and the others in the study is quite substantial given the lifetime normalization. The A320 and A330 generate approximately 11% and 35% of the LKM impacts of the A380.

This is due to the proportional difference in distances traveled by each aircraft in the scenario and the associated fuel consumption over the vehicle lifetime. Essentially, an A380 aircraft designed to fly long routes with many passengers, is going to travel many more kilometers than a shorter haul aircraft under a fixed twenty-year lifetime assumption. In addition, utilization rates for long haul aircraft are greater on average (ICAO, 2012), with less LTO cycles facilitating greater accumulation of lifetime kilometers. It should be noted, however, that the scenarios were chosen to model actual aviation market routes serviced by the corresponding Airbus aircraft in the study.

Table 12 Total GHGs/Vehicle Lifetime

Scenario:	**kt CO_2-eq**
Scenario 1: LHR to MPX	596.3 (469)
Scenario 2: LHR to JFK	1,839.3 (1,525)
Scenario 3: LHR to NRT	5,233.1 (4,400)

One of the most compelling reasons for normalizing by LKM is to communicate the full life cycle impacts over the use phase for a particular transport vehicle over its lifetime. Table 12 shows the total LKM emissions for each aircraft under scenario conditions (tailpipe emissions in parenthesis).

This can be particularly useful for additional research and analysis that may target emission reductions on the global aviation level or for larger markets. Although some bias is associated with it, in that it masks the total number of passengers transported, it is nevertheless important to gain perspective of the net impacts of aviation despite passenger loads.

LKM measurements also provide better insight into the existing and future global fleets of aircraft. By modeling emissions on an LKM basis, one can begin to understand the projected impacts of the current 3,162 A320s, 972 A330s and 103 A380s in operation (Airbus, 2013c). According to Table 12, an A320 operating under scenario conditions will generate 596.3 kt CO_2-eq over its lifetime. Using the fleet in operation given by Airbus, this equates to 1.88 Gt CO_2-eq over the fleet's lifetime. Moreover, 21% of this is due to non-tailpipe emissions, which given the necessity of these sources (e.g. fuel production, airport, plane manufacturing) to air transport, provides a compelling case for further understanding these impacts. Overall, this finding is significant because, as mentioned previously, the A320 and its competitor, the Boeing 737, are the world's two best selling commercial aircraft and hold the largest commercial market shares. Over the next two decades, this jet class has forecasted sales of 5,000-6,900 aircrafts (Wilhelm, 2012).

From a policy and management point of view, this information highlights a sense of scale that can be communicated more readily than PKM and tailpipe only metrics convey. For other stakeholders such as airline and airport operators, the LKM metrics can be used to develop design specifications in aircraft, infrastructure and operations that yield higher lifetime emissions savings.

Contribution Analysis, All Scenarios PKM

Perhaps one of the greatest benefits of visualizing LCA results by process contribution to overall impacts lies in the ability to quickly identify the critical processes involved in environmental categories of concern. The following section presents the contribution analysis for all three scenarios for the functional unit PKM. Absolute values for each indicator category are provided both in the charts and in table form for VKM and LKM functional units to provide scale and context.

Looking at Figures 22-24 for Scenarios 1-3 below, it is immediately apparent that the operation and fuel production phases dominate most environmental categories for all scenarios. With the exception of Ozone Depletion and Metal Depletion, these two life cycle phases account for 80% or more of all remaining impact categories. Upon closer observation, these phases generate larger contributions in each impact category as the scenario flight distance and relative fuel use increases. For example, these phases account for approximately 80% of the total Particulate Matter Formation (PMF) impacts in Scenario 1, just below 90% in Scenario 2 and approximately 94% in Scenario 3. As fuel use drives the majority of environmental impacts in aviation, this trend occurs in all major impact categories. The primary finding being that the share of life cycle phases that are not directly related to aircraft fuel consumption incur contribution decreases as a flights fuel requirement goes up. This can also be seen in Table 9 above where the relative shares of GHG emissions associated with manufacturing, infrastructure operations, and construction increase as trip length decreases while operations and fuel production shares go down.

Scenario 1: 935 km, Airbus A320 Flight

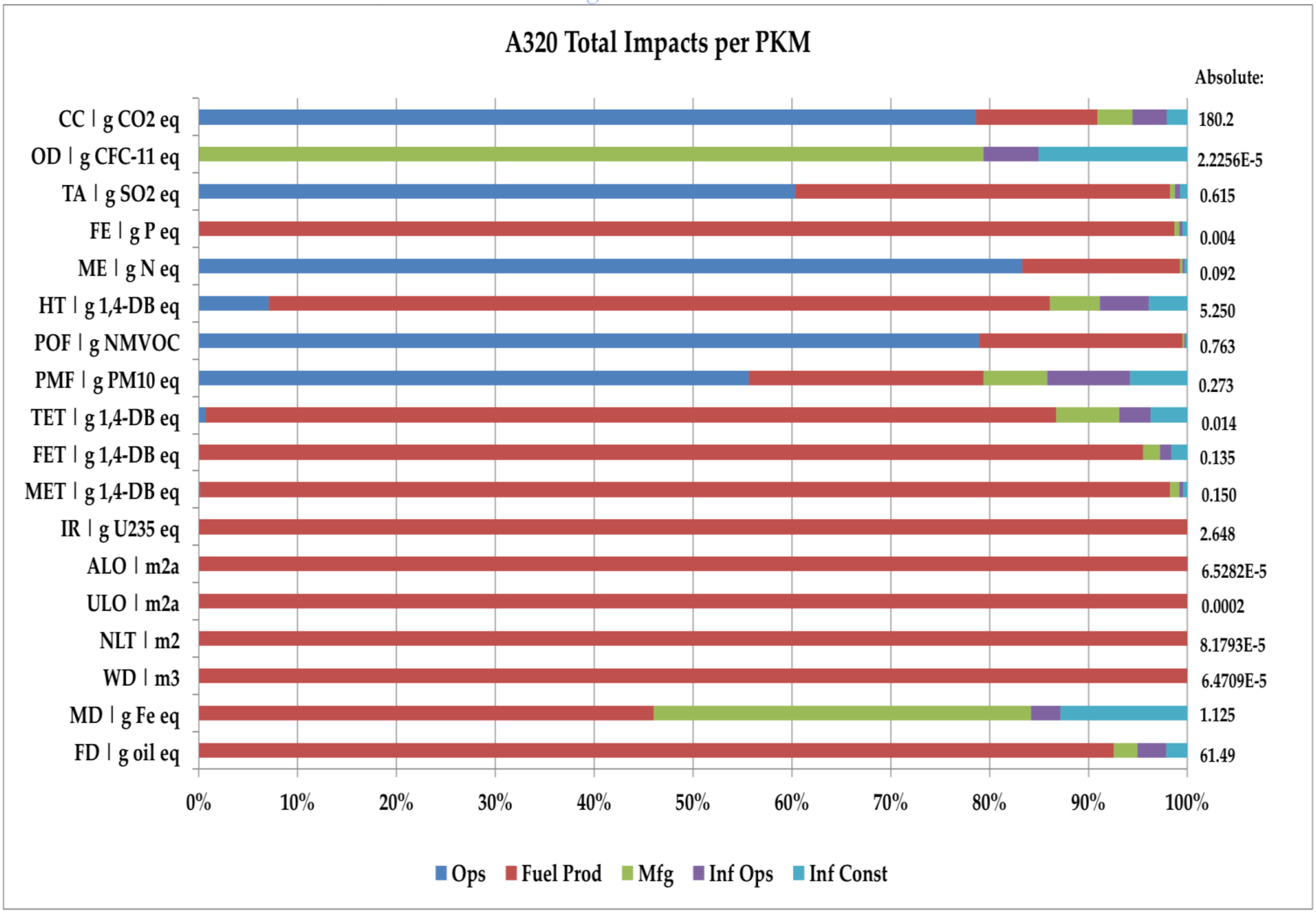


Figure 22 Scenario 1, 935 km Airbus A320 Flight, Contribution Analysis, PKM

Table 13: A320 VKM and LKM Absolute Values

Impact Category	A320 | VKM	Impact Category	A320 | LKM
CC | kg CO2 eq	20.184	CC | kt CO2 eq	596.30
OD | kg CFC-11 eq	0.000	OD | kt CFC-11 eq	0.00
TA | kg SO2 eq	0.069	TA | kt SO2 eq	2.04
FE | kg P eq	0.000	FE | kt P eq	0.01
ME | kg N eq	0.010	ME | kt N eq	0.30
HT | kg 1,4-DB eq	0.588	HT | kt 1,4-DB eq	17.36
POF | kg NMVOC	0.086	POF | kt NMVOC	2.53
PMF | kg PM10 eq	0.031	PMF | kt PM10 eq	0.90
TET | kg 1,4-DB eq	0.002	TET | kt 1,4-DB eq	0.05
FET | kg 1,4-DB eq	0.015	FET | kt 1,4-DB eq	0.45
MET | kg 1,4-DB eq	0.017	MET | kt 1,4-DB eq	0.50

IR ǀ kg U235 eq	0.297	**IR ǀ kt U235 eq**	8.77
ALO ǀ m2a	0.007	**ALO ǀ m2a**	216,124
ULO ǀ m2a	0.025	**ULO ǀ m2a**	727,363
NLT ǀ m2	0.009	**NLT ǀ m2**	270,786
WD ǀ m3	0.007	**WD ǀ m3**	214,228
MD ǀ kg Fe eq	0.126	**MD ǀ kt Fe eq**	3.72
FD ǀ kg oil eq	6.887	**FD ǀ kt oil eq**	203.45

Scenario 2: 5,538 km, Airbus A330 Flight

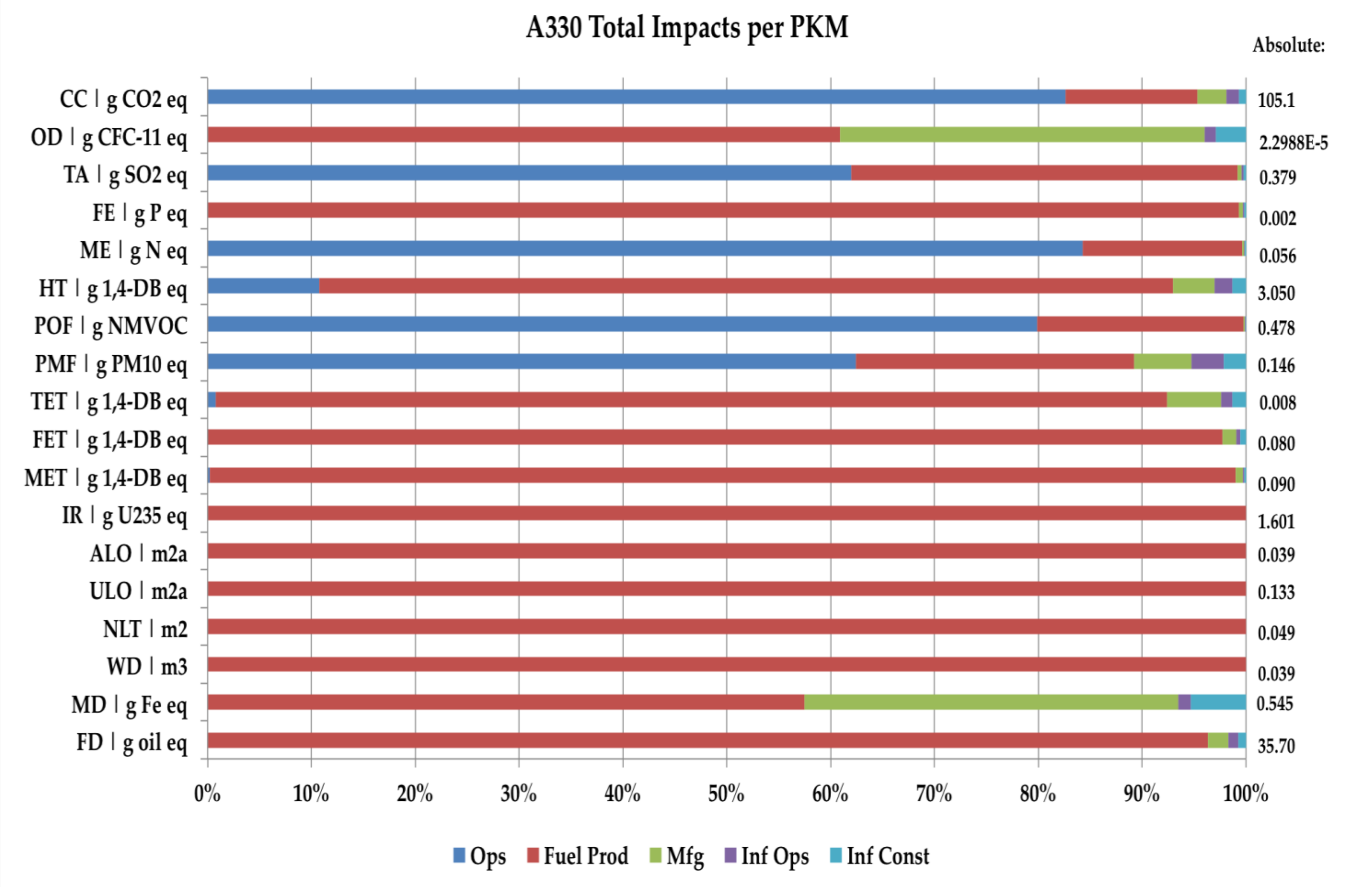


Figure 23 Scenario 2, 5538 km Airbus A330 Flight, Contribution Analysis, PKM

Table 14: A330 VKM and LKM Absolute Values

Impact Category	A330 ǀ VKM	Impact Category	A330 ǀ LKM
CC ǀ kg CO2 eq	27.002	CC ǀ kt CO2 eq	1839.31
OD ǀ kg CFC-11 eq	0.000	OD ǀ kt CFC-11 eq	0.00
TA ǀ kg SO2 eq	0.098	TA ǀ kt SO2 eq	6.65
FE ǀ kg P eq	0.001	FE ǀ kt P eq	0.04
ME ǀ kg N eq	0.015	ME ǀ kt N eq	1.01
HT ǀ kg 1,4-DB eq	0.782	HT ǀ kt 1,4-DB eq	53.28
POF ǀ kg NMVOC	0.123	POF ǀ kt NMVOC	8.39
PMF ǀ kg PM10 eq	0.037	PMF ǀ kt PM10 eq	2.54
TET ǀ kg 1,4-DB eq	0.002	TET ǀ kt 1,4-DB eq	0.14
FET ǀ kg 1,4-DB eq	0.021	FET ǀ kt 1,4-DB eq	1.40
MET ǀ kg 1,4-DB eq	0.023	MET ǀ kt 1,4-DB eq	1.58
IR ǀ kg U235 eq	0.413	IR ǀ kt U235 eq	28.12

ALO ǀ m2a	0.010	**ALO ǀ m2a**	693,221
ULO ǀ m2a	0.034	**ULO ǀ m2a**	2,332,426
NLT ǀ m2	0.013	**NLT ǀ m2**	868,617
WD ǀ m3	0.010	**WD ǀ m3**	686,702
MD ǀ kg Fe eq	0.139	**MD ǀ kt Fe eq**	9.45
FD ǀ kg oil eq	9.176	**FD ǀ kt oil eq**	625.01

Scenario 3: 9,582 km, Airbus A380 Flight

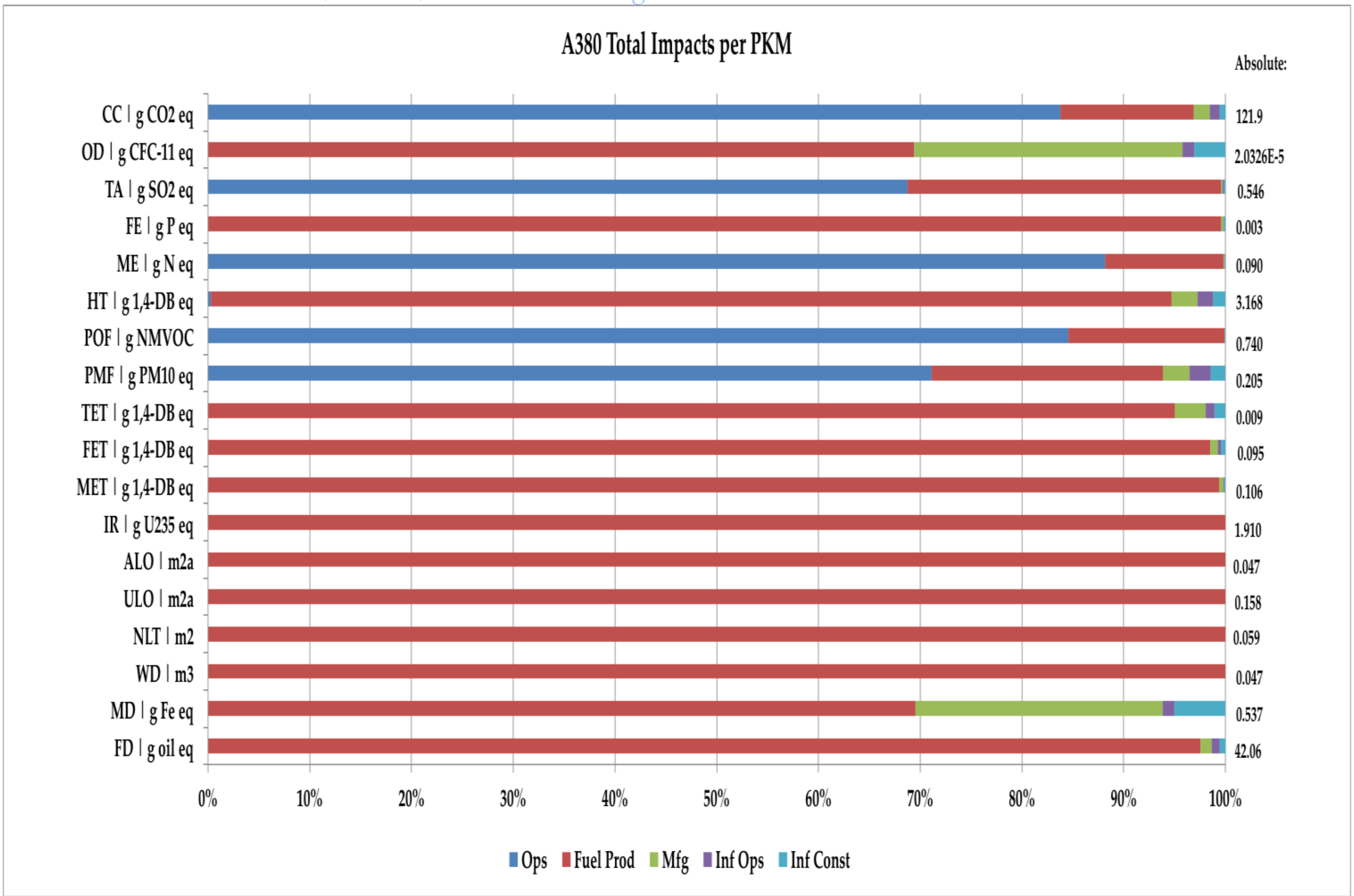


Figure 24 Scenario 3 9582 km Airbus A380 Flight, Contribution Analysis, PKM

Table 15: A380 VKM and LKM Absolute Values

Impact Category	A380 ǀ VKM	Impact Category	A380 ǀ LKM
CC ǀ kg CO2 eq	62.922	**CC ǀ kt CO2 eq**	5,233.13
OD ǀ kg CFC-11 eq	0.000	**OD ǀ kt CFC-11 eq**	0.00
TA ǀ kg SO2 eq	0.283	**TA ǀ kt SO2 eq**	23.51
FE ǀ kg P eq	0.001	**FE ǀ kt P eq**	0.11
ME ǀ kg N eq	0.047	**ME ǀ kt N eq**	3.89

