INTERNATIONAL DESIGN CONFERENCE – DESIGN 2020
https://doi.org/10.1017/dsd.2020.29

SUSTAINABILITY ASSESSMENT OF COMPOSITES IN AERO-ENGINE COMPONENTS

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Abstract

Environmental issues such as climate change are leading to sustainability challenges for the aerospace industry. New materials such as composites allow significant weight reduction, which leads to a lower fuel consumption. However, composites involve complex processes and there is a lack of knowledge on their social and environmental consequences. Through two cases based on real aero-engines components, this paper shows that the weight savings provided by composites reduce significantly the CO2 emissions during flight which compensates the environmental drawbacks from production and recycling.

Keywords: sustainability, life cycle assessment (LCA), lightweight design, composite, aerospace

1. Introduction

Environmental issues such as climate change and global warming are leading to sustainability challenges for the aeronautic industry. By 2050, the targets currently agreed by the European Union and the aviation industry are to reach a 75% reduction in CO2 emissions per passenger kilometre (European Commission, 2011). Hence, it is crucial to think about sustainable design when it comes to future commercial aircrafts. One of the current approaches is to aim for weight reduction, and one way to do so is by using low density polymer composites to replace heavier materials (Soutis, 2005; Yang et al., 2012). To cite an examples in the aero-engines area, General Electrics and Rolls-Royce are currently developing composite fan blades for the front part of the engine (Marsh, 2015).

In addition to the challenges that the engine designers have to face when integrating composite materials in their products, the question of sustainability is also a concern. Even though these materials allow for significant weight reduction, which lead to a lower fuel consumption while in use, composites usually involve complex material architectures with extra costs, hazardous chemicals and dangerous working environments (Chua et al., 2015). In order to design a more sustainable product, it is therefore required to consider its whole life cycle, from cradle to grave including both environmental and social aspects.

A few studies investigated the environmental impact of composite components in aircrafts and showed that over their lifetime, composites are more environmentally-friendly than the metallic baseline materials due to the reduction of emissions during flight of the aircraft (Kara and Manmek, 2009; Scelsi et al., 2011). These few studies do not cover the social and economic dimensions of sustainability and are focused on aero structures instead of aero-engines. Hence, in order to ensure that the next generation of engines will be more sustainable, future aircraft engine designers will need a more complete and comprehensive approach to incorporating sustainability into aero-engine design.

https://doi.org/10.1017/dsd.2020.29 Published online by Cambridge University Press

Therefore, the goal of this paper is to investigate whether or not the introduction of composites in aero-engines is sustainable. The study is based on two composite aero-engine components currently designed and produced by GKN Aerospace. All components are made from polymer matrix reinforced composite and are in the cold part of the commercial aircraft engine.

2. Theory

2.1. Composite materials

Composite materials are made of at least two materials with different physical or chemical properties. Fiber reinforced polymers are made of a polymeric matrix and reinforcements, which are usually fibers in order to reinforce the properties in a specific direction (Åström, 2002).

There is a wide variety of available materials for fiber reinforced polymer composites. The choice of matrix depends on its desired performance, costs, and temperature requirements of the targeted application as the polymers can be very sensitive to heat. Epoxy Resins are the most used polymers for composites, both for traditional applications and high-technology areas such as the example in this case study (Rosato et al., 2010). Thermoset polyimides are also used in the aerospace industry since they have one of the highest temperature of use among the polymers. Thermoplastic matrixes are also emerging technology in the composite field and are promising regarding recycling possibilities and reuse of the material (PolyOne, 2019).

Among the existing reinforcements, carbon fibers exhibit the highest specific strength and stiffness, which is why they are widely used in the aerospace industry. To reach this level of performance, the fibers are produced through complex processes (Chawla, 2012) that are very energy-consuming. This, of course, increases the cost and the environmental footprint considerably (Correia, 2015).

When a composite product reaches its end-of-life, it can be either landfilled, incinerated, or recycled. Most of the recycling routes allow only to recover the reinforcements with reduced properties by mechanical or thermochemical processes (Oliveux et al., 2015). For thermoplastic composites, more fibers can be recovered since thermoplastics can be re-melted and re-shaped. However, current fiber recycling techniques are not cost-competitive with other end-of-life management such as landfill or incineration, and most of the composite waste is not re-used (Bains and Carruthers, 2013).

