

Manuscript Number:

Title: Eco-Efficient Lightweight Carbon-Fiber Reinforced Polymer for Environmentally Greener Commercial Aviation Industry

Article Type: Full Length Article

Keywords: carbon-fiber reinforced polymer; aluminum alloy, fuselage, OpenLCA, Ecoinvent

Corresponding Author: Prof. John F. Khalil, Ph.D., Sc.D.

Corresponding Author's Institution: United Technologies Research Center

First Author: John F. Khalil, Ph.D., Sc.D.

Order of Authors: John F. Khalil, Ph.D., Sc.D.

**Abstract:** This research aims to perform comparative impact assessment for production of conventional aluminum alloy (AlMg3) used in aircraft fuselage and lighter weight carbon-fiber reinforced polymer (CFRP). The assessment framework is demonstrated by postulating an alternative scenario where AlMg3 in Boeing B737-800 fuselage is substituted with CFRP to reduce the fuselage weight by about 4.3 tons. OpenLCA 1.4.2 platform, including Ecoinvent v2.2 database and TRACE 2.1 for impact assessment, is used to quantify and compare impact categories of the base case (using AlMg3) and alternative scenarios. The mass ratio of carbon fiber (CF) to polypropylene (PP) matrix in CFRP is used as a sensitivity parameter and Monte Carlo sampling technique is employed to quantify assessment's uncertainties. The results identify environmental hot spots in CF production process and show that AlMg3 production has the largest global warming footprint followed by CFRP (containing 53.8 wt.% CF), then CFRP (containing 30 wt.% CF). Similar trends are obtained with ecotoxicity, human health (carcinogens and non-carcinogens), and ozone depletion. However, acidification, eutrophication, photochemical ozone (smog) formation, and respiratory effects are largest for CFRP (53.8 wt.% CF), followed by CFRP (30 wt.% CF), then AlMg3. The results support the study's research hypothesis (H1) which claims potential environmental and human health benefits associated with replacing AlMg3 with CFRP in Boeing B737-800 fuselage. Given the assumed alternative scenario, it is estimated that the global fleet of Boeing B737-800 can achieve a net carbon footprint reduction of about 81,000 tons CO<sub>2</sub> eq. This contribution underlines the important roles of CFRP and CF content in CFRP in reducing heat-trapping greenhouse gas emissions attributed to commercial aviation. It also highlights the need for reducing energy intensity of the carbonization step in CF production. Other global commercial aircraft (~26,000 aircraft) could adopt the insights of this contribution to shrink their carbon footprint and cultivate their net positive environmental impacts.

Suggested Reviewers: Knut Vagsaether Ph.D.  
Professor, Telemark College, Norway  
knut.vagsaether@hit.no

Expert on life cycle analysis and green energy.

Deanna Cox

Fellow, Yale University

deanna.cox@yale.edu

Expert in life cycle analysis and OpenLCA platform

Frank Rahn Ph.D.

ANS Fellow, EPRI

frank\_rahn@att.net

Expert on life cycle analysis and green energy systems.

May 30, 2016

Editor, Sustainable Production and Consumption (SPC)

Subject: Submittal of manuscript for publication in SPC

Dear Journal Editor,

I've submitted my manuscript entitled "Eco-Efficient Lightweight Carbon-Fiber Reinforced Polymer for Environmentally Greener Commercial Aviation Industry" for potential publication in SPC.

Best wishes,

Yehia Khalil, Ph.D., Sc.D.  
Professor of Chemical & Environmental Engineering  
Yale University  
USA  
Primary email: [yehia.khalil@yale.edu](mailto:yehia.khalil@yale.edu)

Alternate emails:

[khalilyf@utrc.utc.com](mailto:khalilyf@utrc.utc.com)

[Khalil@alum.mit.edu](mailto:Khalil@alum.mit.edu)

[ykhalil@alumni.stanford.edu](mailto:ykhalil@alumni.stanford.edu)

[ykhalil@fas.harvard.edu](mailto:ykhalil@fas.harvard.edu)

### Highlights

- Quantified potential benefits of replacing AlMg3 with CFRP in aircraft fuselage.
- Compared impact categories for production of AlMg3 and CFRP of different CF content.
- Conducted uncertainty analysis of impact categories using Monte Carlo technique.
- Identified environmental hot-spot steps in PAN-based CF production process.
- Proposed approaches for commercial aviation to cultivate a net positive environment.

# Eco-Efficient Lightweight Carbon-Fiber Reinforced Polymer for Environmentally Greener Commercial Aviation Industry

Yehia F. Khalil, Ph.D., Sc.D.

*Physical Sciences Department, United Technologies Research Center (UTRC)*  
411 Silver Lane, East Hartford, CT 06108 USA  
[khalilyf@utrc.utc.com](mailto:khalilyf@utrc.utc.com)

## Abstract

This research aims to perform comparative impact assessment for production of conventional aluminum alloy (AlMg3) used in aircraft fuselage and lighter weight carbon-fiber reinforced polymer (CFRP). The assessment framework is demonstrated by postulating an alternative scenario where AlMg3 in Boeing B737-800 fuselage is substituted with CFRP to reduce the fuselage weight by about 4.3 tons. OpenLCA 1.4.2 platform, including Ecoinvent v2.2 database and TRACE 2.1 for impact assessment, is used to quantify and compare impact categories of the base case (using AlMg3) and alternative scenarios. The mass ratio of carbon fiber (CF) to polypropylene (PP) matrix in CFRP is used as a sensitivity parameter and Monte Carlo sampling technique is employed to quantify assessment's uncertainties. The results identify environmental hot spots in CF production process and show that AlMg3 production has the largest global warming footprint followed by CFRP (containing 53.8 wt.% CF), then CFRP (containing 30 wt.% CF). Similar trends are obtained with ecotoxicity, human health (carcinogens and non-carcinogens), and ozone depletion. However, acidification, eutrophication, photochemical ozone (smog) formation, and respiratory effects are largest for CFRP (53.8 wt.% CF), followed by CFRP (30 wt.% CF), then AlMg3. The results support the study's research hypothesis ( $H_1$ ) which claims potential environmental and human health benefits associated with replacing AlMg3 with CFRP in Boeing B737-800 fuselage. Given the assumed alternative scenario, it is estimated that the global fleet of Boeing B737-800 can achieve a net carbon footprint reduction of about 81,000 tons CO<sub>2</sub> eq. This contribution underlines the important roles of CFRP and CF content in CFRP in reducing heat-trapping greenhouse gas emissions attributed to commercial aviation. It also highlights the need for reducing energy intensity of the carbonization step in CF production. Other global commercial aircraft ( $\approx$  26,000 aircraft) could adopt the insights of this contribution to shrink their carbon footprint and cultivate their net positive environmental impacts.

**Keywords:** carbon-fiber reinforced polymer; aluminum alloy, fuselage, OpenLCA, Ecoinvent

---

**Abbreviation list:** AlMg3, aluminum 3 wt.% magnesium alloy; CFRP, carbon-fiber reinforced polymer, CF, carbon fiber, EP, epoxy; FU, functional unit; LCA, life cycle assessment; LCIA, life cycle impact assessment; MCS, Monte Carlo sampling; PAN, polyacrylonitrile; PP, polypropylene; VOC; volatile organic compounds.

## 1. Introduction

This Section is divided into two Subsections: Subsection 1.1 provides background information about air pollution from commercial aviation and highlights key contributions of other researchers in this area and Subsection 1.2 outlines the importance and objectives of this research.

### 1.1 Background

Over the past three decades, the annual growth rate of world commercial air transport has averaged  $\approx 5\%$  and is projected to double over the next decade or two (Macintosh & Wallace, 2009). Moreover, Macintosh (2009) reported that by 2026, passenger and cargo traffic will rise by 2.2 fold. On a global scale, environmentalists as well as other governmental and private stakeholders are concerned about air pollution caused by the commercial aviation sector as demand for air transport ramps up year after year. In particular, emissions of  $\text{CO}_2$ , CO,  $\text{NO}_x$ ,  $\text{SO}_x$ ,  $\text{H}_2\text{O}$ , unburned hydrocarbons (UHC)/ VOC, and particulate matter (PM)/ soot, among many other toxic air pollutants, are generated not only during aircraft take-off, cruising and landing phases, but also during all the other phases of the aircraft life cycle including structural materials production, end-of-life disposal, and recycling. As a result, reducing aircraft weight to minimize aviation fuel consumption has become a central goal for the air transport sector. Reduction of aircraft weight can be achieved by substitution of metal-based alloys, commonly used in aircraft structures and components, with lighter weight composite materials. It should be noted that besides their use in aerospace applications, fiber-reinforced composites have broad applications such as structural materials for buildings, power electronics circuit boards, ships, wind turbine blades, and automotive.

