



## Understanding aerospace composite components' supply chain carbon emissions

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# UNDERSTANDING AEROSPACE COMPOSITE COMPONENTS' SUPPLY CHAIN CARBON EMISSIONS

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## ABSTRACT

This paper examines a large structural component and its supply chain. The component is representative of that used in the production of civil transport aircraft and is manufactured from carbon fibre epoxy resin prepreg, using traditional hand layup and autoclave cure. Life cycle assessment (LCA) is used to predict the component's production carbon emissions. The results determine the distribution of carbon emissions within the supply chain, identifying the dominant production processes as carbon fibre manufacture and composite part manufacture. The elevated temperature processes of material and part creation, and the associated electricity usage, have a significant impact on the overall production emissions footprint. The paper also demonstrates the calculation of emissions footprint sensitivity to the geographic location and associated energy sources of the supply chain. The results verify that the proposed methodology is capable of quantitatively linking component and supply chain specifics to manufacturing processes and thus identifying the design drivers for carbon emissions in the manufacturing life of the component.

**KEYWORDS:** Composite Materials, Life Cycle Analysis, Supply Chain

## 1. INTRODUCTION

To improve the sustainability of modern air travel European targets have been set for a 50% reduction in aircraft carbon dioxide (CO<sub>2</sub>) emissions by the year 2020 [1], and by 2050 technologies and procedures are targeted to be available to allow a 75% reduction in CO<sub>2</sub> emissions per passenger kilometre [2]. The aerospace industry is thus moving towards designing lighter, more efficient aircraft structures which in turn will require less fuel in-service. The use of advanced composite materials is a key strategy for reducing vehicle weight [3]. However, high performance materials are typically associated with large complex and global supply chains in which energy intensive production processes are required. Thus to understand the impact of selecting a material for a new design it is fundamentally important to analyse both the in-service and manufacturing carbon emissions. Predictive modelling should allow design trade studies to consider the potential operational benefits versus the production requirements but

often non-specific parameters associated with generic material and processing categories are used. Ultimately, there is a need to consider specific component designs and examine specific supply chain routes to robustly understand and quantify production generated carbon emissions.

The aim of this paper is to investigate the carbon emissions associated with the production of advanced composite materials and components. In particular the paper seeks to quantify the distribution of emissions within a realistic composite component supply chain structure and to calculate emission sensitivity to supply chain geographic locations and energy sources. The focus of the paper is on the production of an upper wing cover of an idealised single aisle aircraft

## **2. BACKGROUND**

Aerospace manufacturers are increasingly using laminated composites to replace metallic materials in primary structures with the objective of reducing aircraft weight and maintenance requirements [3]. The design of wing and fuselage structures seeks to take advantage of the high strength-to-weight, high stiffness-to-weight and design flexibility characteristics of composite materials. However, the manufacture of the constituent composite materials, and in particular fibre production, is energy intensive [4]. Even after the individual constituent materials (reinforcing fibres and polymer matrices) are produced, additional manufacturing processes are required prior to component production (weaving for fibre textile production and fabrication of the prepregs (pre-impregnated) tape or fabric material). Such processes require additional energy, but also typically require the use of solvents and other additives [5]. Ultimately during component production more solvents and energy, in the form of heat and pressure for component curing, are required. Eventually the number of production steps and the energy required throughout the production process results in a significant cost burden with composite components [6–7].

Numerous life cycle analyses (LCAs) for composite structures and components have been reported. The literature covers a wide range of sectors, applications and varying complexities of supply chain architecture, e.g. [7–12]. However, many of these works have limited the analysis of the material production stages to order of magnitude estimates or constructed this portion of the life cycle with crude energy consumption data for the particular material [13]. Moreover, many of the analyses only consider very generic design and manufacturing details which makes it difficult or impossible to link design, process or supply chain decisions to the final results. From these studies it can generally be concluded that for high performance composite materials (used in aerospace structures) the manufacturing phases consume greater energy and produce more emissions than more traditional materials (e.g. aluminium alloys). Of the manufacturing phases, fibre production is generally identified as the most dominant source of emissions [10].

