

Parametric Life Cycle Assessment for the Design of Aircraft

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ABSTRACT

Current methods of life cycle assessment (LCA) include input-output (IO) models and process-based LCA. These methods either require excessive effort and time to reach a conclusion (process LCA) or do not adequately model how a change in a product's design will affect the environmental footprint (IO LCA).

A variation of process-based LCA developed specifically for aircraft is presented in this study. A tool implementing this LCA, "qUWick," is rapid and easily applicable to multi-disciplinary design optimization of aircraft. Models developed for the material production, manufacturing, usage, and end-of-life of an aircraft are examined. Outputs of qUWick are discussed for future air vehicles.

When compared to process LCAs with similar boundaries, qUWick gives similar results, however qUWick models several stages of an aircraft's life cycle more accurately than other aircraft process-based LCAs. Comparison to IO LCAs suggests an underestimation of supply chain as well as maintenance impacts and points towards areas of future improvements for the qUWick LCA tool.

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INTRODUCTION

Concern over the environmental impacts of human activities, including commercial air travel, is growing. Boeing has adopted a Design for Environment approach to systematically reduce the environmental footprint of products throughout their life cycle, including aircraft production, service, and end-of-life. A wide range of environmental impacts are considered, including energy and water use, hazardous material use, and air emissions.

Life cycle assessment (LCA) is a methodology that quantifies the resource usage and environmental releases associated with a product. LCA has been applied to many different products and systems. Recently, LCA has been applied to transportation systems, including aviation. This paper discusses the use of LCA at Boeing in aircraft design for environmental footprint reduction.

QUWICK AIRCRAFT LCA TOOL

In this study, life cycle assessment is performed using a streamlined LCA tool called qUWick. This spreadsheet-based tool rapidly calculates life cycle inventories for aircraft. This section describes the development, methodology, and validation results of the qUWick tool.

Tool Development

Performing LCA for aircraft poses several challenges. Commercial aircraft are complex machines constructed from millions of parts. The supply chain that produces these components involves many tiers of companies that are positioned around the globe. Thus, calculation of aircraft production life cycle inventories requires many assumptions to reduce the scope of the analysis. Additionally, the majority of aircraft life cycle environmental impacts are incurred by Boeing's suppliers and customers, making it difficult to collect direct inventory data. To address these challenges, Boeing has developed an aircraft-focused, streamlined LCA tool called qUWick.

The qUWick tool was initially developed by Joyce Cooper from the University of Washington under contract to Boeing beginning in 2008. Initial versions of the tool used publicly available datasets to estimate environmental impacts associated with the aircraft product life cycle. Since 2011, the tool has been developed internally at Boeing. Current versions of the tool utilize proprietary manufacturing data and aircraft performance methodologies. The tool has been designed to model a variety of aircraft production and operation scenarios of interest in Boeing environmental analyses.

Tool Methodology

The tool calculates life cycle inventories that align with Boeing's seven Environmental Performance Measures (EPMs): global emissions, energy, water, hazardous materials, sustainable materials, community noise, and local emissions. Inventories of indicators for each of these EPMs are calculated based on user-input data to describe the aircraft production and operation scenario being analyzed. A list of key tool inputs and outputs is shown in [Table 1](#).

The aircraft life cycle is divided into four life cycle phases: materials production, manufacturing, aircraft service, and end of service, shown in [Figure 1](#). A description of methods, data sources, and scope definition for each of these phases is described in the following sections.

Table 1. A subset of key inputs and outputs to the qUWick tool.

Inputs	Outputs
Aircraft empty weight	Energy consumption
Aircraft primary material breakdown and buy-fly ratios	Air emissions (greenhouse gases and common air pollutants)
Fabrication and assembly locations	Water consumption
Fuel consumption and emission rates on a representative mission	Solid and hazardous waste generation
Operating lifetime and utilization	Hazardous material use
Certification noise	



Figure 1. Aircraft life cycle, as modeled in the qUWick tool.

Primary material production

The materials production phase includes impacts associated with producing the primary materials from which an aircraft is constructed. Primary materials modeled in qUWick include aluminum, titanium, nickel, steel, carbon fiber reinforced polymer (CFRP), fiberglass, other metals, and other composites. It is assumed that the aircraft's operational empty weight (OEW) can be entirely assigned to these material categories. The current version of qUWick does not estimate impacts associated with producing secondary and consumable materials.

Unit process models for the production of each of these material categories are derived from different sources. Inventories for three key aircraft materials - aluminum, titanium, and CFRP - were developed for the qUWick tool. For all other materials, energy and emissions inventories are taken from GREET 2-2012 [1]. The aluminum model uses

industry inventory data, production locations, and alloy characteristics to estimate impacts associated with aerospace aluminum alloy production [2, 3, 4, 5]. Similarly, a titanium production model is based on published inventory data [6]. The CFRP model combines inventory data for producing resin, carbon fiber precursor, carbon fiber, and prepreg [7, 8, 9, 10].

Aircraft manufacturing

The aircraft manufacturing model includes impacts from transporting primary materials to fabrication sites, fabricating components, transporting components to the final assembly location, and assembling the aircraft. Raw material and component transport impacts are estimated based on fuel consumption and emissions for different transportation and distribution modes from GREET 1-2012 [11]. Impacts from aircraft parts fabrication and assembly are estimated based on analyses of Boeing production data. It should be noted that many aircraft components are fabricated by Boeing's suppliers, and associated environmental impacts are not directly measured by Boeing. The current version of qUWick assumes that supplier manufacturing activities perform at similar environmental impact intensities per unit weight of fabricated part compared with Boeing.

