Abstract
The decision between component reuse, recycling, incineration and landfilling of materials constitute an important part of the management strategy of end-of-life aircraft. However, when developing specific strategies in preliminary analysis also the environmental consequences that arise in the end-of-life phase should be considered. The main objective of this paper is to develop a conceptual framework capable of integrating the decision processes of end-of-life into conceptual aircraft design in order to enable analysis of the recommended prioritization for each alternative (reuse, recycling and remanufacturing – 3R).

1. Introduction
The treatment of the end-of-life (EOL) phase of a product attracts the interest of consumer and producer authorities [1] and aeronautic industry is no different. Studies indicate that a lot of aircrafts are in their end-of-life phase. This number is expected to increase in coming decades [2].

Product strategies in the end-of-life (EOL) should be considered when product concepts are generated; preferably with a combination of certain options [3]. Once the initial specifications are followed, the product can be modified according to the product management of end-of-life, i.e. recycling, re-use, incineration and landfilling. It is essential to assess the financial impact of each alternative as a part of the environmental decision making process. Existing methods for assessing the aircraft life cycle are mainly focused on the life cycle costing [4].

In order to integrate the end-of-life aircraft in the conceptual aircraft design in terms of sustainability, existing methods found by the authors consider only particular characteristics such as geometry, mass, noise and performance. Particularly for a product like an aircraft, whose life cycle extends over about 40 years, decisions taken in the preliminary design phase, such as aircraft size, the material to be used and the ease with which the aircraft can be disassembled, represent a significant environmental impact.

1.1. Goal and scope definition
Environmental concerns are also stimuli for finding new creative solutions and products. However, this does not imply that one can always expect a financial reward from becoming environmentally responsible.

Many companies and organizations have realized the need to become more environmentally responsible. However, many are struggling with the questions how to move towards becoming a more environmentally responsible company in general and how to include environmental issues in conceptual aircraft design in particular.

Therefore, in this paper, the main objective is to develop a conceptual framework capable of integrating the decision processes of end-of-life into conceptual aircraft design in order to enable analysis of the recommended prioritization for each alternative (reuse, recycling and remanufacturing).

As will be shown, for a more comprehensive integration of environmental issues it is necessary to increase the scope of
temporal and organizational concern of conceptual aircraft design.

2. Literature review

Several countries have imposed increasingly expansive environmental regulations upon manufacturers, extending their responsibility well beyond the production processes within their factory gates. Such regulations seek to reduce both the volume and toxicity of waste by creating incentives for manufacturers to more fully incorporate EOL concerns into conceptual aircraft design. Such “extended producer responsibility” (EPR) regulations can be viewed as a natural extension of trends among legislatures, regulatory agencies, and courts to hold manufacturers increasingly responsible for the externalities imposed by their manufacturing operations and products [5]. Regulations that make manufacturers responsible for paying for the collection and disposal of their products seek to simultaneously internalize some of costs that are otherwise externalized to society and transfer a growing cost burden from government to industry [6]. Imposing such responsibilities on manufacturers, as opposed to others in the supply chain, is meant to tap a critical leverage point: Design development and end-of-life [6]. The legislation based on the EPR principle, intends to have an effect on the conceptual design stage and end-of-life of the aircraft (see Table 1).

Table 1. Definition of EOL decisions

| Phase                        | Effects                                                                 |
|------------------------------|------------------------------------------------------------------------|
| Design and development       | Changes in the material composition to an increased use of recyclable and environmentally beneficial materials; |
|                              | Removal of hazardous substances;                                        |
|                              | Increasing “design for disassembly”, “design for re-use” and “design for remanufacture.” |
| End-of-life                  | Increased levels of re-use and remanufacture;                           |
|                              | Increased levels of recycling of materials.                             |

Design is also the key stage where materials are selected, and these decisions—such as employing easily recyclable materials and fewer unusual composites and hazardous materials—can greatly impact the profitability of product recovery.

2.1. Current legislative framework in the aviation industry

At the moment, looking into the aeronautical industry there are no legislation for recycling like the automotive sector of EU ELV Directive [7].

The technologies are waiting for the legislation and better economics of the recycling process. At the same time the technologies are going through further developments, in particular for the increased quality of the recycled products and cost reduction of the recycling operation [8].

According to the report from the European Aeronautic Defense and Space (EADS), released as "Report of the Board Directors" in 2009, will be mandatory for aeronautical industry implement ISO 14001 certification from 2015. This Beacon "on aircraft out of waste" true by 2015? Based on the current technology and industry status, it is not yet possible. This will not only depend on the recycling technologies of various engineering materials, but will also depend on the quality requirements and tolerance in the conceptual aircraft design [8].

Current and future waste management and environmental legislations will require more engineering so that they can be properly recovered and recycled, from end-of-life (EOL) aircraft. The adoption of the best alternatives to recycling will save resources and energy to the production of materials [9]. The development of new technologies is able to increase the quality of recycled products and also reduced operation costs will be a consequence of the new legislation and better economy of recycling processes. The trend in the transportation sector goes to legislation in terms of an extended producer responsibility. Accordingly, the aviation industry could also face legislation similar to the regulations in the automotive industry.