Our review of the literature shows that several life cycle impact assessments (LCIA) of reinforced composites have been conducted using SimaPro platform. For example, Suzuki and Takahashi (2005) performed impact assessment for carbon-fiber reinforced composites used in passenger vehicles and noted that high cost and high energy intensity of producing such composites are major obstacles for their use in broad ranges of industrial applications. Song et al. (2009) reported potential energy savings resulting from use of glass-fiber/unsaturated polyester in the automotive industry. They focused on energy consumption of the pultrusion process (which has an energy intensity of  $\approx 3.1$  MJ/kg) for material production and manufacturing phases of the life cycle. Also, they demonstrated feasibility of using composites as a substitute for steel. In the steel case, Mazumdar (2002) cited a 60-80% reduction in weight can be achieved by replacing steel components with CFRP components. Duflou et al. (2012) used life cycle assessment (LCA) to quantify environmental impacts of fiber-reinforced composites over the life cycle. Also, they estimated potential energy savings that result from substituting metal-based structures with bio-based and traditional fiber-reinforced composites. They compared CFRP versus aluminum and steel for the automotive application and reported  $\approx 50$ -70 wt.% reduction could be achieved by replacing metals like aluminum and steel with CFRP. Scelsi et al. (2011) performed LCA to compare environmental consequences of Al-2024, GLARE (glass fiber Al laminate), and CFRP. They used SimaPro 7.1 together with Ecoinvent database and Eco-indicator 99 (E) to integrate estimated impact categories into a single score. Interestingly, however, the authors expressed their concerns about use of the aggregated single score as it is derived using subjective weighting factors. They concluded that the environmental impacts associated with Al-2024 life cycle are more severe compared to that of CFRP. A similar conclusion was reported by Marcinko (2013) who performed LCA for CFRP as a substitute for a steel tube. He concluded that use of lightweight composites and hybrid composites such as GLARE in commercial aviation would result in positive environmental

benefits. Asmatulu et al. (2013) discussed potential reuse and recycling of some aircraft components such as the engines, landing gears, and avionics but not the fuselage. They also noted that presence of elements such as magnesium (Mg), copper (Cu), zinc (Zn) and titanium (Ti) makes recyclability of aluminum alloys a complex process that involves specialized sorting and separation tasks. In this author's opinion, the assumption made by some researchers that aluminum alloys, like Al-2024, are 100% recyclable at end of life does not apply to the aerospace industry which adopts stringent safety and reliability requirements.<sup>1</sup>

### *1.2 Research importance and objectives*

With increased annual demand for commercial aviation, it becomes critically important to curb emissions of air pollutants attributed to this air transport sector due to the deleterious effects on human health and the environment. From a broader perspective, the importance of this scientific contribution is manifested by its support the overarching goal of the air transport sector in creating an environmentally greener commercial aircraft by replacing aircraft's conventional structural materials by lighter weight composites. To this end, more research is needed to improve our understanding of how lightweight fiber-reinforced composites like CFRP can play a major role in reducing aircraft weight, which leads to reducing fuel consumption and associated emissions of air pollutants.

Currently, commercial aircraft like Boeing B737-800 uses AlMg3 as the primary structural material (Table 1) and very small proportions of composite materials are employed as aircraft structural materials. For example, B737-800 contains 2 wt.% GFRP, 6 wt.% CFRP, 70 wt.% AlMg3, 4 wt.% nickel, 3 wt.% iron-nickel-chromium alloy, 6 wt.% steel, and 9 wt.% titanium (Liu, 2013). Obviously, there is room for increasing the use of CFRP as a structural material to boost fuel economy in commercial aircraft. Accordingly, this scientific contribution has two central objectives as follows:

- a) Use a quantitative cradle-to-gate framework to provide comparative assessment of the environmental and health impact categories associated with production of one functional unit (FU) of AlMg3 (conventional aircraft structural material) and CFRP (substitute material).
- b) Demonstrate utility of the proposed framework by using a hypothetical (alternative) scenario in which AlMg3 in Boeing B737-800 is replaced by CFRP to reduce the fuselage weight by  $\approx$  4.3 metric tons.

As can be seen in Table 1, AlMg3 represents about 92% of the Boeing B737-800 fuselage weight. For the purpose of this study, this proportion denotes the business as usual (BAU) or base case scenario to be compared against the alternative scenario.

---

<sup>1</sup> For safety reasons that are driven by changes in the intrinsic properties of used aluminum alloys, the aerospace industry does not allow recyclable metals to be reused in aircraft structure as substitutes for virgin metals alloys.

**Table 1**

Breakdown of AlMg3 content in the primary components in Boeing B737-800 (Liu, 2013).

Primary Component	Weight, kg	AlMg3 Weight, kg	AlMg3 Content (wt. %)
Fuselage	11,764	10,781	92.0
Wings	13,428	12,628	94.0
Stabilizers	1,519	1,085	71.4
Landing gear	3,416	450	13.2
Nacelles & Pylons	2,664	964	36.2
Engine	5,504	1000	18.2

While focus of the alternative scenario is on reducing the fuselage weight, the proposed cradle-to-gate framework can be applied to other primary components such as the aircraft wings where AlMg3 weight represents about 94% of the wings' weight (Table 1).

The remainder of this manuscript is organized into three sections as follows: Section 2 “Methodology” contains eight subsections. Subsection 2.1 presents the rationale for substituting AlMg3 with CFRP and Subsection 2.2 defines the scope and system boundary of this research. Subsection 2.3 discusses the functional unit (FU) that this research adopts, Subsection 2.4 identifies the impact assessment methodology, and Subsections 2.5 and 2.6 discuss sources of foreground and secondary data used in this research. Finally, Subsection 2.7 highlights key assumptions made in this research and Subsection 2.8 discusses hypothesis testing and defines claims of null hypothesis (denoted  $H_0$ ) and research hypothesis (denoted  $H_1$ ). Section 3 “Results and discussion” is organized into four subsections. Subsection 3.1 discusses results of the comparative impact assessment of cradle-to-gate production of AlMg3 and CFRP (containing 53.8 wt.% CF), Subsection 3.2 compares impact assessment results of AlMg3, CFRP (containing 30 wt.% CF), and CFRP (containing 53.8 wt.% CF) using CF content in CFRP as the sensitivity parameter. Subsection 3.3 discusses uncertainty analysis using Monte Carlo sampling (MCS) technique. Here, uncertainty associated with the inputs in process models (as discussed in Subsections 2.5 and 2.6) are propagated through the calculated impact categories. Finally, Subsection 3.4 presents opportunities that commercial aviation could leverage to cultivate its environmental handprinting (Norris, 2014) and create sustainable net positive impacts on human health and ecosystem. Section 4 “Conclusions” summarizes the key insights of this study and outline pathways for future work.

## 2. Methodology

The framework of life cycle assessment (LCA) has four phases, namely, the goal and scope definition phase, life cycle inventory (LCI) assessment phase, impact assessment (LCIA) phase, and the results interpretation phase. LCIA is governed by the international ISO 14040 (2006) standards and can be used as a quantification methodology to make informed decisions about manufacturing processes, products, and services with respect to their impacts on environment and human health. Moreover, LCIA can drive innovations to produce greener processes, products, and services to conserve energy and efficiently utilize the earth's depletable resources. This research leverages LCIA to provide insights for making commercial aviation an “*environmentally net positive*” industry by advancing novel concepts to shrink its carbon footprint, conserve energy, and minimize its adverse impacts on human health and the ecosystem.



## 2.1 Rationale for substituting AlMg3 with CFRP

The attractiveness of using composite structural materials such as carbon-fiber reinforced polymer (CFRP) is attributed, in part, to their lighter weight, compared to traditional metals such as steel and aluminum alloys, and the resulting energy savings and emission reduction during their use phase in many applications. For example, CFRP has a density of  $1,550 \text{ kg/m}^3$  (Rochling, 2015) which is  $\approx 60\%$  of the density (Matbase, 2015) of aluminum alloy (AlMg3), which is  $2,650 \text{ kg/m}^3$ . Alternately, weight of  $1 \text{ m}^3$  of CFRP is  $\approx 60\%$  ( $= 1,550 / 2,650$ ) of weight of  $1 \text{ m}^3$  of AlMg3. Hence on a mass basis, 1 kg of AlMg3 would be equivalent to 0.6 kg CFRP. Put differently, 1 kg of CFRP has a volume of  $645 \text{ cm}^3$  which is  $\approx 71\%$  greater than the volume of 1 kg of AlMg3, which is  $377 \text{ cm}^3$ . Hence for the same thickness, a CFRP sheet that weighs 1 kg will have 71% larger surface area compared to an AlMg3 sheet of the same weight. Song et al. (2009) argued that the lightweight feature of CFRP can offset some of its associated production cost as less energy would be required to transport this lighter weight material compared to transporting heavier metal alloys of similar volumes.

Other attractive features of using CFRP in broad applications include their excellent material strength, durability, stiffness, fatigue resistance, ease of conformity to different shapes, and being chemically inert which reduces associated maintenance requirements compared to metal structures. Given the aforementioned desirable features of CFRP, its use in aerospace industry seems to be a logical choice. For example, Boeing 787 Dreamliner consists of  $\approx 50 \text{ wt.}\%$  composite materials or equivalently  $\approx 80\%$  by volume (Song et al., 2009). In addition to reducing overall aircraft weight, use of composite structural materials enables reduction of both scheduled and unscheduled maintenance burden on the aircraft (Hale, 2006).