2.2. Previous work on composite sustainability

Since composites have a great potential for weight reduction, numerous studies have evaluated their sustainability potential in the automotive industry. In this application, the weight savings obtained by replacing a component of steel or aluminium with composite are often not enough to compensate the economic or environmental drawbacks. Either the material is too expensive, or it does not provide enough weight savings to compensate the environmental impact of the composite production (Shanmugam et al., 2019; Das, 2011; Duflou et al., 2009; Song et al., 2009; Das et al., 2016).

Chua et al. studied the composite supply chain for composites in the aerospace industry, and highlighted that the two largest sources of greenhouse gas emission come from the carbon fiber production (51%) and the composite part manufacturing (35%). The electricity consumption is the major contributor to these emissions, which can be reduced by two by moving the production to a country with a “greener” energy source like Sweden (Chua et al., 2015). Scelsi et al. investigated the potential emission savings by replacing aluminium panels with fiber/polymer/aluminium composites. They showed that despite being more energy intensive to manufacture and more difficult to dispose of, the use of composites lead to substantial decrease in the overall environmental impact due to lower fuel consumption during flight (Scelsi et al., 2011). Kara and Manmek calculated the embodied energy over life cycle of titanium and composite aircraft hinges fittings and found that, over their lifetime, the composite components provide significant energy and CO2 savings. The energy usage results show that for the raw material, manufacturing, and end-of-life phase, it appears that the metallic solutions are more environmental-friendly due to their recyclability. However, the lower weight of composites during usage stage leads to more significant reduction of the energy consumption and CO2 emissions and creates a gap between the two scenarios, favourable for composites (Kara and Manmek, 2009).

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The papers cited previously show the sustainability potential of composites for aerospace applications with an emphasis on the environmental impact and the aero-structures applications. Hence, there is a need to investigate sustainability of composites in aero-engines as well and in a more global point of view by including social aspects as well.

3. Approach and methods

This paper is divided in three sections. The two first parts focus on the influence of material selection and weight reduction on sustainability. The last part combines the model developed in the previous parts and applies them to real-life applications, i.e. are aero-engine components.

3.1. Influence of material selection

The main concerns about composites are the sustainability issues the carbon fibre production (Chua et al., 2015) and the fact that most of the decommissioned composite products are not recycled yet (Bains and Carruthers, 2013), which is a big disadvantage when comparing to metallic materials. Therefore, the goal of this section is to compare composites with other aerospace materials by considering the production of raw materials, the product manufacturing and the end-of-life management.

The three selected materials, that will be compared, are assumed to constitute four similar products of 100 kg each: Full titanium (100% of titanium alloys), Full aluminium (100% of aluminium alloys), Full composite (100% composite materials) and Composite hybrid (70% titanium alloys and 30% composite materials). The functionnal unit is an aerospace component with a final weight of 100 kg, therefore the input mass of material might be higher depending on how much material is removed during manufacturing. The following assumptions have been made to have a realistic approach of the product lifecycle:

- Raw materials production: titanium and aluminium supply comes from 23 and 43% of recycled materials (Granta Design, 2018). Others are newly produced materials;
- Manufacturing: waste due to machining is estimated to be 5% of the material for casted metals and composites. For forged parts, it goes up to 30-40% (Internal GKN, 2019). Cutting of prepregs or woven fibers generates 25% of waste (Rybicka et al., 2015);
- End of life: composite and plastics are incinerated. Metallic scrap is 100% recycled. Other waste flows are landfilled;

Different data sources have been used for metallic materials and composite manufacturing (Huang et al., 2016) and resin production and incineration of composites (Boustead, 2005; Granta Design, 2018). The rest of the data comes from the ELCD database v3.2. To simplify, the transport phases between the life stages and all the packaging are neglected.

3.2. Influence of weight reduction

In order to assess the consequences of weight reduction on an aircraft and quantify the quantity of fuel saved over a products lifetime, a model that links the fuel consumption of an aircraft and its weight has been developed. It is applied on different aircrafts showed in Table 1. Each case is modelled in “regular” version and “light” version, with 100 kg less. The weight reduction impacts both before and during flight since less fuel needs to be extracted and combusted.