HT ǀ kg 1,4-DB eq	1.631	**HT ǀ kt 1,4-DB eq**	135.61
POF ǀ kg NMVOC	0.383	**POF ǀ kt NMVOC**	31.86
PMF ǀ kg PM10 eq	0.081	**PMF ǀ kt PM10 eq**	8.77
TET ǀ kg 1,4-DB eq	0.005	**TET ǀ kt 1,4-DB eq**	0.40
FET ǀ kg 1,4-DB eq	0.049	**FET ǀ kt 1,4-DB eq**	4.07
MET ǀ kg 1,4-DB eq	0.055	**MET ǀ kt 1,4-DB eq**	4.58
IR ǀ kg U235 eq	0.989	**IR ǀ kt U235 eq**	82.24
ALO ǀ m2a	0.024	**ALO ǀ m2a**	2,027,487
ULO ǀ m2a	0.082	**ULO ǀ m2a**	6,821,535
NLT ǀ m2	0.031	**NLT ǀ m2**	2,540,629
WD ǀ m3	0.024	**WD ǀ m3**	2,008,391
MD ǀ kg Fe eq	0.274	**MD ǀ kt Fe eq**	22.79
FD ǀ kg oil eq	21.713	**FD ǀ kt oil eq**	1,805.87

Life Cycle Stages Results and Analysis

The secondary objective of this work is to understand the relevance of the different life cycle stages across selected environmental impacts. The following sub-sections will examine the results of the life cycle stages of each aircraft, focusing on climate change impacts. The A320 will be used as the primary example aircraft in this section given its popularity and the need for simplification in some results presentations.

Manufacturing Results

Normalization Approach for Manufacturing Phase

To distill total manufacturing results into the three normalized units reported in this study, Equation Set 1 was utilized. Normalizing to VKM and LKM was straightforward as LKM is equal to the total impacts generated from LCA calculations. To model VKM, the annual kilometers flown over the aircraft lifetime were needed. This model parameter, also required for other life cycle phase normalizations, relied on the calculated distance covered per hour in the scenarios multiplied by average utilization rates per day and then annualized. This gave the annual km flown and could readily be multiplied by the aircrafts assumed lifetime of 20 years. To model PKM output, two key parameters were developed: Average PAX Weight Attribution and Avg PAX per Flight. This was accomplished by multiplying the standard aircraft seating configuration by the passenger load factors obtained from ICAO and described in the Case Description section. The average passenger weight attribution is also applied using the same data resource.

Equation Set 1:

$$\boldsymbol{EIOLCA\ Impacts_{Mfg}, PKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Mfg}}{Aircraft\ Lifetime\ km}\right) \times Avg\ PAX\ Weight\ Attribution}{Avg\ PAX\ per\ Flight}$$

$$\boldsymbol{EIOLCA\ Impacts, Mfg, VKM} = \frac{EIOLCA\ Impacts_{Mfg}}{Aircraft\ Lifetime\ km}$$

$$\boldsymbol{EIOLCA\ Impacts, Mfg, Lifetime} = EIOLCA\ Impacts_{Mfg}$$

Climate Change Impacts, Manufacturing

In total, manufacturing life cycle results for GHG emissions accounted for 3.5%, 2.8% and 1.6% of total impacts for the A320, A330 and A380, respectively. These results were compared to relative shares in other studies; similar attributions towards this life cycle phase were found (Mikhail Chester, 2009, 2011). Per PKM, the total values for each scenario were as follows: 6.34 (A320), 2.89 (A330) and 1.46 g CO_2-eq (A380).

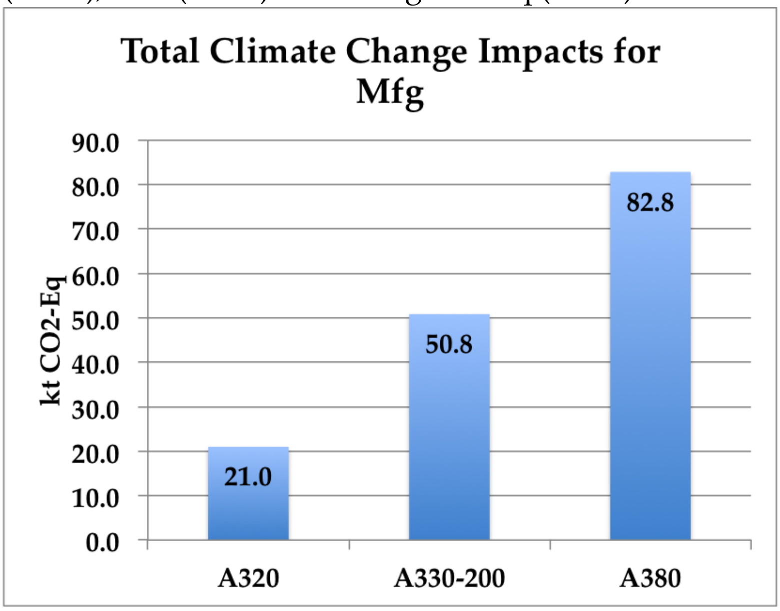


Figure 25 Total Climate Change Impacts, Manufacturing

Despite seemingly small contributions over the total life cycle, manufacturing emissions for the three aircraft amounted to significant per unit absolute values due to their large technical and economic requirements. To manufacture a single A330, the middle-sized aircraft of this size, generates 50.8 kt of GHGs using EIOLCA. Figure 25 displays the total GHG emission profiles for the manufacture of each of the three aircraft used in the study. As non-tailpipe emissions, these impacts are important in understanding the life cycle emissions profile of air transport.

Although some analysis has been provided for the manufacturing EIOLCA results in the Aircraft Operation and Manufacturing section of this study, additional information pertaining to key sectors driving climate impacts will be discussed. Using Simapro's network diagram feature, a helpful visual graphic that maps selected flows throughout the defined system was produced. The impact category "climate change" was used and all sectors with less than a 3.6% cumulative net impact were filtered out for the manufacture of an A320 (see Figure 26) (Simapro, 2011). The size difference depicted on the arrows indicates the relative significance of the direct flow of inputs into another sector. For example, other aircraft parts manufacturing has the largest direct flow of emissions into aircraft manufacturing. The diagram also shows the cumulative contributions. Listed below are the absolute values of each sector (kg CO_2-eq):

1. Electric power generation, transmission and distribution, 5.64E+6
2. Iron and steel mills and ferroalloy manufacturing, 4.43E+6
3. Aircraft manufacturing, 1.85E+6
4. Other aircraft parts and auxiliary equipment manufacturing, 8.71E+5
5. Aircraft engine and engine parts manufacturing, 4.82E+5
6. Aluminum product manufacturing from purchased aluminum, 3.16E+5
7. Management of companies and enterprises, 1.7E+5
8. Semiconductor and related device manufacturing, 1.67E+5
9. Search, detection, and navigation instruments, 1.14E+5

Figure 26 sheds light on some additional interesting aspects when considering the results previously presented using process LCA (ref. Aircraft Operation and Manufacturing section). Particularly, the shares of emissions associated with the Search, detection and navigation instruments, Semiconductor and related device manufacturing, Management of companies etc. and the Iron and steel mills sectors. The first three sectors would have been out of the system boundaries of all process LCAs conducted and published prior to the writing this thesis. This is due to the general exclusion of electronics and aviation equipment due to challenges presented in data collection. Service sectors such as "Management of companies" are also not included in process LCAs making both of these sectors increasingly important in the comparative work between process and EIO life cycle assessment.

The analysis conducted in the process LCAs in this study and others (Lopes, 2010) conclude that CFRP and aluminum are the largest contributing materials towards GHG totals. As such, it is difficult to determine what is driving the large share of emissions from the Iron and steel mill sector using EIOLCA given the material insights provided by process LCA. At a high level, the U.S. Iron and steel mill sector has a large input in USD (2002) from the Electric power generation and transmission sector and the Coal mining sector. They are the fifth and tenth largest inputs to the sector and likely significant emissions contributors (Simapro, 2011). Overall, this highlights the case for better integration between EIOLCA and process LCA results for aircraft manufacturing.

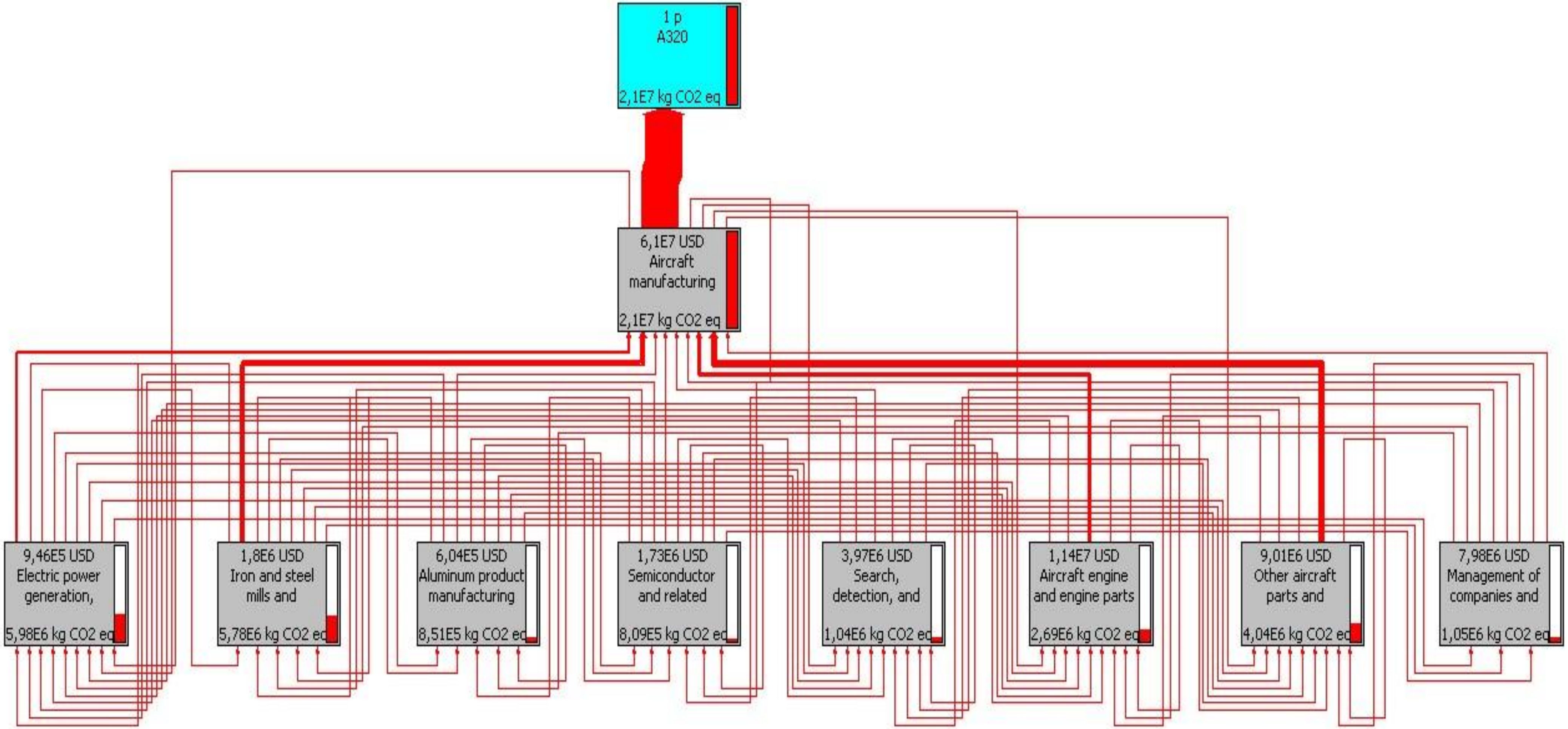


Figure 26 Simapro Network Diagram, A320 Manufacturing

To highlight the additional environmental impacts associated with aircraft manufacturing, Figure 27 is presented for all impact categories except for climate change, fossil depletion, ionizing radiation, agricultural land occupation, urban land occupation and natural land transformation. These impact categories are excluded in order to evaluate the environmental impacts that are not directly associated with fossil fuels and GHGs. Aircraft manufacturing does not influence the impacts outside of CC and FD that are excluded[14].

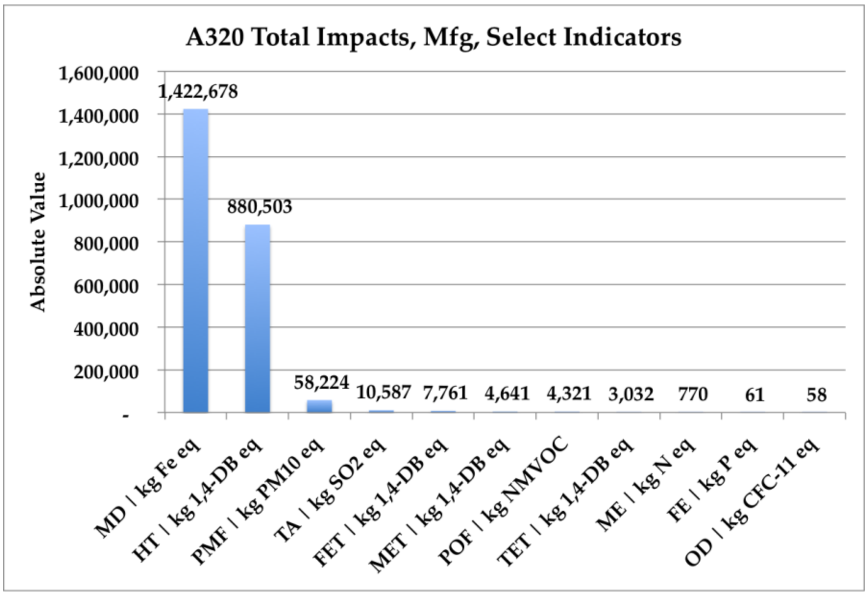


Figure 27 A320 Total Manufacturing Impacts, Select Indicators

Metal depletion and human toxicity are two key impact categories when results are assessed in this way. Additionally, particulate matter formation will be examined in more detail in the following section. This in no way insinuates that the remaining impact categories are irrelevant; however, as climate change is the primary focus of this report, exclusions of some of the less relevant impact categories were necessary.

One hundred percent of the metal depletion impact is attributable to the Iron ore mining sector. Subsequently it is dispersed amongst sub-sectors with the primary share going to the Iron and steel mill sector before entering Aircraft Manufacturing. This is likely due to the same underlying requirements driving the climate impacts previously discussed, which are readily explained by the material requirements of the aircraft. A partial explanation may be in the steel inputs to aircraft hangars for manufacture. Looking into the inputs from the technosphere to Aircraft Manufacturing using Simapro, the Iron and steel mills sector is the eighth largest input at 0.01498 USD (2002). The first and second being Other aircraft parts and auxiliary equipment manufacturing and Aircraft engine manufacturing with 0.1372 and 0.1331 USD (2002),

[14] Agricultural land occupation has an absolute value of 0.08 m2a but is omitted.

respectively (Simapro, 2011). Overall, there is a substantial economic requirement from the iron and steel sector for aircraft manufacturing.

Human toxicity impacts often stem from heavy industrial activity as many of the secondary production processes required to alter primary products involve high temperature reactions, physical modifications and other processing techniques that require immense resources and contribute to toxic loading. In a product as large and technologically complex as an aircraft, these loads can be very significant. As can be seen from Figure 27 the production of one complete A320 creates 880.5 metric tons of 1.4 DB-eq. Overall, the impacts are generated from a diverse group of sectors with the primary contributors being Electric power, generation, transmission and distribution, Iron and steel mills, Other aircraft parts manufacturing and Aircraft engine manufacturing with 29.5%, 21.5%, 17.6% and 13% of the total impacts, respectively.

The last graphic presented in this section, Figure 28, provides a better sense of scale for the selected environmental categories as total values are given per PKM for the A320 case. Although this chart is visually identical to Figure 27, the values given provide additional perspective on the influence the manufacturing phases have on life cycle results. As can be seen, the PKM impacts for metal depletion, the largest of the selected categories, are approximately 430 mg FE-eq per passenger kilometer of travel.