The studies also demonstrate the potential impact that supply chain logistics can have (distances travelled between supply chain elements and the transportation type (water, road or rail)) [12]. However, the general consensus throughout the majority of the literature is that composite material will result in a lower product weight and resulting fuel savings, and given an appropriately long product service life the manufacturing emissions may be offset [13]. Beyond the

fidelity issues of the foregoing studies a notable gap in the literature is emission sensitivity to supply chain geographic locations and energy sources. Such sensitivity is considered [10] but again only generic average energy mixes have been studied. Focusing on energy mix, this has generally been noted to have a strong influence on environmental impact. Clearly relocating portions of a supply chain to lower cost economies to reduce costs may inadvertently increase impacts from production depending on the local energy mix. Likewise locating material manufacturing in geographical regions with cleaner energy may be an effective approach to reduce impact.

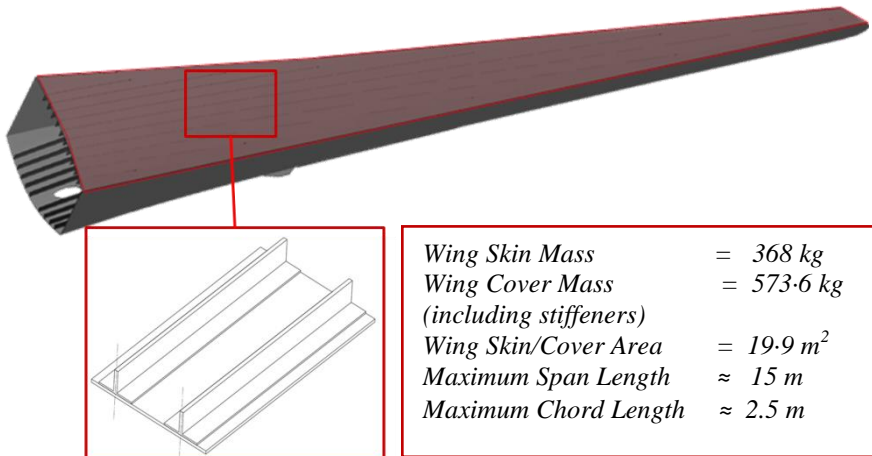
### 3. METHODOLOGY

#### 3.1 Overview

The analysis was carried out using LCA, which is defined by the ISO [14] as a technique for assessing the environmental aspects and potential impacts associated with a product. The LCA was conducted in line with the standard framework and followed the four main steps of goal and scope definition; inventory analysis; impact assessment; and interpretation.

