Life cycle assessment of novel aircraft interior panels made from renewable or recyclable polymers with natural fiber reinforcements and non-halogenated flame retardants

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<heading level 1> Summary

A comprehensive life cycle assessment of panels for aircraft interiors was conducted, including both a conventional glass fiber-reinforced panel and different novel sustainable panels. The conventional panel is made of a glass fiber-reinforced thermoset composite with halogenated flame retardant, whilst the sustainable panels are made of renewable or recyclable polymers, natural fiber reinforcements and non-halogenated flame retardants. Four different sustainable panels were investigated: a geopolymer based panel, a linseed oil-based biopolymer panel, and two thermoplastic panels, one with polypropylene (PP) and another with polylactic acid (PLA). All the sustainable panels were developed to fulfil fire resistance requirements and to be lighter than the conventional panels in order to reduce fuel consumption and air pollutant emissions from the aircraft. The environmental impacts associated with energy consumption and air emissions were assessed, as well as other environmental impacts resulting from the extraction and processing of materials, transportation of materials and waste, panel manufacturing, use, maintenance, and end-of-life. All the sustainable panels showed better environmental performance than the conventional panel. The overall impacts of the sustainable panels were offset by the environmental benefits in the use stage due to weight reduction. One square meter of the novel panels could save to 6000 kg $CO_{2\text{-eq}}$. The break-even point in months at which the sustainable panels would yield an environmental benefit was as follows: 1.2 for the geopolymer panel, 1.7 for the biopolymer panel, 10.4 for the PLA panel, and 54.5 for the PP panel.

Keywords: Fiber-reinforced polymer composite; Biopolymer; Renewable polymers; Lightweight materials; Transportation

<heading level 1> Introduction

Aircraft interiors are subjected to stringent performance requirements since the parts have to deliver mechanical strength, dimensional stability, and low heat and smoke release in the event of a fire, while keeping aircraft weight as low as possible for maximum efficiency. The environmental benefits of using lightweight materials in aircraft components include fuel savings and reduction of sustainable house gas emissions. These issues have been discussed in several studies (e.g., Scelsi et al. 2010; Beck et al. 2011; Howe et al. 2013).

The conventional panels for aircraft interior sidewalls considered here comprise a core of aramid fiber paper and two outer skins of phenolic resin and glass fibers with decabromodiphenyl ether (decaBDE). DecaBDE is a brominated flame retardant that belongs to the group of polybrominated diphenyl ethers (PBDEs), which are persistent, bioaccumulative and toxic to both humans and the environment. Human exposure to PBDEs can occur during the manufacture of flame retardants or products containing flame retardants, and also during waste treatment processes. The aircraft crew and passengers may also receive significant PBDE exposure via inhalation when flame retardants including PBDEs are used in aircraft (Christiansson et al. 2008).

The question of how to dispose of thermoset composite parts at the end-of-life is also growing in interest, as traditional disposal routes such as landfill and incineration are becoming increasingly restricted (Jacob 2011). Hence, composites companies and their customers are looking for more sustainable solutions. The replacement of fiber-reinforced thermoset composites currently used for aircraft interior panels with environmentally friendly solutions implies the development of new materials able to meet the stringent requirements of aircraft interior parts.

Four novel sustainable panels were developed to substitute conventional panels in the CAYLEY project (patents: US2012/0148824 A1 and US 2015/0190987 A1), which do not contain noxious substances and meet all technical requirements in terms of mechanical properties and fire resistance. The four panels are distinguished according to the material used for the matrix: (i) an inorganic thermoset resin from natural sources (geopolymer panel), (ii) a natural thermoset resin from renewable sources (biopolymer panel), (iii) a recyclable thermoplastic polymer (polypropylene panel or PP panel), and (iv) a biodegradable thermoplastic polymer (polylactic acid panel or PLA panel). These novel composite materials are easy to dispose of or recycle with low waste production at their end-of-life. In addition, the novel sustainable panels are lighter than conventional panels, which could save fuel during the operation of aircraft and reduce the emissions of greenhouse gases and other air pollutants.

In previous studies about environmental performance in aviation, the Life Cycle Assessment (LCA) methodology was applied mainly for fuel alternatives: kerosene (Koroneos et al. 2005a), hydrogen (Koroneos et al. 2005b,), natural gas (Pereira et al. 2014) and bio-jet fuels (Hileman et al. 2009, Stratton et al. 2011, Agusdinata et al. 2011, Elgowainy etal. 2012, Fan et al. 2013, Fortier et al. 2014, Cox et al. 2014). LCA was also applied in aviation to lightweight materials (Scelsi et al. 2011, Witik et al. 2013, Timmis et al. 2015) and Howe et al. (2013) performed the LCA of each of the service life phases of a passenger aircraft.

The aim of this article is to assess the environmental impact of aircraft interior panels during their entire life cycle, including both the conventional panel and the four novel sustainable panels, using the LCA methodology. The environmental impact associated with energy consumption and air emissions were assessed, but other environmental impacts were also assessed from the extraction and processing of materials, transportation of materials and waste, panel manufacturing, use, maintenance, and end-of-life.

<heading level 1> Material and methods

The LCA methodology was used in this study to calculate the environmental impacts of aircraft interior panels throughout all the stages of the life cycle (i.e., from cradle to grave). LCA was applied according to the guidelines provided by the ISO (2006a, 2006b).