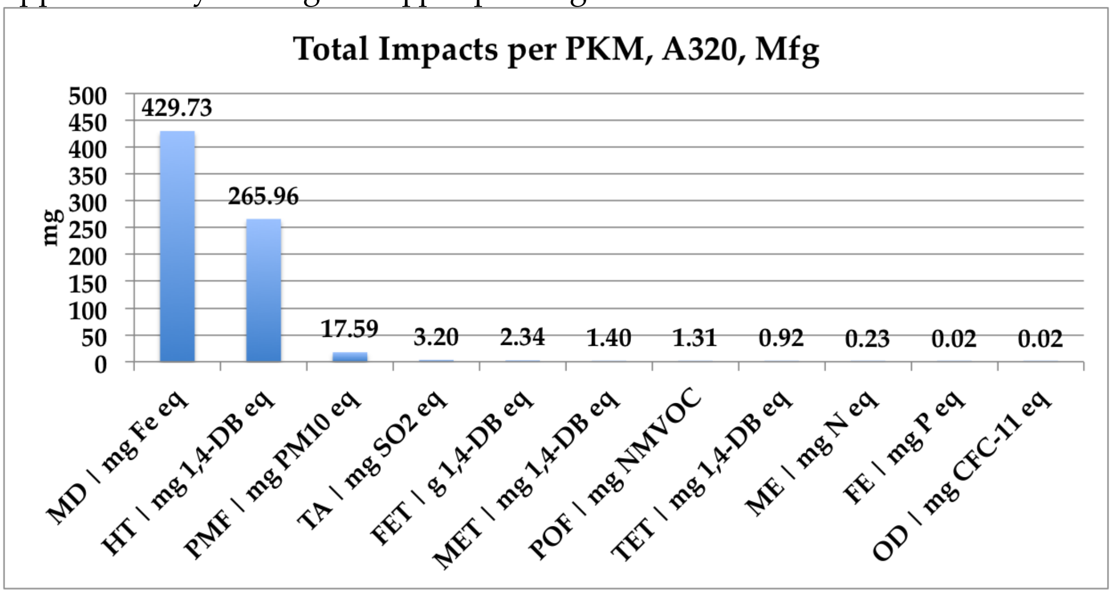


Figure 28 Total Manufacturing Impacts, Selected Indicators, PKM

Operations Results

Equation Set 2 outlines the approach used to normalize aircraft operations across the three different metrics used. Two subtle differences from the normalization outlined in the manufacturing section are the use of process LCA impacts and the actual case flight distances for each functional unit.

Equation Set 2:

$$\boldsymbol{PRO\ LCA_{Ops}, PKM} = \frac{\left(\frac{PROLCA\ Impacts_{Ops}}{Case\ Flight\ km}\right) \times Avg\ PAX\ Weight\ Attribution}{Avg\ PAX\ per\ Flight}$$

$$\boldsymbol{PRO\ LCA_{Ops}, VKM} = \frac{PROLCA\ Impacts_{Ops}}{Case\ Flight\ km}$$

$$\boldsymbol{PRO\ LCA_{Ops}, LKM} = \left(\frac{PROLCA\ Impacts_{Ops}}{Case\ Flight\ km}\right) \times Aircraft\ Lifetime\ km$$

The operation phase of the air transport life cycle assessment is the fundamental driver behind climate change related impacts. It is also the most widely discussed and reviewed aspect in literature, policy and industry from an environment and aviation context. This holds true for many modes of transport as the heavy use of fossil fuels has given rise to efforts to better understand environmental contributions from both the full life cycle perspective as well as other non-GHG environmental implications (Chester, 2008). Additionally, the direct fuel requirement of aircraft operations and the production from fuel refineries contributes to an extensive amount of emissions, extending the indirect effects of the operating component. When combined with those from operations, a more diverse and significant emissions profile emerges. The intent of this section is to examine the operations contributions to GHGs in more detail, as well as present other environmental impacts resulting from aircraft propulsion.

The Total Life Cycle Impacts of Selected Scenarios section has covered the main climate change findings for each normalization metric from the life cycle perspective for each scenario in this study. To provide better perspective of the direct operation effects, Figure 30 illustrates total impacts by aircraft operation phase for Scenarios 1-3 using selected impact categories[15]. The chart is configured such that the cruise phase emissions are presented first followed by the LTO cycle. Additionally, the scenarios are grouped by impact categories and listed in ascending order (using the A320) by absolute value. The results indicate that the cruise phase is responsible for approximately 80% or more of all environmental impacts with the exception of human toxicity. Furthermore, climate impacts are clearly the environmental category of concern given the magnitude differences between it and all other environmental stressors presented. These two conclusions were expected considering the vast amount of jet fuel required to propel an aircraft.

Climate Impacts from Aircraft Operation

This section will analyze the CO_2 intensity of the different operating segments flown in each scenario. Figure 30 outlines the contribution margins and absolute values of GHGs associated with each flight scenario. The total kg CO_2-eq amounted to 14,847 for the A320 flight, 123,962 for the A330 and 506,964 for the A380. As expected, the cruise phase is responsible for the majority of these emissions with approximately 81%, 95% and 97% for each aircraft, respectively. The next largest segment is the taxi-out phase which was estimated to be on average 19 minutes of taxi time (Chester, 2008; Eurocontrol, 2013). Climb, approach, taxi-in, take-off and landing, in descending order, drive the remaining fuel use and net emissions shares for both the A320 and A380. Interestingly, the A330 has a more efficient taxi-out phase than the other two aircraft resulting in more emissions being attributed to the climb than taxi-out. As fuel burn drives all emissions in the operations phase, Figure 29 shows the energy intensity in kilograms of fuel used per minute for each scenario. This chart provides good visualization of the energy requirements of the different phases while outlining the respective fuel use by aircraft type. From a GHG emissions standpoint, this chart helps illustrate which phases are the most GHG intensive in terms of energy requirement. This understanding can serve towards working to lower emissions through measures such as applying more efficient air traffic control measures.

[15] Impact categories were cut off at less than or equal to absolute values of 0.01

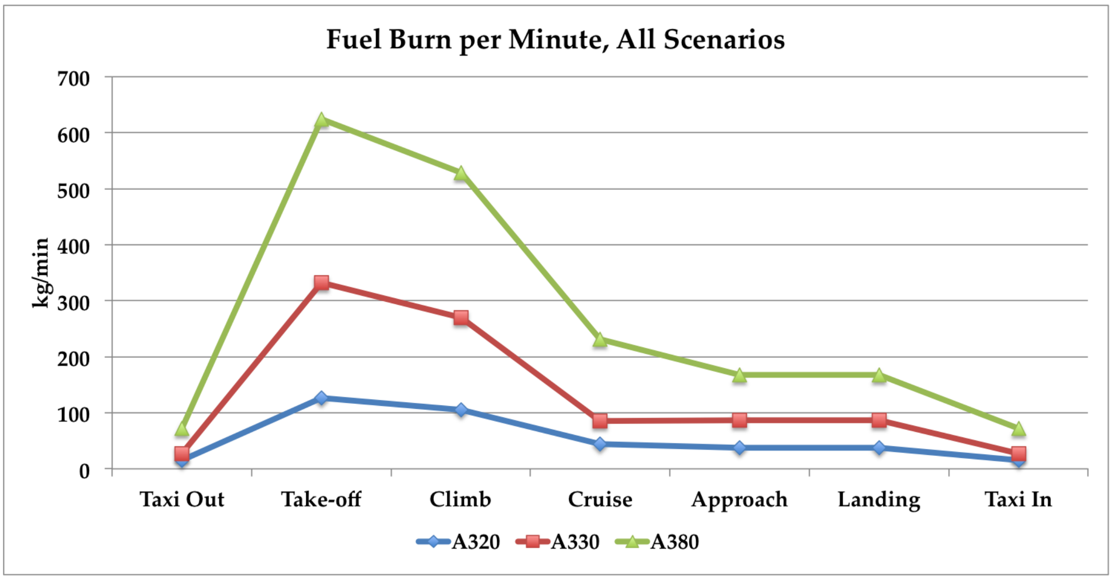


Figure 29 Fuel Burn per Minute, All Scenarios

Given the relative importance of the aircraft operation phase for all three scenarios and emissions output, fuel use was benchmarked throughout the LTO and cruise phases to compare and check results.

A key element introduced in this thesis that has been absent from previous studies is the use of the Advanced Emissions Model (AEM) to calculate fuel burn and emissions. In the absence of this, LTO cycle emissions can be calculated using ICAO standards and reported engine emissions by LTO phase. However, the cruise phase emissions are not reported and so must be estimated. Plus, fuel burn over this phase is not always well understood and reported fuel use is not readily available. As the AEM calculates this information, it is assumed that the emission results over the operation phase yield a higher level of accuracy than would otherwise be attainable. In addition, the cruise phase emissions for the A320 were checked against cruise fuel burn averages provided by a major airliner for the same model aircraft (Berlin, 2013). Using the provided average of 2,500 kg/hour/cruise and this study's A320 cruise time of 1:45, the total fuel burn over the cruise phases could be compared. The airliners' A320 would have burned 3,625 kg of fuel on average while the A320 in this study burned 3,798, a fuel burn difference that can be considered negligible.

In addition to benchmarking the cruise phase fuel use, the LTO metrics for fuel burn were compared to the ICAO Engine Emissions Databank for the A320 (ICAO, 2013). As this data is what the AEM uses, results were not expected to differ. This was primarily conducted to ensure there was no error in the use of AEM model as it is a tool that is designed for aviation industry professionals. This comparison confirmed that the model had been run correctly and that the proper fuel burn rates for the LTO cycle had been utilized.

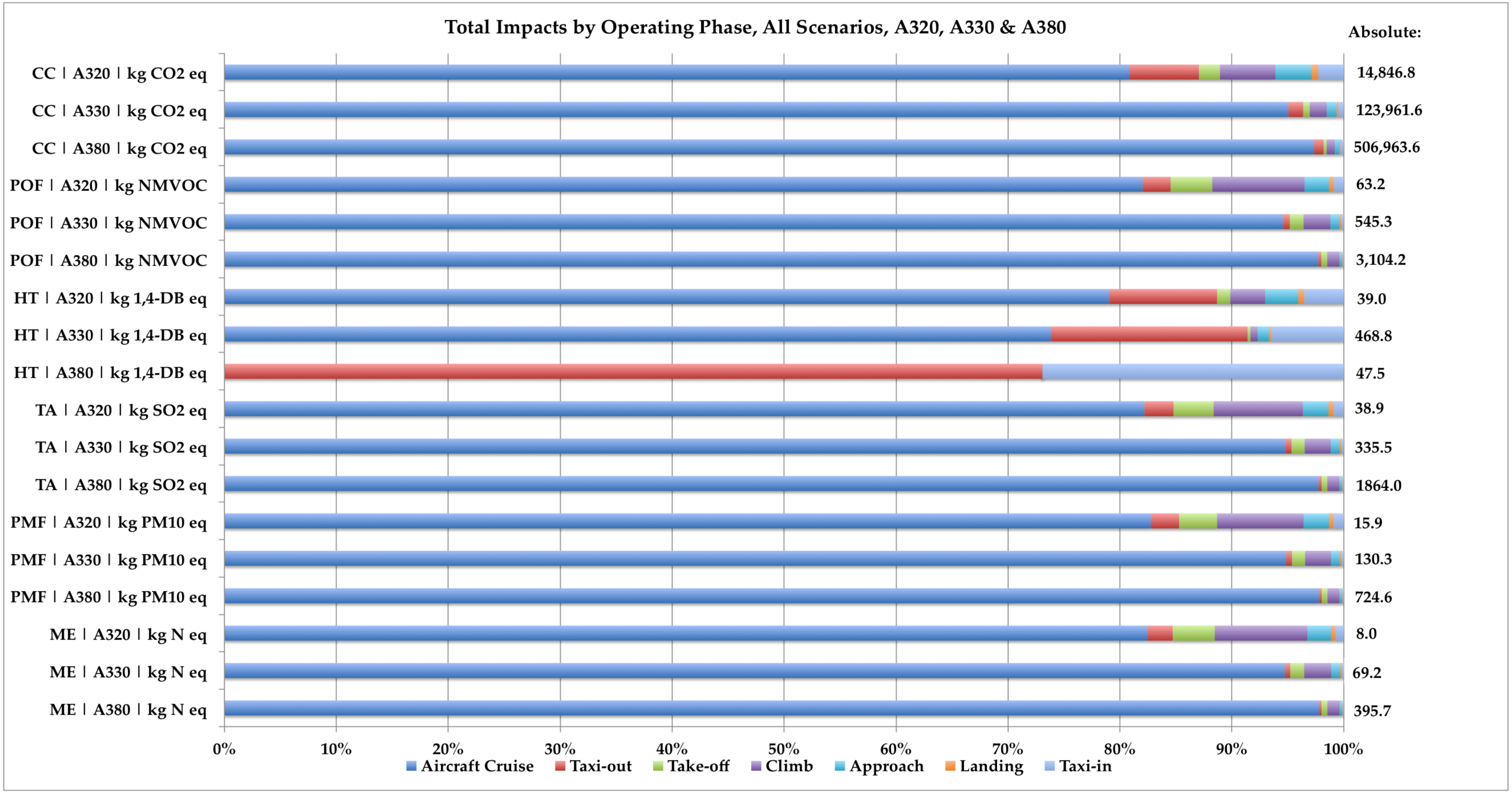


Figure 30 Total Impacts by Operating Phase, All Scenarios

Selected Non-GHG Environmental Impacts

Additional stressor observations can be drawn from Figure 30 such as the absolute contributions of other pollutants that result form hydrocarbon combustion for each scenario flight. As is evident by the pollutants present in the graphic, all are directly attributable to the combustion of fossil fuel products. Photochemical oxidant formation (POF, kg NMVOC) ranks as the second largest pollutant by absolute value for each flight followed by human toxicity (HT, kg 1.4 DB-eq), terrestrial acidification (TA, kg SO2-eq), particulate matter formation (PMF, kg PM10-eq) and marine eutrophication (ME, kg N-eq).

POF is caused by the photochemical reactions of NO_x and non-methane volatile organic compounds (NMVOC) and can lead to the creation of ozone and adversely affect human health. This characterization factor is produced by a combination of NO_x and NMVOC emissions from the engines as well as temporal conditions (Mark Goedkoop, 2009). One common visual effect of POF is smog production, particularly in the summer time when photochemical oxidation intensity is greater. Outside of the cruise phase, this emission is predominately generated when the aircraft is taking-off and climbing (see Figure 30).

HT is clearly another human health concern and is expressed in kilograms of 1-4 dichlorobenzene (1-4 DB) equivalents. As one of three different toxicity indicators in the ReCiPe method (human, terrestrial, freshwater), it is characterized using fate and exposure calculations. It is well understood that this 1-4 DB is toxic to humans (CDC, 2013); however, determining direct exposure to humans and fate of toxins can be challenging. In the aircraft operation scenario, the LTO cycle emissions are of concern due to the direct presence of ground crew personnel and the proximity of many major airports to large urban centers. This can be observed in the results by the increased significance of the taxi-in and taxi-out phases where fuel is combusted in significant quantities closer to ground and human occupied areas. It should also be noted that the AEM results for the A380 only provided emission data for HC during taxi-out and taxi-in. This could be intentional or due to a lack of data given the A380's newer market entry and will not be explored in this study.

TA quantifies the acidifying gases that may dissolve in water or attach to solid particles and impair the health living organisms and buildings. This is the fourth largest stressor by absolute value with a total of 38.9 kg SO_2-eq from the A320 flight. Outside of the cruise phase, it is predominately produced when the aircraft is climbing. An examination of this category, and all others, will show the close alignment of fuel burn to emission quantity.

HT and ME represent the most diverging impact categories from this perspective however with 21% and 17.5% of total emissions attributed to LTO versus 19% for fuel for Scenario 1. PMO and ME are both key environmental stressors as PM10 can cause adverse human health effects and the introduction of nitrogen to marine ecosystems leads to harmful impacts towards ecosystems and species (Mark Goedkoop, 2009).

A key consideration to take away from the non-GHG impacts is that the lifetime use and related emissions (see Appendix 1 inventory for LKM) that have been reported and explored in this study implicates large quantities of these pollutants. Total selected environmental impacts per PKM for the A320 scenario are also presented in Appendix 1 by life cycle phase to provide an additional context. As such, these emissions, which are typically outside of mainstream focus, have large environmental contributions over time and are important to consider for best management practices. In addition to this, understanding the LTO and specific operating phase contributions for these emissions is imperative to better understand the potential impacts to geographic regions and ground-level organism exposure.

Infrastructure, Construction and Operations Results

Equation sets 3 and 4 were used to normalize the total life cycle results obtained for both the construction and operations phases of this study. New variables were introduced in these calculations including the total airport passengers and the average flight distance. The total airport passenger number was obtained by using the current total passenger average in Berlin[16] multiplied by the assumed lifetime component for the airport (Brandenburg, 2013). In consideration of the methodological approach, it was determined that the lifetime would be represented as 20 years. This was also confirmed to be within comparable range of several U.S. airport facilities as well as the Federal Aviation Administration's standard operational pavement lifetime (Airport Commission, 2012; Navneet Garg, 2004). For the infrastructure operation normalization, the passenger capacity number for the corresponding airport was applied (Airport Commission, 2012). Further, to account for the full impacts required to transport passengers from one destination to another, total impacts divided by the lifetime passenger capacity is multiplied by two. Finally, the average flight distances were obtained for average trip lengths reported by the Federal Aviation Association (FAA, 2012).

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[16] Ref. the Case Description section on use of Berlin Airport

Equation Set 3:

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Const},PKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Const}}{Total\ PAX\ Lifetime}\right)}{Avg\ Flight\ km}$$

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Const},VKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Const}}{Total\ PAX\ Lifetime}\right) \times Avg\ PAX\ per\ Flight}{Avg\ Flight\ km}$$

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Const},LKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Const}}{Total\ PAX\ Lifetime}\right) \times Avg\ PAX\ per\ Flight}{Avg\ Flight\ km} \times Aircraft\ Lifetime\ km$$

Equation Set 4:

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Ops},PKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Ops}}{Total\ PAX\ per\ yr}\right)}{Avg\ Flight\ km}$$

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Ops},VKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Ops}}{Total\ PAX\ per\ yr}\right) \times Avg\ PAX\ per\ Flight}{Avg\ Flight\ km}$$

$$\boldsymbol{EIOLCA\ Impacts_{Inf\ Ops},LKM} = \frac{\left(\frac{EIOLCA\ Impacts_{Inf\ Ops}}{Total\ PAX\ per\ yr}\right) \times Avg\ PAX\ per\ Flight}{Avg\ Flight\ km} \times Aircraft\ Lifetime\ km$$

Infrastructure Construction Results

Total impacts for infrastructure construction represented the smallest share of life cycle contributions across all normalization categories. In total, it accounts for 2% of climate impacts for the A320 using PKM normalization. This is the highest attribution this phase incurs as the A330 and A380 scenarios have shares of 0.71% and 0.57% respectively (PKM). Each passenger on the scenario flights would have generated a total of 3.5 (A320), 4.0 (A330) and 6.7 kg CO_2-eq (A380) from the infrastructure construction input. Despite total emissions per flight, the A320 case is substantially higher on a PKM basis than the A330 or A380. The values equate to 3.73, 0.74 and 0.70 g CO_2-eq respectively. A brief examination of the climate change network diagram provided by Simapro, showed that the largest cumulative sector contributions to the climate change category were: electric power generation (20.3%), iron and steel mills (14.2%), cement manufacturing (8.5%), petroleum refineries (7.69%), plate work and fabricated structural products (6.5%) and ornamental and architectural metal products (5.67%) (Simapro, 2011).