## 2.2 Scope definition and system boundary

The scope of this research covers three activities: a) quantification of human health and environmental benefits as a result of replacing AlMg3 by CFRP to lighten fuselage weight in Boeing B737-800, b) comparison of impact categories associated with production of CFRP of different CF content, and c) identification of potential emissions hot spots associated with cradle-to-gate production processes of AlMg3 and CFRP (of different CF content). In the base case scenario (BAU), the fuselage contains 10,781 kg of AlMg3, which represents 92% of fuselage weight (Table 1). This study compares environmental and health impacts of this base case scenario with those of a hypothetical (alternative) scenario where AlMg3 is substituted with CFRP to reduce fuselage weight by  $\approx 4.3$  tons.

The system boundary of this study excludes some phases that would otherwise be included in cradle-to-grave LCAs. Hence for the purpose of this research, the system boundary is limited to cradle-to-gate (at plant) production of each AlMg3 and CFRP, respectively. The selected system boundary is intentional to avoid introduction of many sources of subjectivity and uncertainty associated with including other life cycle phases such as transportation and end-of-life (EOL) recycling and/ or disposal. Moreover, for demonstrability of the study's comparative assessment framework, the central focus is on Boeing B737-800 fuselage.

## 2.3 Functional unit (FU)

Production of  $1 \text{ m}^3$  of aircraft structural material (whether it is CFRP or AlMg3) has been adopted as the FU. Table 2 shows CFRP / AlMg3 mass ratio, which correspond to  $1 \text{ m}^3$  material. Accordingly, comparing environmental and health impacts of producing one volume-based FU of

AlMg3 and CFRP, respectively, would be equivalent to comparing those impacts associated with producing 1 kg AlMg3 and 0.6 kg CFRP, respectively.

**Table 2**

CFRP / AlMg3 mass ratio that corresponds to a FU of 1 m<sup>3</sup> structural material.

Boeing B737-800 Fuselage Structural Material	Material Density kg/m <sup>3</sup>	CFRP/AlMg3 Mass Ratio Corresponding to 1 FU ( <i>i.e.</i> , 1 m <sup>3</sup> of material)
Carbon-fiber reinforced polymer (CFRP)	1,550	1,550 kg / 2,650 kg $\approx$ 0.6
Aluminum alloy (AlMg3)	2,650	

#### 2.4 Impact assessment (LCIA) methodology

TRACI v2.1 impact assessment tool enables quantification of stressors with potential impacts on the environment and human health. These stressors, or impact categories, include: ozone (O<sub>3</sub>) depletion, global warming, acidification, eutrophication, photochemical ozone (smog) formation, human health particulate matter, human health carcinogens, human health non-carcinogens, ecotoxicity, and fossil fuel depletion (Bare, 2012). Table 3 lists the transport media associated with aforementioned impact categories.

In this research, TRACI 2.1, which is part of the OpenLCA software, has been selected for performing comparative impact assessments among the selected materials.

**Table 3**

Transport media associated with TRACC v2.1 impact categories.

Impact Category	Media
Ozone (O <sub>3</sub> ) depletion, kg CFC-11 eq	Air
Global warming, kg CO <sub>2</sub> eq	
Photochemical ozone (smog) formation, kg O <sub>3</sub> eq	
Human health particulate matter, kg PM <sub>2.5</sub> eq	
Acidification, kg SO <sub>2</sub> eq	Air & Water
Eutrophication, kg N eq	
Human health (carcinogens), CTUh	Air (urban & nonurban) Air, Freshwater, Seawater, Soil (natural & agricultural)
Human health (non-carcinogens), CTUh	
Ecotoxicity, CTUe	

#### 2.5 Foreground data sources

Since CFRP production process does not exist in Ecoinvent v2.2 database (can be downloaded from Ecoinvent.org), relevant inputs (including energy requirements) and outputs data are gathered from De Vegt & Haije (1997) and the more recent studies performed by Suzuki & Takahashi (2005), Huang (2009), Lopes (2010) and Das (2011). The gathered data is then used for developing the OpenLCA model for CFRP production process. Carbon fiber (CF) is produced from its petroleum-based precursor polyacrylonitrile (PAN) and the production process of this PAN-based CF has been extensively discussed by Huang (2009). This process involves polymerization of acrylonitrile (AN) to produce polyacrylonitrile (PAN) which is then carbonized and graphitized (in the presence of nitrogen as an inert gas) at  $\approx$  1700°C and 2100°C, respectively to produce CF

(precursor for CFRP production). For the carbonization step, “*nitrogen, liquid, at plant, RER*” has been used as an input to this step. During the carbonization process,  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{HCN}$ , and  $\text{CH}_4$  are emitted and, hence, are modeled as output streams from the carbonization process (Duflou et al., 2009).

Since PAN production process does not exist in Ecoinvent v2.2 database, production of acrylonitrile, AN, at plant (from Ecoinvent v2.2 database) has been used as an input to model production of polyacrylonitrile (PAN) via a polymerization step. To produce CFRP, CF is mixed with polypropylene (PP) in presence of heat energy. Fortunately, PP production process, at plant, is available in Ecoinvent v2.2 database.

Although production cost of PAN-based CF is not addressed in this research but cited as part of the pathways for future work, there are other methods for producing low-cost CF from the bio-renewable lignin (a polyaromatic polymer consisting of phenylpropane units) which is generated as a byproduct of paper pulping and cellulosic ethanol fuel production processes (Huang, 2009; Otani et al., 1969; Sudo et al., 1993. More information on lignin-based CF can be found in the work conducted by Uraki et al. (1995), Kubo et al. (1998), and Kadla et al. (2002).

## 2.6 Secondary data sources

The Ecoinvent v2.2 database, part of OpenLCA 1.4.2 software, has been employed as a secondary source for some materials production processes according to their availability in this database. In this respect, the following cradle-to gate production processes are taken from Ecoinvent v2.2 database after being modified to the purpose of this study.

- 1) “*Aluminum alloy, AlMg3, at plant, RER.*” This process model describes production of this aluminum alloy which contains 3% of magnesium.
- 2) “*Acrylonitrile from Sohio process, at plant, RER.*”
- 3) “*Nitrogen, liquid, at plant, RER.*”
- 4) “*Polypropylene, granulate, at plant, RER.*”

In Ecoinvent v2.2 database, the abbreviation “*RER*” refers to the country code for Europe.

## 2.7 Key assumptions

Several key assumptions are made to model the production process of CFRP as follows:

- 1) CFRP is produced by mixing PP polymer matrix, compared to epoxy (EP) resin, with CF in a heated environment. Subsection 3.4 provides the rationale for replacing EP resin with PP polymer matrix.
- 2) CFRP production is assumed to be a mass production process as compared to being a batch process. This large-scale production assumption eliminates the energy expended to maintain the intermediate process materials under certain environmental conditions while in storage (Suzuki & Takahashi, 2005; Song et al., 2009). Subsection 3.4 provides supporting discussion to this assumption.
- 3) For the developed CFRP production model, it is assumed that the produced CFRP contains 53.8 wt.% CF and 46.2 wt.% PP matrix. The ratio of CF to PP (expressed in wt.% CF) is used as sensitivity parameter as discussed in Subsection 3.2.

## 2.8 Hypothesis testing

Hypothesis testing is a commonly used statistical inference technique that consists of two mutually exclusive propositions; a null hypothesis (denoted  $H_0$ ) and a research hypothesis (denoted  $H_1$ ). The former being the default hypothesis and the latter being the alternative hypothesis to be tested. In this study, claims of  $H_0$  and  $H_1$  are articulated as follows:

- $H_0$ :** Based on results of the comparative impact assessment of materials production processes, there are no environmental and human health benefits due to substituting AlMg3 with CFRP in Boeing B737-800 fuselage.
- $H_1$ :** Based on results of the comparative impact assessment of materials production processes, there are potential environmental and human health benefits due to substituting AlMg3 with CFRP in Boeing B737-800 fuselage.

Accordingly, if the comparative impact assessment results do not demonstrate quantitative evidence of environmental and human health benefits as a result of substituting AlMg3 with CFRP,  $H_1$  claims should be rejected; otherwise  $H_1$  claims should be accepted.

## 3. Results and discussion

### 3.1 Base cases: AlMg3 vs. CFRP (53.8 wt.% CF)

Tables 4, 5, and 6 summarize the results of comparative impact assessments associated with the base case scenario (AlMg3 use in Boeing B737-800 fuselage) and the alternative scenario in which AlMg3 is replaced with CFRP (containing 53.8 wt.% CF). Table 4 displays cradle-to-gate (at production plant) comparative impact assessment expressed as emission factors for AlMg3 vs. CFRP (53.8 wt.% CF). As can be seen, AlMg3 cradle-to-gate production process has the highest impact categories as follows: ozone depletion, ecotoxicity, global warming, human health impacts (carcinogenics and non-carcinogenics). However, CFRP cradle-to-gate production process has the highest impact categories that represent acidification, eutrophication, and photochemical ozone (smog) formation. The primary hot spot for these three impact categories can be attributed to the carbonization step in the CFRP production process.