<heading level 2> Goal and scope definition

The present study aimed to calculate the environmental impacts of aircraft interior panels during their entire life cycle, including the following stages: extraction and processing of materials, transportation, manufacturing, use, maintenance, and end-of-life. The panels investigated included a conventional panel made of a glass fiber-reinforced thermoset composite and four novel sustainable panels made of renewable or recyclable polymers reinforced with natural fibers. All the sustainable panels were developed to fulfil the fire resistance requirements according to the Federal Aviation Administration (FAA):

- Heat release: peak heat release rate ≤ 65 kW/m^2, and total heat release ≤ 65 kW-min/m^2.
- Flammability: burn length ≤ 152 mm, flame time ≤ 15 s, and flaming time of drippings ≤ 3 s.
- Smoke density: specific optical smoke density in the flaming mode ≤ 200.
- Smoke toxicity (toxic gases in ppm): HCL < 150, HF < 100, SO2 < 100, NOX < 100, HCN < 150, and CO < 1000.

In addition, novel panels needed to have a surface density below 2 kg/m^2 (density of the conventional material) in order to the lightening of the panels to reduce fuel consumption and air pollutant emissions from the aircraft.

Because all panels were designed to meet the same requirements, 1 m^2 of aircraft interior panel was considered as the functional unit for every panel.

There is no need to incorporate the service life of the panels into the functional unit because it is the same as the service life of the aircraft, both for conventional panel and for all the sustainable panels.

<heading level 2> Inventory analysis

Field data supplied by partners within the CAYLEY project were used to gather information about the inputs and outputs for each stage of the life cycle. For those elements where no field data were available, data were collected from scientific literature and LCA databases, mainly the Ecoinvent® database (Frischknecht et al. 2004).

<heading level 3> Materials

The materials of the aircraft panels can be classified into three panel components: core, outer skins, and decorative film. Table 1 shows the material composition of each layer for 1 m^2 of finished aircraft panel

Table 1 Material composition of 1 m^2 of finished aircraft panel

Component	Material	Amount (kg)				
		Conventional panel	Geopolymer panel	Biopolymer panel	PP panel	PLA panel
Core	Aramid fiber paper	0.41				
	Polyetherimide		0.09	0.16	0.22	0.21
Skins, polymer matrix	Phenolic resin	0.42				
	Geopolymer resin		0.60			
	Biopolymer resin			0.75		
	PP + nanoparticles				0.41	
	PLA + nanoparticles					0.41
Skins, reinforcement	Glass fiber	0.73				
	Flax fiber yarn		0.22	0.25	0.27	0.27
Skins, flame retardants	DecaBDE	0.07				
	Non halogenated		0.08	0.20	0.75	0.72
Decorative film	PVC film	0.37	0.39	0.35	0.35	0.34
Total		2.00	1.39E	1.71	1.99	1.95

The core of the conventional panel is a honeycomb of aramid fiber paper manufactured via the expansion process. The LCI of aramid fiber paper was based on data from a manufacturer of aramid fibers (Teijin Aramid 2009, 2010, 2011).

The cores for all the sustainable panels are manufactured from polyetherimide, which is foamed using non-ozone depleting blowing agents (only inventory data of energy and CO_2 eq from CES EduPack® software).

The skins of the conventional panel are prepregs composed of glass fibers and phenolic resin modified with a flame-retardant additive as discussed in Moliner et al. 2013. The phenolic resin matrix consists of 95% phenol and 5% formaldehyde. The LCI of phenolic resin was taken from the Eco-profiles of the European Plastics Industry (Boustead 2005).

The skins of the geopolymer panel are prepregs composed of geopolymer resin and natural flax fiber reinforcements with a flame-retardant additive. The geopolymer resin matrix is synthesized with metakaolin, an alkali metal hydroxide and silicate solution

The LCI of metakaolin was based on LCI of kaolin (Industrial Minerals Association Europe, ELCD 3.2) as raw material with the addition of energy for the flash calcination in a gas suspension calciner (Tecklay et al. 2015 based on Weber et al. 1965). Calcination temperature was assumed 1200 K, and the specific heat capacity of metakaolin was taken from Michot et al. (2008). An additional 10% of energy losses was also included.

The skins of the biopolymer panel are prepregs composed of biopolymer resin and natural flax fiber reinforcements with a flame-retardant coating. The biopolymer resin matrix is synthesized by polymerization of epoxidized linseed oil (90 wt%) with acrylic acid (8 wt%) in presence of an initiator (2 wt%). The LCI of epoxidized linseed oil was based on a study by Diehlmann and Kreisel (2000) and it is included in the table S1 of the supplementary material. The LCIs of acrylic acid and initiator were taken from the Ecoinvent® database.

The skins of the PP panel are composed of two sheets of PP with nanoparticles (graphene and nanoclay) and a flame-retardant additive, which are sandwiched around natural flax fiber reinforcements with another flame-retardant additive. The skins of the PLA panel are almost identical to those of the PP panel; the only difference is that PLA is used as thermoplastic polymer matrix instead of PP. The LCIs of PP and PLA were taken from the Ecoinvent® database, whilst the LCI of nanoclay was based on a study by Roes et al. (2007). As previously considered by Arvidsson et al. (2014), the LCI of graphene was based on patent US8226801B2 by ultrasonication method and the use of diethyl ether. Distillation of diethyl ether was estimated with Ecosolvent (Capello et al. 2007). This LCI is included in the table S2 of the supplementary material.