Table 1. Main characteristics of the aircrafts studied

Aircraft type	Regional	Short-haul	Medium-haul
Typical range (km)	750	1,300	5,500
Passenger capacity	90	200	250
Maximum Take-off weight (t)	45	80	100
Lifetime flight time (h)	5,000	6,000	6,000

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The model to quantify the fuel consumption over a lifetime, for these examples, has been developed based on data from aircraft manufacturers and validated by engine specialists within GKN Aerospace Sweden AB. The model developed in this research shows fuel savings in the same order of magnitude than another research paper on this topic (Kara and Manmek, 2009), however it is a lot lower than the airline Lufthansa's study on their fuel efficiency (Lufthansa Group, 2012). The emissions associated to kerosene production and combustion come respectively from ELCD database v3.2 and ICAO tier 1 model (European Environment Agency, 2016).

3.3. Application to aero-engine components

The material data and the weight reduction data is compiled to model the life cycle of real industrial cases. Table 2 shows the main characteristics of the chosen components. They are located in the cold part of the engine, on two different engines and aircrafts with some material variations, and are representative of composites that can be found in current design of aero-engines.

Table 2. Main characteristics of the components studied

Component name	**Case 1: Alu vs Hybrid**	**Case 2: Ti vs Hybrid**
Aircraft type	Short-haul	Medium-haul
Temperature area in engine	Cold	Intermediate
Weight reduction with composites	14%	16%
Metallic component wt composition	100% aluminium alloys	100% titanium alloys
Composite hybrid component wt composition	50% titanium alloys 30% composite materials 20% steel alloys	76% titanium alloys 24% composite materials

3.4. Methods and tools

The environmental assessment is made with the software OpenLCA 1.7, which is an open source and free software for Sustainability and Life Cycle Assessment. For each activity occuing during a products life, the user chooses inputs and outputs and the software combines them to model the lifecycle. The European life cycle database (ELCD) v3.2 (October 2015) with ILCD Midpoint v1.0.10 (2011) is used as an impact method. The environmental results are displayed as numbered values in 13 different impact categories. As an example, the Climate Change category is expressed in kg of CO2 equivalent and each scenario studied has different results for each category.

The method to evaluate the social impact of the products has been developed based on two articles (Mesquita et al., 2016; Gould et al., 2017) on social assessment for product innovation process in which GKN Aerospace was involved. The social impact is assessed both on workers in the factory and on nearby population that might be affected by the product. The evaluation of the activities is based on several references: polymers production and composite manufacturing (Åström, 2002; Mellema, 2002), carbon fiber production (Chen, 2014), aluminium production and manufacturing (Wesdock and Arnold, 2014), others are based on interviews with specialists and company internal documents. A score of one is given when the source considers the activity as safe, a score of two is considered as medium and a score of three indicaes a high social risk, meaning workers could be injured or contaminated as well as the nearby population. The final score is determined by averaging the scores at different life stages.

In both assessments, a product is more sustainable when it has a lower score. The results have been reviewed and accepted by various design, mechanical and environmental engineers.

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4. Results

4.1. Influence of material selection

Figure 1 below shows the CO2 emissions associated with different life cycle stages for the four material scenarios. The fully composite scenario has the most CO2 emissions with 9.4t produced in total and the fully aluminium component has the lowest environmental impact with 1.5t of CO2 emitted during the studied life stages. The high score of composites is due to the energy-consuming processes required to produce carbon fiber and polymer matrixes, in addition to the fact that the manufacturing processes generally produce a lot of scrap. Titanium and composite hybrid materials have an intermediate result with 5t and 6.2t of CO2 emitted.