**Table 4**

Cradle-to-gate (at production plant) comparative impact assessment: Emission factors for AlMg3 vs. CFRP (53.8 wt.% CF).

Impact Category	AlMg3	CFRP (53.8 wt.%)	Reference Units
Ozone depletion	3.240E-7	1.116E-7	Kg CFC-11 eq
Ecotoxicity	33.646	5.320	CTUe
Acidification	0.018	0.552	Kg SO2 eq
Photochemical ozone formation	0.168	13.135	Kg O3 eq
Eutrophication	0.017	0.549	Kg N eq
Respiratory effects	0.002	0.006	Kg PM2.5 eq
Global warming	6.094	3.246	Kg CO2 eq
Human health (non-carcinogenics)	1.457E-6	2.205E-7	CTUh
Human health (carcinogenics)	9.258E-7	8.930E-8	CTUh

Table 5 shows the impact categories (displayed as percentages instead of absolute values) associated with AlMg3 production process (at plant). As can be seen, AlMg3 cradle-to-gate production (at plant) has the highest contributions in all the impact categories. Table 6 displays impact categories associated with CFRP (53.8 wt.% CF) cradle-to-gate production process (at plant). As shown in Table 5, the carbonization step represents the primary hot spot in the CFRP production process as it contributes the most to all the impact categories. In particular, Table 6 shows that 95.2% of the respiratory effect and 99.7% of the photochemical ozone formation are attributed to the carbonization step that produces CF from its petroleum-based precursor polyacrylonitrile (PAN).

**Table 5**

Impact categories associated with AlMg3 production process (at plant).

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
AlMg3 Production	49.69%	75.43%	81.14%	75.27%	80.88%	77.85%
Electricity mix	8.75%	3.49%	6.21%	14.90%	7.87%	10.30%
Magnesium (Mg) Production	39.25%	0.80%	1.35%	5.01%	7.79%	7.89%
Chromium (Cr) Production	1.35%	18.41%	0.96%	1.88%	2.37%	2.25%

**Table 6**

Impact categories associated with CFRP (53.8 wt.% CF) production process (at plant).

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
Carbonization Process	68.95%	50.40%	58.26%	99.69%	77.79%	95.18%
Electricity mix	14.12%	33.47%	39.45%	0.14%	22.03%	3.05%
Polypropylene (PP) Production	16.93%	16.13%	2.30%	0.17%	0.17%	1.77%

### 3.2 Sensitivity study

In this research, the ratio of CF-to-PP polymer matrix (expressed in wt.% CF in CFRP) is used as a sensitivity parameter. In the base case of CFRP production process, the CF-to-PP ratio is assumed to be 53.8 wt.% (Table 6). In the sensitivity case, CF-to-PP ratio is arbitrarily reduced to 30 wt.% in order to reveal impact of CFRP composition change on the calculated impact categories. Table 7 displays the calculated impact categories associated with cradle-to-gate production of 1 FU

of CFRP containing 30 wt.% CF. Again, it is clear that the carbonization step still dominates the calculated impact categories but to lesser extent compared to the case of CFRP containing 53.8 wt.% CF (Table 6). As can be seen, reducing CF concentration in CFRP from 53.8 wt.% to 30 wt.% has resulted in reducing contributions of carbonization step to global warming potential from 68.95% (Table 6) to 53.42% (Table 7) and to human health (carcinogenics) from 50.4% (Table 6) to 39.47% (Table 7). Additionally, there are smaller reductions associated with the other four impact categories (shown in Tables 6 and 7) as CF concentration in CFRP is reduced from 53.8 wt.% to 30 wt.%.

**Table 7**

Impact categories associated with CFRP (30 wt.% CF) production process (at plant).

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
Carbonization Process	53.42%	39.47%	56.04%	99.39%	77.57%	92.37%
Electricity mix	10.94%	26.21%	37.95%	0.14%	21.97%	2.96%
Polypropylene (PP) Production	35.64%	34.32%	6.00%	0.47%	046%	4.67%

It should be noted that impact of changing CF content on mechanical properties of the produced CFRP is outside the scope of this study and should be evaluated in a separate work to identify the optimum CF-to-PP ratio that minimizes associated environmental and health impacts without sacrificing the desired physical and mechanical properties of this composite material.

Table 8 compares the impact categories of these two CFRP cases (Tables 6 and 7) as well as impact categories of the BAU case (Table 5) where AlMg3 is used as the primary fuselage structural material in Boeing B737-800. The comparison includes global warming potential (kg CO<sub>2</sub> eq.), human health (carcinogenics and non-carcinogenics, CTUh), ecotoxicity (CTUe), ozone depletion (kg CFC-11 eq), acidification (kg SO<sub>2</sub> eq.) & eutrophication (kg N eq), respiratory effects (PM<sub>2.5</sub> eq), and photochemical ozone formation (kg O<sub>3</sub> eq), respectively. As can be seen, reduction of CF content in CFRP from 53.8 wt.% to 30 wt.% results in improved environmental and health benefits. With exception of acidification, eutrophication, respiratory effects, and photochemical ozone formation, CFRP (30 wt.% CF) and CFRP (53.8 wt.% CF) show improvements over AlMg3 for only five impact categories, namely: global warming, human health (carcinogens and non-carcinogens), ecotoxicity, and ozone depletion. Moreover as can be observed from Table 8, AlMg3 has the lowest impact categories for acidification, eutrophication, respiratory effects and photochemical ozone formation compared to CFRP. This latter observation can be attributed to the chemical compositions of input materials to the CFRP production process.

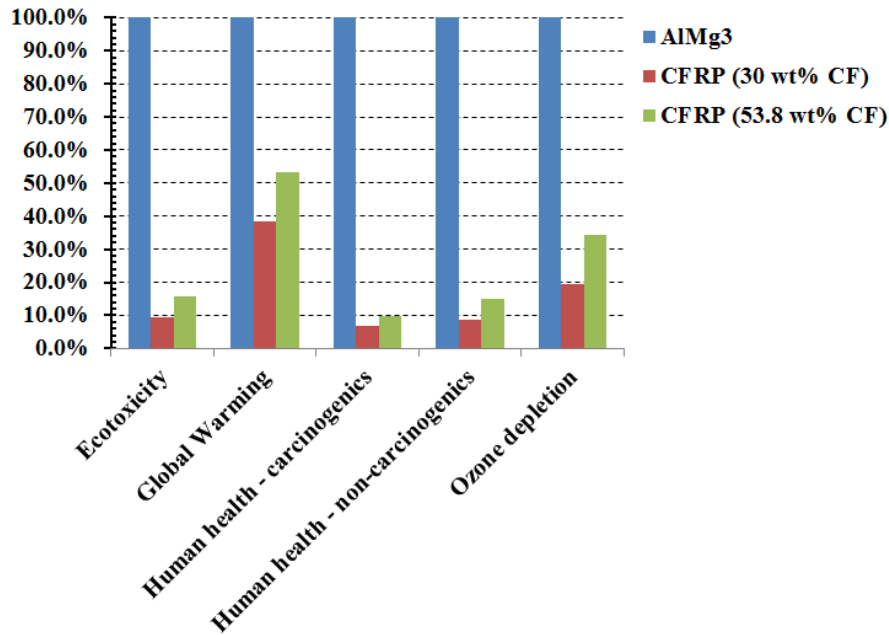


**Table 8**

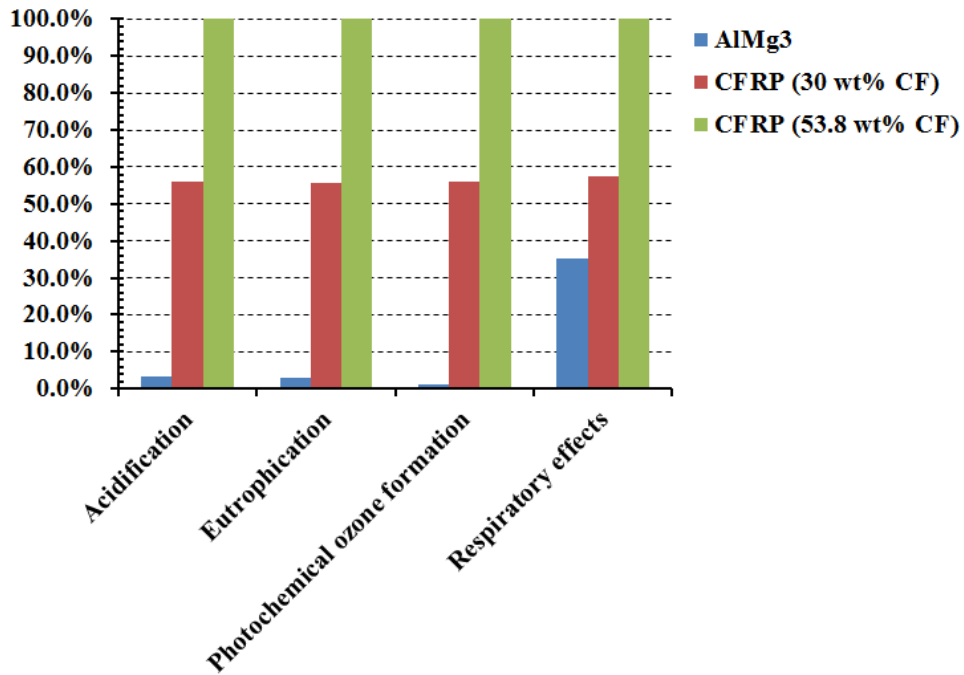
Comparative impact assessment summary for AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively, per 1 FU (1 m<sup>3</sup> of product material).