The glass fibers used as reinforcement in the conventional panel are prepared from a mixture of the so-called E-glass in the form of continuous strands with a size coating and a binder. The LCI of glass fiber was based on the reference document on best available techniques for the manufacture of glass (JRC 2013).

All the sustainable panels contain flax fiber yarns as reinforcement. The LCI of flax fiber yarn was based on cultivation data from Dissanayake et al. (2009) with some improvements: 1. Yarn production process was taken from Deng et al. (2016), discarding the wet spinning process considered by Dissanayake et al. (2009) to produce high quality textile. For flax yarns as reinforcement material, it is not necessary to reach this grade, moreover, bleaching is harmful to flax fiber properties. 2. Dissanayake et al. (2009) allocate all environmental impact to flax fiber, however flax fiber extraction is a consequence of multi outputs processes that generates at the same time flax fiber, tows, shives and seeds. All outputs are highly useful. For this reason, economical allocation from Le Duigou et al. (2011) was included. This LCI is included in table S3 of the supplementary material.

The LCIs of flame retardants were taken directly from the Ecoinvent® database or calculated through stoichiometric reactions with chemical compounds inventoried in the mentioned database:

- The flame-retardant additive used in the conventional panel is decaBDE, a brominated compound which is produced by reacting diphenyl ether with bromine in presence of a catalyst (e.g., aluminum chloride) and heated to 59ºC. LCI of bromine was taken from Deng et al. (2016).
- The flame-retardant additive used in the geopolymer panel is produced by dissolving anhydrous borax in water.

- The flame-retardant coating used in the biopolymer panel is a formulation of organophosphorus compounds dissolved in dipropylene glycol monomethyl ether, ammonia and water.
- The PP and PLA panels include both a flame-retardant additive and a flame-retardant coating. The flame-retardant additive is a high molecular-type ammonium polyphosphate, which can be produced by reacting concentrated phosphoric acid with ammonia. The flame-retardant coating is a formulation of organophosphorus compounds and betonite dissolved in phosphoric acid and water.

The decorative film is the same for all panels, and is made of polyvinyl chloride (PVC) with phthalate plasticiser, stabiliser (zinc) and filler (limestone). Other materials present in the decorative film to a lesser extent are zinc borate, antimony trioxide and epoxy resin. The LCIs of the materials composing the film and the film extrusion process were taken from the Ecoinvent® database, except the LCI of phthalate plasticiser (Simonson et al. 2001).

<heading level 3> Panel manufacturing

Two technological approaches for panel manufacturing are distinguished here according to the type of polymer matrix (Figure 1). The use of technologies based on thermoset matrices is the most similar approach to current manufacturing processes and has the advantage of an easy adaptation of the existing facilities to the new materials, minimizing the cost of retrofitting. Technologies based on thermoplastic matrices require an additional process step, but the processing time is lower than in the other technologies.

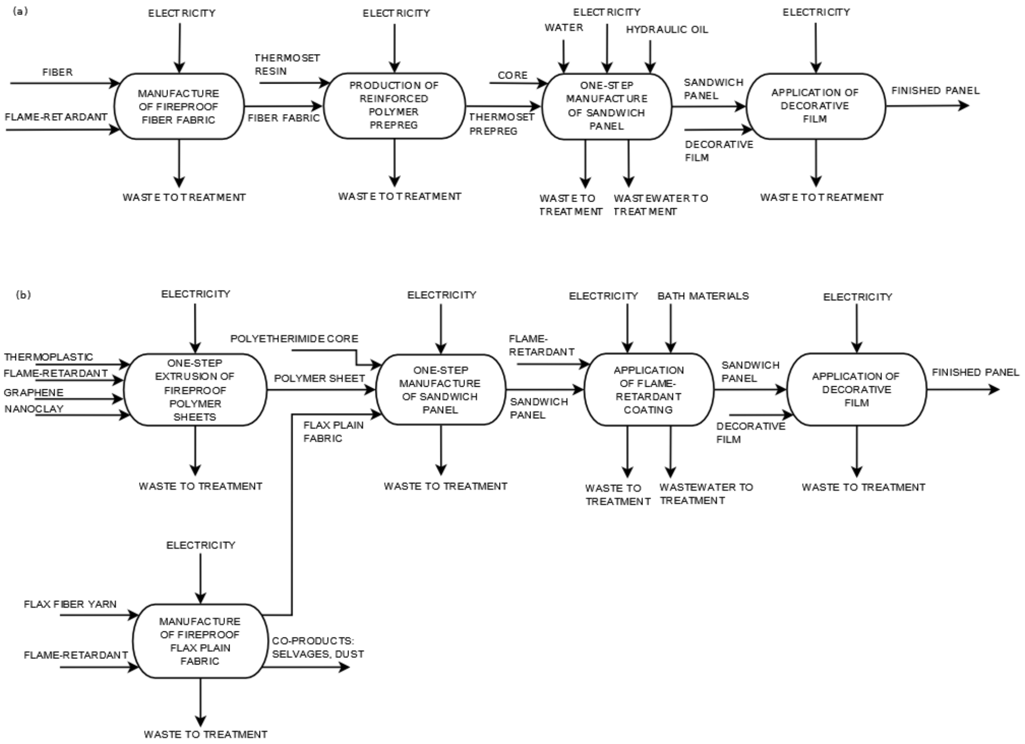


Figure 1 Manufacturing processes diagram: (a) thermoset panels (conventional, geopolymer, and biopolymer panels; (b) thermoplastic panels (PP and PLA panels).

