Evaluating Eco-Efficiency of 3D Printing in the Aeronautic Industry

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Summary

New technologies such as 3D printing, also known as rapid manufacturing or additive manufacturing, are promising technologies to support the aeronautics sector moving toward its ambitious environmental goals. An eco-efficiency method combining life cycle costs and life cycle environmental assessment is developed to support eco-design initiatives in the aeronautics industry that accounts for specific reduction targets. Eco-efficiency results are computed through a normalization procedure and a target-driven trade-off and displayed as an XY diagram. Applied to an aircraft doorstop manufacturing, results show that 3D printing has clear benefits both in terms of costs and environmental impacts compared to conventional machining. Nevertheless, 3D printing equipment costs are still high, and a sensitivity analysis shows that, for lower productivity levels, the optimal scenario relies on the chosen trade-off between environmental impacts and costs reduction.

Introduction

Responsible for approximately 3% of global greenhouse gas emissions, the aeronautics sector projects an increase in levels of 70% in 2025 and of between 300% and 700% in 2050 as compared to 2005 (EC 2015). The International Civil Aviation Organization and the International Air Transport Association have set ambitious reduction goals for air transport: an annual increase in fuel efficiency of 1.5% between 2009 and 2020; a cap on net aviation carbon dioxide (CO_2) emissions in 2020 (carbon-neutral growth); and a 50% reduction in net aviation CO_2 emissions by 2050 relative to 2005 levels (CAEP 2010; GIACC 2009). New technologies such as 3D printing—also known as rapid manufacturing or additive manufacturing (AM)—are promising technologies to support these goals by enhancing aircraft eco-design initiatives. But quantifying the potential environmental improvements brought about by these technologies, considering current global challenges and limited economic resources availability, is key. This research contributes to the development of an eco-efficiency driven decision-making tool based on environmental and cost targets to support eco-design initiatives in the aeronautics industry.

The 3D printing technology produces objects by adding materials layer upon layer and is often presented as an industrial revolution of the numerical era. Indeed, U.S. President Barack Obama stated that "a once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything" (Gross 2013, 1). The technology is driven by investments of all kinds, notably in the United States by the government, federal agencies, and other organizations (White and Lynskey 2013). AM presents several benefits as compared to traditional manufacturing methods (e.g., machining, die casting), such as reduction in lead time, reduction in material losses during production, elimination of physical

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production constraints and subassemblies, and better adapts to mass customization. While the economic benefits of AM in plastics and metallic parts manufacturing in low to medium production volumes have been demonstrated in the literature (Atzeni et al. 2010, 2014), very few studies have explored the topic from the life cycle perspective (Lindemann et al. 2013). AM in the aeronautics sector is promising and could reduce costs in the aeronautics supply chain (Walter et al. 2004) and fuel consumption in the use phase by decreasing the weight of aircraft components (Lindemann et al. 2013). Thus, taking a life cycle perspective is key to evaluate the potential environmental benefits and costs of AM in the aeronautics context.

Design for environment, or eco-design, refers to the integration of environmental aspects into the design of products during their life cycles (ISO 14040 2006). In order to efficiently manage and reduce environmental emissions through eco-design, emissions must be measured and interpreted. Life cycle assessment (LCA) is a recognized tool that is widely used by industry to evaluate the potential environmental impacts of products from materials extraction to end of life (EoL), through manufacturing and use (Witik et al. 2012). But LCA indicators are numerous and differ in terms of units, making it difficult to interpret the results when costs are added, while on their own, the latter are simple to understand and justify (Kicherer et al. 2007; Rüdenauer et al. 2005).

Eco-efficiency aims to bring environmental concerns into decision making by integrating costs and environmental aspects. The concept was introduced in 1992 by the Business Council of Sustainable Development, which later became the World Business Council of Sustainable Development (WBCSD) in 1995, and promoted in "Changing Course" (Schmidheiny 1992). The principle is simple: produce more with less. The WBCSD defines eco-efficiency as the ratio between the production value to maximize and the environmental impacts to minimize. Despite certain known limitations, such as the possible rebound effects (Abukhader 2008; Hauschild 2015; Mizobuchi 2008; Small and Dender 2005; Sorrell et al. 2009), eco-efficiency has been widely applied throughout the past 20 years to support the eco-design of products (Huppes and Ishikawa 2007; Kicherer et al. 2007; Rüdenauer et al. 2005). It provides a relative metric to compare design options ensuring the same function (or utility). Eco-efficiency has only recently been standardized (ISO 14045 2012). Until then, decision makers had been tailoring the concept to their needs.

Eco-efficiency may be understood as a three-step procedure: the quantification of the environmental score over the whole product life cycle; the quantification of the product system value; and the combination of the two scores into one or more measures for decision makers. The International Organization for Standardization (ISO) provides a broad definition of the product system value, which may, for example, be represented by a functional value or a monetary one.

ISO 14045 recommends applying LCA to assess the environmental dimension. Depending on the goal and scope of the study, LCA impact scores may be kept disaggregated, meaning that each impact category represents an independent environmental dimension that must then be combined with the economic dimension for interpretation, or aggregated into a single score. Designers and engineers usually prefer the latter calculation procedure because it simplifies the interpretation of the results when combining a single environmental dimension and an economic one (Kicherer et al. 2007; Michelsen et al. 2006; Weiss et al. 2011).