#### 3.2 Goal and Scope

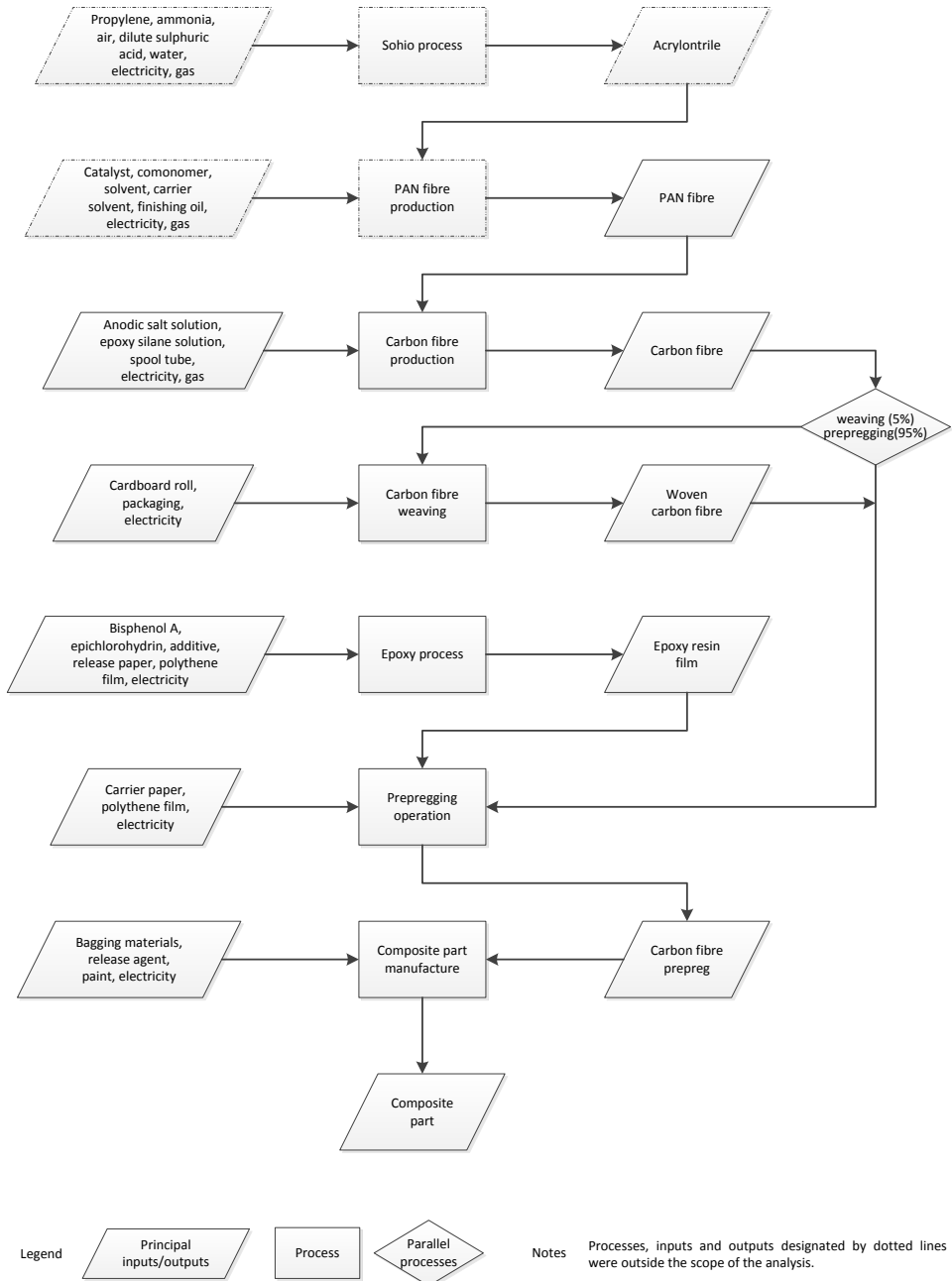
This cradle-to-gate study considered the manufacture of an upper wing skin of an idealised single aisle aircraft, Figure 1 [6]. The upper wing skin, with a mass of 368 kg, was selected as the functional unit (FU). The wing skin design represents the product of standard aerospace check stress sizing methods and includes best practice guidelines on panel manufacturability, damage tolerance, as well as other aspects. The composite wing cover is manufactured through seven main production processes (Figure 2). For brevity a single carbon-fibre epoxy material system was assumed, along with a single manufacturing route using manual ply lay-up and autoclave cure (described in Box 1).



**Figure 1** – Upper wing cover design

The environmental impact under consideration is greenhouse gas (GHG) emissions, reported in kgCO<sub>2</sub>e (the terms carbon and GHG emissions are used

interchangeably in this paper). Both direct and indirect emissions were taken into account. Direct emissions are those arising directly from processes within the system (e.g. from the combustion of natural gas), while indirect emissions are those that result from the production of something which is then used within the system boundaries (e.g. emissions from the production of bought-in components).



