Assessing the Life Cycle Environmental Performance and Economic Costs of Composite Materials in Certain Aircraft Structure

Minghui Wu*, Jhuma Sadhukhan, Richard Murphy, Ujjwal Bharadwaj, and Xiaofei Cui

***Abstract*—The aviation sector is looking to replace conventional metals for aircraft doors with composite materials due to the latter's potentially favorable combination of mechanical properties and low weight. However, little is known about the environmental impacts and economic costs associated with the production of such composite doors. This study conducts a Life Cycle Assessment and Life Cycle Costing on an example composite aircraft door to quantify its environmental and economic impacts. In addition, uncertainty analysis has been performed to enhance the quality of the assessment.**

***Index Terms*—Life Cycle Costing, Life Cycle Assessment, composite, aircraft door, Monte Carlo simulation**

I. Introduction

Composite materials have been widely used in the aeronautical industry over the last decade due to their favourable combination of mechanical properties and low weight. Manufacturers are increasingly interested in replacing conventional materials, such as aluminium, with composite materials [1]. A project named 'thermoplastic on doors' aims to manufacture a composite door to replace the conventional aluminium door for aircraft, using carbon fibre thermoplastics and thermosets. However, little is known about the environmental impacts associated with economic performance of such composite doors. This study aims to analyse life cycle environmental impact and economic cost of the composite door using thermoplastics and thermosets replacing the conventional aluminium door for aircraft. Work on assessing the environmental and economic impacts of composites used in aircraft structures is limited. Especially, no such composite door is currently available in the aircraft market, let alone the relevant Life Cycle Costing (LCC) or Life Cycle Assessment (LCA). Therefore, LCA and LCC of the composite door are required to be developed to identify and reduce the negative effects derived from the production process.

This research conducts LCC and LCA of the composite door during the production stage. It provides new databases and guidance for the manufacturers to choose more sustainable materials and manufacturing processes.

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II. Methodology

The research aims to evaluate the environmental and economic performance of the composite door and identify the critical processes and materials with the highest environmental burdens and economic costs. The system boundary defined in this work is the production stage of the aircraft door.

The LCA is performed to estimate the environmental impacts of the aircraft door in accordance with the standards ISO 14040–14044 [2, 3]. Fig. 1 is the general framework of LCA that is followed in this research. It contains four steps:

1) Goal and scope identification, which confirms the basic requirements and baseline of the research;
2) Life cycle inventory development, where all required inputs to the assessment are collected;
3) Life cycle impact analysis, which quantifies the environmental impact of the production process;
4) Results interpretation, which translates the quantified environmental impact as per requirements set in the step of goal and scope identification and meanwhile, the completeness, sensitivity and consistency need be checked.

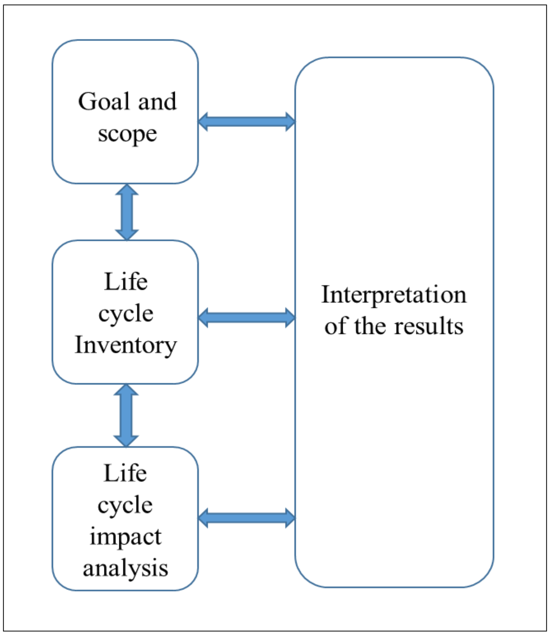

Fig. 1. The framework of life cycle assessment [2, 3].

In this research, the environment impacts are assessed with the help of the software package SimaPro 8.4 [4]. The Impact 2002+ methodology [5] is selected as it enables the impacts to be observed at the midpoint level with 15 impact categories,

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i.e., Carcinogens, Non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction, and the endpoint level with four damage categories, i.e., climate change, human health, ecosystem quality and resources.

The LCC is applied to estimate the manufacturing cost of the composite aircraft door, and the bottom-up method has been selected for developing the cost estimation model in this study. This method needs to develop a cost breakdown structure (CBS) first.