The LCI of prepreg production was based on a study by Suzuki et al. (2005) and data from a Spanish company that manufactures fiber-reinforced thermoset composites for the automotive sector. The LCI of sandwich moulding was based on data provided by the mentioned company. The LCI of application of decorative film was based on data supplied by partners within the CAYLEY project.

The LCIs for the manufacture of sustainable panels were based entirely on field data provided by manufacturing companies and pilot plants within the CAYLEY project. Data on auxiliaries, electricity consumption and waste generation were directly measured from the production processes. It should be mentioned that solid waste from panel manufacturing is typically landfilled, except wood and cardboard that are recycled. Only solid waste from the manufacture of the biopolymer panel is incinerated rather than landfilled. Inventory data for all panels are included in Table 2.

Table 2 LCI of the manufacture of 1 m^2 of finished aircraft panel

Input/output	Amount				
	Conventional panel	Geopolymer panel	Biopolymer panel	PP panel	PLA panel
Electricity, MV (MJ)	57.6	82.4	4.4	16.9	15.2
Auxiliary, hydraulic oil (kg)	8.16E-03				
Auxiliary, water (kg)	0.9	0.5		0.8	0.8
Waste, polymer (kg)	0.24	0.08	0.19	0.02	0.02
Waste, nanoparticles (kg)				1.51E-04	1.25E-04
Waste, flame retardant (kg)			5.01E-02	1.54E-03	1.67E-03
Waste, wood and cardboard(kg)		3.67E-03	5.13E-03	4.37E-03	4.41E-03
Waste, garbage (kg)		3.19E-03	4.45E-03	3.80E-03	3.87E-03
Waste, flax fabric (kg)		3.07E-03	3.74E-02	4.22E-03	3.81E-03
Waste, hydraulic oil (kg)	3.92E-03				
Wastewater (m^3)	4.64E-06		5.61E-06	7.72E-04	7.56E-04

<heading level 3> Transportation

The materials are transported by road from the material suppliers to the panel manufacturing plant. Distances were estimated from the suppliers to the panel manufacturing plant.

The wastes generated throughout the life cycle of the panels are also transported by road to the facilities where they are treated. The distances travelled by waste to the treatment facilities vary depending on the waste treatment to be applied: 20 km for landfill or recycling, and 55 km for incineration. These distances are also applicable to the panels at the end-of-life stage.

To account for the transport of materials and waste, an articulated truck-trailer with a Euro II diesel engine was modelled. Fuel consumption and direct airborne emissions of gaseous substances, particulate matters and heavy metals from this vehicle were inventoried based on the ‘EMEP/EEA air pollutant emission inventory guidebook’ (EEA 2009).

<heading level 3> Use

The use of the panels is here related to the operation of the aircraft in which they are placed, thus being possible to take into account the environmental benefit of lightweight panels with respect to the conventional panel.

To account for the use of the panels, an aircraft Boeing 747-400 was modelled. The operating conditions of this aircraft are shown in the supplementary material. Fuel consumption and direct airborne emissions of gaseous substances and particulate matters from the aircraft were estimated based on the 'EMEP/EEA air pollutant emission inventory guidebook' (EEA, 2009). Fuel consumption and emissions from the aircraft throughout its service life can be calculated as a function of average flight distance and number of flights throughout the service life. The service life of the aircraft was assumed to be 20 years, which is neither the most nor the least restrictive among the minimum design service life objectives. All data considered in the operating conditions are in the table S4 of the supplementary material.

The service life of the panels is the same as the service life of the aircraft. Fuel consumption and emissions from the aircraft throughout its service life can therefore be divided by the aircraft weight to estimate the environmental burdens associated with the use of the panels based on their weight. The aircraft weight (AW, in kg) was estimated by applying the following equation:

$$AW \cong OEW + PLF/100 \cdot MP + FC$$

where *OEW* is the operating empty weight, *PLF* is the passenger load factor, *MP* is the maximum structural payload, and *FC* is the estimated amount of fuel consumed per flight. The LCI of the use of 1 kg of aircraft panel thus obtained for the aircraft modelled is included in the table S5 of the supplementary material. A direct relationship between fuel consumption and aircraft weight was here assumed as a first approach to take into account the environmental benefit of lightweight panels with respect to the conventional panels. (Scelsi et al. 2011; Howe et al. 2013); i.e., each kg of weight saved with lighter panels avoids the fuel consumption and emissions.

Brominated flame retardants including PBDEs are often used in commercial aircraft, where crew and passengers may receive significant PBDE exposure via inhalation (Christiansson et al. 2008; Allen et al. 2012).

<heading level 3> Maintenance

The maintenance of panels basically involves the replacement of the decorative film. This includes the dismantling and end-of life of the worn film and the placement of a new film. Thus, the burdens due to the laying of a new film were modelled according to the burdens of the decorative film registered in the LCIs of the stages outlined above. Likewise, the burdens due to the dismantling and end-of-life of the worn film were modelled according to the LCI of the end-of-life stage for the decorative film.