**Figure 2** – Inputs, outputs and production processes in the manufacture of a composite upper wing cover

## **Box 1** – Composite component production using hand lay-up process

The manual lay-up processing of the wing skin involves depositing B-staged resin pre-impregnated plies (unidirectional tape in 0°, 90°, +45° and -45° orientations, and biaxial non-crimped fabrics in ±45°, 0° and 90° formats) into a female mould tool. The plies will have been previously cut and sorted into component kits using a CNC (computer numerical control) ultrasonic cutter. A debulking operation will be assumed to occur after the first ply has been deposited and after every three subsequent plies. Once lay-up is complete the component is sealed under a release film, caul plate tooling, bleeder cloths, breather plies and vacuum bag before it is cured in an autoclave at ~180°C under vacuum for ~8 hours within an inert atmosphere. Manufacturing is assumed to involve curing the skin before co-curing manually preformed back-to-back L-section stiffeners to create the final integral structure. Following the resin curing operation the component is removed from the tool and automated CNC ultra-sonic and water-cutting equipment completes component inspection and trimming.

All production processes assessed (Figure 2) were initially assumed to take place in the UK. Emissions from transporting components between UK sites were excluded from the analysis. Emissions from transport can be difficult to quantify due to the wide range of variables (e.g. vehicle type, size and loading), but if transport is by road/rail over relatively short distances, the associated emissions are typically responsible for only a small portion of overall emissions. It is therefore not expected that neglecting transport between UK sites will have a significant impact on the overall result. Emissions from the transport of bought-in components were also neglected (unless already included in the emission factor used), due to a lack of data regarding supplier locations. Emissions from waste disposal were not taken into account. Scenario analyses investigated the effect on carbon emissions of moving production to different countries.

### **3.3 Inventory Analysis and Impact Assessment**

Data on production processes were obtained from previous work by the authors on the manufacture of aerospace composite components [6]. The data comprised the quantities of principal inputs in each production stage (Figure 2). Carbon emission factors (Table 1) were applied to each input to each sub-process to calculate the overall carbon footprint of the manufacturing chain. UK values were chosen where available; if not, European values were used as far as possible. As only preliminary manufacturing data were available for the Sohio and PAN (polyacrylonitrile) fibre production processes, detailed modelling was not conducted for these stages and values from the literature were assumed for the LCA calculation. While input quantities and associated carbon factors were available for carbon fibre production, no specific data on process emissions were available. These process emissions were estimated based on previous work by Das [15].

**Table 1** – Carbon factors for LCA calculation

Input	Carbon factor <sup>a</sup> (kgCO <sub>2</sub> e/unit)	Unit	Notes	References
Additive	-		Excluded from analysis as specific type of additive not known and quantity required is relatively minor	-
Anodic salt solution	-	-	Neglected from analysis as only minor quantity required (<1 kg)	-
Bagging materials	1.39	kg	Polythene bags assumed	[16] cited in [17]
Bisphenol A	4.88	kg	-	[18] cited in [17]
Cardboard roll	1.00	kg	Typical value for board packaging	[17]
Carrier paper	1.69	kg	Bleached kraft paper assumed	[18] cited in [17]
Electricity	0.50	kWh	UK scope 2 emissions plus emissions from transmission and distribution	[19]
Epichlorohydrin	3.37	kg	-	[18] cited in [17]
Epoxy silane solution	3.40	kg	Limited information available in literature; carbon factor for chlorosilane assumed	[20]
Gas	0.18	kWh	Natural gas from UK mains gas grid network <sup>b</sup>	[19]
Packaging	1.15	kg	Corrugated board boxes assumed	[21] cited in [17]
Paint	2.91	kg	Paint – general	[22]
PAN fibre	5.70	kg	-	[21] cited in [17]
Polythene film	2.57	kg	Average of typical values	[18, 23] cited in [17]
Release agent	0.40	kg	Average value for naphtha (principal ingredient) assumed	[21, 23] cited in [17]
Release paper	1.69	kg	Bleached kraft paper assumed	[18] cited in [17]
Spool tube	-	-	Excluded from analysis as only minor quantity required (<1 kg)	-

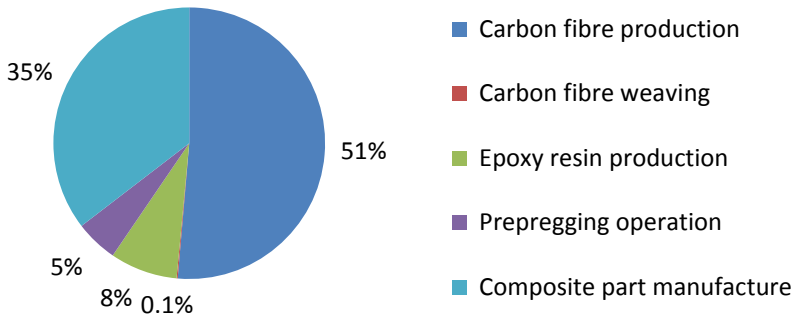
<sup>a</sup>Numbers are rounded to two decimal places.