Impact Category	AlMg3	CFRP (53.8 wt.%)	CFRP (30 wt.%)
Ozone depletion, Kg CFC-11 eq	3.240E-7	1.116E-7	6.240E-8
Ecotoxicity, CTUe	3.360E+1	5.32E+0	3.210E+0
Acidification, Kg SO2 eq	1.750E-2	5.520E-1	3.090E-1
Photochemical ozone formation, Kg O3 eq	1.680E-1	1.310E+1	7.350E+0
Eutrophication, Kg N eq	1.690E-2	5.490E-1	3.060E-1
Respiratory effects, Kg PM2.5 eq	2.240E-3	6.370E-3	3.660E-3
Global warming, Kg CO2 eq	6.094E+0	3.246E+0	2.340E+0
Human health (non-carcinogenics), CTUh	1.457E-6	2.205E-7	1.280E-7
Human health (carcinogenics), CTUh	9.258E-7	8.930E-8	6.360E-8

Fig. 1 depicts the relative values (as percentages) of five impact categories for the three variants: AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.%), respectively. For each impact category, the maximum result is set to 100% and the results of the other two variants are displayed in relation to this result. As can be seen, the relative impacts of the shown five categories are driven by AlMg3 followed by CFRP (53.8 wt.% CF), and then CFRP (30 wt.% CF). Fig. 2 shows the relative values (as percentages) of four impact categories for the same three variants. Again for each impact category, the maximum result is set to 100% and results of the other two variants are displayed in relation to this maximum result. As can be seen, the relative values of the shown four categories are driven by CFRP (53.8 wt.% CF) followed by CFRP (30 wt.% CF) and then AlMg3.



**Fig. 1.** Relative values (as percentages) of five impact categories associated with cradle-to-gate production processes of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively.



**Fig. 2.** Relative values (as percentages) of four impact categories associated with cradle-to-gate production processes of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively.

### 3.3 Uncertainty analysis

This research focuses on cradle-to-gate rather than cradle-to-grave impact assessment. Adoption of this choice is intentional in order to avoid numerous sources of uncertainty associated with



typical cradle-to-grave studies. Examples of sources of uncertainty include those associated with aircraft operational phase such as aviation fuel consumption (kg/hour) which depends not only on distance travelled/ routes, but also on type, capacity, and weight of aircraft as well as the engine model<sup>2</sup> and performance. Other sources of uncertainty and subjective judgment are associated with end-of-life (EOL) materials disposal method and recycling proportions. Materials disposal at EOL could be either landfilling or incineration, with or without energy recovery. Moreover, complexity of aircraft supply chain is attributed in part to the fact that its components are typically manufactured at different geographical locations and then assembled at yet another location. Thus, it would be difficult to accurately quantify environmental and human health burdens associated with transport phases of the aircraft LCA. Finally as revealed by our review of aircraft full LCA literature, subjective judgments were unsurprisingly made whenever aircraft data were scarce or cannot be obtained from the manufacturers. Based on the aforementioned reasons, the scope of this research is limited to the cradle-to-gate (at plant) production phase of aircraft structural materials (AlMg3 and CFRP) where accurate and reliable data are readily available.

Ecoinvent v2.2 database contains AlMg3 production process (denoted in OpenLCA by “*aluminum alloy, AlMg3, at plant, RER*”), acrylonitrile production process (denoted in OpenLCA by “*acrylonitrile from Sohio process, at plant, RER*”), liquid nitrogen production process (denoted in OpenLCA by “*nitrogen, liquid, at plant, RER*”). In this research, the latter two processes are employed to develop a model network for CFRP production process. Uncertainties of inputs in these processes are described by log-normal distributions (means and standard deviations).

Monte Carlo sampling (MCS) technique (using 1000 trials) is employed to quantify the uncertainty associated with calculated impact categories associated for production of one functional unit (FU) of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively. Table 9 summarizes statistics (means and standard deviations) associated with this uncertainty analysis.

**Table 9**

Uncertainty analysis of impact categories associated with production of 1 FU of AlMg3, CFRP (53.8 wt.% CF), and CFRP (30 wt.% CF), respectively.

Statistics <sup>(1)</sup> ( $\mu$ , $\sigma$ )	Calculated impact Categories for AlMg3				
	Human Health (carcinogenics) CTUh	Human Health (non- carcinogenics) CTUh	Ozone Depletion Kg CFC-11 eq	Photochemical Ozone Formation kg O3 eq	Respiratory Effects Kg PM2.5 eq
$\mu$	1.664E-6	5.294E-6	4.078E-7	0.193	2.651E-3
$\sigma$	9.191E-7	6.726E-6	1.259E-7	0.029	4.354E-4
<b>Calculated impact Categories for CFRP (53.8 wt.% CF)</b>					
$\mu$	3.609E-7	7.774E-7	1.416E-7	13.142	6.466E-3
$\sigma$	8.743E-8	7.614E-7	3.837E-8	6.765E-3	8.345E-5
<b>Calculated impact Categories for CFRP (30 wt.% CF)</b>					
$\mu$	2.651E-7	4.405E-7	7.588E-8	7.350	3.711E-3
$\sigma$	6.585E-8	4.745E-8	2.190E-9	3.66E-3	4.513E-5

<sup>(1)</sup>  $\mu$ : statistical mean       $\sigma$ : statistical standard deviation

<sup>2</sup> Engine model could be PW4000, Rolls-Royce Trent 700, and GE/CF6-80E1.

Based on MCS uncertainty analysis for global warming (in kg CO<sub>2</sub> eq), the resulting statistics ( $\mu$ ,  $\sigma$ ) associated with production of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF) are: (6.406, 1.57), (2.380, 0.062), and (3.334, 0.104), respectively. The associated upper bounds (95<sup>th</sup> percentiles) global warming (in kg CO<sub>2</sub> eq) for these three materials are: 10.649, 2.50, and 3.533, respectively. The upper bound values represent the worst case GHG emissions (measured in kg CO<sub>2</sub> eq) scenarios. The observation to be made here is that the upper bound value of global warming associated with AlMg3 production process is about three times greater than that associated with production of CFRP (containing 53.8 wt.% CF) and about four times greater than that associated with CFRP (containing 30 wt.% CF). This observation brings forth two important insights: 1) Use of CFRP as a substitute structural material for AlMg3 in aircraft can play an important role in reducing global warming attributed to commercial air transport and 2) The carbonization step in CFRP production greatly impacts GHG emissions from this process. Hence, future research efforts should be focused on identifying novel ways to reduce energy intensity of the carbonization step such as using lignin-based precursor, compared to using the petroleum-based precursor (PAN) for CF production.

### *3.4 Environmental protection opportunities and creation of net positive impacts*

About 5% of global carbon emission is attributed to the aviation sector with the U.S. airline fleet contributing about 30% of the global air pollution caused by this sector (Waitz, I. et al., 2004). However, global commercial aviation has an opportunity to not only nurture its environmental handprinting (Norris, 2014) impact by shrinking its carbon footprint, but also to cultivate environmental net positive impacts by creating breakthrough technologies that reduce energy intensity of aircraft structural materials production using sustainable sources. Other industries such as automotive and buildings construction can then adopt these breakthrough technologies to shrink their carbon footprint.

The following example quantifies anticipated reduction of carbon footprint should the global fleet of Boeing 737-800 aircraft adopts the insights of this study.