Approximately 4 panels per aircraft per year need to be repaired for aircraft with a total of 40 panels. The service life of the aircraft was assumed to be 20 years. Hence, the decorative film has to be replaced two times during the lifetime of each panel.

<heading level 3> End-of-life

When panels reach this stage, they are dismantled from the aircraft and become waste. The environmental burdens associated with this stage can be quite different depending on the waste treatment applied to panels.

The better solution for thermoplastic materials is mechanical recycling (Garraín et al. 2007). In the case of thermoset composites, several technological, economical and environmental constraints hinder recycling (Pickering 2006; Yang et al. 2012). One of the technologies available is mechanical recycling resulting in size reduction that can be reincorporated into new composite materials. Several promising applications for fiber reinforced polymer wastes were investigated over the last years (a complete review can be found in Meira Castro et al., 2013), eg. filler or reinforcement material for artificial wood.

Comentari [SV1]: Answer to editor

Recycling of panels with decaBDE is not allowed if this one is targeted by Stockholm Convention. For this reason, mechanical recycling and incineration as alternative are assessed in the EOL.

Mechanical recycling starts with size reduction of the composite waste by low speed cutting or crushing (to 50–100 mm). The size is then reduced down to 10 mm to 50 µm through a hammer mill or other high speed millings for fine grinding. Because conventional, geopolymer and biopolymer panels contain thermoset resins, the mechanical recycling is only able to produce short milled fibers used as filler. The PP and PLA panels can, however, be further processed to produce recycled thermoplastics. The decorative film is dismantled from the panels and processed separately to produce recycled PVC, while the core and skins are recycled together.

The LCI of recycling of core and skins for the thermoset panels was based on a study by Hedlund-Åström (2005). It was assumed that the production of 1 kg of filler is avoided as a result of recycling 1 kg of thermoset composite. Limestone was assumed to be the avoided filler product.

The LCI of recycling of core and skins for the thermoplastic panels and also the recycling of decorative film was based on studies by Garraín et al. (2007, 2008). It was assumed that the production of 0.7 kg of thermoplastic polymer is avoided by recycling 1 kg of thermoplastic composite and the recycling of 1 kg of decorative film avoids the production of 0.7 kg of PVC. Inventories of recycling 1 kg of waste from different panel components are included in the table S6 of the supplementary material.

A matter of concern in the recycling of conventional panels is the presence of decaBDE. The use of decaBDE in the conventional panel may cause impacts on the health of workers in the process of dismantling and recycling. Unfortunately, there are some unknown data in previous studies, which hinders the inclusion of PBDE concentrations in LCA.

The model of Doka (2009) was used to develop the LCIs of incineration for the different aircraft panels. Although panel components are incinerated all together, each component was modelled separately in order to ease calculations. The elemental waste composition was first determined for the core, skins and decorative film based on the composition of the materials in each component. The lower and upper heating values for each panel component were also determined. Additional burdens from the preparation of waste for being incinerated were based on the study by Hedlund-Åström (2005). Detailed inventories are included in the tables S8-S14 of the supplementary material.

Moreover, since the environmental burdens from the incineration of brominated flame retardants are not included in the model of Doka (2009), the burdens associated with decaBDE contained in the conventional panel were inventoried based on literature data (Wang et al. 2010) and explained in the supplementary material and included in table S7.

<heading level 2> Impact assessment

The impact assessment was conducted by applying the impact assessment method ReCiPe v 1.12 (Goedkoop et al. 2009), which is incorporated within the SimaPro® software.

ReCiPe assesses the environmental impacts according to midpoint and endpoint impact categories. Eighteen impact categories can be assessed at the midpoint level, including climate change (GWP). These midpoint categories are further converted and aggregated into three endpoint categories: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA). Both midpoint and endpoint impacts were assessed in this study according to the hierarchist perspective. Furthermore, the cumulative energy demand (CED) v 1.09 was also assessed to ease energy comparisons. CED assessment was based on the method published by Ecoinvent® (Frischknecht et al., 2004) and expanded within the SimaPro® software.

<heading level 1> Results

As a first result, it was observed that the use stage caused most of the impact, with a contribution to the overall impact above 98% for every aircraft panel and endpoint impact category. This result was expected, since the impact of the use stage is due to fuel consumption and air emissions from the aircraft throughout its entire service life, which were attributed to each panel based on its weight. The impact of the use stage was excluded from further analysis in order to avoid masking other lower impacts that may vary from one aircraft panel to another.

<heading level 2> Comparison between panels

The overall environmental impacts of each aircraft panel are showed in Figure 2. It should be noted that both of the end-of-life strategies are displayed: incineration is displayed with solid refill and recycling with no refill and border with dash line.