Much has been written on the links between cost and value creation (Cooper 1995; McNair et al. 2001). Cost increase/reduction for a producer should be related to the added value for the consumer and market mechanisms. Still, data for a quantitative relationship between product cost and value are rarely available. Hence, cost reduction is mostly used as a proxy of increasing value for the consumer (e.g., reduction in acquisition and/or operation costs) or producer (reduction in production costs) when eco-efficiency is applied at a product level to support eco-design (Michelsen et al. 2006; Rüdenauer et al. 2005; Saling et al. 2002; Suh et al. 2005). Costs are generally calculated using life cycle costing (LCC) (Hunkeler et al. 2008).

There are various ways to combine LCA and LCC indicators, including as a ratio (Verfaillie and Bidwell, 2000; Hellweg et al. 2005), sum (Kicherer et al. 2007), or set of different graphic representations (Kicherer et al. 2007; Suh et al. 2005). The interpretation may vary significantly depending on the adopted approach. It should therefore be selected with care considering available data and the context of application. There are several instances in the literature in which eco-efficiency metrics were not carefully thought out, leading either to inconsistencies or a lack of links with sustainability goals or reduction targets (Hellweg et al. 2005; Kicherer et al. 2007; Michelsen et al. 2006; Suh et al. 2005), thus preventing eco-efficiency from becoming a robust and consistent approach for sustainable development. In their framework for quantified eco-efficiency, Huppes and Ishikawa (2005) presented three approaches to interpret eco-efficiency and suggested one—marginal eco-efficiency—to guide micro-level improvements toward macro-level targets. The approach relies on a graphic representation that combines value against environmental impacts to improve both variables. The approach is easily transposable to costs and aims to attain an optimal point on the optimality curve of social level points by applying the same trade-off between value and environmental impacts throughout society.

In order to support the design of eco-efficient initiatives in the aeronautics sector, we proposed to develop an approach that combines monetary product value and environmental performance based on the industry's environmental targets. We then applied the methodology to evaluate and compare 3D printing and conventional machining to manufacture an aircraft doorstop. Recommendations for the eco-efficient application of 3D printing in the aircraft industry are also discussed. The assessment of technical performances and considerations related to 3D printing and conventional machining technologies are beyond the scope of this study.

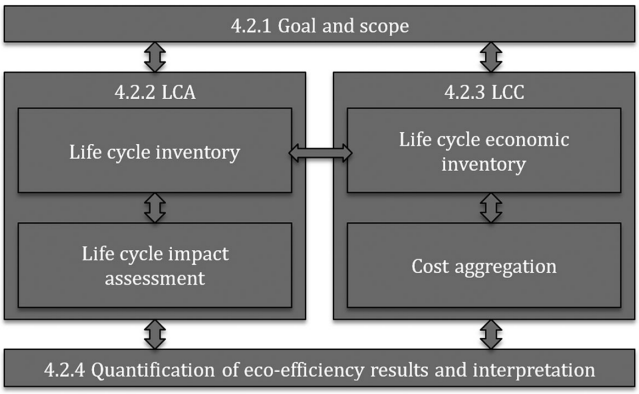

Figure 1 Eco-efficiency methodology.

Methodology

Presented in figure 1, the methodology follows the main guidelines of ISO 14045 and was adapted to meet the specific context of the study. It is meant to support design choices and promote sustainable aircraft component production processes based on specific aircraft life cycle target emissions.

Environmental LCA is in line with ISO 14040 and ISO 14044. A life cycle inventory (LCI) is computed by combining primary data from the evaluated product and figures from generic LCI databases to estimate environmental intervention to and from the environment across the supply chain. Environmental impact scores are calculated using attributional LCA and aggregated into a single score based on a distance to target method—a well-established aggregation method for eco-efficiency assessment (Barba-Gutiérrez et al. 2009; Rüdenauer et al. 2005). The method derives a weighting factor between multiple normalized impact scores from the distance between a current state (e.g., current emissions of an aircraft) and a target state (e.g., target emissions of an aircraft). This choice is consistent with the pollutant emission reduction goals adopted by the aeronautics industry. The distance-to-target method proposed here is enhanced by considering the time left to reach the targets (Rüdenauer et al. 2005) and an ecological factor setting the equivalency of damages at target levels (Goedkoop 1995). Impact scores are first characterized per impact category considering only LCI flows addressed by aeronautics targets (i.e., CO_2, nitrogen oxides [NO_x], particulate matter [PM], and noise), normalized by the corresponding impact category score of the entire aircraft and finally aggregated into a single score through weighting factors as per equation (1):

$$I_i = \sum_c \sum_j \frac{e_{ij} \times f_{jc}}{I_c} \times \frac{w_c}{\sum_{c=1}^{k} w_c} \tag{1}$$

where (equations 2, 3, and 4),

$$w_c = \frac{I_c/T_c}{\sum_c I_c/T_c} \times \frac{\bar{Y}_c}{\sum_c Y_c} \times \frac{D_c}{\sum_c D_c} \tag{2}$$

$$I_c = \sum_j E_j \times f_{jc} \tag{3}$$

$$T_c = \sum_j T_j \times f_{jc} \tag{4}$$

I_i: Aggregated environmental impacts score for the assessed scenario i
e_{ij}: Emissions of inventory substance j for the assessed scenario i
f_{jc}: Characterization factor of inventory substance j to impact category c
w_c: Weighting factor of impact category c
I_c: Impact score of the aircraft life cycle for impact category c
E_j: Current emissions of the aircraft life cycle for inventory substance j
T_c: Aggregated target emissions of the aircraft life cycle for impact category c
T_j: Target emissions of the aircraft life cycle for inventory substance j
$\bar{Y}_c$: Mean of the reverse of the years left to reach target reductions of impact category c
D_c: Damage at target value for impact category c

The weighting parameter w_c is the product of three factors: distance to target, time to target, and damage equivalency at target level. Each factor is normalized to 1 and therefore treated on an equal basis. The normalization figures correspond to the life cycle of a selected aircraft that meets specific target values.