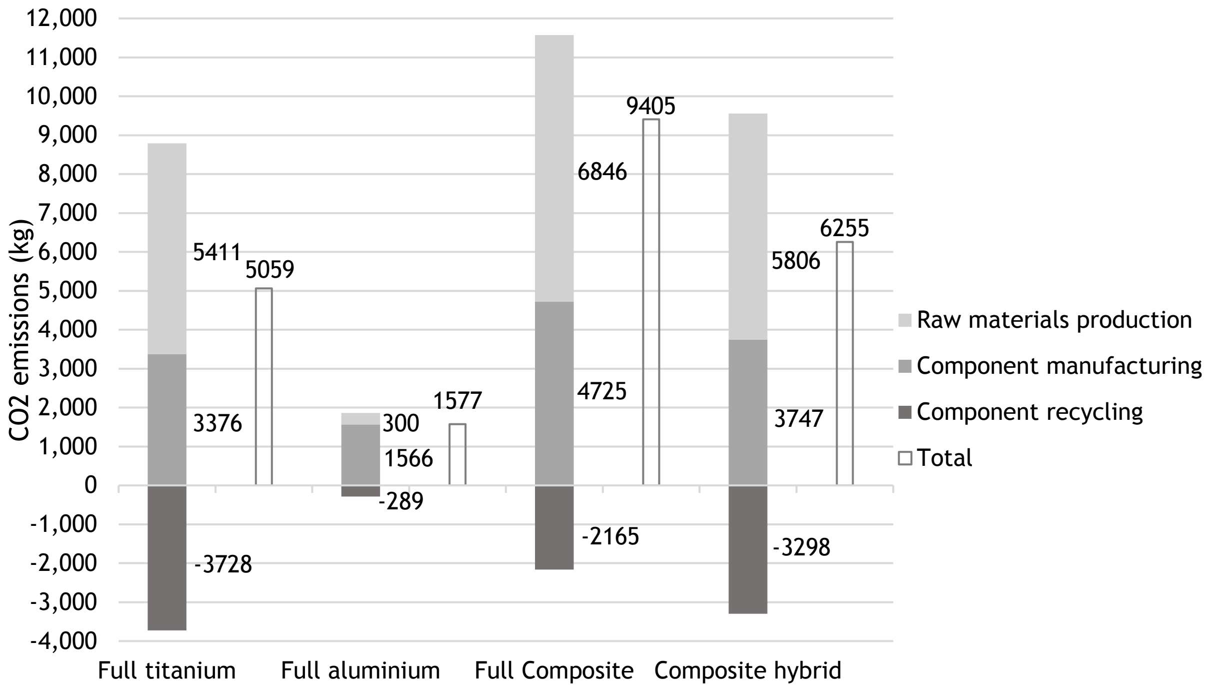

Figure 1. CO2 emissions associated to the transformation steps of a 100 kg component

In the case of metallic materials, the end-of-life CO2 emissions are directly correlated to the raw material production phase; since the material is recycled, it will avoid having to extract more resources in the future, resulting in the negative CO3 emissions shown on the graph. In the case of composite materials, the CO2 savings of incineration make up for only 32% of the emissions associated with raw material production while this compensation is about 70% for the full titanium scenario.

These results highlight the high environmental impact of composites during production and manufacturing, which is not compensated for by the recycling of the component. It also shows that in this scope, aluminium is the best material choice to lower the environmental impact of the component.

In Table 3 the social scores for the four scenarios are displayed. The materials follow a similar trend as in the environmental assessment: the highest score is obtained with full composite and the lowest is full aluminium. The high score of composite materials is connected to the high temperature processes of carbon fiber production and the handling of chemicals when polymer resin is used. It appears that for all the materials, the production of raw materials has the greatest impact. The social impact then decreases then until the end of life where the social consequences are the lowest. These results show that the early life cycle stages of a product present the highest social risk and it is therefore important for the engine manufacturers to choose sustainable suppliers.

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Table 3. Social impact of the four material scenarios on workers in the factory and nearby populations (Pop.) - 1 corresponds to the minimum impact and 3 to the maximum-

Materials	Full titanium		Full aluminium		Full composite		Composite hybrid	
Impact on	Workers	Pop.	Workers	Pop.	Workers	Pop.	Workers	Pop.
Raw materials	2.11	2.44	2.11	2.33	2.33	2.67	2.20	2.53
Supplier	2.00	1.58	1.67	1.50	1.87	1.87	2.00	1.83
Manufacturing	1.33	1.46	1.19	1.38	1.44	1.17	1.46	1.31
End of life	1.00	1.00	1.00	1.00	1.17	1.50	1.11	1.33
Mean	**1.61**	**1.62**	**1.49**	**1.55**	**1.70**	**1.80**	**1.69**	**1.75**
	1,62		**1,52**		**1,75**		**1,72**	

4.2. Influence of weight reduction

Figure 2 below shows the lifetime fuel consumption of different aircraft sizes and highlights the fuel savings provided when compared to a 100 kg lighter aircraft. The fuel reduction is relatively similar between the different scenarios and is between 124t and 129 t of fuel over lifetime, the highest savings being associated to the largest aircraft.