The mass of AlMg3 in Boeing B737-800 fuselage is 10,781 kg (see Table 1) and the carbon footprint associated with production of this mass can be calculated as follows:

$$\begin{aligned} \text{Carbon footprint associated with production of AlMg3 present in the fuselage} = \\ (10,781 \text{ kg AlMg3/aircraft}) \times (6.094 \text{ kg CO}_2 \text{ eq/kg AlMg3}) \approx 65,699 \text{ kg CO}_2 \text{ eq/aircraft} \approx 65.7 \text{ tons} \\ \text{CO}_2 \text{ eq/aircraft.} \end{aligned} \quad \dots\dots (1)$$

Based on the postulated alternative scenario, net reduction in carbon footprint per aircraft can be obtained by subtracting from Eq.(1) the carbon footprint associated with cradle-to-gate production of the substitute CFRP (containing 30 wt.% CF) in Boeing B737-800 fuselage. Hence:

$$\begin{aligned} \text{Net reduction in carbon footprint per aircraft} = 65,699 \text{ kg CO}_2 \text{ eq.} - [(2.336 \text{ kg CO}_2 \text{ eq./0.6 kg} \\ \text{CFRP}) \times (10,781 \text{ kg AlMg3} \times 0.6 \text{ kg CFRP/kg AlMg3})] = 65,699 \text{ kg CO}_2 \text{ eq} - 25,184 \text{ kg CO}_2 \text{ eq} \\ = 40,515 \text{ kg CO}_2 \text{ eq/aircraft} \approx 40.5 \text{ tons CO}_2 \text{ eq/aircraft} \end{aligned} \quad \dots\dots (2)$$

The calculated net reduction in carbon footprint per aircraft per Eq. (2) can then be multiplied by  $\approx 2,000$  (which is the global fleet of Boeing B737-800) to obtain the associated net reduction in carbon footprint. Hence, based on the postulated alternative scenario and impact assessment model assumptions (Subsection 2.7), the anticipated global carbon footprint reduction would be  $\approx 81,000$  tons CO<sub>2</sub> eq for the global fleet of Boeing 737-800.

Global commercial aviation, estimated to be around 26,000 aircraft (Centre for Aviation, 2013), can create net positive impacts by implementing sustainable technologies to further reduce energy intensity of petroleum-based CFRP production to levels much below that of AlMg3 production. For example, lignin-based CFRP can be used instead of using the PAN-based<sup>3</sup> CFRP (Das S., 2011). The rationale here is that there is no energy burden associated with bio-renewable lignin production as this biomass lignin is generated as a byproduct of paper pulping and cellulosic ethanol production processes. Moreover, unlike petroleum-based CFRP production, lignin-based CFRP production process does not emit hydrogen cyanide (HCN), which is a toxic gas. Other approaches that global commercial aviation could implement to achieve environmental and health net positive impacts may include the following:

- 1) Adopt the 3R (reduce, reuse, and recycle) concept in CFRP production process to lessen need for virgin CFRP. This would result in savings in production energy intensity (MJ/kg-CFRP produced). The lesser the production energy intensity, the lower is the associated environmental burden. With respect to recyclability option, use of thermoplastics would be more advantageous compared to using thermosets like epoxy and saturated polyester resins (Duflou et al. 2012).
- 2) Eliminate need for epoxy (EP), a thermoset polymer commonly used as a matrix resin for CFRP production, as the energy intensity of EP production is relatively large,  $\approx 76$ -80 MJ/kg (Das, 2011). The energy intensity of matrix resin could be reduced by using another resin type such as high-density polyethylene ( $\sim 20.3$  MJ/kg) or PP ( $\sim 24.4$  MJ/kg), as reported by Suzuki & Takahashi (2005, November 29-December 2) and Duflou et al. (2012).
- 3) Leverage economies of scale and mass production of CFRP using less energy-intensive automated processes. This will eliminate need for the 'PrePreg' step (required prior to integrating reinforcing-CF with the polymer matrix) which requires  $\sim 40$  MJ/kg CFRP (Suzuki & Takahashi, 2005; Song et al., 2009). This energy is spent on atmospheric control to store intermediate materials and products in CFRP production process. The strategy for CFRP mass production can be achieved by using CFRP for other industries (besides aircraft) such as automotive manufacturing and buildings construction, where CFRP has been perceived as a promising alternative to steel.

#### 4. Conclusions

Global concern about emissions of air pollutants attributed to commercial air transport has driven major interest in lightening aircraft weight to reduce fuel consumption during flight and, hence, boost emissions reduction. Lightweight composites<sup>4</sup> offer similar strength and stiffness to that of AlMg3, which is the commonly used material for aircraft structure (Das, 2011).

---

<sup>3</sup> The conventional petroleum-based polyacrylonitrile (PAN) precursor for producing CFRP.

<sup>4</sup> Composites are up to 35 wt.% lighter than aluminum and up to 60 wt.% lighter than steel.

This research provides a framework for estimating cradle-to-gate environmental and human health benefits of substituting conventional AlMg3 used in commercial aircraft fuselage with CFRP. A hypothetical (alternative) scenario is used to quantitatively demonstrate these benefits. In the alternative scenario, it is assumed that CFRP substitutes AlMg3 in Boeing 737-800 fuselage, which leads to  $\approx 4.3$  tons reduction in fuselage weight. Lighter aircraft weight leads to lesser aviation fuel consumption during flight and, thus, fewer emissions of air pollutants to the atmosphere.

The OpenLCA 1.4.2 platform, including Ecoinvent v2.2 and TRACI 2.1 for impact assessment, has been employed to model AlMg3 and CFRP cradle-to-gate (at plant) production processes. For production of CFRP, ratio of CF-to-PP (expressed in wt.% CF) has been used as a sensitivity parameter to quantify the effect of varying CF content in CFRP on the calculated impact categories.

The main highlights of this comparative impact assessment of AlMg3 and CFRP production processes (given the assumptions made in this study) are as follows:

- Overall, the results supports the study's  $H_1$ -hypothesis's claims that there are potential environmental and human health benefits associated with replacing AlMg3 with CFRP in Boeing B737-800 fuselage.
- Substitution of 1 volume-based FU of AlMg3 with CFRP (containing 53.8 wt.% CF) would lead to a relative reduction of carbon footprint (kg CO<sub>2</sub> eq) by  $\approx 46.1\%$  and by  $\approx 61.7\%$  if AlMg3 is replaced by CFRP (containing 30 wt.% CF).
- AlMg3 production has the largest global warming footprint followed by CFRP (containing 53.8 wt.% CF), then CFRP (containing 30 wt.% CF). Similar trends are obtained with the ecotoxicity, human health (carcinogens and non-carcinogens), and ozone depletion impact categories.
- Acidification, eutrophication, photochemical ozone (smog) formation, and respiratory effects are largest for CFRP (53.8 wt.% CF), followed by CFRP (30 wt.% CF), then AlMg3. These observations are attributable to the carbonization step of the petroleum-based PAN to produce CF.
- Carbonization step represents the main environmental hot spot in PAN-based CF production.
- The energy intensity of a composite material production is not only highly dependent on the technology being employed, but also sensitive to the nature of reinforcing fiber precursor as well as type of polymer matrix being employed (e.g., epoxy resin, polypropylene, polyethylene, PVC, polyester, etc.).
- Given the postulated alternative scenario (i.e., replacing fuselage's AlMg3 by CFRP), it is predicted that the global fleet of Boeing B737-800 can achieve a net carbon footprint reduction of  $\approx 81,000$  tons CO<sub>2</sub> eq.

- Other global commercial aircraft ( $\approx 26,000$  aircraft) and industries like automotive and building materials could embrace the insights of this study to shrink their carbon footprint and cultivate an environmentally net-positive culture.

The current study opens many pathways for further research particularly in areas where quantitative information is either scarce, or nonexistent. Examples of future work may include:

- Optimization of reinforcing-CF/PP-matrix ratio in CFRP production process to determine the best ratio that maximizes environmental and human health benefits without sacrificing the lightweight advantage and desired physical and mechanical properties of this composite. In this respect, it is critically important to preserve equivalent functionality between aircraft conventional metal-based structural materials and CFRP as a substitute material.
- It would be insightful to perform comparative impact assessment for the case of lignin-based vs. petroleum-based precursor for the carbonization step to produce CF. As reported in the literature (Das, 2011), the energy required for carbonization of the bio-renewable lignin precursor is  $\approx 25\%$  less than the energy needed for the traditional petroleum-based (PAN) precursor. Lignin requires shorter time for the carbonization/ graphitization step as well as less stabilization/ oxidation processing time due to its oxygenated nature.
- Additional impact assessment is needed for the new classes of bio-based fiber reinforced polymers in which either the reinforcing fibers, or polymer matrix come from renewable resources (Duflou et al. 2012). In particular, it would be informative to generate quantitative impact assessment for cradle-to-gate production phase of these bio-based composites.
- Evaluation of long-term reliability of other bio-based fiber reinforced polymers (such as cotton, linen, sisal, flax, and wood pulp) as sources of low-cost alternatives for the petroleum-based CFRP.
- Since aircraft wings represent the heaviest component followed by the fuselage (in Boeing 737-800, for example, the wings weight 13,428 kg while fuselage weighs 11,764 kg) it would be useful to quantify environmental and human health benefits that result from reducing the weight of aircraft wings by replacing AlMg3 with CFRP.
- Estimate collateral environmental and health benefits, in addition to quantifying benefits associated with weight reduction of primary components such as aircraft fuselage. Lighter weight aircraft means lower aviation fuel consumption, smaller engines/ power train, and lighter payloads. Such collateral benefits also include energy savings related to other phases of the aircraft life cycle.