Costs are calculated using environmental LCC, as described in Swarr and colleagues (2011). The physical life cycle of the aircraft (as opposed to its commercial life cycle) is used as a reference to remain consistent with the environmental assessment. The costs categories are presented in table 1.

Research and development (R&D) costs are calculated without violating system boundary equivalency with the environmental impact assessment (Hunkeler et al. 2008) as R&D environmental impacts occurring upstream the company are also not included. The use-phase cost categories were chiefly obtained from Khan and Houston (1999). The production and assembly phases are adapted from Dhillon (2011). To avoid double counting when the acquisition cost in the production or assembly phase is already calculated, all upstream costs should be 0 (Rebitzer and Hunkeler 2003). Maintenance and spare parts costs are assigned to the use phase since they are borne by the user. Costs are discounted to a year of reference to account for the time preference of present versus future costs. The discounting process takes into account many economic and social factors, including the cost of capital, productivity of capital, uncertainty of the data, risks, and time preference of the decision maker (Schmidt 2003). We have found that a discounting rate of approximately 9% net of inflation is representative of the cost of capital and the risk exposure of the air transportation industry (Damodaran 2015). Nevertheless, LCC results are generally highly sensitive to the discounting rate, especially for long-lasting products (Schmidt 2003). A sensitivity analysis of the parameter must therefore be carried out. Finally, past costs (e.g., R&D already spent) are not taken into account because they do not influence the decision making (Kuosmanen 2005).

Table 1 Cost categories for the life cycle cost (LCC) of the eco-efficiency model

Life cycle phases	*Cost categories*	*Description*
Research and development (R&D)	Labor	Labor refers to future R&D hours needed to make the scenario operational.
	Tests	In-flight or on-ground test operations
	Subsidies	Subsidies for future R&D costs
Production	Labor	Labor hours to produce the scenario
	Materials	Materials to produce the scenario
	Indirect costs	Indirect costs to produce the scenario (e.g., equipment, energy, overhead, etc.)
	Transport	Transport of the product to the assembly line
Assembly	Acquisition	Cost of the scenario before assembly. Set to 0 if production costs are calculated.
	Labor	Labor hours for assembly in the scenario
	Materials	Materials for assembly in the scenario
	Indirect costs	Indirect costs of aircraft assembly in the scenario (e.g., equipment, energy, overhead, etc.)
	Transport	Transport of the product to the operator site
Use	Acquisition	Cost of the scenario before assembly. Set to 0 if assembly/production costs are calculated.
	Initial spare parts	Includes acquisition, insurance, and storage of initial spare parts
	Fuel costs	Fuel costs due to weight, drag, and specific fuel consumption in the scenario
	Maintenance	Include labor and materials for scheduled and unscheduled maintenance in the scenario
	Crew	Crew cost for use in the scenario
End of life	Treatment costs	Includes infrastructure, transport, labor, and overhead for end-of-life processing in the scenario
	Residual value	Resale value of the scenario at end of life. Depends on treatment costs, if applicable.

We adapted the marginal eco-efficiency approach set out by Huppes and Ishikawa to combine the two dimensions of eco-efficiency. Indeed, because costs and environmental impacts must be minimized, a ratio format is not relevant to our context even if some models have tried to do so (Fet 2003; Michelsen et al. 2006), though with no link to sustainability or a set of targets. The aeronautics sector has set environmental emission targets for numerous substances (CO_2, NOx, etc.). Once they are aggregated and added to cost targets, the interpretation may be guided as it was for the Huppes and Ishikawa curve of optimality. The trade-off between environmental impact scores and costs corresponds to the slope of the line linking the current reference state (baseline life cycle of an aircraft today) and the target reference state (life cycle of an aircraft compliant with the sustainability emission targets). The Y-coordinate and X-coordinate of the reference state correspond to the selected aircraft life cycle costs and aggregated environmental impacts score, respectively. Figure 2 presents the trade-off calculation as a graph.

As shown in figure 2, costs must be normalized according to the aircraft life cycle costs (or, alternatively, limited to the life cycle phases accounted for based on the goal and scope of the study) and treated on the same basis as the environmental figures before applying the trade-off. The trade-off is therefore interpreted as the ratio of reduction percentages of aircraft life cycle costs and environmental impacts. When the trade-off is set to 1 (as in figure 2), the aim is to reduce the aircraft life cycle costs and environmental impacts by the same percentage. The eco-efficiency indicator is calculated by the product of the normalized cost score and the trade-off value and then