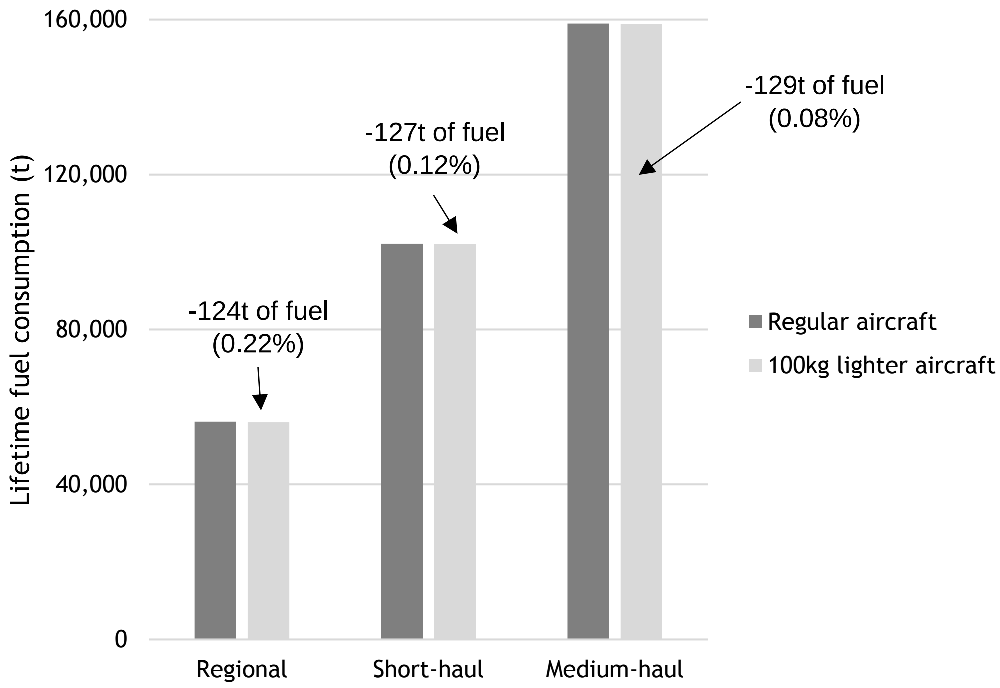

Figure 2. Influence of weight reduction over lifetime fuel consumption for different aircraft sizes

These fuel savings can be converted into an environmental impact using the same method as before. The emissions that are avoided by using a 100 kg lighter aircraft for various impact categories are shown in Table 4. The climate change impact shows that this weight reduction in an avoidance between 439 t and 457 t of CO2 for the scenarios studied which is directly proportional to the mass of fuel saved.
A imilar result will be observed for the social impact. Since there are less toxic emissions in the air, the populations health will be better preserved, and therefore, a lighter component will reduce the

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social impact. Of course, this result is assuming that the base and the light aircraft have similar characteristics such as safety, noise and lifetime duration

Table 4. Avoided emissions to the environment with 100 kg lighter aircrafts over lifetime

Impact category	Unit	Regional	Short haul	Medium haul
Acidification	molc H+ eq	1.97E+03	2.02E+03	2.05E+03
Climate change	kg CO2 eq	4.39E+05	4.50E+05	4.57E+05
Freshwater ecotoxicity	CTUe	9.47E+03	9.71E+03	9.84E+03
Freshwater eutrophication	kg P eq	8.03E-02	8.24E-02	8.35E-02
Human toxicity, cancer effects	CTUh	3.18E-04	3.26E-04	3.30E-04
Human toxicity, non-cancer effects	CTUh	4.35E-03	4.46E-03	4.52E-03
Ionizing radiation ecosystems	CTUe	6.52E-03	6.68E-03	6.77E-03
Ionizing radiation human health	kBq U235 eq	4.47E+02	4.59E+02	4.65E+02
Land use	kg C deficit	7.46E+02	7.65E+02	7.76E+02
Marine eutrophication	kg N eq	7.19E+02	7.37E+02	7.47E+02
Mineral & fossil resource depletion	kg Sb eq	2.10E-01	2.15E-01	2.18E-01
Ozone depletion	kg CFC-11 eq	1.16E-04	1.19E-04	1.20E-04
Particulate matter	kg PM2,5 eq	2.92E+01	2.99E+01	3.03E+01
Photochemical ozone formation	kg NMVOC eq	2.00E+03	2.05E+03	2.08E+03
Terrestrial eutrophication	molc N eq	7.86E+03	8.06E+03	8.17E+03
Water resource depletion	m3 water eq	3.85E+04	3.94E+04	4.00E+04