Aircraft service

The aircraft service life cycle phase models environmental impacts from aircraft operations and maintenance. Impacts from airport infrastructure construction and maintenance are outside of the scope of LCAs estimated by qUWick. User inputs to qUWick describe the type and number of missions flown by the aircraft over its lifetime. Energy use and exhaust emissions from aircraft operations are calculated using proprietary performance methods. Upstream environmental impacts due to fuel production are estimated from GREET 1-2012 fuel production pathway information [11]. Additionally, aircraft maintenance impacts are modeled using industry data [12] and information from Boeing's Aircraft Maintenance Manuals.

End of life

At the end of the aircraft service lifetime, aircraft are retired. This life cycle phase assesses impacts from aircraft disposal. Materials on the aircraft can be reused, recycled for use in different industries, or landfilled. In this life cycle phase, impacts from aircraft dismantling, shredding, separation, and transportation are estimated based on automobile industry data [13]. The dispositions of materials on the aircraft are determined based on projections of aircraft material recyclability or user-input assumptions. The overall sustainability of each material is quantified based on material origin and disposition properties using the Boeing's Material Sustainability Index (MSI) methodology.

Comparison to Results from Other Studies

Outputs from the qUWick tool are compared to publicly available aircraft LCA studies from a variety of sources for tool validation. Six sources are considered for results comparison: two process-based LCAs, one database, one hybrid LCA, and two input-output LCAs.

Process LCA studies

The first process LCA study considered is described in a master's thesis completed in collaboration with the Portuguese LCA consulting company 3 Drivers and the airline TAP Portugal [14]. The study, authored by Lopes, describes an environmental life cycle impact assessment for an A330-200 aircraft, modeled using SimaPro software.

There are several key differences between the manufacturing model adopted in the Lopes study and the model in qUWick. First, the assumed set of primary materials varies between the studies. Secondly, the study does not state the amount of material that is purchased for fabrication, so buy-fly ratios are implicitly assumed to be one. In qUWick, assumed buy-fly ratios for the A330 range from 1.5 for composites to 5-7 for metals [12]. Both models estimate impacts associated with transporting fabricated components to the final assembly location. However, the Lopes model does not estimate impacts associated with either fabricating parts from primary materials or assembling those parts on the aircraft. In qUWick, fabrication and assembly impacts account for approximately 50% of cradle to gate impacts for a typical commercial aircraft. To calculate in-service impacts, the Lopes study estimates fuel use per passenger-mile based on data from the open literature. The study estimates service impacts by applying the ecoinvent "Operation, aircraft, passenger, intercontinental/RER U" model with the calculated fuel efficiency replacing the ecoinvent default value.

Table 2. Comparison of A330-200 greenhouse gas emissions estimates from ref. 14 and qUWick.

Life cycle phase	Units	qUWick ¹ A330	Lopes A330	Difference
Full life cycle	kg CO2e/pax-km	1.38E-1	1.26E-1	-8.6%
Aircraft manufacturing	kg CO2e/aircraft lifetime	1.59E+6	1.54E+6	-3.1%
Aircraft service	kg CO2e/pax-km	1.37E-1	1.26E-1	-8.4%

Table 2 compares greenhouse gas (GHG) emissions estimates from Lopes with qUWick, each calculated based on inventories of CO₂, CH₄, and N₂O. For Table 2, a qUWick A330 model is developed based on identical assumptions and system boundaries to the assessment for direct comparison.

Similar material breakdowns, buy-fly ratios, fabrication and assembly locations, weights, and operating characteristics are applied. If instead default system boundaries and assumptions are applied, qUWick cradle-to-gate GHG emissions values more than double.

Agreement is seen between Lopes and qUWick estimates of full life cycle and aircraft service climate change, as CO₂-equivalents. This is expected since the majority of impacts are realized during aircraft service and the qUWick model was developed with identical lifetime fuel use assumptions. A difference of approximately 8% is attributed to slightly different fuel production models and emissions rates. Comparing manufacturing climate change impacts per aircraft lifetime, Lopes and qUWick estimates are nearly identical despite different models for materials production and component logistics.

The next study considered for comparison is a master's thesis, written by Howe [15], that evaluates the life cycle impacts of producing, operating, and decommissioning an A320 aircraft. This LCA study was performed using SimaPro v7.1.8 and the ecoinvent v2.0 database. This study takes a similar approach to ref. 14. Environmental impacts are calculated and aggregated in ref. 15 exclusively as a single score, using the Eco-Indicator 99 (H) method. No other details of the calculation are provided. Because of this aggregation, results cannot be compared directly with those from qUWick. In the Howe study, manufacturing accounts for 0.089% of total impact (as measured by the Eco-Indicator 99 score). In qUWick, with identical system boundaries and modeling assumptions, manufacturing accounts for 0.086% of greenhouse gas emissions and 0.101% of energy use. Both studies predict in-service impacts are approximately 1000x greater than cradle-to-gate impacts.

ecoinvent database

The ecoinvent Database contains life cycle inventory data for thousands of unit processes, including materials production, energy, services, transport, and other industries. There are two relevant unit process models for a full aircraft life cycle: aircraft production (cradle to gate) and air transportation (service). This paper considers open documentation for version 2.0 models of "aircraft production, medium haul" found in section 14.7.4, and "operation, aircraft, passenger, Europe" from section 14.7.6, of ref. 16.

In ecoinvent, each aircraft is assumed to be composed of 90% aluminum and 10% HDPE (plastic), and buy-fly ratios are implicitly assumed to be one. Additionally, the ecoinvent model neglects impacts associated with transporting materials and components between fabrication and assembly sites. Impacts associated with aircraft manufacturing, including both fabrication and assembly, are estimated from Airbus environmental reports. A comparison of manufacturing impact estimates are shown in Table 3. In this table, the qUWick data gives resource usage and emissions from the

¹ Assuming identical system boundaries and assumptions to [14] in place of default boundaries and assumptions.