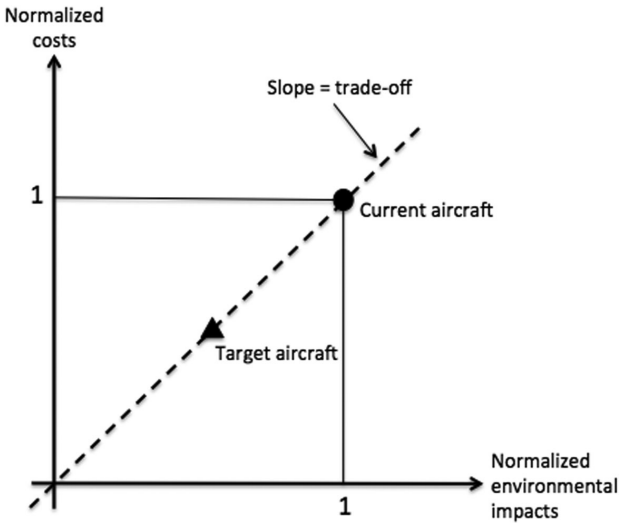

Figure 2 Trade-off between normalized costs and environmental impacts.

added to the normalized environmental score. The lowest score represents the most eco-efficient alternative.

With a slight modification, the marginal eco-efficiency metric also makes it possible to only account for the processes that are different from one design alternative to the next. Before the normalization step, all costs and environmental figures must be subtracted from the baseline figures so that the new figures represent cost reductions and environmental improvements brought about by an alternative design relative to the baseline. Then, after normalization, the same final measure as above is computed. In this case, the highest score is the most eco-efficient alternative. This approach has the advantage of entailing less effort to collect life cycle data, especially for LCA.

A graphic representation on an XY diagram makes it possible to interpret the results and ensure transparency. As a variant of figure 2, one could express values of x- and y-axes in terms of environmental improvement and cost reduction, respectively. It results in a zero-centered diagram relative to the baseline scenario, used to represent the results of this case study.

Case Study: Eco-Efficiency of 3D Printing versus Traditional Processes to Manufacture a Doorstop

Goal and Scope

The case study aims to compare aircraft doorstops manufactured by 3D printing and traditional machining techniques based on the eco-efficiency metric developed here. A schematic drawing of the technical component is provided in the Supporting Information available on the Journal's website. The specific goals are to (1) assess the environmental impacts throughout the entire life cycle of an aircraft doorstop made by AM and by machining, (2) determine the life cycle costs of the methods, and (3) identify optimal options by applying the proposed eco-efficiency model and comparing the manufacturing techniques. The results of the study are meant to support internal decision making for eco-efficient aircraft design and provide a better understanding of the potential benefits and limitations of using 3D printing to support eco-design initiatives in aeronautics. The doorstop (see figure in the supporting information on the Web) has been selected within consortium of researchers of a larger project on additive manufacturing where we were involved in (Consortium for research and innovation in aerospace in Québec).

When defining the goal and scope of the study, the function provided by the evaluated component must be related to a specific function provided to the aircraft. Moreover, the functional unit must provide *function* to the aircraft during its *lifetime*. Therefore, the lifetime of the aircraft is the study period, and the costs and physical flows must all be related to it. Knowing that most of the cost categories of the use phase are parametric estimations based on the lifetime of the aircraft, the lifetime-based approach is helpful to maintain consistency between costs and environmental impacts calculation. In this case study, the functional unit is stated as "Ensure the closure of an aircraft door throughout the aircraft's lifetime" (35 years). Three scenarios are compared: conventional machining (CMA), 3D printing (3DP), and 3D printing with topology optimization (3DO). Each scenario needs to produce one doorstop in Ti-6Al-4V with the same technical requirements (i.e., ensuring the same mechanical strength). For the CMA and the 3DP scenarios, the part weighs 342 grams (g). For the 3DO scenario, the part weighs 273.6 g. The 3DO doorstop is obtained from a topology optimization thanks to 3D printing that reduces the part's weight by 20%. This topology optimization is part of a specific project, which is not discussed here. Aidibe and colleagues (2016) provide further technical details in term of technical performances, repeatability, and geometric and dimensional capabilities of the specific 3D technology used in the project. All three components are designed to last 35 years—the lifetime of the aircraft.

The life cycle perspective is taken into account: production, assembly, use, and EoL. Table 2 describes the processes considered for the environmental and cost assessments throughout the life cycle. Blank-shaded processes are taken into account; dark gray–shaded processes are similar in the compared methods of production (and thus are not taken into account), and light gray–shaded processes are neglected either through cut-off or missing data. As past costs, R&D expenses are not taken into account.

The equipment used to produce the components is considered in the analysis for both traditional machining and 3D printing. The 3D machine (including maintenance) was allocated based on the ratio between the weight of the product system and the annual production volume of the machine. Infrastructure costs (plant lighting, heat, general administration, etc.) are considered equivalent between the scenarios and were therefore disregarded. Titanium swarf is recycled and the environmental benefits were calculated through system expansion considering 90% material recovery. The benefit of swarf resale is considered for LCC. Doorstops are assumed to be recycled at their

Table 2 Description of the life cycle processes accounted for in the environmental and cost assessment of the doorstop (blank-shaded)