4.3. Application to aero-engine components

Figure 3 shows the CO2 emissions associated to the life cycle stages of the modelled components. For scaling reasons, the emissions of the use phase have been divided by a factor of 100,000.
For the first case study, it appears that the aluminium component has a much lower environmental impact regarding the production of raw materials and manufacturing. Proportional to the low CO2 emissions associated with production, the savings provided by recycling are also relatively low. The hybrid component has higher emissions associated to the production of materials and manufacturing, which correlates with what has been shown in part 4.1. In the second case study, it appears that the full titanium component has more emissions associated with materials production and manufacturing than the hybrid one. This is mainly due to the higher weight of the metallic component.
The reduction of CO2 emissions with the lighter component is in the same order of magnitude than the results found in part 4.2 and is slightly higher in case 2 since the component is located on a larger aircraft. By cumulating the CO2 emissions over the products lifetime, it appears that the composite hybrid component reduces the CO2 emissions by 163 t and 172 t for case 1 and 2. The major contribution to this gap is the use phase which highlights the great positive impact that weight reduction has on sustainability in the aircraft industry.
In case 1, composite materials allow significant CO2 savings over the products lifetime, despite their high production emissions and non-recyclability. It also shows that composite materials need to provide

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significant weight savings in order to be more sustainable than aluminium alloys which in comparison have a very little environmental footprint. The case 2 shows that composite hybrid components can have a lower environmental impact during all live stages if they provide as much weight savings as the case in this application. Composite materials appear to be a sustainable alternative to titanium alloys.

Regarding the social impact, it appears that the different component scenarios do not have a significant difference in their score when the whole life cycle is considered because each phase has the same importance.