## References

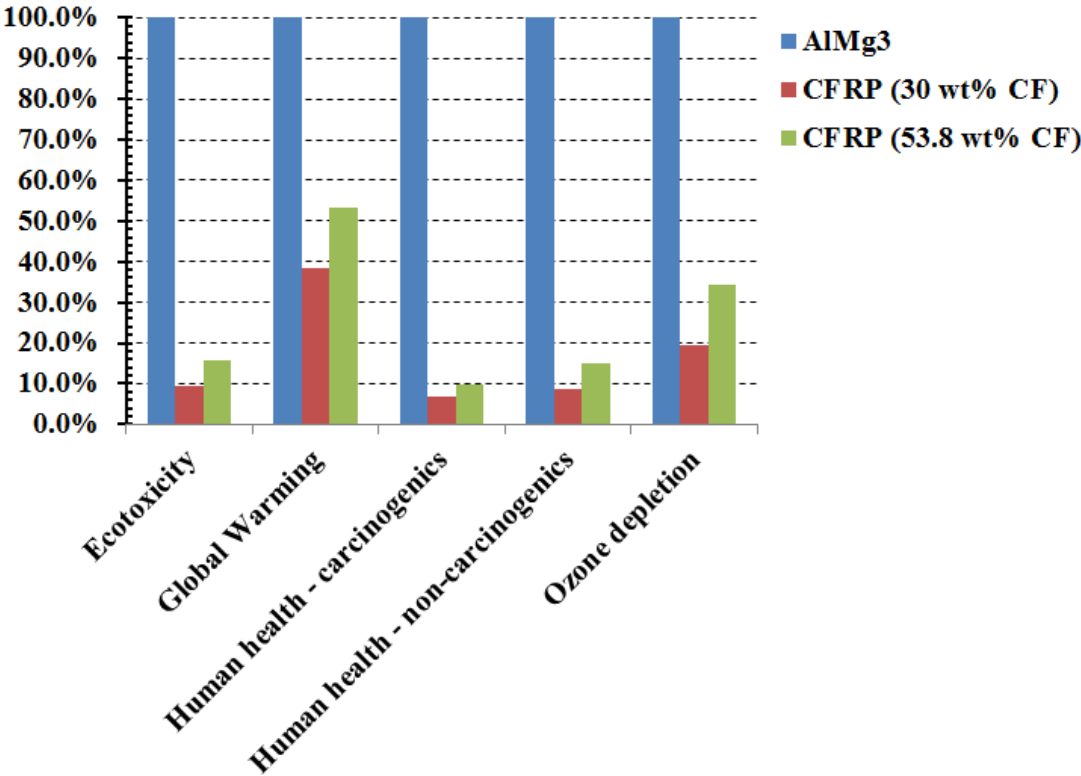
- Asmatulu, E. et al. (2013). Recycling of aircraft: state of the art in 2011. *Journal of Industrial Engineering*, Vol. 2013, 1-8.
- Bare, J. (2012, June 22). Tool for the reduction and assessment of chemical and other environmental impacts (TRACI). U.S. Environmental Protection Agency (EPA), ORD/NRMRL/Sustainable Technology Division, TRACI 2.1 Document # S-10637-OP-1-0, 1-24.
- Centre for Aviation, CAPA. (2013). Berlin Brandenburg Airport, About. Retrieved October 12, 2015 from <http://centreforaviation.com/profiles/airports/berlin-brandenburgairport-ber>
- Das, S. (2011). Life cycle assessment of carbon fiber0reinforced polymer composites. *Int. J. Life Cycle Assessment*, 16, 268-282.
- De Vegt, O.M. and Haije, W.G. (1997). Comparative environmental life cycle assessment of composite materials. ECN-1-97-050, 1-37. Source: <http://www.ecn.nl/docs/library/report/1997/i97050.pdf>
- Duflou, J.R. et al. (2009). Environmental impact assessment of composite use in car manufacturing. *CIRP Annals – Manufacturing Technology*, 58 (1), 9-12.
- Duflou, J.R. et al. (2012, April). Do Fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. *MRS Bulletin*, 37, 374-381.
- Hale, J. (2006). Boeing 787 from the ground up. *Aero Quarterly*, QTR\_04, 17-23. Source: [http://www.boeing.com/commercial/aeromagazine/articles/qtr\\_4\\_06/article\\_04\\_2.html](http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html)
- Huang, X. (2009). Fabrication and properties of carbon fibers. *Materials*, 2, 2369-2403.
- ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework. Source: [http://www.iso.org/iso/catalogue\\_detail?csnumber=37456](http://www.iso.org/iso/catalogue_detail?csnumber=37456)
- Kadla, J.F. et al. (2002). Lignin-based carbon fibers for composite fiber applications. *Carbon*, 40, 2913-2920.
- Kubo, S. et al. (1998). Preparation of carbon fibers from softwood lignin by atmospheric acetic acid pulping. *Carbon*, 36, 1119-1124.
- Liu, Z. (2013). Life cycle assessment of composites and aluminum use in aircraft systems. Cranfield University. Source: <http://dspace.lib.cranfield.ac.uk/handle/1826/8573>
- Lopes, João Vasco de Oliveira Fernandes. (2010). Life Cycle Assessment of the Airbus A330-200 Aircraft. Instituto Superior Tecnico Universidade Tecnica de Lisboa, Portugal.
- Macintosh, A. and Wallace, L. (2009). International aviation emissions to 2025: Can emissions be stabilized without restricting demand? *Energy Policy*, 37, 264-273.



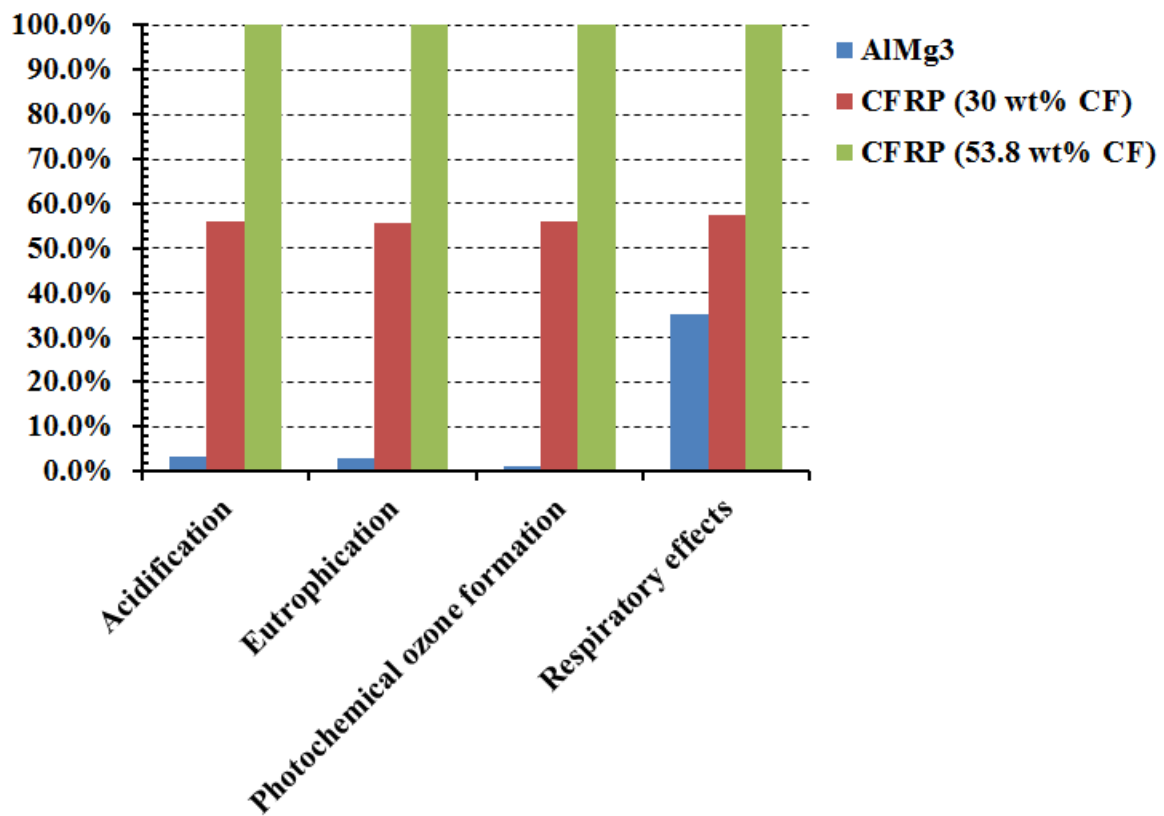
- Macintosh, A. (2009, January). Is it time to restrict demand for air travel? *Science for Environment Policy*, European Commission DG ENV, News Alert Issue 37, 1.
- Marcinko, L. (2013). Life cycle assessment of structural aircraft materials. *Acta Avionica*, XV (27), 1-3.
- Matbase.com AlMg3 material characterization. Retrieved on 12/15/2015 from: <http://www.matbase.com/material-categories/metals/non-ferrous-metals/wrought-aluminium/material-properties-of-almg3-5754a-wrought-aluminium-grade.html>
- Mazumdar, S. (2002). Composites manufacturing: materials, products, and process engineering. New York: CRC Press.
- Norris, G. (2014). Environmental Handprinting. *Trim Tab*, Fall Issue, 61-64.
- OpenLCA 1.4.2, GreenDelta. Source: <http://www.openlca.org>
- Otani, S. et al. (1969). Methods for producing carbonized lignin fiber. *U.S. Patent*. 3461082.
- Rochling.com. CFRP/ carbon fiber reinforced composites. Retrieved on 12/14/2015 from: <http://www.roechling.com/en/high-performance-plastics/composites/fibre-reinforced-plastics/composite-profiles/cfrp-carbon-fibre-reinforced-composites.html>
- Scelsi, L. et al. (2011). Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. *eXPRESS Polymer Letters*, 5(3), 209–217.
- Song, Y.S. et al. (2009). Life cycle energy assessment of fiber-reinforced composites. *Composites: Part A*, 40, 1257-1265.
- Sudo, K. and Shimizu, K. (1992). A new carbon-fiber from lignin. *J. Appl. Polym. Sci.*, 44, 127-134.
- Sudo, K. et al. (1993). A new modification method of exploded lignin for the preparation of carbon fiber precursor. *J. Appl. Polym. Sci.*, 48, 1485-1491.
- Suzuki, T. and Takahashi, J. (2005, November 29 – December 2). Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. *The Ninth Japan International SAMPE Symposium*, 14-19.
- Suzuki, T. and Takahashi, J. (2005). LCA of lightweight vehicles by using CFRP for mass-produced vehicles. *Department of Environmental and Ocean Engineering, the University of Tokyo*, Tokyo, 113-8656, Japan.
- Uraki, Y. et al. (1995). Preparation of carbon-fibers from Organosolv lignin obtained by aqueous acetic-acid pulping. *Holzforschung*, 49, 343-350.