Life cycle	*Process*	*Environmental impact (I)—Costs (C$)*		*Comments*
Production	Materials and energy supply	I	C$	Required amount depends on scenario.
	Transport to the semifinished products manufacturing site	I		
	Manufacturing of the semifinished products	I		Semifinished product depends on scenario (powder or plate).
	Total semifinished product cost			Cost includes all upstream processes.
	Infrastructure for finished products	I	C$	Includes all equipment (machines, tools, software, hardware, maintenance, etc.) for the production of finished products
	Fluids	I		Includes consumables for the production of finished products. Cost is negligible.
	Labor to produce finished products		C$	Labor is negligible for the environmental impacts.
	Postproduction	I	C$	Not taken into account due to lack of data
	Transport to the assembly site	I	C$	
Assembly	Labor for assembly		C$	Not taken into account because identical for both scenarios
	Assembly infrastructures	I	C$	Not taken into account because identical for both scenarios
	Transport to operator	I	C$	Not taken into account because identical for both scenarios
Use	Initial spare parts acquisition		C$	Negligible
	Spare parts storage	I	C$	Negligible
	System contribution to aircraft fuel consumption	I	C$	Contribution due to system weight
	Maintenance	I	C$	Not taken into account because identical for both scenarios
End of life	Transport to recycling facility	I		Boundaries expanded for environmental impacts. Costs not taken into account because not borne by stakeholders in the value chain relevant to decision making.
	Recycling	I		Boundaries expanded for environmental impacts. Costs not taken into account because not borne by stakeholders in the value chain relevant to decision making
	Environmental credit for the production of raw material	I		Boundaries expanded for environmental impacts. Costs not taken into account because not borne by stakeholders in the value chain relevant to decision making.
	Resale of the product at end of life before recycling		C$	Benefits for the operator from the resale of the product at end of life

Note: Dark gray–shaded are not taken into account because they are similar in the compared methods of production. Light gray–shaded processes are neglected either through cut-off or missing data. C$ refers to Canadian dollars.

EoL and are modeled like titanium swarf recycling. Aircraft fuel consumption over 35 years is allocated to the doorstops' use phases based on their mass fraction of the overall aircraft weight.

For the 3D printing scenarios, equipment data were mainly obtained from the technical sheet of an EOS M280 machine and completed with an internal LCA study on the three scenarios considered in the study. For the conventional machining

scenario, data were mainly obtained from a partner in the aeronautics sector. Missing data were found in ecoinvent v2.2, a generic LCI database. For confidentiality reasons, proprietary primary data cannot be disclosed, but in the Supporting Information on the Web, we provide as many details as possible on the data and hypotheses used to model the three scenarios. The impact IMPACT2002+ methodology (Jolliet et al. 2003) was used to calculate the environmental impact scores accounting for the entire LCI.

Environmental LCC was used to calculate cost reductions for the producer and user. They were calculated by adding production, assembly, and use cost differences between the 3D (optimized and nonoptimized) scenarios. Only the benefits generated by the resale of the product systems at EoL were considered. The detailed cost analysis of the EoL process was not further analyzed. Double counting was avoided by setting acquisition costs to zero when they were already accounted for in the production or assembly costs. For the conventional machining scenario, cost data were obtained from a partner in the aeronautics sector. For the 3D printing scenario, equipment and material cost data were obtained from online sources. In the interest of representativeness, partner data were used whenever available (e.g., labor rate) to overwrite the generic figures from the literature.

Use costs occurring during the aircraft life cycle were discounted to the year of reference (i.e., the year in which the aircraft was manufactured). The discounting rate net of inflation is 9% (Damodaran 2015). All costs were expressed in 2014 U.S. dollars. Normalization data were obtained from several public sources (see details in SI in the supporting information on the Web).

Results combining life cycle impact scores and costs through the eco-efficiency metric only consider inventory flows for which targets are accounted in the aeronautics sector: CO_2, NO_x, and PM (OACI 2013). Noise was considered identical in the compared product systems and not taken into account. The results were then aggregated into a single impact score as per equation (1).

Normalization reference data were obtained from a study on the environmental impacts of the aircraft under study from our partner in the aeronautics sector. Target levels and the time left to reach the targets were obtained from several sources in the aeronautics sector (CAEP 2004; GIACC 2009). For CO_2, NO_x, and PM, 23% over 15 years, 60% over 22 years, and 65% over 20 years were used, respectively. Damages at target levels were presumed to be equivalent. Environmental experts and representatives of the aircraft manufacturer may be able to refine the assumption.

Results

Results in figure 3 are normalized by the conventional machining scenario (CMA). The optimized 3D printing scenario (3DO) shows an impact reduction of over 20% as compared to the conventional machining scenario (CMA) for all the impact categories, essentially due to the reduction in fuel consumption in the use phase from the lighter weight (figure 3a). 3D printing without optimization (3DP) shows improvements of less than 1% as compared to conventional machining. Benefits stem from the production phase because the doorstops weigh the same as CMA.

Figure 3b shows that 3D printing provides a net reduction in environmental burdens, mainly in terms of energy and materials consumption, as compared to conventional machining, even despite greater impacts from fluids. In fact, 3D printing considerably reduces the amount of waste generated during the production. Even assuming that CMA waste is totally recycled, the materials impacts of conventional machining are more significant. Greater impacts from fluids for 3D printing are due to the use of argon gas in addition to compressed air (see details provided in the Supporting Information on the Web).

Figure 4 shows the life cycle cost results of the alternatives. Data are normalized to the CMA.

The net LCC of 3DP is approximately 8% higher than CMA because of greater production costs, specifically the indirect costs of equipment acquisition. Note that labor costs in the conventional scenario are aggregated under the indirect cost category because of a lack of data and are therefore not interpreted here. This means that the cost differences due to the indirect costs category are lower *than* in reality and may be higher if the indirect costs of the conventional machining were disaggregated.