To assess additional impact categories, select indicators that were greater than 0.5 mg per PKM in absolute value were chosen to look at in more detail. The impact categories CC (3.73g CO2-eq/PKM) and FD (1.31g oil-eq/PKM) are not included nor are those that relate to land use. The results indicated that the most significant of the selected categories were human toxicity with 205.5 mg 1.4-DB-eq, metal depletion with 144.2 mg Fe-eq and particulate matter formation with 15.8 mg PM10-eq.

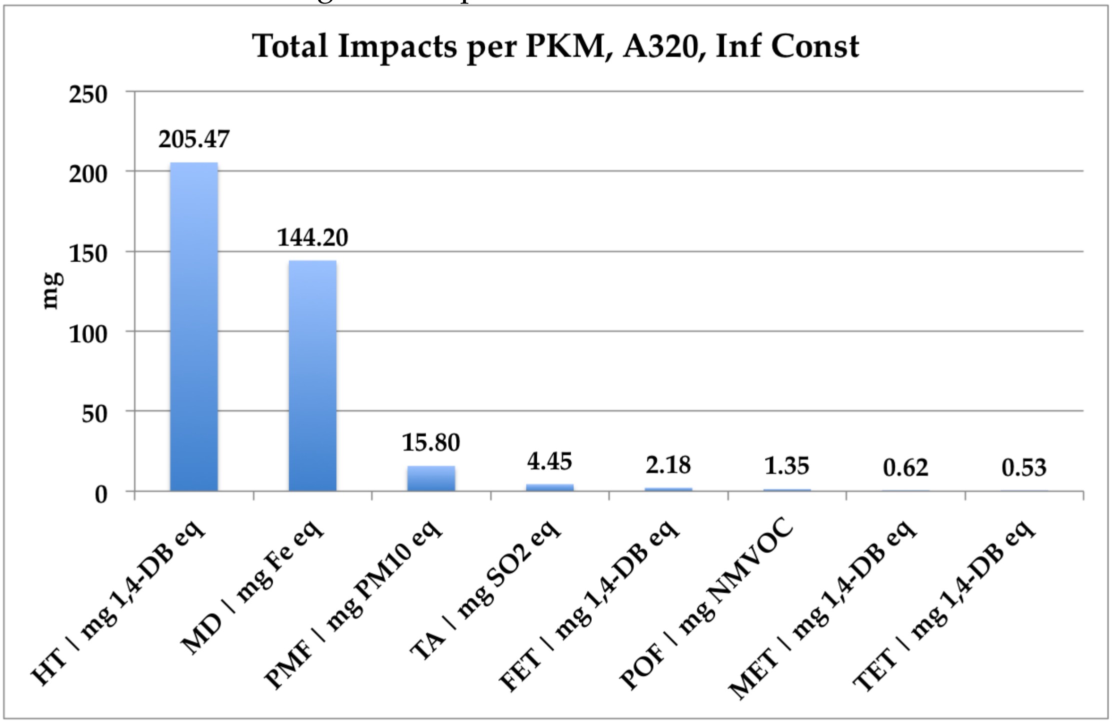


Figure 31 Total Infrastructure Construction Impacts, Selected Indicators, PKM

Though the sector contributions were more diverse under the HT characterization, the main sector contributions come from electric power generation (16%), brick, tile and other structural clay products (12.3%) and cement manufacturing (11.7%). As was the case in the manufacturing phase, the primary sector responsible for metal depletion is the iron and steel mill sector. Closer examination of the network diagram flows indicated that the primary requirements from the EIOLCA sector used for airport construction are from plat work and fabricated structural products and ornamental and architectural metal products. The primary contributing sector towards PMF is the truck transportation sector (Simapro, 2011). This is likely due to the extensive amount of heavy material shipping required by the commercial construction sector.

Infrastructure Operation Results

After operations, fuel production and manufacturing, the infrastructure operations phase was the next largest climate change contributor, with the exception of equal contributions of 3.5% from manufacturing and infrastructure operations in the A320 scenario. The A330 and A380 life cycle shares ranged between 0.7% and 1.2% (Table 9). Similar to the infrastructure construction phase, the A320 has the highest emission value per PKM at 6.3 g CO_2-eq. The A330 and A380 had approximately 1.3 and 1.2 g CO_2-eq per PKM. Flight totals per passenger were 5.9, 6.7 and 11.3 kg CO_2-eq for the infrastructure operation life cycle component (A320, A330 and A380, respectively).

Analyzing the Simapro network diagram for this phase yielded some additional insights into the sector contributions towards climate change. Of the sectors used to calculate total impacts through EIOLCA, the relative shares of GHG emissions were appropriated as shown in Figure 32. Not surprisingly, electric power generation held the largest share at 61% followed by management of companies and enterprises (15%) and transit and ground transportation (15%).

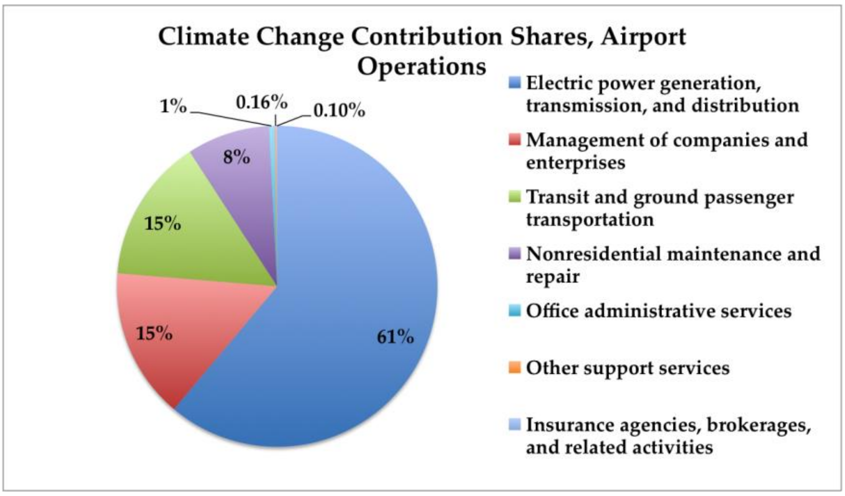


Figure 32 Climate Change Contribution Shares, Airport Operations

In an effort to maintain consistent reporting on selected environmental impacts for the life cycle phases, the values from the A320 under PKM normalization were used. Again, the impact categories CC (6.3 g CO_2-eq/PKM) and FD (1.77 g CO_2-eq/PKM), all categories pertaining to land use and any that were under 0.5 mg/PKM in absolute value were not assessed. Figure 32 also shows that the infrastructure operations phase has the same sequence of environmental impacts as infrastructure construction. HT is driven by the requirements from the electric power generation sector (65%), MD by nonresidential maintenance and repair (37%) and transit and ground passenger transport

(35%) while PMF stems from electric power generation (46%) and transit and ground passenger transport (29%).

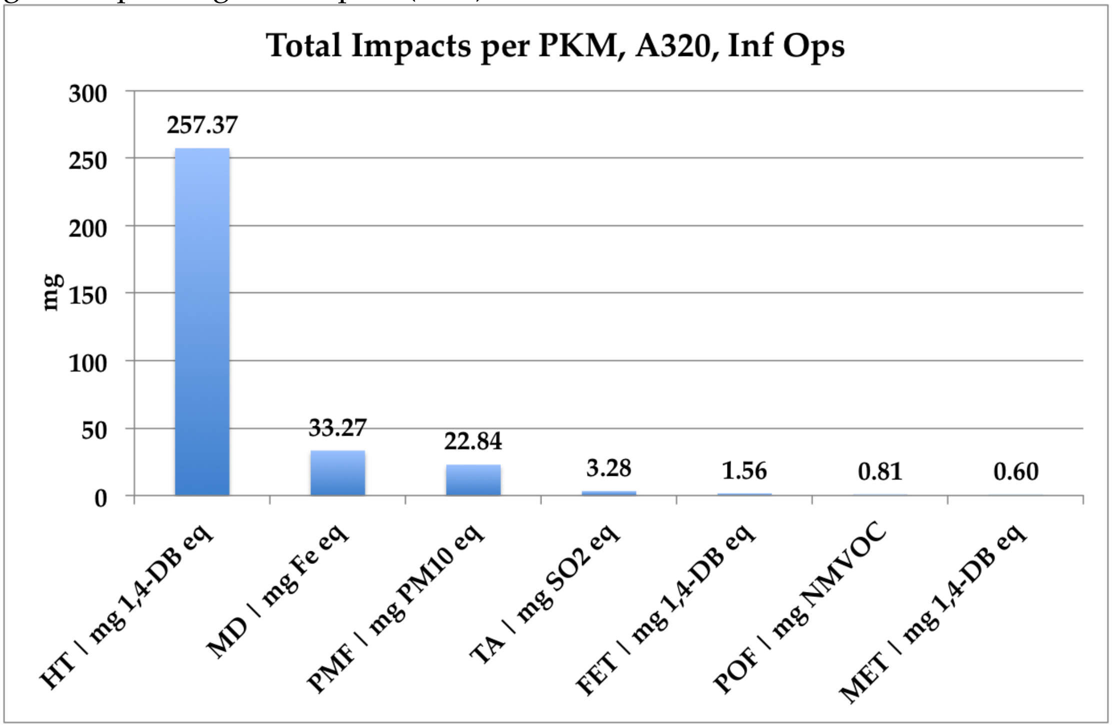


Figure 33 Total Infrastructure Operations Impacts, Selected Indicators, PKM

In all, the impacts derived from infrastructure construction and operations and their relative influence on life cycle emissions have proven to be important areas to consider if the aim is to develop climate mitigation strategies with respect to air transport. Representing up to 5.5% of the GHG emissions in the A320 life cycle (PKM), these two phases are important as air transport is extremely energy intensive. Furthermore, by developing results for these phases, comparative efforts amongst different modes of transport can be accomplished. From a non-GHG environmental perspective, understanding that these two phases have larger influence on HT, MD and PMF impact indicators may prove beneficial in designing environmental plans for future projects.

Fuel Production Results

The fuel production and aircraft operation phases are closely linked as the environmental impacts from the fuel production process LCA are calculated per kilogram of jet fuel demand. As such, the operations and fuel production phase have a linear relationship where fuel production impacts are always proportional to operations demand. For climate change impacts, this amounts to approximately 15.5% of net emissions from operations. So, for every kilogram of GHGs emitted from the aircraft, 0.155 kg will result from the fuel production requirement. This finding was consistent with results obtained in other literature (Chester, 2008).

Normalization equations utilized for the aircraft operation phase are exactly the same for fuel production with the exception of the newly calculated environmental impacts ($PROLCA\ Impacts_{Fuel\ Prod}$) from producing and transporting jet fuel. Equation Set 5 provides the details of how values for PKM, VKM and LKM were generated.

Equation Set 5:

$$\boldsymbol{PRO\ LCA_{Fuel\ Prod}, PKM} = \frac{\left(\frac{PROLCA\ Impacts_{Fuel\ Prod}}{Case\ Flight\ km}\right) \times Avg\ PAX\ Weight\ Attribution}{Avg\ PAX\ per\ Flight}$$

$$\boldsymbol{PRO\ LCA_{Fuel\ Prod}, VKM} = \frac{PROLCA\ Impacts_{Fuel\ Prod}}{Case\ Flight\ km}$$

$$\boldsymbol{PRO\ LCA_{Fuel\ Prod}, LKM} = \left(\frac{PROLCA\ Impacts_{Fuel\ Prod}}{Case\ Flight\ km}\right) \times Aircraft\ km\ Lifetime$$

The total GHG impacts from this phase are substantial due to the relationship described above and the relative energy demand for aircraft operation. This phase represents the second largest of all life cycle phases and accounts for approximately 12.3% (A320), 12.7% (A330) and 13.1% (A380) of net GHG impacts from the PKM perspective. This amounted to 22.15 (A320), 13.39 (A330) and 15.97 g CO_2-eq (A380) per PKM for each of the scenarios modeled.

Fuel refineries are very energy intensive and account for about 7% of total U.S. energy consumption. Of this vast requirement, approximately 80% of the energy necessary for refinery production and operations is derived from refinery byproducts such a petroleum coke, refinery gas, liquefied petroleum gas, and fuel oil (Michael Wang, 2004). This is represented in the structural path analysis for climate change impacts conducted for this study where the largest contributing processes to GHG emissions in the fuel production LCA are: the combustion of refinery gases burned in the furnace (22.5%), the combustion of heavy fuel oil burned in the furnace (10.4%) and sour natural gas flaring (5.6%) during production, relative to total impact.

In addition to having the second largest climate impact over the life cycle, the fuel production phase accounts for the largest share of 13 of the 18 different ReCiPe midpoint indicators (ref. Figures 22-24). As can be seen in Figure 34, selected environmental stressors are modeled by their contribution per PKM. It should be noted that there are impacts pertaining to the ReCiPe land use categories, however these, FD (56.91 g oil-eq) and CC (22.15 g CO_2-eq) have been omitted. Fuel production derives the largest life cycle contributions to HT, which is the largest environmental impact category (absolute value) outside of CC and FD in the study. Major causes of HT in this phase are the discharge of produced water onshore with a relative impact of 15% of total, the burning of heavy fuel oil (5.75%) and the disposal of drilling waste (2.4%).

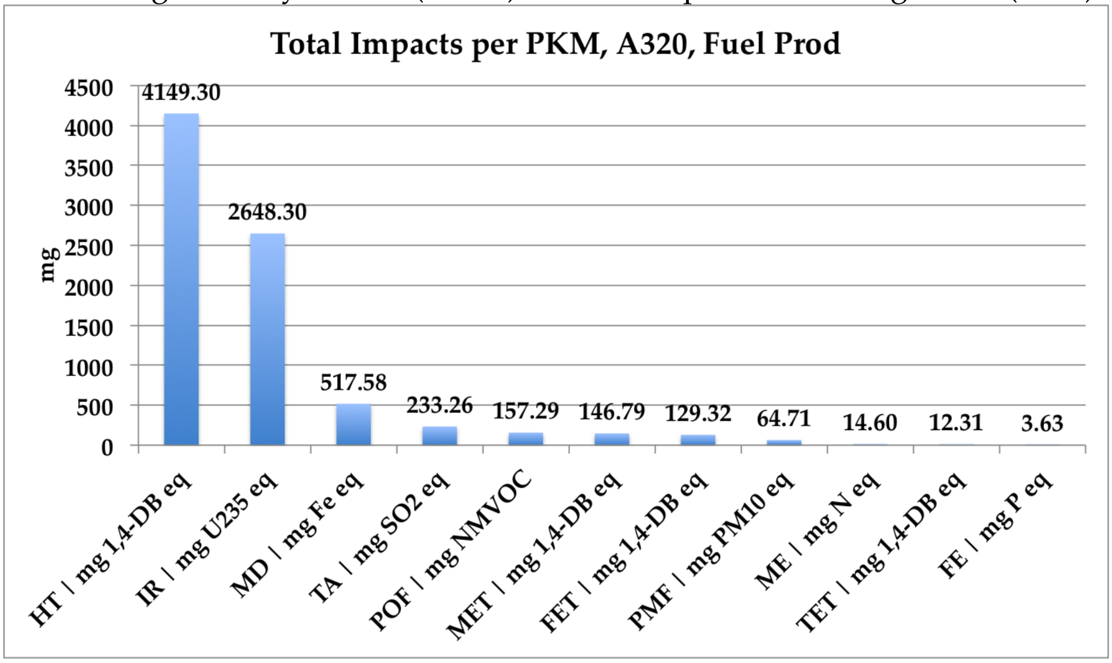


Figure 34 Total Fuel Production Impacts, Selected Indicators, PKM

This phase is also the largest contributor to MD throughout the life cycle with approximately 45% of total (PKM), which proved interesting as one may initially assume that the vehicle manufacturing phase would likely have the largest share. IR is interesting in that it is only generated by the fuel production phase and is largely due to the production of electricity through nuclear power plants. As the fuel refinery process contributions were modeled using Ecoinvent data, these impacts are unique to the electricity mix provided in that dataset and would become obsolete outside of a nuclear powered grid.

The last impact categories discussed here are TA and POF. TA is primarily produced through the refinery process of burning off sour natural gas; this is responsible for 39.3% of total relative impact. Following this process with 11.7% of impact is the burning of heavy fuel oil in the refinery furnace. Approximately 20% of the POF generation in the A320 and A330 scenarios is due to the fuel refinery phase. POF production in fuel refineries is much more distributed amongst different processes. The chief contributors are the flaring of sour natural gas (8.5%), the venting of natural gas (12%) and offshore crude oil production and transport (8.1%). Similar comparisons can be made using the contribution analysis provided in Figures 22-24 for each of the different scenarios.

Sensitivity Analysis and Uncertainty

This section covers sensitivity analysis as it pertains to key parameters in the model used to calculate results. Huijbregts (1998) outlines an approach to present uncertainty in LCA development with regard to model, choice and parameter uncertainty (Cristiano Facanha, 2006; Huijbregts, 1998). Following this approach, parameter uncertainty will be addressed through applying sensitivity analysis on selected key model parameters in the first section. A qualitative approach to analyzing model and choice uncertainty will be discussed in the following section.

Sensitivity Analysis

This study has integrated a variety of parameters into the calculation of emissions per functional unit for each scenario. This section will apply basic sensitivity analysis techniques to evaluate the relative sensitivity of some the most important parameters used to model this air transport LCA. The focus here will be on understanding how much influence key inputs utilized have over the final functional unit result. To do this, an assessment of the most critical model parameters was conducted and has been listed in Table 16, along with related source information. In addition to this, “Sensitivity Tests” that modify the original parameter by a selected value are used to test the overall influence of each individual input. Results will be compared using appropriate CO_2-eq for each of the model scenarios.