Waitz, I. et al. (2004, December). Aviation and the environment: A national vision statement, framework for goals and recommended actions. *Report to the United States Congress, Massachusetts Institute of Technology*, Cambridge, MA, 1-55.





**Fig. 1.** Relative values (as percentages) of five impact categories associated with cradle-to-gate production processes of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively.



**Fig. 2.** Relative values (as percentages) of four impact categories associated with cradle-to-gate production processes of AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively.

Table 1 - Breakdown of AlMg3 content in the primary components in Boeing B737-800 (Liu, 2013).	
Primary Component Type and Weigh	Aluminum Alloy (AlMg3) Content
Fuselage (weight = 11,764 kg)	10,781 kg (~ 92 wt. %)
Wings (weight = 13,428 kg)	12,628 kg (~ 94 wt. %)
Stabilizers (eight = 1,519 kg)	1,085 kg (~ 71.4%)
Landing gear (weight = 3,416 kg)	450 kg (~ 13.2 wt. %)
Nacelles & Pylons (weight = 2,664 kg)	964 kg (~ 36.2 wt. %)
Engine (weight = 5,504 kg)	1000 kg (~ 18.2 wt. %)

Table 2 - CFRP / AlMg3 mass ratio that corresponds to a FU of 1 m <sup>3</sup> structural material.		
Boeing B737-800 Fuselage Structural Material	Material Density kg/m <sup>3</sup>	CFRP/AlMg3 Mass Ratio Corresponding to 1 FU ( <i>i.e.</i> , 1 m <sup>3</sup> of material)
Carbon-fiber reinforced polymer (CFRP)	1,550	1,550 kg / 2,650 kg $\approx$ 0.6
Aluminum alloy (AlMg3)	2,650	

**Table 3 - Transport media associated with TRACC v2.1 impact categories.**

Impact Category	Media
Ozone (O <sub>3</sub> ) depletion, kg CFC-11 eq	Air
Global warming, kg CO <sub>2</sub> eq	
Photochemical ozone (smog) formation, kg O <sub>3</sub> eq	
Human health particulate matter, kg PM <sub>2.5</sub> eq	
Acidification, kg SO <sub>2</sub> eq	Air & Water
Eutrophication, kg N eq	
Human health (carcinogens), CTUh	Air (urban & nonurban) Air, Freshwater, Seawater, Soil (natural & agricultural)
Human health (non-carcinogens), CTUh	
Ecotoxicity, CTUe	

**Table 4 - Cradle-to-grate (at production plant) comparative impact assessment: Emission factors for AlMg3 vs. CFRP (53.8 wt.% CF).**

Impact Category	AlMg3	CFRP (53.8 wt.%)	Reference Units
Ozone depletion	3.240E-7	1.116E-7	Kg CFC-11 eq
Ecotoxicity	33.646	5.320	CTUe
Acidification	0.018	0.552	Kg SO2 eq
Photochemical ozone formation	0.168	13.135	Kg O3 eq
Eutrophication	0.017	0.549	Kg N eq
Respiratory effects	0.002	0.006	Kg PM2.5 eq
Global warming	6.094	3.246	Kg CO2 eq
Human health (non-carcinogenics)	1.457E-6	2.205E-7	CTUh
Human health (carcinogenics)	9.258E-7	8.930E-8	CTUh

**Table 5 - Impact categories associated with AlMg3 production process (at plant).**

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
AlMg3 Production	49.69%	75.43%	81.14%	75.27%	80.88%	77.85%
Electricity mix	8.75%	3.49%	6.21%	14.90%	7.87%	10.30%
Magnesium (Mg) Production	39.25%	0.80%	1.35%	5.01%	7.79%	7.89%
Chromium (Cr) Production	1.35%	18.41%	0.96%	1.88%	2.37%	2.25%

**Table 6 - Impact categories associated with CFRP (53.8 wt.% CF) production process (at plant).**

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
Carbonization Process	68.95%	50.40%	58.26%	99.69%	77.79%	95.18%
Electricity mix	14.12%	33.47%	39.45%	0.14%	22.03%	3.05%
Polypropylene (PP) Production	16.93%	16.13%	2.30%	0.17%	0.17%	1.77%



**Table 7 - Impact categories associated with CFRP (30 wt.% CF) production process (at plant).**

Process	Impact Categories (% contributions with 0.8% cutoff limit)					
	Global Warming	Human Health (carcinogenics)	Human Health (non-carcinogenics)	Photochemical Ozone Formation	Ozone Depletion	Respiratory Effects
Carbonization Process	53.42%	39.47%	56.04%	99.39%	77.57%	92.37%
Electricity mix	10.94%	26.21%	37.95%	0.14%	21.97%	2.96%
Polypropylene (PP) Production	35.64%	34.32%	6.00%	0.47%	046%	4.67%

**Table 8 - Comparative impact assessment summary for AlMg3, CFRP (30 wt.% CF), and CFRP (53.8 wt.% CF), respectively, per 1 FU (1 m<sup>3</sup> of product material).**

Impact Category	AlMg3	CFRP (53.8 wt.%)	CFRP (30 wt.%)
Ozone depletion, Kg CFC-11 eq	3.240E-7	1.116E-7	6.240E-8
Ecotoxicity, CTUe	3.360E+1	5.32E+0	3.210E+0
Acidification, Kg SO2 eq	1.750E-2	5.520E-1	3.090E-1
Photochemical ozone formation, Kg O3 eq	1.680E-1	1.310E+1	7.350E+0
Eutrophication, Kg N eq	1.690E-2	5.490E-1	3.060E-1
Respiratory effects, Kg PM2.5 eq	2.240E-3	6.370E-3	3.660E-3
Global warming, Kg CO2 eq	6.094E+0	3.246E+0	2.340E+0
Human health (non-carcinogenics), CTUh	1.457E-6	2.205E-7	1.280E-7
Human health (carcinogenics), CTUh	9.258E-7	8.930E-8	6.360E-8

**Table 9 - Uncertainty analysis of impact categories associated with production of 1 FU of AlMg3, CFRP (53.8 wt.% CF), and CFRP (30 wt.% CF), respectively.**

Statistics <sup>(1)</sup> ( $\mu$ , $\sigma$ )	Calculated impact Categories for AlMg3				
	Human Health (carcinogenics) CTUh	Human Health (non- carcinogenics) CTUh	Ozone Depletion Kg CFC-11 eq	Photochemical Ozone Formation kg O3 eq	Respiratory Effects Kg PM2.5 eq
$\mu$	1.664E-6	5.294E-6	4.078E-7	0.193	2.651E-3
$\sigma$	9.191E-7	6.726E-6	1.259E-7	0.029	4.354E-4
<b>Calculated impact Categories for CFRP (53.8 wt.% CF)</b>					
$\mu$	3.609E-7	7.774E-7	1.416E-7	13.142	6.466E-3
$\sigma$	8.743E-8	7.614E-7	3.837E-8	6.765E-3	8.345E-5
<b>Calculated impact Categories for CFRP (30 wt.% CF)</b>					
$\mu$	2.651E-7	4.405E-7	7.588E-8	7.350	3.711E-3
$\sigma$	6.585E-8	4.745E-8	2.190E-9	3.66E-3	4.513E-5

<sup>(1)</sup>  $\mu$ : statistical mean       $\sigma$ : statistical standard deviation