For 3DO, there is a net LCC reduction of approximately 12% as compared to CMA, essentially due to lower fuel consumption because of lighter weighting. Indirect costs are also lower as compared to the 3D printing without optimization scenario because the 3D printing equipment is allocated to the 3DO scenario according to weight. Set out based on data availability, the latter allocation hypothesis implies that the machine uses the same parameters (parts design, batch size, etc.) for each production process during the year, which approximates a more sophisticated time allocation base when machine downtime is equal between the processes over the year. This means that, given a fixed annual volume of parts produced, the equipment is assumed to be allocated to equivalent tasks (process time versus downtime) during the year to meet annual volume requirements. Note that use costs are relatively low as compared to what is expected because a discount rate was applied over a recurrent use cost over 35 years.

Figure 5 shows the eco-efficiency results. CMA is the baseline and is placed at the origin of the diagram. The results of the two 3D printing scenarios are expressed relative to the CMA baseline. The dotted line represents the optimal solutions for a trade-off of 1 at which cost and environmental data are equally balanced. Optimized 3D printing is more eco-efficient than the two other scenarios from both an environmental and a cost perspective. It dominates the other scenarios for all trade-offs. CMA is more eco-efficient than 3D printing without optimization unless cost results are valued close to 0 against environmental burdens. This would be shown by a quasi-vertical dotted line representing equivalent optimal solutions.

A sensitivity analysis was conducted to evaluate the change in the results due to uncertain input parameters and test the

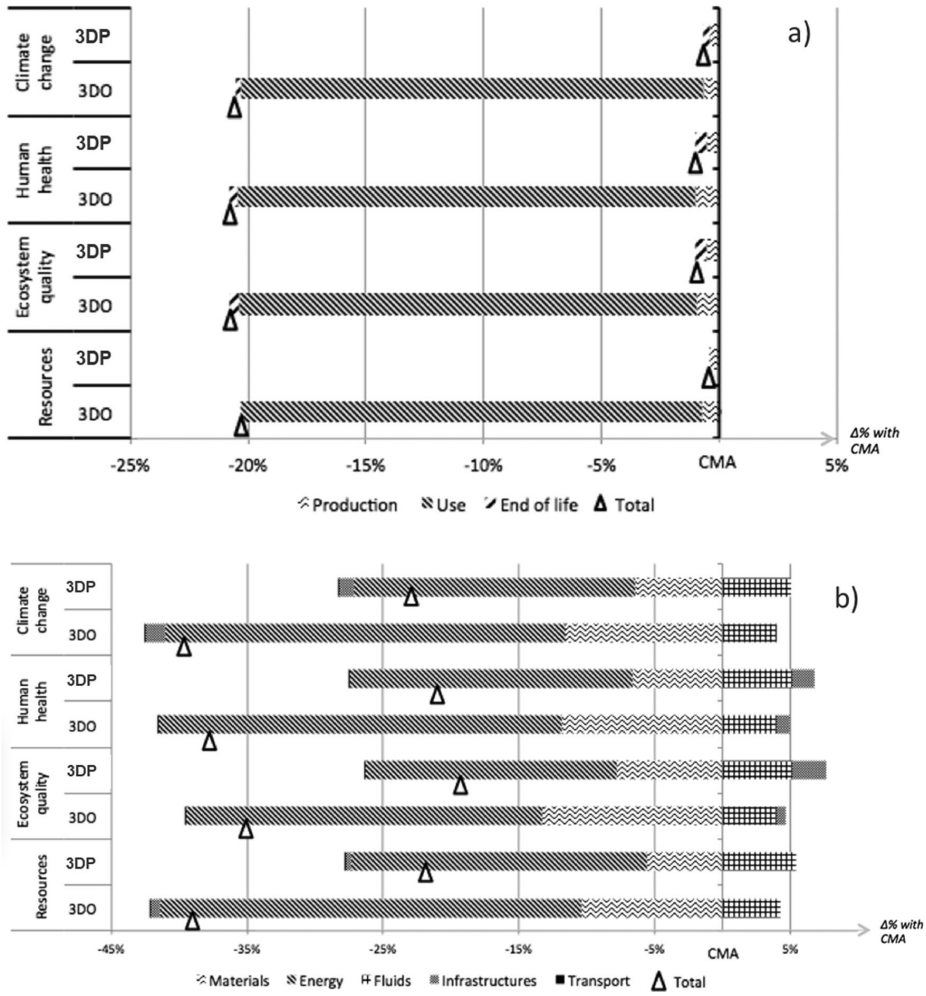

Figure 3 Environmental life cycle assessment results of the three analyzed scenarios: conventional machining (CMA), 3D printing (3DP), and optimized 3D printing (3DO). Results are normalized by the CMA scenario (0%). (a) shows overall life cycle results. (b) focuses on the cradle-to-manufacturing-gate life cycle phases, excluding use and end of life.

influence of the modeling assumptions. Figure 6 summarizes the sensitivity analysis of the eco-efficiency results for four parameters: (1) one component per 3D printing batch instead of six; (2) titanium powder costs of 700 Canadian dollars (C$) instead of C$300 per kilogram; (3) discounting rate 0% instead of 9%; and (4) life cycle cost of aircraft equal to 10% of acquisition costs instead of 25%.