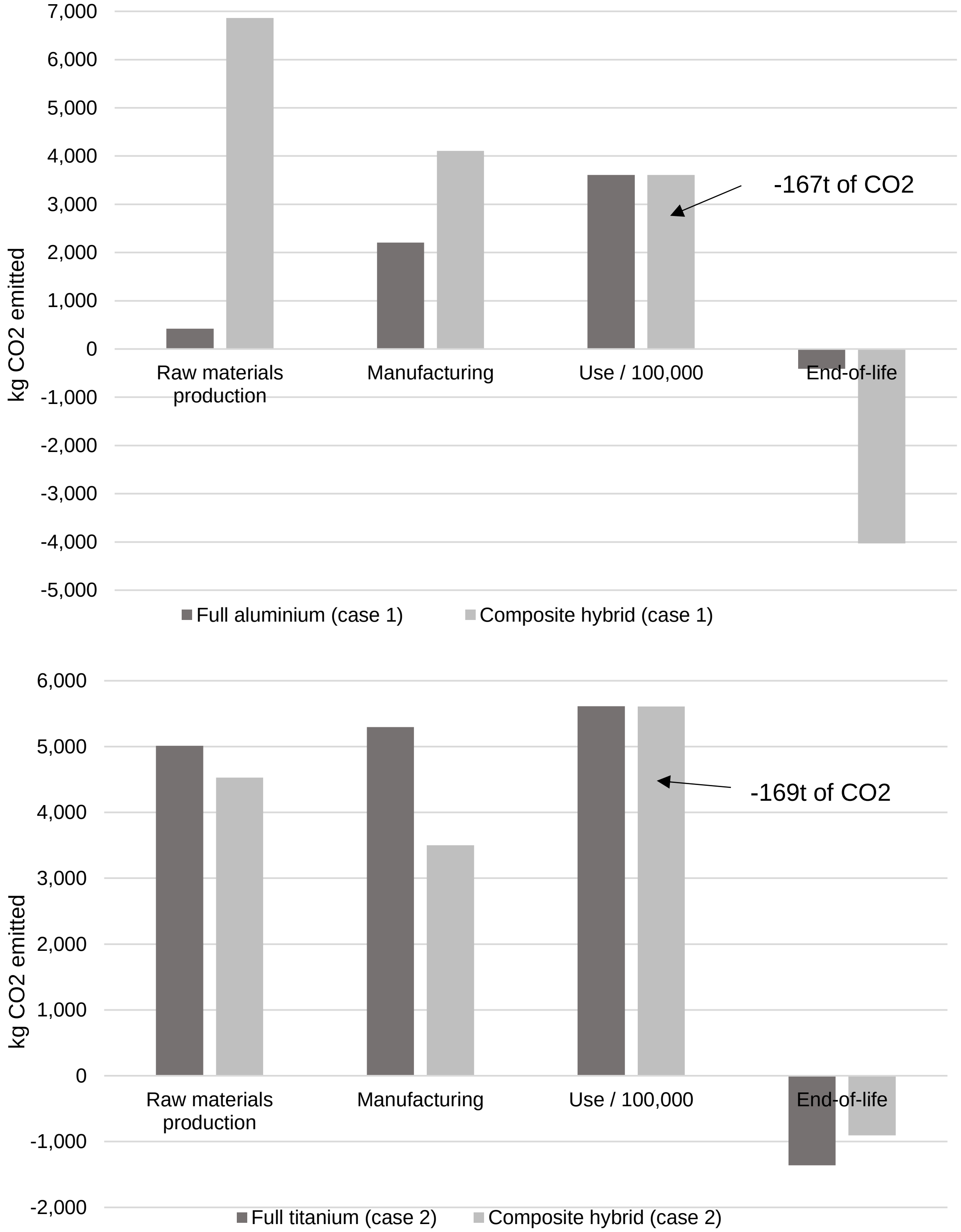

Figure 3. CO2 emissions associated to various life cycle stages of aero-engine components

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5. Conclusions

The environmental assessment shows that composite and titanium components have rather similar environmental footprint when they are produced, while aluminium components have a much lower impact. Additionally, the use phase contributes the most to the environmental impact of the components. Hence, the two cases studied are more favorable for the composite component. The largest improvements in terms of environmental sustainability is case 2, because its composite design provides weight savings and its baseline is titanium.

The social assessment held on aero-engine components pointed out that metallic and composite components have rather close results. In both cases, the social impact is the most severe at the earliest life stages with the production of raw materials followed by manufacturing. This highlights the importance for aero-engine manufacturers to choose suppliers who care about social sustainability to ensure a more sustainable life cycle for their products. However, the social results would be different if the activities would be weighted and not considered as equally important. For example, it is possible to calculate the score according to the number of persons affected (then the use phase will gain importance) or increase the importance of the activities where people are closest to the component (then the manufacturing phase will gain importance).

Composite components have a great potential to contribute to sustainable aviation and this paper highlights the importance of life-cycle thinking when developing new composite products. The weight reduction has a main role to play, but it is important to consider the other life steps of the component and try to work with sustainable raw materials, manufacturing processes and components that can be recycled or reused.

References

Åström, B.T. (2002), *Manufacturing of Composite Polymers*, Nelson Thornes Ltd.

Bains, M. and Carruthers, J. (2013), *Composite materials: a resource efficiency action plan*, Composites UK.

Boustead, I. (2005), *Eco-profiles of the European Plastics Industry*, PlasticsEurope.

Chawla, K.K. (2012), *Composite Materials. Science and Engineering*, Springer. https://doi.org/10.1007/978-0-387-74365-3

Chen, M.C.-W. (2014), *Commercial Viability Analysis of Lignin Based Carbon Fibre, Faculty of Business Administration*, Simon Fraser University.

Chua, M.H. et al. (2015), *Understanding aerospace composite components' supply chain carbon emissions*.

Correia, J.R. (2015), "Fibre-Reinforced Polymer (FRP) Composites", In: Gonçalves, C. and Margarido, F. (Eds.), *Materials for Construction and Civil Engineering*, Springer, pp. 501-556. https://doi.org/10.1007/978-3-319-08236-3_11

Das, S. (2011), "Life cycle assessment of carbon fiber-reinforced polymer composites", *The International Journal of Life Cycle Assessment*, Vol. 16 No. 3, pp. 268-282. https://doi.org/10.1007/s11367-011-0264-z

Das, S. et al. (2016), "Vehicle lightweighting energy use impacts on U.S. light-duty vehicle fleet", *Sustainable Materials and Technologies*, Vol. 8, pp. 5-13. https://doi.org/10.1016/j.susmat.2016.04.001

Duflou, J.R. et al. (2009), "Environmental impact analysis of composite use in car manufacturing", *CIRP Annals*, Vol. 58 No. 1, pp. 9-12. https://doi.org/10.1016/j.cirp.2009.03.077

European Commission (2011), *Flightpath 2050 Europe's vision of aviation: maintaining global leadership and serving society's needs*.