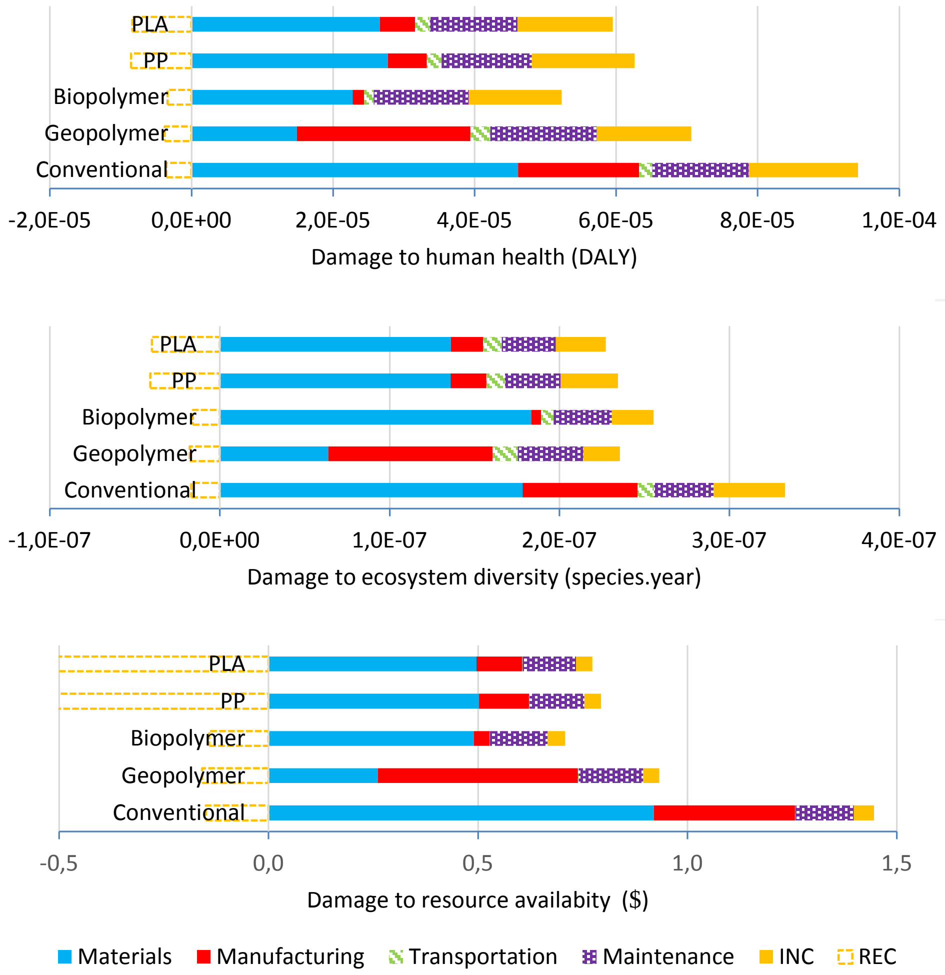


Figure 2 Endpoint impacts per m^2 of aircraft panel by life cycle stage.

It can be observed in Figure 2 that the conventional panel has the highest environmental impacts. Comparing only the novel panels and excluding EOL, biopolymer panel has the lowest values in HH and RA, meanwhile it has the highest value in ED. Geopolymer presents the opposite behavior, the highest values in HH and RA, and the lowest value in ED. The explanation is fundamentally in the environmental impacts of materials and manufacturing for each panel.

By not taking into account the use stage, materials and panel manufacturing became the life cycle stages with the greatest impacts, followed by maintenance, and transportation.

The impacts of the maintenance were roughly equal for all the aircraft panels investigated.

The three endpoint impacts of manufacturing were mainly by electricity consumption. Geopolymer panel was the most demanding electricity during manufacturing.

By comparing both end-of-life scenarios, it was found that mechanical recycling is advantageous over incineration in terms of environmental impact. The recycling of panels avoids the impacts of the extraction and processing of virgin raw materials. The core and skins of thermoset panels (i.e., conventional, geopolymer and biopolymer panels) can be processed to produce filler materials. Moreover, the core and skins of thermoplastic panels (i.e., PP and PLA panels) can be processed to produce recycled thermoplastics. The decorative film can be dismantled and processed separately to produce recycled PVC. This leads to a net environmental benefit, which is greater in thermoplastic panels because the avoided thermoplastics are more valuable in environmental terms than the filler materials avoided by recycling thermoset panels.

Moreover, all the sustainable panels investigated are lighter than the conventional panel. This weight reduction allows to save fuel and decrease air pollutant emissions throughout the service life of the aircraft. These benefits correspond to the impacts avoided throughout the entire service life of an aircraft Boeing 747-400 due to weight reduction in sustainable panels. Table 3 shows the net environmental benefits of each sustainable panel. These results show that all the sustainable panels have better environmental performance than the conventional panel. The overall impacts of the sustainable panels are offset by the environmental benefits in the use stage. The geopolymer panel was found as the best alternative among the panels investigated, followed by the biopolymer panel. One square meter of the geopolymer panels could save to 6000 kg CO_{2-}eq and 81777 MJ of energy. The production of thermoplastic panels has higher environmental impacts, and these panels are not as lightweight as the other sustainable panels. Consequently, the environmental benefits of thermoplastic panels with respect to conventional panel are much lower than those from the other sustainable panels.