The results of the sensitivity analysis show that optimized 3D printing is the most eco-efficient scenario at any trade-off, except for batch size. When reducing the number of doorstops per batch to 1, the optimal (dashed) line comes closer to the origin. Optimized 3D printing remains the most eco-efficient solution for a trade-off of 1 (equivalence between impact score and costs), whereas conventional machining and optimized 3D printing becomes equivalent for a trade-off equal to 2.7 (dotted line). In other words, when the cost reduction is 2.7 times higher than the environmental improvement, CMA is the most eco-efficient scenario. Also, the batch size parameter only influences cost reduction due to the negligible contribution of the infrastructure construction on the environmental results. Moreover, labor time, which is fixed regardless of batch size, does not contribute to the environmental results. Cost reduction is also sensitive to the cost of titanium powder. With a cost of C$700 per kilogram, the LCCs of CMA and 3DO are equivalent, meaning that the most eco-efficient solution is only based on environmental impact scores. Other parameters, including EoL costs, were tested and the results were not found to be sensitive to them. Their contribution to the LCC is also negligible when considering a 0% discount rate over 35 years.

It is important to note that production cost data for the 3D printing scenarios as well as normalization cost data were estimated from several online sources. However, environmental normalization data are more reliable. Postproduction processes were excluded from the 3D printing scenarios due to lack of data.

Finally, environmental impact scores in the eco-efficiency assessment only address the three substances for which reduction targets were set by the aeronautics sector: CO_2, NO_x, and PM.

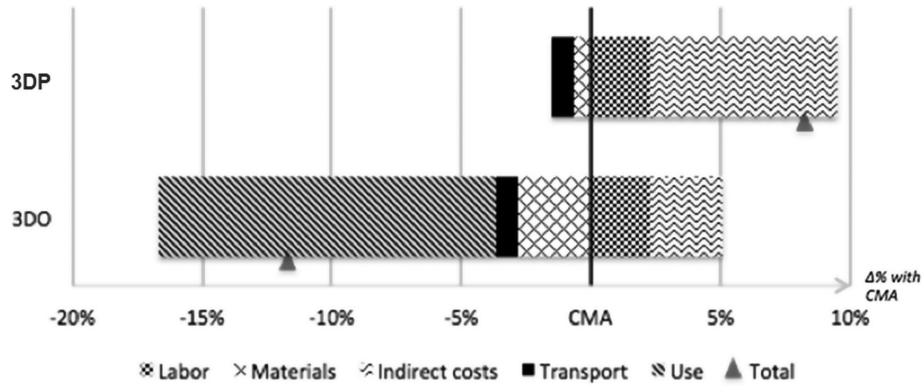

Figure 4 Comparison of the three scenarios' life cycle costs: conventional machining (CMA), 3D printing (3DP), and optimized 3D printing (3DO).

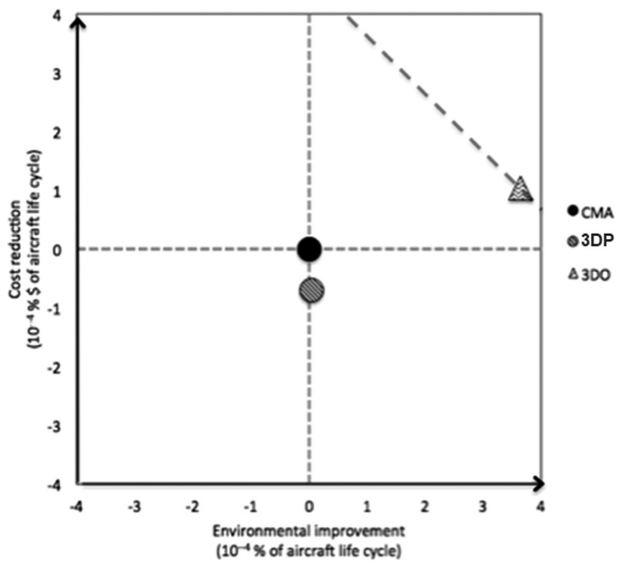

Figure 5 Eco-efficiency diagram of the compared scenarios: conventional machining (CMA), 3D printing (3DP), and optimized 3D printing (3DO). Positive numbers represent reduction in cost and environmental impacts, respectively.

Discussion

Rooted in Huppes and Ishikawa's marginal eco-efficiency method, the approach developed here is consistent with the reduction targets set by the aeronautics industry. Simple and transparent, it may readily be applied to support decision making in an eco-design context. The proposed approach has the advantage of minimizing the efforts required in the data collection phase, which is known to be time-consuming. It was simplified in a way that is consistent with the eco-efficiency indicator. Moreover, the normalization procedure enables the user to choose the trade-off and understand the underlying meaning. The XY diagram to display the results provides the user with an overview of the scenarios' trade-offs between environmental and costs scores. At a strategy level, a trade-off that is consistent with target reductions for the aircraft as a whole was applied. The reference state for the normalization procedure can also rely on a company's strategic objectives without a detailed knowledge of the whole aircraft, based on information gathered from an existing aircraft or on other reference states such as the industry emissions or even the global emissions of industrial activities. It is up to the company to define which is the most appropriate normalization reference. A more sophisticated approach may be followed to more adequately define a trade-off with aircraft subassemblies that, once combined, lead to an overall trade-off for the aircraft at a whole. Thus, it would be possible to pursue a comprehensive set of targets more effectively than in this study.