In order to estimate the cost breakdown structure, the cost elements associated with the whole life cycle of the aircraft door were identified. The identification process carried out complies with the mutually exclusive and collectively exhaustive (MECE) principle [6] to ensure there is no overlap or gap among these identified elements.

The total manufacturing cost can be estimated as the total of recurring cost and non-recurring cost Eq. (1):

$$Production\ cost = Recurring\ cost + Non-Recurring\ cost \quad (1)$$

The recurring cost means the repeated cost required in each operation included in the production process, including the cost of materials, scraps, consumables, labour and energy. The non-recurring cost included equipment cost and tooling cost. Eq. 2 and Eq. 3 are used to estimate the recurring cost and the non-recurring cost.

$$Recurring\ cost = \sum Material\ cost + \sum Labour\ cost + \sum Energy\ cost + \sum Scrap\ treatment\ cost \quad (2)$$

$$Non-Recurring\ cost = \sum Equipment\ cost + \sum Tooling\ cost \quad (3)$$

Uncertainty occurs when there is a lack of data or low quality of data in this research; therefore, the Monte Carlo simulation (MCS) [7] based on triangular distributions [8] is used to address the uncertainty. The overall uncertainty analysis process can commence, as shown in Fig. 2.

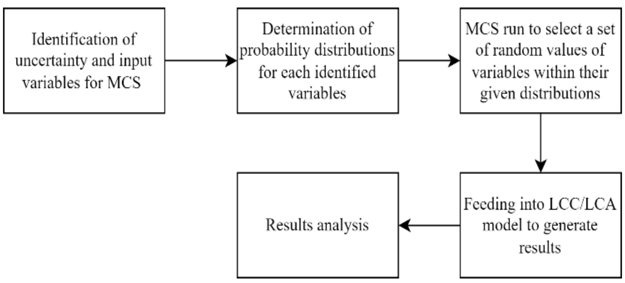

Fig. 2. Uncertainty analysis framework.

III. Results and Discussion

The damage to these four categories is measured using the equivalent CO_2 emissions (kg CO_2 eq), Disability Adjusted Life Years (DALY), resource extraction and non-renewable energy (MJ) and Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year ($PDF\cdot m^2\cdot y$), respectively. For easy interpretation and comparison, the total environmental impact is estimated by normalizing and weighting the results to a single score providing in unit points (Pt), i.e., Pt are equal to 'pers·yr'. One Pt represents the average impact in a specific category caused by one European for one year [9, 10]. The damage to each category is further normalized. The characterization and normalization results are shown in Table I. It can be seen that the composite door has the highest score on the human health damage category (2.47 Pt) and nearly the same score on both climate change and resources categories, but relatively lower than that of human health. There is only 0.18 Pt in the ecosystem quality category.

TABLE I: Impacts of Input Parameters toward the Four Damage Categories on the Production Process

Damage category	Damage assessment		Normalization	
	Total	Unit	Total	Unit
Human health	2.47E+00	DALY	2.47E+00	Pt
Ecosystem quality	1.82E−01	$PDF\cdot m^2\cdot y$	1.82E−01	Pt
Climate change	1.88E+00	kg CO_2 eq	1.88E+00	Pt
Resources	1.85E+00	MJ primary	1.85E+00	Pt

The LCA is also performed on the conventional aluminium door (Al door), and the results are compared with that of the composite door (Fig. 3). It can be seen that all impact categories are higher in composite door production than in Al door.

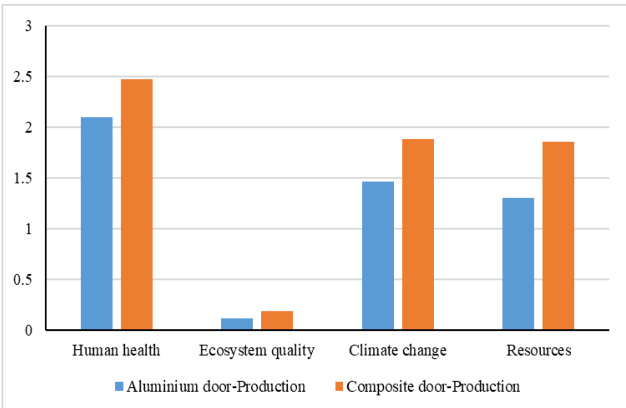

Fig. 3. Comparative impact assessment for Al door vs. composite door.