Table 16: Parameter Information

Parameter & Abbreviation	Current Scenario	Current Scenario Source	Sensitivity Tests
Aircraft Lifetime, VL15,	20 years	(A.J. Kolios, 2013;	+/- 25%

VL25		Chester, 2008)	
Load Factor, PAX (%), LF+/-5, LF +/-10	Scenario 1: 0.7396 Scenario 2: 0.8289 Scenario 3: 0.7591	(ICAO, 2012)	+/- 5% & 10%
PAX versus Freight Weight Attribution (%), FA5	Scenario 1: 0.99 Scenario 2: 0.8132 Scenario 3: 0.7695	(ICAO, 2012)	+5%
Average Utilization Rate (hours), UR5	Scenario 1: 8.7 Scenario 2: 13.85 Scenario 3: 13.4	(Javad Gorjidooz, 2010; Leahy, 2010; Wright, 2010)	+5%
Average Airport Lifetime, AL30, AL45	20 years	(Airport Commission, 2012; Navneet Garg, 2004)	+50%, +120%

As the operations and fuel productions phases have been demonstrated to have the overall greatest environmental impacts, the parameters (aircraft lifetime, load factor) that are part of the equations used to model them were examined first. Aircraft lifetime seemed to be a logical place to begin testing model sensitivity as it is also involved in at least one of the normalization equations for each of the different life cycle phases.

Previous research supported the use of a twenty-year lifetime for commercial aircraft (A.J. Kolios, 2013; Chester, 2008) however, twenty-five to thirty years has been cited as an upper-limit figure (Chester, 2008; Clark, 2013). At the same time, a report by PricewaterhouseCoopers indicates that aircraft lifetimes are exhibiting a decreasing trend. This is due aircraft demand and manufacturing backlog being high and the economics of owning second hand narrow-body aircraft subsequently unattractive. According to the report, rapidly evolving models of aircraft produced with higher fuel efficiency have a disproportionate effect on the value of the existing fleet. In all, the report states that some narrow-body aircraft are being retired after seven or eight years of operation (Clark, 2013; Shamshad Ali, 2013). With this information in mind, testing the sensitivity of the aircraft lifetime with a positive and negative range of +/- 25% was used to cover both angles.

The sensitivity results below will show that the scenarios normalized under VKM and PKM conditions exhibit virtually no sensitivity with just over 1% change from base case emissions occurring in the A320 scenario and progressive decreases in the A330 and A380. The subtlety of this change is likely due to the singular use of the aircraft lifetime component in the manufacturing calculations for VKM and PKM however; it is utilized in all of the LKM calculations. Although this parameter can be considered benign under the conditions assumed for VKM and PKM, it is clearly significant under the LKM perspective where positive and negative impacts of 25% occur for all three scenarios. This is attributable to the direct relationship between vehicle age and the production of GHGs over the lifetime component. As such, the LKM functional unit moves proportionately with aircraft lifetime.

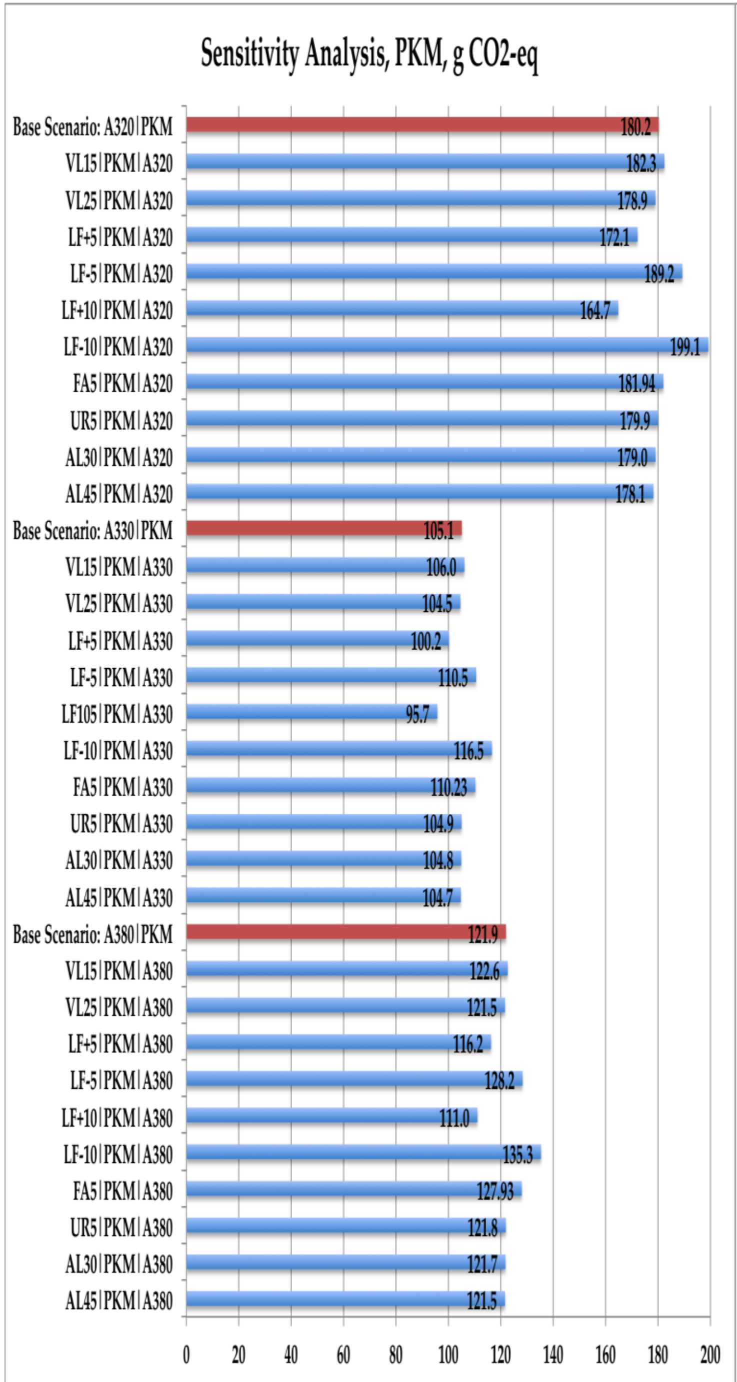
Testing the overall sensitivity of the load factors applied was critical as this parameter was the most influential in the model with respect to the PKM functional unit. The study adopts average 2010 load factors that both align with aircraft type and regional routes (ICAO, 2012). This helped mitigates uncertainty with this parameter however; it is fair to assume that there are fair shares of flights that occur above and below these averages. As such, testing deviations from the base parameter at two intervals (+/-5% and +/-10%) seemed prudent. The outcome showed that VKM and LKM functional units have less than +/-1% sensitivity to the variable changes. Total emissions under the PKM perspective are within a range of +/-10% with the A320 near the 9% range and the A380 with the highest sensitivity at 10%. When normalized by the 5% adjustment similar findings occurred for this scenario. The results showed that PKM normalization is highly sensitive to PAX loads; an outcome that aligns with the equation assumptions.

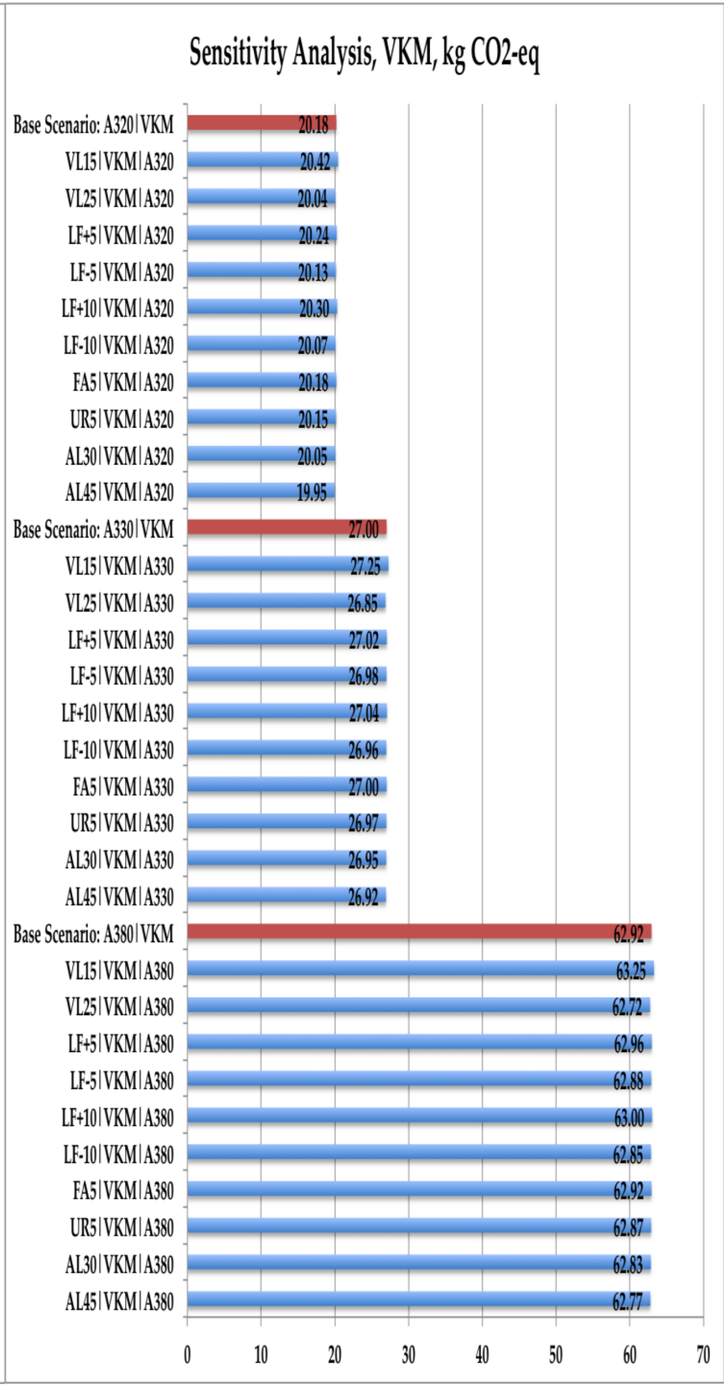
The freight attribution parameter was only sensitive under the PKM functional unit as well. Variations between the A320, A330 and A380 were approximately 1%, 4.8% and 4.9% when increasing the parameter by 5%. Although this parameter is similar to the load factor in that it may fluctuate, the adjustment for sensitivity was only made at 5% assuming that variability will be negated by economic incentive to maximize returns on scheduled flights. As the A320 was modeled at 99% weight attribution to passengers, it could not be adjusted by the full value as the other scenarios were. It can be postulated that the parameter would have some influence in the negative direction, however the capacity within an A320 to store larger volumes of freight is limited by its cargo space allotment. This parameter is useful to consider particularly as it is more susceptible to influence by external market factors outside of commercial transport. For example, supply and demand economics of goods between particular routes.

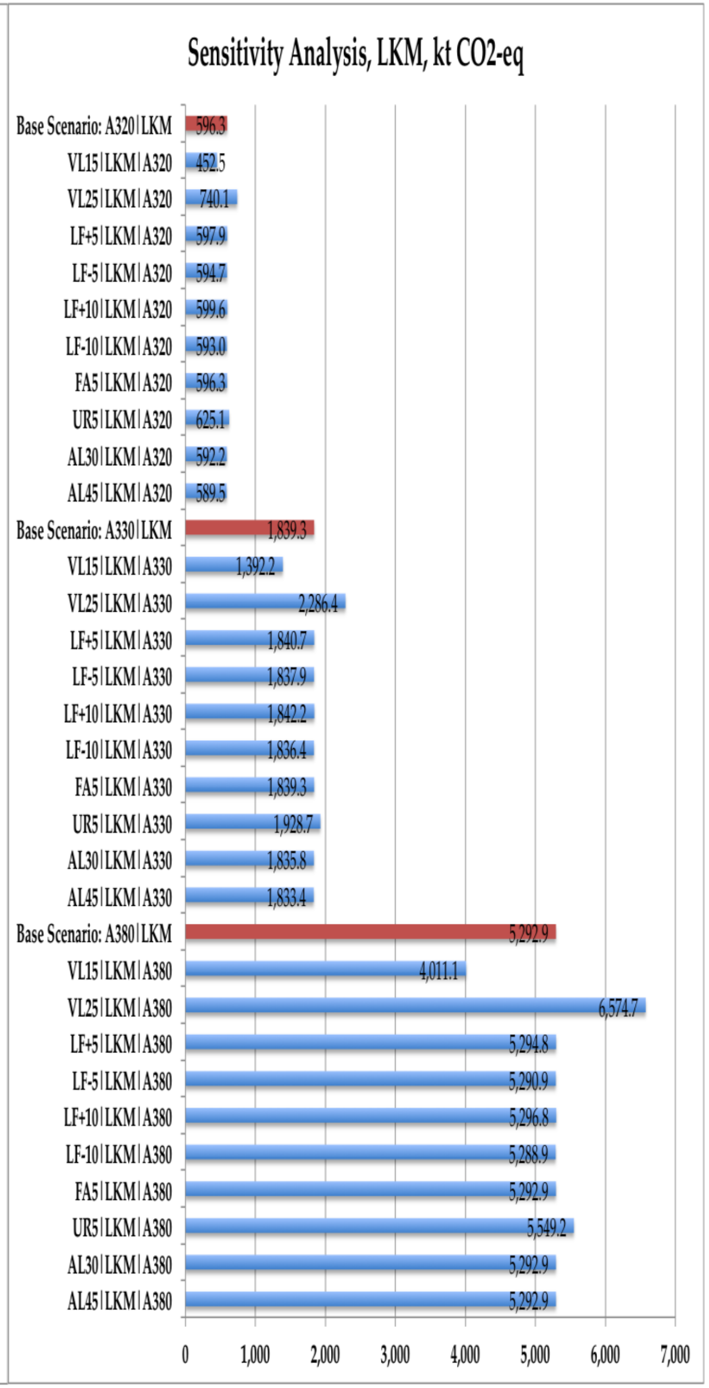
Average utilization rates and airport lifetimes were the final two parameters tested of which neither proved to be sensitive under PKM and VKM normalization. The single exception was found in the utilization rate influence on the LKM functional units. When tested, the result was influenced by approximately 5% for all three scenarios. PKM and VKM normalization were influenced by a margin of less then 1%. The adjustments made to airport lifetimes modified the A320 scenario using the PKM functional unit by just over 1% with all other instances less than 1%. This finding was interesting as the assumption for airport infrastructure lifetime is generally hard to quantify given the continual need for infrastructure improvement and repair, large capital investments and unconventional physical characteristics (e.g. high volumes of concrete/asphalt). The airport lifetime parameter is part of the infrastructure life cycle equation set; given the smaller net contributions of this phase the outcome is logical.

In all, the sensitivity analysis pointed out that the most influential parameters from a passenger transport standpoint are the load factor assumption and passenger versus freight contribution. Both demonstrated equal influence when increased by 5% (see A330, PKM) indicating that these two variables are key to consider. The remaining sensitivity tests applied to the PKM functional unit yielded small percentage changes. The VKM functional unit was largely unaffected with the largest fluctuation at 1.5% when the A320 scenario aircraft lifetime was adjusted to 15 years. This was likely due to aircraft manufacturing impacts having a greater life cycle influence, as the parameter is not a part of any other VKM calculations. Perhaps the most significant reason for low sensitivity in the VKM functional unit is the linear relationship between direct operation impacts and fuel production impacts with total vehicle kilometers (see Equation Sets). As such the impacts for these phases are only dependent on direct data obtained from the LCA inventory. The operation and fuel production phases represent majority fractions of net GHG emissions, consequently influence from others life cycle phases due to parameter sensitivity tests are generally too small to significantly impact overall results.

The tests also indicted that the LKM function unit was highly sensitive to vehicle lifetime adjustments as could be expected. In addition, the utilization rate tests influenced this metric as well. The general findings showed that there are some key parameters that do influence functional unit results. Those parameters have been sourced using the best available information in literature and industry to improve the overall quality of the results obtained. Additionally, many of the key data inputs (e.g. PAX capacity, PAX weight attribution) are not only constrained by physical limits but also supported by industry wide averages thereby reducing some of the uncertainty associated with adopted values. Overall, the findings regarding parameter sensitivity in modeling life cycle GHG emissions should be carefully considered for future modeling efforts and analysis.


Sensitivity Analysis, PKM, g CO2-eq
Base Scenario: A320|PKM 180.2
VL15|PKM|A320 182.3
VL25|PKM|A320 178.9
LF+5|PKM|A320 172.1
LF-5|PKM|A320 189.2
LF+10|PKM|A320 164.7
LF-10|PKM|A320 199.1
FA5|PKM|A320 181.94
UR5|PKM|A320 179.9
AL30|PKM|A320 179.0
AL45|PKM|A320 178.1
Base Scenario: A330|PKM 105.1
VL15|PKM|A330 106.0
VL25|PKM|A330 104.5
LF+5|PKM|A330 100.2
LF-5|PKM|A330 110.5
LF105|PKM|A330 95.7
LF-10|PKM|A330 116.5
FA5|PKM|A330 110.23
UR5|PKM|A330 104.9
AL30|PKM|A330 104.8
AL45|PKM|A330 104.7
Base Scenario: A380|PKM 121.9
VL15|PKM|A380 122.6
VL25|PKM|A380 121.5
LF+5|PKM|A380 116.2
LF-5|PKM|A380 128.2
LF+10|PKM|A380 111.0
LF-10|PKM|A380 135.3
FA5|PKM|A380 127.93
UR5|PKM|A380 121.8
AL30|PKM|A380 121.7
AL45|PKM|A380 121.5
0 20 40 60 80 100 120 140 160 180 200


Sensitivity Analysis, VKM, kg CO2-eq
Base Scenario: A320|VKM 20.18
VL15|VKM|A320 20.42
VL25|VKM|A320 20.04
LF+5|VKM|A320 20.24
LF-5|VKM|A320 20.13
LF+10|VKM|A320 20.30
LF-10|VKM|A320 20.07
FA5|VKM|A320 20.18
UR5|VKM|A320 20.15
AL30|VKM|A320 20.05
AL45|VKM|A320 19.95
Base Scenario: A330|VKM 27.00
VL15|VKM|A330 27.25
VL25|VKM|A330 26.85
LF+5|VKM|A330 27.02
LF-5|VKM|A330 26.98
LF+10|VKM|A330 27.04
LF-10|VKM|A330 26.96
FA5|VKM|A330 27.00
UR5|VKM|A330 26.97
AL30|VKM|A330 26.95
AL45|VKM|A330 26.92
Base Scenario: A380|VKM 62.92
VL15|VKM|A380 63.25
VL25|VKM|A380 62.72
LF+5|VKM|A380 62.96
LF-5|VKM|A380 62.88
LF+10|VKM|A380 63.00
LF-10|VKM|A380 62.85
FA5|VKM|A380 62.92
UR5|VKM|A380 62.87
AL30|VKM|A380 62.83
AL45|VKM|A380 62.77
0 10 20 30 40 50 60 70


Sensitivity Analysis, LKM, kt CO2-eq
Base Scenario: A320|LKM 596.3
VL15|LKM|A320 452.5
VL25|LKM|A320 740.1
LF+5|LKM|A320 597.9
LF-5|LKM|A320 594.7
LF+10|LKM|A320 599.6
LF-10|LKM|A320 593.0
FA5|LKM|A320 596.3
UR5|LKM|A320 625.1
AL30|LKM|A320 592.2
AL45|LKM|A320 589.5
Base Scenario: A330|LKM 1,839.3
VL15|LKM|A330 1,392.2
VL25|LKM|A330 2,286.4
LF+5|LKM|A330 1,840.7
LF-5|LKM|A330 1,837.9
LF+10|LKM|A330 1,842.2
LF-10|LKM|A330 1,836.4
FA5|LKM|A330 1,839.3
UR5|LKM|A330 1,928.7
AL30|LKM|A330 1,835.8
AL45|LKM|A330 1,833.4
Base Scenario: A380|LKM 5,292.9
VL15|LKM|A380 4,011.1
VL25|LKM|A380 6,574.7
LF+5|LKM|A380 5,294.8
LF-5|LKM|A380 5,290.9
LF+10|LKM|A380 5,296.8
LF-10|LKM|A380 5,288.9
FA5|LKM|A380 5,292.9
UR5|LKM|A380 5,549.2
AL30|LKM|A380 5,292.9
AL45|LKM|A380 5,292.9
0 1,000 2,000 3,000 4,000 5,000 6,000 7,000

Uncertainty

Due to data limitations and necessary model assumptions, a level of uncertainty is inherent in the results. Some of the uncertainty associated with the model parameters has been analyzed and discussed above; however, a broader more qualitative effort addressing the methodology selected for each phase, the functional units selected, the system boundary definition and some of the allocations used in modeling results is required. The following sub-sections will discuss these issues in more detail.