Table 3 net environmental benefits of 1 m^2 of sustainable panel with respect to conventional panel including the use stage and recycling as EOL

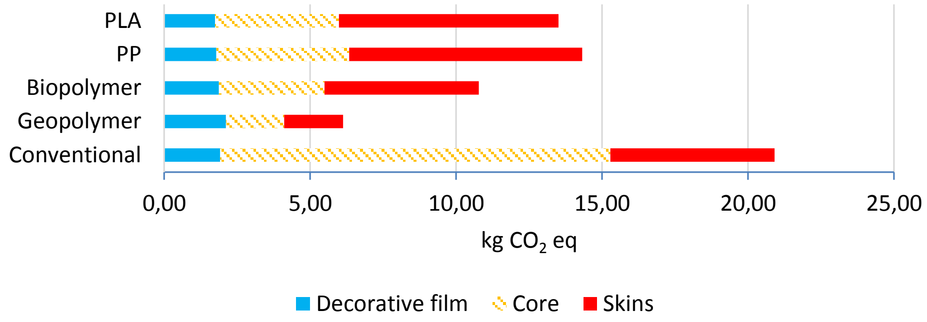
Panel	Net environmental benefit				
	Damage to HH (DALY)	Damage to ED (species.yr)	Damage to RA ($)	Impact on GWP (kg CO_2 eq)	CED (MJ)
Geopolymer panel	1.1E-02	5.3E-05	19.18	6012	81777
Biopolymer panel	5.1E-03	2.5E-05	9.60	2871	39164
PP panel	2.1E-04	9.7E-07	1.35	114	1784
PLA panel	9.1E-04	4.4E-06	2.59	508	7160

<heading level 2> Environmental impacts of materials

The environmental impacts of the materials stage were assessed in more detail to determine determine the impacts of each panel component. To this end, the environmental impacts of the core, skins and decorative film were assessed at the midpoint level according to nineteen midpoint impact categories. The impacts on climate change for the materials, and in particular for the skin, are shown in

Figure 3.

(a) Materials, climate change



(b) Skins, climate change

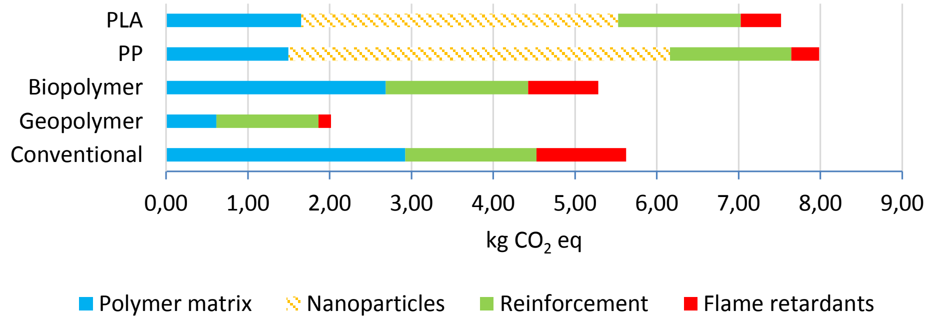


Figure 3 (a) Climate change impacts for materials production per m^2 of aircraft panel component; (b) Climate change impacts for skins production per m^2 of aircraft panel.

It can be observed that the core was the component with the greatest impact for the conventional panel. The core of the conventional panel is a honeycomb of aramid fiber paper. The production of aramid fiber requires a high amount of energy, which leads to significant air pollutant emissions from the life cycle of the electricity consumed.

The core also had high impacts for the novel panels, but it only accounts for 6.7-11.2% of the panel weight. The core of these panels is made of polyetherimide foam, whose production had higher impacts than those from the other materials composing the panel.

The impacts of the decorative film were roughly equal for all the aircraft panels investigated. This was due to the fact that all the panels contain the same decorative film in very similar amounts.

The skins were the components with the greatest variability in composition and, consequently, in environmental impacts (figure 3B). Thermoplastic panels resulted with the highest impacts in skins. Most of the impacts caused by the skins of these panels were due to the addition of graphene. This material is added in amounts below 2% by weight. However, the production of graphene is very energy intensive and is not yet optimized.

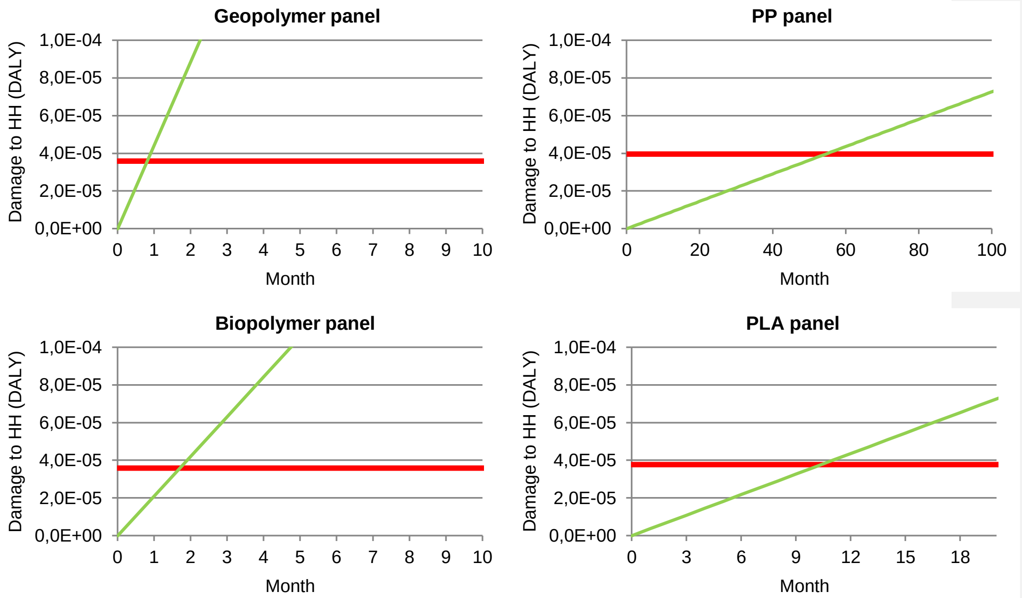
Phenolic resin had the highest environmental impacts per weight. Oppositely, metakaolin-based geopolymer had the lowest impacts, followed by the thermoplastic resins. Although, it has to be noticed in figure 3B that non-halogenated flame retardant based on ammonium polyphosphate was included in the polymer matrix of the thermoplastic panels, increasing significantly the impacts.