European Environment Agency (2016), *EMEP/EEA air pollutant emission inventory guidebook 2016*, pp. 20-22.

GKN Aerospace Sweden (2019), Information from internal sources.

Gould, R., Missimer, M. and Mesquita, P.L. (2017), "Using social sustainability principles to analyse activities of the extraction lifecycle phase: Learnings from designing support for concept selection", *Journal of Cleaner Production*, Vol. 140, pp. 267-276. https://doi.org/10.1016/j.jclepro.2016.08.004

Granta Design (2018), *CES Selector 2018 (APA Edition) Version 18.3.1*, G.D. Limited.

Huang, R. et al. (2016), "Energy and emissions saving potential of additive manufacturing:the case of lightweight aircraft components", *Journal of Cleaner Production*, Vol. 135, pp. 1559-1570. https://doi.org/10.1016/j.jclepro.2015.04.109

Kara, S. and Manmek, S. (2009), *Composites: Calculating their embodied energy*.

Lufthansa Group (2012), *Fuel efficiency at the Lufthansa Group - Cutting costs and protecting the environment*.

Marsh, G. (2015), "*Aero engines loose weight thanks to composites*", *Reinforced Plastics*, Vol. 56 No. 6, pp. 32-35. https://doi.org/10.1016/S0034-3617(12)70146-7

https://doi.org/10.1017/dsd.2020.29 Published online by Cambridge University Press

Mellema, G. (2002), *Safety issues with advanced composite materials [online]*. Available at: https://www.aviationpros.com/home/article/10387483/safety-issues-with-advanced-composite-materials (accessed 18.04.2019)
Mesquita, P.L. et al. (2016), “An introductory approach to concretize social sustainability for sustainable manufacturing”, *Tools and Methods of Competitive Engineering*.
Oliveux, G., Dandy, L.O. and Leeke, G.A. (2015), “Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties”, *Progress in Materials Science*, Vol. 72, pp. 61-99. https://doi.org/10.1016/j.pmatsci.2015.01.004
PolyOne (2019), *Performance Advantages & Applications of Continuous Fiber Thermoplastic Composite [webinar]*, Composite World.
Rosato, D.V., Rosato, M.G. and Schott, N.R. (2010), *Plastics Technology Handbook*, Fourth Edition.
Rybicka, J. et al. (2015), “Capturing composites manufacturing waste flows through process mapping”, *Journal of Cleaner Production*, Vol. 91, pp. 251-261. https://doi.org/10.1016/j.jclepro.2014.12.033
Scelsi, L. et al. (2011), “Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment”, *Express Polymer Letters*, Vol. 5 No. 3, pp. 209-217. http://doi.org/2010.3144/expresspolymlett.2011.20
Shanmugam, K. et al. (2019), “Advanced High-Strength Steel and Carbon Fiber Reinforced Polymer Composite Body in White for Passenger Cars: Environmental Performance and Sustainable Return on Investment Under Different Propulsion Modes”, *ACS Sustainable Chemistry & Engineering*. https://doi.org/10.1021/acssuschemeng.8b05588
Song, Y.S., Youn, J.R. and Gutowski, T.G. (2009), “Life cycle energy analysis of fiber reinforced composites”, *Composites Part A: Applied Science and Manufacturing*, Vol. 40 No. 8, pp. 1257-1265. https://doi.org/10.1016/j.compositesa.2009.05.020
Soutis, C. (2005), “Fibre reinforced composites in aircraft construction”, *Progress in Aerospace Sciences*, Vol. 41 No. 2, pp. 143-151. https://doi.org/10.1016/j.paerosci.2005.02.004
Wesdock, J.C. and Arnold, I.M.F. (2014), “Occupational and Environmental Health in the Aluminum Industry, Key Points for Health Practitioners”, *Journal of Occupational and Environmental Medicine*, Vol. 56, pp. S5-S11. https://doi.org/10.1097/JOM.0000000000000071
Yang, Y. et al. (2012), “Recycling of composite materials”, *Chemical Engineering and Processing: Process Intensification*, Vol. 51, pp. 53-68. https://doi.org/10.1016/j.cep.2011.09.007