Methodology Selection

Although EIOLCA serves as one of the only approaches for evaluating the entire supply chain, it relies on assumptions about timescale, process boundary, quality of data and estimation methodology, all of which foster some level of uncertainty (Chester, 2008). With respect to timescale, input-output data is collected every five years and as such lends itself to susceptibility in sectors where technology development may advance rapidly or price and economic variables are not stable. Boundary implications with EIOLCA have been widely discussed in terms of aggregation issues and alignment of process or products with accompanying sectors. This issue introduces uncertainty when a clear delineation between the two cannot be achieved and economic sectors are defined too broadly. Data ramifications could foreseeably arise in the collection and collation of sector data reported by industry. In light of the significant Iron and Steel Mill sector direct emissions to aircraft manufacturing found in this study, there is potential for further research and investigation. According to Chester 2008, EIOLCA methodology is linear and does not assume increasing or decreasing returns to scale implying average, as opposed to marginal, estimates. In addition, it does not differentiate based on geographical considerations, which could impact price and economic variables in certain sectors. For the most part, EIOLCA can be a beneficial tool to incorporate into LCA calculations.

Process LCA can also be assessed with respect to its uncertainty, particularly with regard to the reliance on Ecoinvent data for this study. The fuel production phase impacts are dependent on the assumptions and analysis made by the authors that developed the fuel refinery process for Europe in the database. To do this, a significant amount of data collection had to be accomplished, analyzed and tested for accuracy. Allocations had to be made in order to assign appropriate impacts to the various co-products produced by oil refineries. Short of re-creating another detailed LCI for this process, this data proved to be the most reliant. It is used in numerous studies due to the widespread use of Ecoinvent and the relevance of fuel production in life cycle scenarios. The way this method was utilized for the operations phase of this study was simplistic enough to minimize uncertainty to the characterization aspect of impact assessment. As the use of process LCA was limited to two processes in the fuel production phase and the described application in the operations phase, related uncertainty in this study is considered to be minimal.

Functional Unit Selection

This study employed three functional units and reported results in all three units to overcome some of the uncertainty and functional unit bias that can occur when reporting transport results using a single metric.

Chester 2008 offers support of this type of normalization by noting that simply looking at all three aircraft by VKM can mask the number of passengers transported which is the intended function. Looking solely at PKM ignores the overall value of a given trip and LKM provides a scaled up metric that may not be comparable across transport. For example, normalization by PKM omits the emission values on a given flight that are attributed to freight and mail where VKM does not. Normalizing by both highlights the full environmental significance of the passenger transport objective to move people (Chester, 2008).

In order to understand the emissions impacts from a life cycle inventory perspective, the use of the selected normalization factors is essential. Consequentially, the geographic and temporal impacts of these emissions are not differentiated. This increases the potential for uncertainty when the objective is to understand exposure and effects of emissions. For example, the human toxicity emissions (1.4-DB-eq) from the manufacture of the aircraft under study are largely produced from electricity and steel production in specific geographic locations over a short period of time, yet they are normalized by PKM. Another example is the GHG related emissions occurring from powering the aircraft throughout the use phase as they are emitted over large geographic boundaries, but are still expressed using PKM. Moreover, the introduction temporal and geographic variables to a model of this nature may prove to be too complex given current data availability and air transport dynamics.

Although reporting on a single functional unit is often a stated objective in many studies, and no doubt contributes to the transport body of knowledge, this study reports on the selected three in an effort to provide more information for future work.

System Boundary Definition

The system boundary in this study excludes some components that would otherwise be included in full cradle to grave LCA. Particularly, the EOL phase of air transport for all elements was left out of the boundary. The EOL phase for aircraft vehicles is not well documented and some of the studies that do model them have shown relatively small positive contributions to overall life cycles (A.J. Kolios, 2013; Lopes, 2010). These studies as well as other sources propose that aircraft are generally salvaged for parts for reuse (Clark, 2013). It is not, however, clear how long aircraft are stored or what percentage of materials is reused, leaving a higher level of uncertainty with this phase (Cristiano Facanha, 2006). This study opts to leave this phase for a future research endeavor. Although this phase is typically considered in full cradle to grave studies, it was excluded in this work due to the inherent uncertainty in modeling and emphasis on larger impacts.

This study also excludes the use of auxiliary power units (APU), which can be used to power the aircraft when a direct power connection to the terminal or a maintenance building cannot be made. There are relevant emissions associated with these units (Chester, 2008); however, they are only used in situational circumstances and therefore are best modeled in studies where the entire air transport system is under study versus three flight scenarios. This study essentially assumes that APUs were not used.

As this thesis elects to analyze three specific scenario flights, the comparisons, analysis and related discussions are all specific to the assumed model and conditions and parameters. The aviation sector and transport mode is very dynamic and the results generated for the different routes in this model may not be applicable to all markets and similar routes.

Allocation of Impacts

In this thesis it was demonstrated that the passenger and freight load assumptions held significant influence on emissions attributed per PKM. As discussed previously, the allocation factors used for this functional unit were obtained from average annual traffic data for each region that the route occurred in (ICAO, 2012). Due to the relative influence of these factors on any

PKM value, this information provided the most balanced approach and best available data to mitigate uncertainty.

Allocation of freight and mail impacts for the infrastructure components was omitted from this study. It was concluded that the distinction would not be a simple one as many airports segregate their freight terminal and traffic from that of passengers and the related infrastructure is not as sophisticated or material intensive as passenger terminals. In addition, fright traffic at different airports can vary widely and does not appear to have any correlation with passenger capacity. Overall, this issue presented complications that were not considered to have a significant enough impact on overall results to pursue. It is acknowledged that some level of uncertainty is associated with either decision taken on this allocation issue.

Data and Software

Modeling air transport has a number of inherent issues that can influence the results and these have been highlighted throughout this thesis . Any given commercial flight will likely exhibit different PAX loads, freight amounts, destinations, vehicle types, LTO cycle times, fuel used, weather conditions and cruising elevations, among other potential factors. This means that a vast majority of energy use and emissions modeling for this mode must rely on best available information and averaged data in order to communicate a functional unit such as PKM. To accomplish this, a number of data sets and software applications were utilized to reach the most realistic results short of having actual direct data for all life cycle elements.

The input data used to generate LCI data and resulting output are subject to a number of tools and assumptions. The use of the AEM for emissions, Ecoinvent data and processes, ReCiPe characterization factors and CEDA data and matrices for EIOLCA are all tools and datasets that carry a level of uncertainty in the assumptions made to provide useful information, albeit at a high level of quality and acceptance in literature. The AEM model is one of the preeminent tools available to model total aircraft operations energy and emissions; however, it is built on a number of assumptions. For example, the fuel burn calculation relies on three different data sets and must apply a set of model constraints to generate a final emissions number (ref. Figure 15). As the AEM has been reviewed and accepted by ICAO, the methodology and assumptions are deemed to have an acceptable level of uncertainty.

Discussion and Conclusion

General Findings and Policy Implications

The objective of this thesis was to assess the life cycle impacts of passenger air transport on selected planes and routes and additionally, understand the relevance of different life cycle stages across selected environmental stressors. The results generated herein have met those objectives and provided a comprehensive assessment of total life cycle impacts as well as individual analysis of the contributing phases for three different flight and aircraft scenarios. Moreover, results have been normalized to three different functional units and a complete inventory of total impacts has been provided.

This thesis illustrates that there are a number of key variables at play when calculating total life cycle impacts for air transport. Impacts were modeled using popular aircraft vehicles and appropriate case flight assumptions yielding impacts across market and technological classes. By incorporating the life cycle phases, a more complete understanding of supply chain contributions and total impact was introduced. Through normalizing impacts to three different functional units highlighting the passenger, vehicle and vehicle lifetime perspectives, the study conveyed the range of impacts that air transport has when viewed from different functional contexts. Finally, a detailed assessment of process LCA versus EIOLCA for the manufacturing phase of the aircraft life cycle exposed the inherent challenges in modeling manufacturing impacts, as structural process assessments may not capture sufficient shares of relative emissions. The culmination of all of this analysis yielded a more holistic understanding of environmental effects and demonstrated the variation in results that occur in such a dynamic market.

From purely a climate perspective, the overarching outcomes showed that the tailpipe emissions were the largest contributing element to climate change impacts while the production of fuel for this phase held the second largest GHG influence, as well as the primary share of other impact category life cycle contributions. When results were normalized by PKM, the A320 flight became the most GHG intensive on a per kilometer basis for the three scenarios modeled. Having found the fuel burn per passenger/km of the A320 and A380 to be almost equal for the two scenarios, it became clear that the passenger load, LTO inputs and distance assumptions were key elements in the PKM outcome. Additionally, the passenger weight attribution due to freight transport further differentiates these outcomes as larger aircraft typically have higher freight attributions (Chester, 2008; ICAO, 2012; MIT, 2013). Of the three, the A330 scenario turned out to be the most energy efficient[17] per PKM flight to move passengers. This may partially explain aircraft manufacturer focus on the next generation A350XB and Boeing 787 models that have similar passenger capacities and sizes.

Further examination of the model and other literature confirmed that shorter flights by commercial jet aircraft are more emissions intensive per kilometer traveled on a passenger basis (Chester, 2008; M. Federici, 2009). High capacity longer-range aircraft transport passengers more efficiently per PKM as the energy and emissions for LTO are distributed over a longer travel distance and amongst larger volumes of passengers and freight. For example, the LTO fuel burn for Scenario 1 is 19% of the total fuel use while it is only 2.7% for Scenario 3. Simply stated, efficiency increases per kilometer of passenger travel with longer distances and higher passenger loads. Of course, total emissions generated by the longer flights are much higher. This presents a complex dichotomy when attempting to manage aviation emissions and compare transport logistics and policy from a passenger travel standpoint.

Fuel production also proves significant to climate impacts as it produced a total CO_2-eq that was 15.5% of the operation GHG total for all scenarios. This is a substantial contribution to overall emissions that could potentially be improved upon with the introduction of new energy technologies. It is also an important consideration given the often exclusive focus on tailpipe emissions in policy and planning discussions.

After climate and fossil depletion impacts, the production of 1.4 DB-eq had the highest absolute impacts making human toxicity an area of interest in aviation transport. The largest contributing life cycle phase was fuel production with 94% of the total impacts in the case of the A380. The operations phase also contributed to other important impact categories causing 77% of total POF, over 61% of TA and 55% of PMF over the A320 life cycle. Of all life cycle components examined in this research, the construction of infrastructure held the lowest overall impacts in key indicator categories with the exception of metal depletion where contributions exceeded 10% of total in the A320 scenario and 5% for the other cases (PKM). Manufacturing also contributed to metal depletion with up to 38% of the total Fe-eq for the A320. Outside of GHG impacts, infrastructure operation exhibits smaller

[17] Relative to passenger load per km

contributions to a number of key impact categories. In the A320 scenario, these are 7.3% of PMF, 5% of HT, 2.8% of FD, 2.6% of MD to name a few.

The additional stressors examined all became increasingly important when the aircrafts are considered over their VKM and LKM output as accumulation of impacts becomes quite significant. For example, an A380, used under the scenario conditions, will create 412 t 1.4 DB-eq from its operation alone over its lifetime (136 kt 1.4 DB-eq over all life cycle components). Although the fate of all of these pollutants cannot be precisely determined due to the nature of air transport, municipalities that already have elevated HT concerns may have added interest in understanding the LTO contributions they may incur by accommodating this aircraft. There is not much literature analyzing other environmental impacts resulting from aviation; as such, the data presented in this thesis may provide beneficial and unique data.

The findings of this thesis highlight several key points for a policy or management initiative aimed at reducing aviation-based emissions. Foremost, environmental evaluations must consider life cycle emissions to fully understand the implications of aviation transport decisions. Tailpipe assessments are valuable but limited as they can exclude up to 21% of the total emissions associated with the transport of passengers on shorter flights[18]. Exclusion of these emissions could compromise regional environmental targets and agreements, contribute to problem shifting and misinform the policy and planning process. In addition, greater transparency into life cycle issues may facilitate better supply chain coordination and related policy measures. In all, the passenger air transport sector is very dynamic and an understanding of the interactions between different aircraft technologies, life cycle inputs and net energy requirements would prove beneficial.

Benchmarking Findings

To provide context to the results, some comparative work has been done. Benchmarking the results of aviation emissions is challenging in that there are a number a key variables that heavily influence the final result. Of them, vehicle type, distance traveled, PAX capacity, load factors and freight attributions were previously shown to have significant impacts. Despite this, an effort has been made to compare the outcome of Chester's 2008 work as it exhibits the most comparable and accessible LCA results to date. Between the three scenarios reported in this study, findings showed that shorter flights at the 935 km range using a standard A320 produce a total VKM GHG emission of 20 kg CO_2-eq when averaged over the flight duration. The passenger

[18] Assuming the Scenario 1 conditions.

allocation amounted to a total PKM output of 180 g CO_2-eq. The A330 and A380 totals for flights between London, New York and Tokyo were 27 and 63 kg CO_2-eq (per VKM) while PKM totals were 105 and 122 g CO_2-eq, respectively.

Chester's 2008 findings of approximately 130 g CO_2-eq for the Boeing 737 and 124 g CO_2-eq for the Boeing 747 per PKM compare reasonably well to the most conducive Airbus models presented in this thesis given differences in models and vehicle technologies. The variation between the 737 and the A320 is likely due to a difference in aircraft size and related fuel burn as well as the fact that Chester's work is geared towards modeling the U.S. fleet and adopts average data for small, medium and large aircraft types. Relative shares of operating impacts versus other life cycle phases were similar at 19% and 21%, respectively.

Chester also uses an average capacity of 101 passengers implying a load factor of approximately 92% for the 111 passenger 737-600 vehicle used for operations calculations. As was mentioned previously, this thesis utilizes the ICAO factor data with a 74% load factor for the A320. The most comparable 737 model would be the 800 series with its 162 passenger capacity and 5,767 km range. According to AEM data, when this model and the A320 are cruising at the same altitude under nominal conditions, they burn fuel at 43.2 kg/second and 42.4 kg/second, respectively, suggesting an emissions comparison under similar model assumptions would yield close results for the majority share of air transport life cycle emissions (Eurocontrol, 2013). Operational assumptions had to be applied for a specific aircraft and engine model to calculate cruise emissions and it appears that Chester 2008 has adopted the data from the 600 series. Overall, the difference between the aircraft is relative to vehicle size and normalization conditions applied; however, it also demonstrates the wide variability in emission intensities that can occur when modeling global fleets.

The larger Boeing 747-400 is the A380's competition and the two aircraft do have subtle differences despite the close PKM results between this and Chester's work. Non-tailpipe emissions were 16% of total in this study and 25% of total in Chester's. The size difference of the two vehicles is also quite substantial with the A380 seating 525 PAX and the 737-400 seating 416 in typical three-class configuration. The maximum take-off weights reported by the manufacturers are 560mt and 397mt, respectively. The studies also use varying loads with the A380 at 398 PAX while Chester's is 305. This information implies that the A380 is a larger, more fuel intensive vehicle overall but that a combination of the life cycle phase assumptions for the 747, allocations for this vehicle and passenger total leveled the emissions disparity from operations.

Another comparison was made between the results in this thesis and the Ecoinvent database processes for aircraft transport systems. Again, these results were within a comparable range given the dynamic properties of air transport systems. The database contains three different processes that compare the entire transport systems including: operation of aircraft; production of aircraft; construction and land use of airport; operation, maintenance and disposal of airport. Results were normalized to PKM and are reported in GWP 100 CO_2-eq.

The first process "transport, aircraft, passenger, intercontinental, RER, [pkm] (#1897)" was compared to the A380 scenario as it adopted an average passenger capacity of 320 per flight; specific aircraft information was not provided (Ecoinvent, 2012). The total CO_2-eq per PKM was 107 g CO_2-eq which turned out to only be 15 grams lower than the A380 flight results. Operational data was also compared and yielded a PKM attribution of 106 g CO_2-eq, only four grams per PKM higher than scenario 3. As for the A330 scenario, the process "transport, aircraft, passenger, RER, [pkm] (#1895)" was utilized as it adopts an average passenger capacity of 256, ten more than the A330 standard two class cabin. The resulting output per PKM was 125 g CO_2-eq or 20 grams more than scenario 3. Finally, the process "transport, aircraft, passenger, Europe, RER, [pkm] (#1896)" was examined and was found to have a PKM output of 167 g CO_2-eq for life cycle emissions compared to the 180 g CO_2-eq from the A320. The conclusion gained from this was two fold. First, the results generated in this thesis are within an acceptable range of those produced by other studies and databases and second, the dynamic aspects of aviation transport and modeling create challenges when comparing the flight results.