The amount of flax fibers in the novel panels was almost half of the amount of glass fiber in the conventional panel, thus offsetting its greatest impact per unit of weight.

Regarding flame retardants, geopolymer panel required less amount of flame retardants to accomplish with the fire resistance requirements of FAA. Similar amount required conventional panel, although with higher impacts. Thermoplastic panels required one order of magnitude more of non-halogenated flame retardants with relatively low impact.

<heading level 2> Break-even analysis

Finally, a break-even analysis was conducted to determine at which point in the service life of the aircraft the sustainable panels would yield an environmental benefit due to the lightweight materials used. In Figure 4, the red and horizontal line represents the impact of panels during their life cycle without including the use stage; the light green line represents the benefit of panels during the use stage; the point at which the benefit line intersects the impact line corresponds to the break-even point in months. Damage to HH was the impact category used to determine the break-even point as this was the most restrictive among the impact categories assessed (i.e., the damage to HH was the impact category that required more time to be offset by the environmental benefit in the use stage). Thus, the environmental break-even point in months for the different sustainable panels was as follows: 1.2 for the geopolymer panel, 1.7 for the biopolymer panel, 54.6 for the PLA panel, and 10.4 for the PP panel.



<heading level 2> Sensitivity analysis

A number of input parameters included in the assessment are uncertain in the sense that their values may vary. Their influence on the results of the environmental impacts was therefore tested in a sensitivity analysis. The inputs investigated in the sensitivity analysis are the halogenated flame retardant (+50% impact), the non-halogenated flame retardants (+100% impact), polyetherimide (+100% impact), graphene (-50% and +50% in energy consumption), panel manufacturing (-50% in energy consumption).

The main reasons to choose them are due to the incomplete LCI for flame retardants and polyetherimide; the high variability in energy consumption for graphene production (Healy et al. 2008); the use of different graphene production techniques, e.g. the modified Hummers'process (Arvidsson et al. 2014); and the reduction of the energy required to manufacture the panels as a consequence of future improvements in industrial-scale production.

Comentari [SV2]: Answer Reviewer #2

Figure 5 shows the minimum, maximum and the baseline values for each panel in the endpoint impact categories damage to human health and damage to ecosystems. Excluding the use stage in the analysis, the environmental impacts of the novel panels are clearly lower than the environmental impacts of the conventional panel and, as a consequence of the uncertainty, no conclusion can be stated about the best environmental performance within the novel panels.

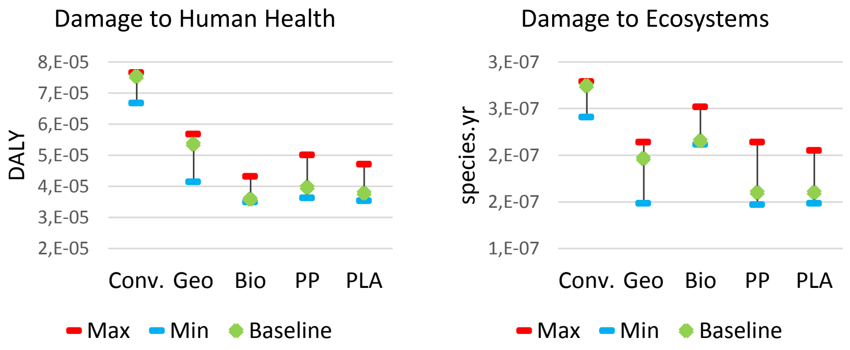


Figure 5 Sensitivity analysis (use stage is not included).

If use stage was included in the analysis, uncertainties in the input parameters were not significant in the total environmental impacts (differences lower than 0.05%) and the novel panel more environmental friendly was the one with the highest weight reduction.

<heading level 1> Conclusions

A comprehensive life cycle assessment of panels for aircraft interiors was conducted, including both conventional panels and novel sustainable panels from renewable polymers and natural fiber reinforcements. Four different sustainable panels were assessed: a geopolymer panel, a biopolymer panel, and two thermoplastic panels, one with PP and another with PLA. All the sustainable panels were developed to fulfil the requirements for fire resistance.

The use stage causes most of the impact, with a contribution to the overall impact above 98% for every aircraft panel investigated. By not taking into account the use stage, the materials stage is the life cycle stage with the greatest impacts.

Excluding the use stage in the analysis, the environmental impacts of the novel panels are clearly lower than the environmental impacts of the conventional panel.

Moreover, the sustainable panels are lighter than the conventional panel, which can save fuel during the use of aircraft and reduce the emissions of climate change gases and other air pollutants. The overall impacts of the sustainable panels were offset by the environmental benefits in the use stage due to weight reduction. The break-even point in months at which the sustainable panels would yield an environmental benefit was as follows: 1.2 for the geopolymer panel, 1.7 for the biopolymer panel, 10.4 for the PLA panel, and 54.5 for the PP panel.

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