<sup>b</sup>Based on the gross calorific value of natural gas (most bills are reported in terms of gross calorific value [19]).

## 4. RESULTS AND DISCUSSION

### 4.1 Emissions by Process

Total emissions from the production of the composite upper wing skin were calculated as 17,725 kgCO<sub>2</sub>e/FU. Similar to the results reported by Witik et al [10], carbon fibre production was the most dominant source of GHG emissions (Figure 3). The manufacture of the composite part was also a significant contributor to total emissions, at 35% of the total. By comparison, the weaving of the carbon fibre was responsible for only 0.1% of overall emissions, while the prepregging operation and epoxy resin production stages together accounted for less than 15%.



**Figure 3** – GHG emissions from each stage of the production process in the manufacture of an upper wing cover from composite materials

The emissions associated with the carbon fibre production stage arise from three main sources: the use of electricity (36%); the production of the principal input material, PAN fibre (28%); and release of gases from chemical processes (36%). During composite part manufacture, the final stage of the overall manufacturing process, the principal source of emissions is from the use of electricity. Several high energy demand processes are involved in this stage (Box 1), in particular the use of the autoclave in the curing step. The associated carbon emissions account for approximately one third of emissions in the entire production chain.

### 4.2 Tackling the Carbon Hotspots

Electricity, which is responsible for 55% of total GHG emissions, is by far the single largest contributor to the carbon footprint of the supply chain analysed. It was initially assumed that all manufacturing processes were carried out in the UK. Although low carbon sources account for around 30% of the UK electricity mix (20% nuclear, ~10% renewables) [24] and targets are in place to reduce the carbon intensity further [25], the country is still heavily reliant on coal and gas, each of which accounts for 34% of the mix [24]. The emissions intensity of UK electricity is therefore relatively high, and is approximately 100 gCO<sub>2</sub>e/kWh above the average in the EU-27 [26]. The EU-27 country with the lowest carbon intensity for electricity generation is Sweden [26], which at 43 gCO<sub>2</sub>e/kWh is less than 10% that of the UK [26]. Sweden's electricity mix is principally focused around hydro (44.1%) and nuclear (40.5%), with biofuels and waste contributing



8.5%, and wind a further 4%; carbon intensive fossil fuels contribute less than 2% [27].

By moving production to a country with low carbon electricity, such as Sweden in this scenario, emissions are reduced by over 50% to ~8800 kgCO<sub>2</sub>e/FU (Figure 4), and the portion attributed to electricity falls from 55% to 7%. The largest reduction is in the final stage of the process, composite part manufacture, where savings of over 5500 kgCO<sub>2</sub>e/FU can be achieved. If only this final stage is moved from the UK to Sweden, the bulk of the savings can still be realised, although emissions from transporting the carbon prepreg to the composite manufacturing facility also need to be taken into account. For each produced upper wing skin with a mass of 368 kg, 446 kg of carbon fibre prepreg are required. It is assumed that transport is by road and sea. Even when the mode of sea freight transport with the highest emission factor (large ropax ferry) is assumed, the emissions per FU (Table 2) increase by only 2% of the total process emissions.