Future Work

This thesis provides an attributional perspective in an effort to facilitate easier adoption of data and future benchmarking for other LCA studies. One of the aims of this work was to provide life cycle environmental data for three popular aircraft and flights using average data. With this in mind, it is important to consider what additional efforts could be made to improve upon this work and the literature and studies currently in existence. The suggestions presented below are based on some of the observations from completing this work but are not exhaustive.

This study opted to omit the end-of-life phases for both the vehicles and infrastructure associated with transport as it was determined to be out of scope. After consideration, it was concluded that this phase carries a higher level of uncertainty in relative treatment and has been shown to have little impact where attempts have been made in other literature (A.J. Kolios, 2013; Chester, 2008; Lopes, 2010). This does not imply that the phase is irrelevant, as it is generally understood there is some net positive contribution to overall life cycle impacts from material re-use and recycling. It is also understood that as global fleets are replaced and some aircraft retired prematurely due to technology advancements, EOL treatment is increasingly becoming more important (Clark, 2013). However, the extent to which actual reuse versus landfilling or incineration is occurring is not presently reported. In addition to this, both operating and next generation aircraft are increasingly being manufactured using much larger portions (+50%) carbon fiber reinforced plastics (CFRP), which currently present a more complicated recycling problem than traditional aluminum materials as it cannot be readily melted down and recycled material is not as strong as virgin (Schelmetic, 2012)

Touching on CFRP also brings to light issues associated with fully understanding the aircraft manufacturing processes and material requirements. Understanding of the material inputs and production processes has been shown to be limited due to data availability in this thesis and thus EIOLCA was used to determine impacts. Although EIOLCA affords the benefit of capturing a wide system boundary and related emissions, the limitations of it inhibit the ability to understand the intricacies of aircraft production and relative environmental impacts in the supply chain. Moreover, as technologies evolve and new materials become increasingly important, understanding their relative environmental contributions becomes increasingly important. An example of this can be seen in CFRP as it is becoming a critical material and is also extremely energy intensive to produce due to high heating temperatures required for production (Das, 2011; Schelmetic, 2012). It is also not documented in LCA databases and as such several attempts have been made to create proxy processes using input assumptions (Lopes, 2010). Overall, the manufacturing phase for aircraft represents an area for continued development to close the gap between EIOLCA and structural component based process LCAs.

The allocation of impacts to passengers is another area that could be analyzed further as airliners utilize a variety of seating configurations to accommodate varying classes. This study did not take into account the differences between class seating arrangements in allocating related weight attributions or load factors. This was not within the scope of the study and was not considered to be feasible to develop given time constraints. Nevertheless there is some interesting work currently being conducted that proposes an allocation approach that depends on average class-specific occupied floor space (Heinrich Bofinger, 2013). Further research into this type of allocation method may be beneficial to quantify impacts in instances when airliners purchase superjumbo aircraft and implement amenities that detract from usable passenger space. Or, to work towards better impact assignments between economy, business and first class arrangements across different vehicle types.

Two final points for potential future work is related to the use of on-aircraft auxiliary power units and the modeling of infrastructure construction in modeling aircraft transport. Chester 2008 has incorporated the use of auxiliary power units into his work; however, the actual usage attribution is difficult to estimate due to the actual use time and provision of power connections at some airports. Additionally, their use is often a concern due to the associated emissions thus providing room for additional research efforts to better model their average contribution to LTO cycles. With regard to infrastructure construction, this study demonstrated that using EIOLCA is possible however; the sector alignment is not completely ideal. Although, it is likely conservative, future efforts aimed at capturing both the unique features (e.g. tarmac, paved surfaces, electronic technology) and services associated with construction would be productive.

Conclusion

This thesis provides a complete life cycle assessment of three different flight scenarios and aircraft vehicles, reporting results using ReCiPe midpoint (H) indicators. Individual life cycle stages are further analyzed and discussed to highlight the significance of their contributions to overall air transport impacts. Results have been presented in graphic and tabular form for all three scenarios and normalized to three different functional units to effectively communicate findings and facilitate further research initiatives. Detailed assessments and discussions pertaining to key findings have been outlined throughout the work to expand the understanding of overall environmental impacts associated with air transport. In addition, it has been shown that life cycle inputs to air transport provide important contributions to overall impacts and that vehicle and flight characteristics are central to passenger environmental outcomes. In all, the work presented has accomplished the stated research goals of this thesis.

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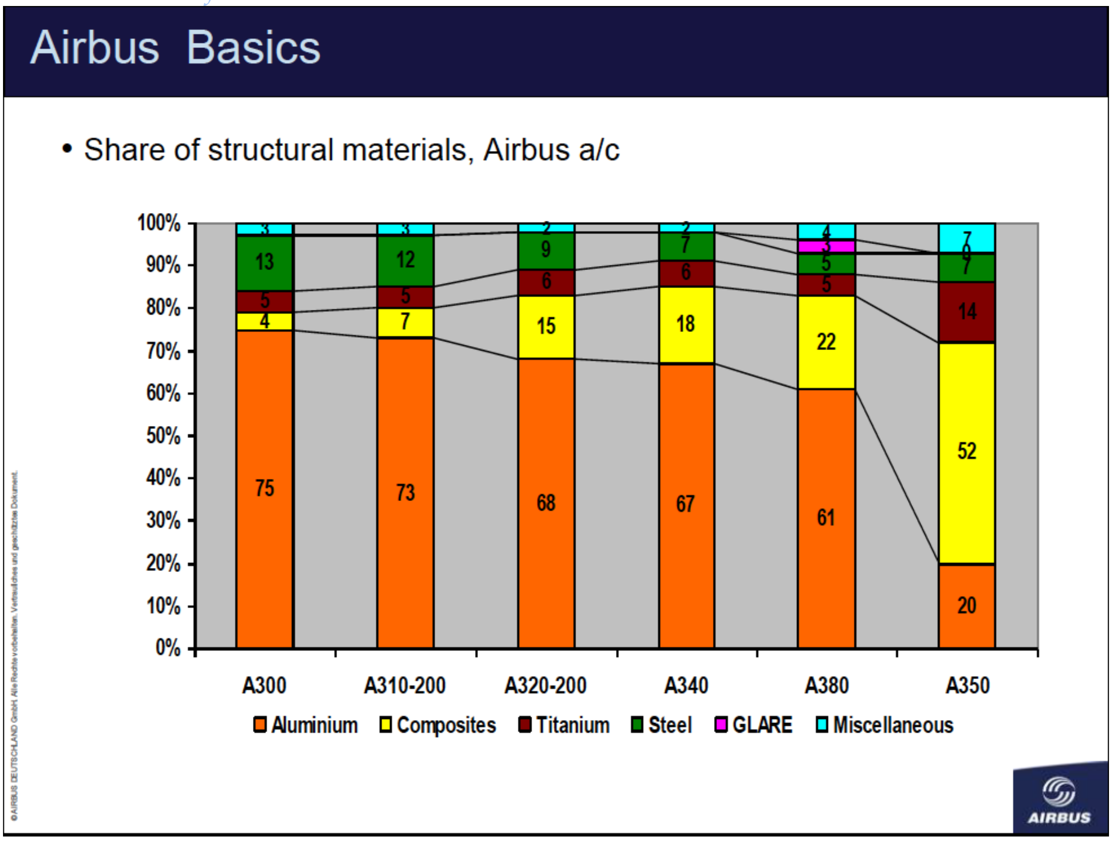
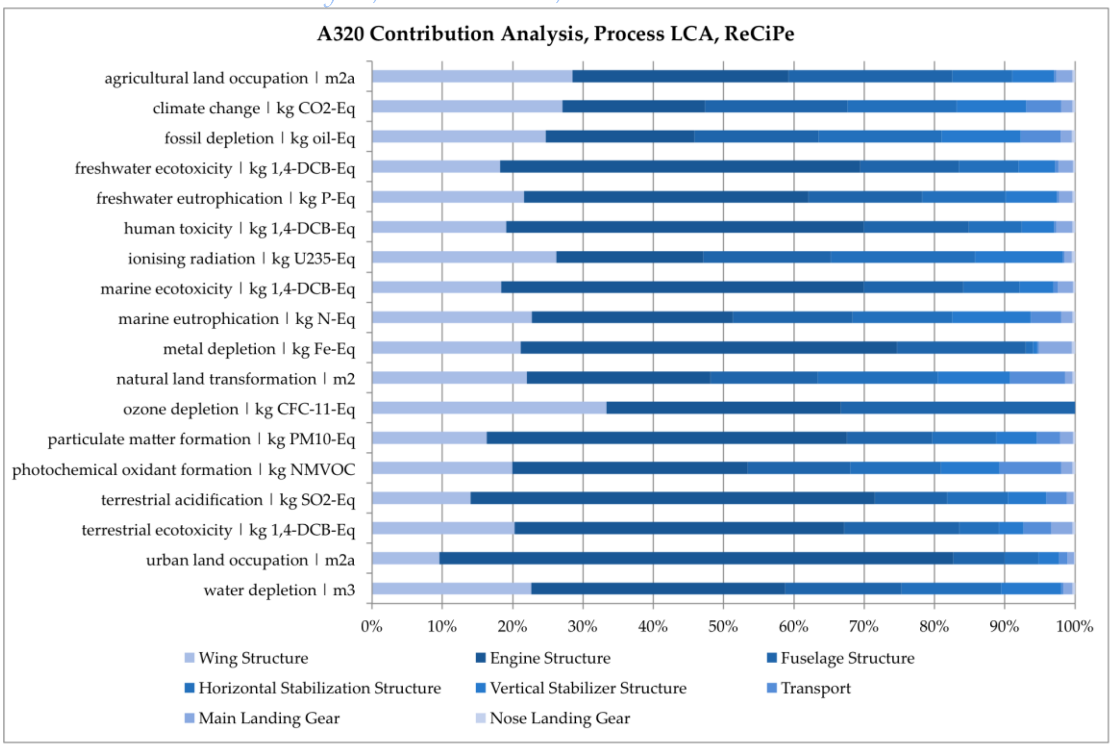
Appendix

Appendix 1: Supplementary Charts, Tables and Diagrams

Airbus Shares of Structural Materials



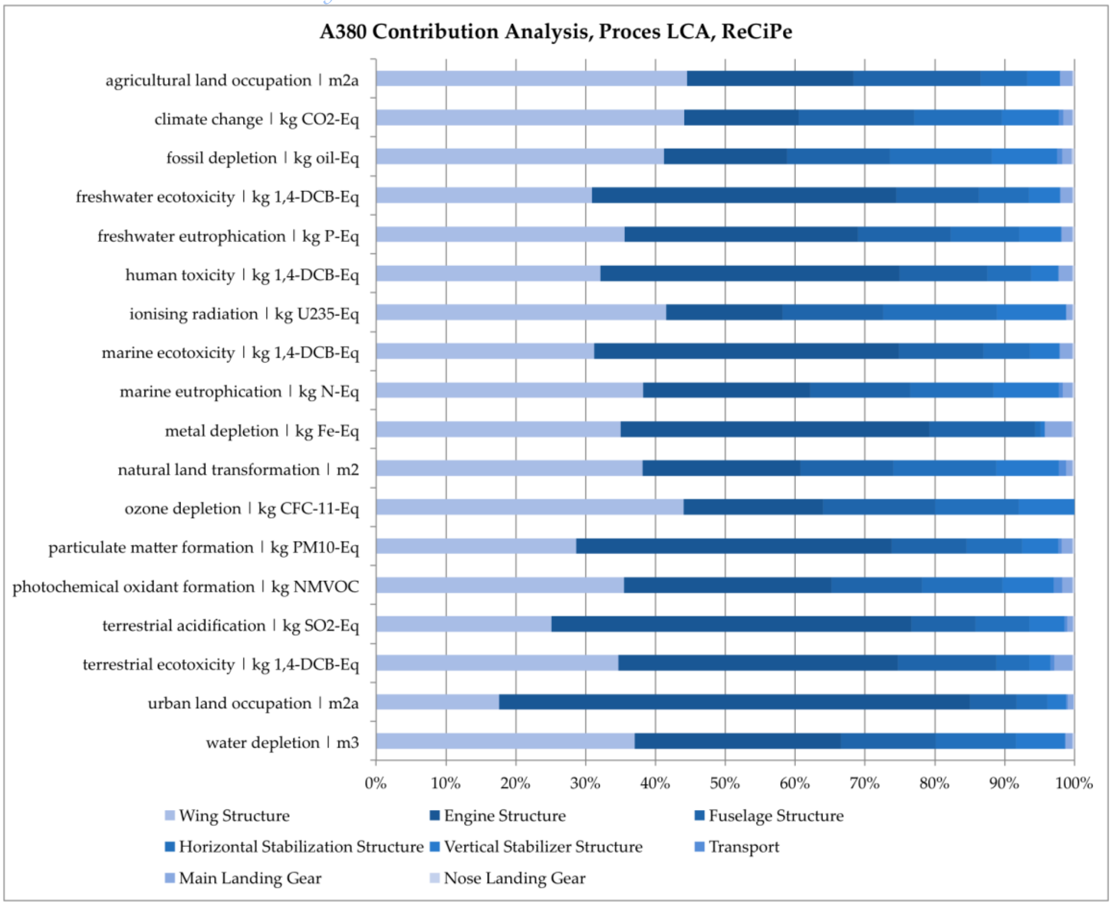
A320 Contribution Analysis, Process LCA, ReCiPe



Corresponding A320 Absolute Values:

agricultural land occupation | m2a	8106.65
climate change | kg CO2-Eq	625138.55
fossil depletion | kg oil-Eq	190718.14
freshwater ecotoxicity | kg 1,4-DCB-Eq	6388.3
freshwater eutrophication | kg P-Eq	310.3
human toxicity | kg 1,4-DCB-Eq	348022.13
ionising radiation | kg U235-Eq	293632.2
marine ecotoxicity | kg 1,4-DCB-Eq	6990.76
marine eutrophication | kg N-Eq	445.69
metal depletion | kg Fe-Eq	86187.1
natural land transformation | m2	192.2
ozone depletion | kg CFC-11-Eq	0.03
particulate matter formation | kg PM10-Eq	1313.95
photochemical oxidant formation | kg NMVOC	1918.54
terrestrial acidification | kg SO2-Eq	4274.89
terrestrial ecotoxicity | kg 1,4-DCB-Eq	73.69
urban land occupation | m2a	7345.71
water depletion | m3	4137.33