The case study on the potential of 3D printing in the aeronautics sector demonstrates that, based on the stated assumptions, the technology is more eco-efficient than CMA when the component to be manufactured is redesigned. In fact, production costs are higher for 3D printing and weights must be decreased to offset them in the use phase and obtain a positive net cost reduction over the entire life cycle of the component. When weight reduction is achieved through optimal aircraft component design, 3D printing has the potential to become the most eco-efficient manufacturing technology, both in terms of costs and environmental results. The sensitivity analysis revealed that 3D printing productivity is key since the results may change depending on the chosen trade-off between environmental improvement and cost reduction. 3D printing equipment costs constitute a major contributor. Nevertheless, the technology is still new, and equipment acquisition and titanium powder costs should decrease over time through mass production.

The assessment of technical performances and considerations related to 3D printing and CMA technologies are beyond the scope of this study. The proposed approach solely focuses on the eco-efficiency evaluation under the assumption that 3D printing is capable of generating sufficient mechanical properties for aerospace applications. We therefore assume that the compared components fulfill with the same technical requirements (mechanical strength). Presently, 3D printing in aerospace still faces many challenges regarding safety aspects, such as printing patterns, porosity built-up, and uneven print flow (Joshi and Sheikh 2015). Nevertheless, examples of

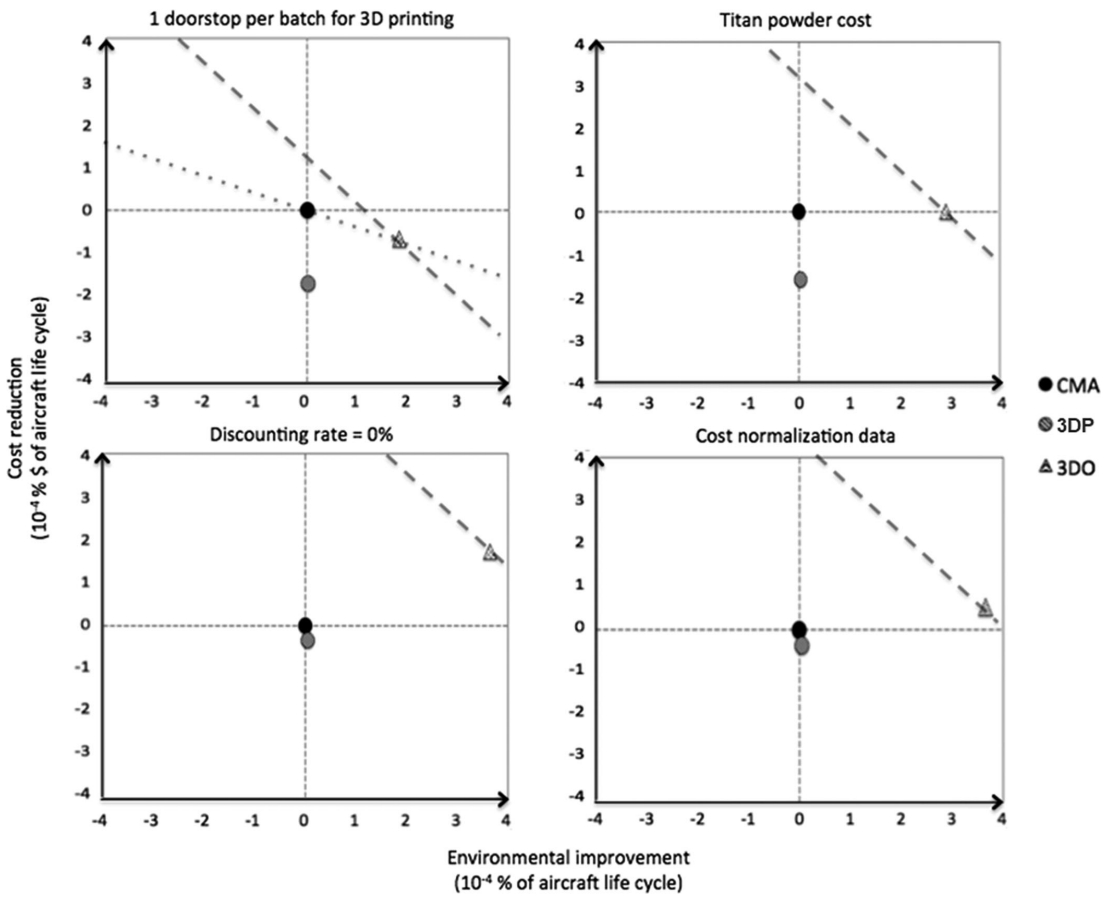

Figure 6 Results of the sensitivity analysis on the comparison between conventional machining (CMA), 3D printing (3DP), and optimized 3D printing (3DO). Positive numbers represent reduction in cost and environmental impacts, respectively.

safety-critical applications of 3D printing already exist, such as the fuel nozzles of the leading edge aviation propulsion jet engine produced by a joint-venture between GE and France's Snecma (Beyer 2014).

Conclusion

This paper explores how eco-efficiency may be used to assess promising new technologies for greener production through eco-design. Eco-efficiency may constitute a robust and widely accepted tool when the user is fully aware of the underlying mechanisms that lead to the attainment of reduction targets. Moreover, the findings show that, at full potential, 3D printing provides significant improvements over conventional machining in aeronautics. As the technology becomes more pervasive, further improvements through equipment and materials costs reductions are expected.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes a schematic drawing of the basic design of the technical component of an aircraft door under study and for which eco-design alternatives are compared. It also includes a list of assumptions that were set out to compare the eco-design alternatives, information about the batch size sensitivity analysis, and information about data sources.