**Table 2** – Estimated emissions from transporting carbon fibre prepreg from the UK to Sweden

Route <sup>a</sup>	Distance <sup>b</sup> (km)	Mode <sup>c</sup>	Unit emissions <sup>c</sup> (kgCO <sub>2</sub> e/t.km)	Total emissions (kgCO <sub>2</sub> e/t)
Road travel in the UK	280	Artic truck	0.088	25
Sea transport	1000	Large ropax ferry	0.387	387
Road travel in Sweden	470	Artic truck	0.088	41
Total				453
Emissions per FU				202 kgCO <sub>2</sub> e/FU

<sup>a</sup>The assumed route is by road from Birmingham to Harwich, then by sea to Gothenburg, and finally by road to Stockholm. Gothenburg and Harwich were selected as both are large international ports. Stockholm and Birmingham were selected as large urban centres.

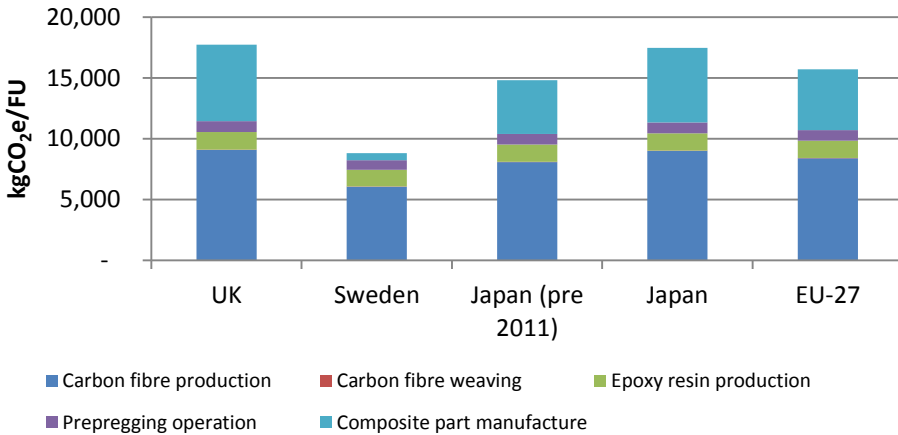
<sup>b</sup>Road distances are from [28] and sea distances from [29].

<sup>c</sup>Mode of transport and related emissions are from freight information in [19]. Average UK percentage loading and payload are assumed. Numbers may not sum exactly due to rounding.

Globally, a significant portion of carbon fibre installed production capacity is located in Japan [13]. Before the Fukushima accident in 2011, Japan relied heavily on nuclear power for electricity generation, and average emissions in the year prior to the accident were 350 gCO<sub>2</sub>e/kWh [30], which is below both the UK value and the EU-27 average of 396 gCO<sub>2</sub>e/kWh [26]. Based on this lower emissions intensity, moving the production chain from the UK to Japan would therefore have offered a 17% reduction in emissions over the life cycle (Figure 4). However, following the Fukushima accident, there has been a move away from nuclear to fossil fuel based electricity in Japan [30] and as a result emissions rose to 487 gCO<sub>2</sub>e/kWh in 2012/13 [31]. Under the current electricity generation mix, production chain emissions in Japan are similar to those in UK (and higher than if the EU-27 average value is assumed) (Figure 4).

Rather than relocating production to different part of the world, an option for reducing electricity emissions is to use renewable electricity that has been

generated on-site (or purchased from a ‘green’ supplier). The cost implications, such as capital investment and increased fuel costs versus higher transportation distances, require further research.



Note: Emissions from carbon fibre weaving are <1% in all cases.

**Figure 4** – Effect of electricity generation mix on the carbon footprint of an upper wing cover manufactured from composite materials

## 5. CONCLUSIONS

The carbon footprint LCA of the manufacture of a carbon fibre upper wing skin revealed electricity (which was responsible for 55%) to be the largest single contributor to GHG emissions. In terms of process stages, composite part manufacture and carbon fibre production were the two largest sources of GHG emissions, and electricity consumption was the largest contributor to each of these steps. The analysis assumed all production was carried out in the UK; an option for reducing emissions is outsourcing to a location with lower carbon-intensity electricity. A scenario analysis considered moving the production chain to Sweden, the EU country with the lowest GHG intensity of electricity. Although such a move could reduce emissions by half, further research is required to analyse the overall cost implications.

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