A380 Contribution Analysis, Process LCA, ReCiPe

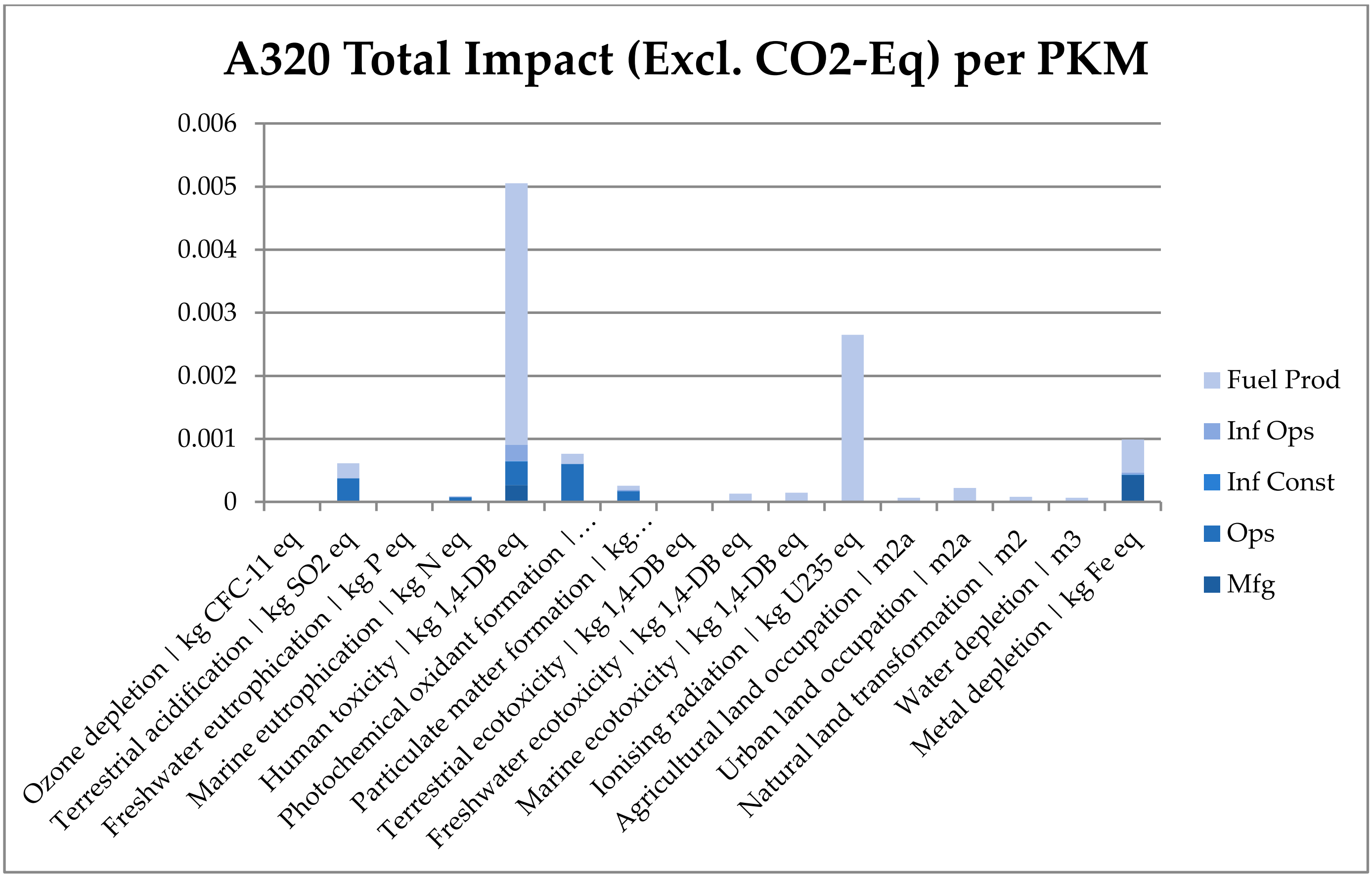


Corresponding A380 Absolute Values

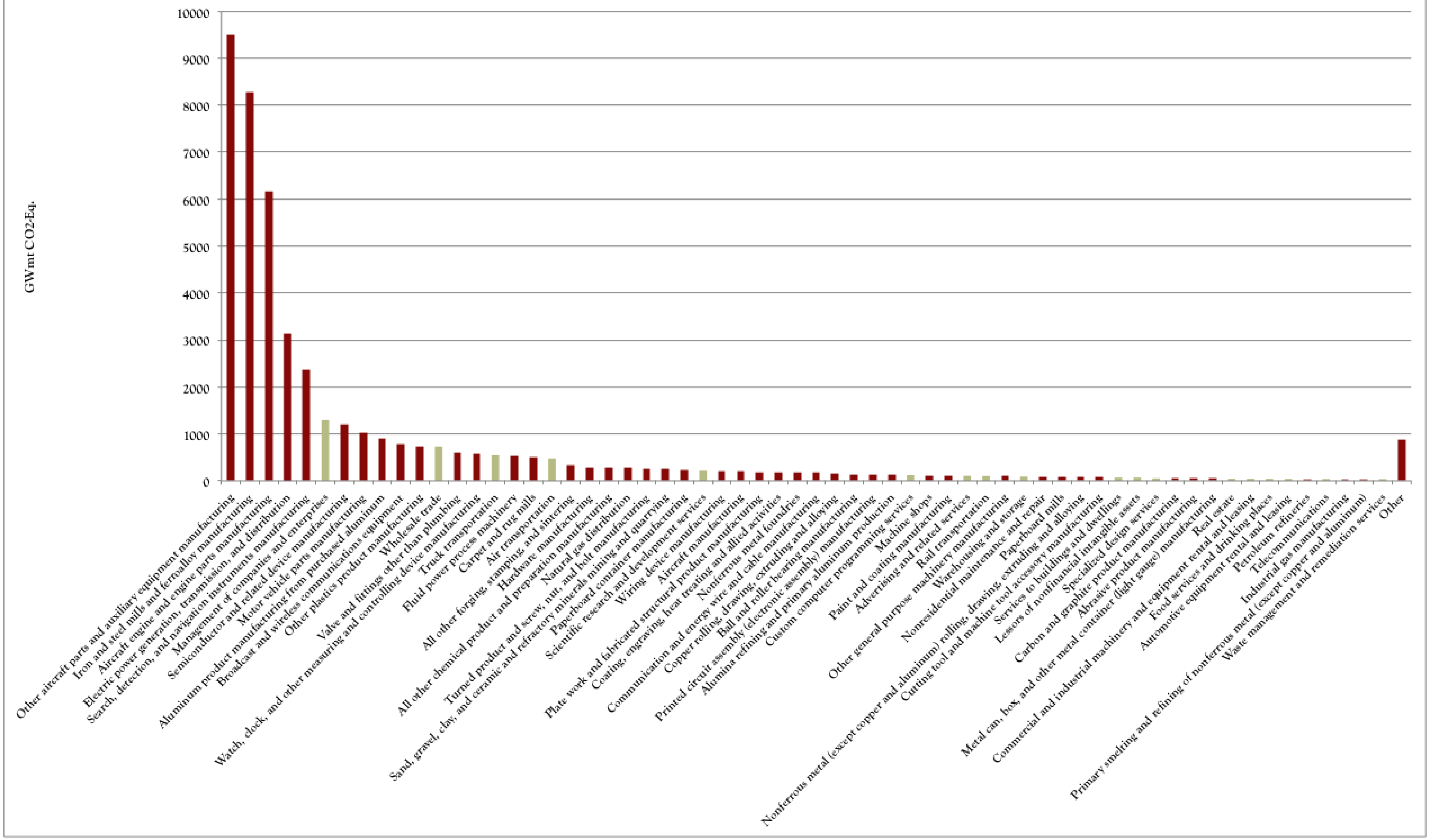
agricultural land occupation | m2a	66117.86
climate change | kg CO2-Eq	4886010.76
fossil depletion | kg oil-Eq	1454559.58
freshwater ecotoxicity | kg 1,4-DCB-Eq	47859.83
freshwater eutrophication | kg P-Eq	2394.03
human toxicity | kg 1,4-DCB-Eq	2628677.97
ionising radiation | kg U235-Eq	2351106.5
marine ecotoxicity | kg 1,4-DCB-Eq	52406.34
marine eutrophication | kg N-Eq	3374.47
metal depletion | kg Fe-Eq	662888.31
natural land transformation | m2	1409.81
ozone depletion | kg CFC-11-Eq	0.26
particulate matter formation | kg PM10-Eq	9482.36
photochemical oxidant formation | kg NMVOC	13735.18
terrestrial acidification | kg SO2-Eq	30322.43
terrestrial ecotoxicity | kg 1,4-DCB-Eq	548.03

urban land occupation | m2a	50693.5
water depletion | m3	32177.53

Life Cycle Total Impacts for Selected Environmental Impacts per PKM



Tier 1+ Sector GHGs for Aircraft Manufacturing; Goods Producing vs Services



Life Cycle	ReCiPe Midpoint	Unit	A320 | LKM	A320 | VKM	A320 | PKM	A330 | LKM	A330 | VKM	A330 | PKM	A380 | LKM	A380 | VKM	A380 | PKM
Mfg	**Climate change**	**kg CO2 eq**	20981272	7.10E-01	6.34E-03	50839236	7.46E-01	2.89E-03	82841544	9.96E-01	1.92E-03
	Ozone depletion	**kg CFC-11 eq**	58	1.98E-06	1.77E-08	142	2.08E-06	8.07E-09	231	2.78E-06	5.36E-09
	Terrestrial acidification	**kg SO2 eq**	10587	3.58E-04	3.20E-06	25653	3.77E-04	1.46E-06	41802	5.03E-04	9.70E-07
	Freshwater eutrophication	**kg P eq**	61	2.06E-06	1.84E-08	147	2.16E-06	8.39E-09	240	2.89E-06	5.58E-09
	Marine eutrophication	**kg N eq**	770	2.61E-05	2.33E-07	1866	2.74E-05	1.06E-07	3041	3.66E-05	7.06E-08
	Human toxicity	**kg 1,4-DB eq**	880503	2.98E-02	2.66E-04	2133527	3.13E-02	1.21E-04	3476541	4.18E-02	8.07E-05
	Photochemical oxidant formation	**kg NMVOC**	4321	1.46E-04	1.31E-06	10469	1.54E-04	5.96E-07	17059	2.05E-04	3.96E-07
	Particulate matter formation	**kg PM10 eq**	58224	1.97E-03	1.76E-05	141080	2.07E-03	8.03E-06	229888	2.76E-03	5.34E-06
	Terrestrial ecotoxicity	**kg 1,4-DB eq**	3032	1.03E-04	9.16E-07	7347	1.08E-04	4.18E-07	11972	1.44E-04	2.78E-07
	Freshwater ecotoxicity	**kg 1,4-DB eq**	7761	2.63E-04	2.34E-06	18806	2.76E-04	1.07E-06	30644	3.68E-04	7.11E-07
	Marine ecotoxicity	**kg 1,4-DB eq**	4641	1.57E-04	1.40E-06	11246	1.65E-04	6.40E-07	18325	2.20E-04	4.25E-07

	Ionising radiation	**kg U235 eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Agricultural land occupation	**m2a**	0	2.70E-09	2.41E-11	0	2.84E-09	1.10E-11	0	3.79E-09	7.32E-12
	Urban land occupation	**m2a**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Natural land transformation	**m2**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Water depletion	**m3**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Metal depletion	**kg Fe eq**	1422678	4.82E-02	4.30E-04	3447257	5.06E-02	1.96E-04	5617238	6.75E-02	1.30E-04
	Fossil depletion	**kg oil eq**	4950622	1.68E-01	1.50E-03	11995738	1.76E-01	6.83E-04	19546821	2.35E-01	4.54E-04
Ops	**Climate change**	**kg CO2 eq**	469112981	1.59E+01	1.42E-01	1524712231	2.24E+01	8.68E-02	4400282194	5.29E+01	1.02E-01
	Ozone depletion	**kg CFC-11 eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Terrestrial acidification	**kg SO2 eq**	1227860	4.16E-02	3.71E-04	4126978	6.06E-02	2.35E-04	16178925	1.95E-01	3.76E-04
	Freshwater eutrophication	**kg P eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Marine eutrophication	**kg N eq**	252460	8.55E-03	7.63E-05	851644	1.25E-02	4.85E-05	3434463	4.13E-02	7.97E-05
	Human toxicity	**kg 1,4-DB eq**	1230388	4.16E-02	3.72E-04	5766183	8.47E-02	3.28E-04	412111	4.96E-03	9.57E-06

	Photochemical oxidant formation	**kg NMVOC**	1996299	6.76E-02	6.03E-04	6707247	9.85E-02	3.82E-04	26943378	3.24E-01	6.26E-04
	Particulate matter formation	**kg PM10 eq**	502709	1.70E-02	1.52E-04	1602182	2.35E-02	9.12E-05	6289297	7.56E-02	1.46E-04
	Terrestrial ecotoxicity	**kg 1,4-DB eq**	316	1.07E-05	9.54E-08	1107	1.63E-05	6.30E-08	87	1.04E-06	2.02E-09
	Freshwater ecotoxicity	**kg 1,4-DB eq**	0	0.00E+00	0.00E+00	492	7.22E-06	2.80E-08	0	0.00E+00	0.00E+00
	Marine ecotoxicity	**kg 1,4-DB eq**	632	2.14E-05	1.91E-07	2829	4.15E-05	1.61E-07	174	2.09E-06	4.03E-09
	Ionising radiation	**kg U235 eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Agricultural land occupation	**m2a**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Urban land occupation	**m2a**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Natural land transformation	**m2**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Water depletion	**m3**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Metal depletion	**kg Fe eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Fossil depletion	**kg oil eq**	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
Inf Const	**Climate change**	**kg CO2 eq**	12209809	4.13E-01	3.73E-03	10619747	1.56E-01	7.43E-04	23111183	2.78E-01	6.97E-04
	Ozone depletion	**kg CFC-**	11	3.71E-07	3.35E-09	10	1.40E-07	6.68E-10	21	2.50E-07	6.27E-10

	11 eq									
Terrestrial acidification	kg SO2 eq	14575	4.93E-04	4.45E-06	12677	1.86E-04	8.87E-07	27587	3.32E-04	8.32E-07
Freshwater eutrophication	kg P eq	60	2.03E-06	1.83E-08	52	7.64E-07	3.64E-09	113	1.36E-06	3.42E-09
Marine eutrophication	kg N eq	954	3.23E-05	2.91E-07	830	1.22E-05	5.81E-08	1806	2.17E-05	5.45E-08
Human toxicity	kg 1,4-DB eq	673442	2.28E-02	2.05E-04	585741	8.60E-03	4.10E-05	1274715	1.53E-02	3.85E-05
Photochemical oxidant formation	kg NMVOC	4418	1.50E-04	1.35E-06	3843	5.64E-05	2.69E-07	8362	1.01E-04	2.52E-07
Particulate matter formation	kg PM10 eq	51777	1.75E-03	1.58E-05	45035	6.61E-04	3.15E-06	98006	1.18E-03	2.96E-06
Terrestrial ecotoxicity	kg 1,4-DB eq	1732	5.86E-05	5.28E-07	1506	2.21E-05	1.05E-07	3278	3.94E-05	9.89E-08
Freshwater ecotoxicity	kg 1,4-DB eq	7153	2.42E-04	2.18E-06	6222	9.13E-05	4.36E-07	13540	1.63E-04	4.09E-07
Marine ecotoxicity	kg 1,4-DB eq	2045	6.92E-05	6.24E-07	1779	2.61E-05	1.25E-07	3872	4.66E-05	1.17E-07
Ionising radiation	kg U235 eq	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
Agricultural land occupation	m2a	0	3.78E-09	3.41E-11	0	1.43E-09	6.80E-12	0	2.54E-09	6.38E-12

	Urban land occupation	m2a	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Natural land transformation	m2	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Water depletion	m3	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Metal depletion	kg Fe eq	472610	1.60E-02	1.44E-04	411063	6.03E-03	2.88E-05	894574	1.08E-02	2.70E-05
	Fossil depletion	kg oil eq	4309134	1.46E-01	1.31E-03	3747963	5.50E-02	2.62E-04	8156489	9.81E-02	2.46E-04
Inf Ops	Climate change	kg CO2 eq	20673735	7.00E-01	6.31E-03	17981431	2.64E-01	1.26E-03	39132018	4.71E-01	1.18E-03
	Ozone depletion	kg CFC-11 eq	4	1.38E-07	1.24E-09	4	5.20E-08	2.48E-10	8	9.26E-08	2.32E-10
	Terrestrial acidification	kg SO2 eq	10753	3.64E-04	3.28E-06	9353	1.37E-04	6.55E-07	20354	2.45E-04	6.14E-07
	Freshwater eutrophication	kg P eq	39	1.32E-06	1.19E-08	34	4.98E-07	2.37E-09	74	8.87E-07	2.23E-09
	Marine eutrophication	kg N eq	526	1.78E-05	1.60E-07	457	6.71E-06	3.20E-08	995	1.20E-05	3.00E-08
	Human toxicity	kg 1,4-DB eq	843541	2.86E-02	2.57E-04	733688	1.08E-02	5.14E-05	1596686	1.92E-02	4.82E-05
	Photochemical oxidant formation	kg NMVOC	2639	8.93E-05	8.05E-07	2296	3.37E-05	1.61E-07	4996	6.01E-05	1.51E-07
	Particulate matter formation	kg PM10 eq	74874	2.53E-03	2.28E-05	65123	9.56E-04	4.56E-06	141724	1.70E-03	4.28E-06
	Terrestrial	kg 1,4-	1485	5.03E-05	4.53E-07	1292	1.90E-05	9.04E-08	2811	3.38E-05	8.48E-08

	ecotoxicity	DB eq									
	Freshwater ecotoxicity	kg 1,4-DB eq	5111	1.73E-04	1.56E-06	4445	6.53E-05	3.11E-07	9674	1.16E-04	2.92E-07
	Marine ecotoxicity	kg 1,4-DB eq	1967	6.66E-05	6.00E-07	1711	2.51E-05	1.20E-07	3723	4.48E-05	1.12E-07
	Ionising radiation	kg U235 eq	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Agricultural land occupation	m2a	0	2.04E-09	1.84E-11	0	7.71E-10	3.68E-12	0	1.37E-09	3.45E-12
	Urban land occupation	m2a	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Natural land transformation	m2	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Water depletion	m3	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00
	Metal depletion	kg Fe eq	109057	3.69E-03	3.33E-05	94854	1.39E-03	6.64E-06	206427	2.48E-03	6.23E-06
	Fossil depletion	kg oil eq	5794425	1.96E-01	1.77E-03	5039827	7.40E-02	3.53E-04	10967904	1.32E-01	3.31E-04
Fuel Prod	Climate change	kg CO2 eq	73322453	2.48E+00	2.21E-02	235156331	3.45E+00	1.34E-02	687764521	8.27E+00	1.60E-02
	Ozone depletion	kg CFC-11 eq	0	0.00E+00	0.00E+00	246	3.61E-06	1.40E-08	608	7.31E-06	1.41E-08
	Terrestrial acidification	kg SO2 eq	772231	2.61E-02	2.33E-04	2476581	3.64E-02	1.41E-04	7243280	8.71E-02	1.68E-04
	Freshwater	kg P eq	12007	4.06E-04	3.63E-06	38499	5.65E-04	2.19E-06	112575	1.35E-03	2.61E-06

	eutrophication									
	Marine eutrophication	**kg N eq**	48343	1.64E-03	1.46E-05	155101	2.28E-03	8.83E-06	453774	5.46E-03	1.05E-05
	Human toxicity	**kg 1,4-DB eq**	13736802	4.65E-01	4.15E-03	44056073	6.47E-01	2.51E-03	128851160	1.55E+00	2.99E-03
	Photochemical oxidant formation	**kg NMVOC**	520719	1.76E-02	1.57E-04	1670446	2.45E-02	9.51E-05	4885705	5.87E-02	1.13E-04
	Particulate matter formation	**kg PM10 eq**	214228	7.25E-03	6.47E-05	687440	1.01E-02	3.91E-05	2010474	2.42E-02	4.67E-05
	Terrestrial ecotoxicity	**kg 1,4-DB eq**	40760	1.38E-03	1.23E-05	130625	1.92E-03	7.44E-06	381993	4.59E-03	8.87E-06
	Freshwater ecotoxicity	**kg 1,4-DB eq**	428140	1.45E-02	1.29E-04	1373158	2.02E-02	7.82E-05	4016175	4.83E-02	9.32E-05
	Marine ecotoxicity	**kg 1,4-DB eq**	485962	1.64E-02	1.47E-04	1558272	2.29E-02	8.87E-05	4557440	5.48E-02	1.06E-04
	Ionising radiation	**kg U235 eq**	8767540	2.97E-01	2.65E-03	28118998	4.13E-01	1.60E-03	82240060	9.89E-01	1.91E-03
	Agricultural land occupation	**m2a**	216124	7.32E-03	6.53E-05	693221	1.02E-02	3.95E-05	2027487	2.44E-02	4.71E-05
	Urban land occupation	**m2a**	727363	2.46E-02	2.20E-04	2332426	3.42E-02	1.33E-04	6821535	8.20E-02	1.58E-04
	Natural land transformation	**m2**	270786	9.17E-03	8.18E-05	868617	1.28E-02	4.94E-05	2540629	3.05E-02	5.90E-05
	Water depletion	**m3**	214228	7.25E-03	6.47E-05	686702	1.01E-02	3.91E-05	2008391	2.41E-02	4.66E-05

Metal depletion	**kg Fe eq**	1713506	5.80E-02	5.18E-04	5495709	8.07E-02	3.13E-04	16073380	1.93E-01	3.73E-04
Fossil depletion	**kg oil eq**	188400361	6.38E+00	5.69E-02	604228941	8.87E+00	3.44E-02	1767195202	2.12E+01	4.10E-02

Note: All additional supporting materials for evaluation are accessible in an online cloud folder. To obtain access, email the author at ty.m.lewis@gmail.com.