It can be seen that the composite door gives limited or negative environmental benefits than the counterpart Al door according to the comparison assessment. The composite door is heavier than the counterpart Al door due to the design engineers adopting more conservative safety factors than those used for the metallic door. Further investigation is also performed on the LCA of two doors with the same weight. However, even if the weight of the novel door is reduced after optimising the structure to reach the same weight as the Al door, the composite door cannot achieve a similar environmental performance as the metal door did. This is despite not covering the end-of-life assessment of the composite door and Al door within the remit of the study that is focused only on the manufacturing stage.

Moreover, the LCC result shows that the total cost of producing the first door is calculated as €89,753, and the cost breakdown is shown in Fig. 4. As can be seen, the main cost for production is labour, which contributes 54% of the total cost. Material cost is the second highest contributor at 26% of the total. The equipment, tooling and energy costs only account for 7%, 7% and 6% of the total cost, respectively. Scrap treatment cost contributes a negative cost which represents the revenue. Meanwhile, the same cost models are also applied to the convention door production and the Al door production cost is estimated as €47,986. It can be observed that the composite door costs more than its metal counterpart.

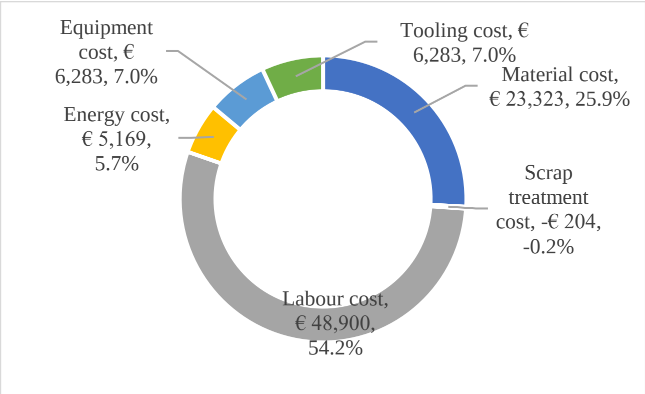

Fig. 4. The contribution of each cost category in the production of the composite door.

At last, uncertainty analysis is performed on the labour rate and material unit cost parameters. An MCS model is developed in an excel spreadsheet. And then, the probability distribution under the MCS 10,000 runs for the composite door production cost can be calculated as shown in Fig. 5. The distributions can then be characterised statistically through mean and standard deviation and by providing the respective percentiles, as shown in Table II. As can be seen, the mean value is € 90,148 per door; having a 95% chance of making a door is between € 83,556 and €97,461.

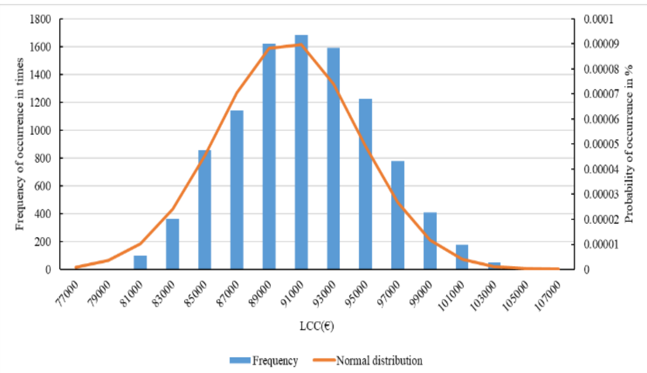

Fig. 5. Probability distribution of door production cost with variables of labour rate and material unit costs.

TABLE II: STATISTICAL DESCRIPTION OF RESULTS FROM MONTE CARLO SIMULATION

Distribution		Percentiles	
μ	σ	5%	95%
€90,148	€4,370	€83,556	€97,461

IV. CONCLUSIONS

Based on the data acquired from door manufacturers [11], a range of comprehensive assessments has been performed to study the economic and environmental impact of the composite door during the production stage. In addition, a comparison analysis of the environmental and economic performance of the composite door and its equivalent aluminium door has been conducted. The assessments present a comprehensible way of evaluating the overall environmental and economic impacts of different alternatives and provide rational decision support for selecting of materials and processes. It is possible to identify the hotspots and allow decision-makers to observe impact improvement opportunities as well as uncertainty attached to a range of model parameters. Two main conclusions that can be drawn from this study are: A composite door has more negative environmental benefits than an aluminum door; The mean value of producing a composite door is higher than an aluminum door. Then, composite materials are very good for some applications, for their mechanical properties and low weight, but they are not appropriate for aircraft doors if only the production phase is considered.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Minghui Wu contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. Jhuma Sadhukhan, Richard Murphy, Ujjwal Bharadwaj and Xiaofei Cui critical reviewed of the paper, discussed the results and commented on the manuscript.

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