3. Integrating alternatives end-of-life (3R) in conceptual aircraft design (IAELAD)

A new concept of integrated alternatives EOL in conceptual aircraft design is proposed for the purpose of closing the aircraft life cycle loop. This concept focuses on the feedback in terms of both physical products and information from the EOL stage to a suitable earlier stage. The Integrated End-of-Life in Conceptual Aircraft Design (IEOLCAD) is a framework concept that combines the management of every stages and activities across the entire manufacturing and EOL line with the considerations for the environment. The concept in Fig. 1 is the overall framework and the dotted lines represent the feedback paths for information while the solid lines are meant for the feedback of physical aircraft.

In this concept, there is a coordinated effort to exchange and share knowledge for optimal operations from the conceptual aircraft design to the end-of-life. The environmental considerations will be taken care of in the decision-making and information sharing process. The entire life cycle in this new framework was closed and segregated into many stages namely, in sequential order, materials, design, supply chain, manufacturing, transport, aircraft operations and EOL (to be connected back to materials). The EOL stage will be focused in this paper.

![Fig. 1. IAELAD concept](image-url)

This concept features feedback loops of tangible aircraft and non-tangible aircraft information, which helps to close up the flow of materials and enhance the flow of information and knowledge. Amongst all stages, conceptual aircraft design is the most information intensive one whereby most of the information and knowledge from other stages will be feedback
to. The most significant one and is of concern in this paper is from conceptual aircraft design to EOL. The information apropos EOL stage is important and very useful to the designers, given the fact that the activities in this stage are often independent from the rest of the stages in nature and largely depended on experience instead of tacit formal knowledge.

EOL, stakeholders are normally disjointed with the rest of the stages in particular, to the conceptual aircraft design stage. They do not have the proper knowledge and expertise on the aircraft and there is also no established system in both formal and informal way for knowledge in the EOL stage to be forwarded back to the relevant actors to improve the conceptual aircraft design. The information will be beneficial to the designers during conceptual aircraft design stage when certain design decisions need to be made.

3.1. Remanufacturing, recycling and reuse

Remanufacturing is the only process where used products are brought at least to Original Equipment Manufacturer (OEM) performance specification from the customer’s perspective and, at the same time, are given warranties that are equal to those of equivalent new products [10]. The reasoning here being that if a remanufactured product has quality equal to that of a new equivalent then its warranty must also be the same. Of all the current “secondary market” (used product) processes, remanufacturing involves the greatest degree of work content and as a result its products have superior quality and reliability. This is because remanufacturing requires the total dismantling of the product and the restoration and replacement of its components. Remanufacturing is particularly applicable to complex electro-mechanical and mechanical products which have cores that, when recovered, will have value added to them which is high relative both to their market value and to their original cost [11].

Recycling is “the series of activities by which discarded materials are collected, sorted, processed, and used in the production of new products” [12]. It is clear that it is environmentally better to recycle materials rather than take them to a landfill site. Indeed, for aluminium, the energy saving can be as high as 91% by recycling scrap compared with the process of using the primary raw material, bauxite [13].

However, although it is currently the most mature waste avoidance strategy, with established rates as high as 80% for certain products [14], many designers are reluctant to use recycled materials because of uncertain quality or supply standards [15]. One attempt to address the issue of quality has been to further define a recyclable material as one that can reacquire the material properties it had in its virgin state and thus to develop a measure of the “recyclability” of different materials by assessing virgin, scrap and processed economic values [16].

In addition, whilst the materials recycled reduce virgin material use, they do still require additional energy to be used to reform them into manufactured products.

Reuse is clearly essential component. It extended the product life cycle, reduce the amount of waste generated, reduce the amount of virgin materials and energy usage [17], and most important, it is likely to achieve waste diversion at a net profit. Hence it is surprising that most waste laws start to focus on recycling as their ultimate goal. The downsides of incorporating reuse goals appear to be the question of whether a newer device will have sufficiently improved environmental performance that it out that it outweighs the benefits of waste diversion [18], and the complications that can arise in managing and accounting for the contributions of reuse and operations in a traditional take-back setting. Also from a social perspective, incorporating reuse is a complicated issue; mass exporting of waste becomes possible under the guise of reuse.

4. End-of-life (EOL) stage

The aircraft EOL alternative stage will be focused here. Aircraft end-of-life management is a relatively new area that is concerned with how aircraft are being handled after the useful lifespan. The activity in this stage starts from the moment the owner or operator decides not to use it anymore and want to discard it. The few sub-stages that a aircraft will go through are collection including transportation, disassembly and then EOL options. To better represent and formalize the concept of EOL options, a taxonomy for EOL options is being developed here as shown in Fig 2. EOL options are divided into two main categories, recovery and disposal. For recovery, it involves the feedback of the aircraft to other earlier stages physically in various forms such as materials, components or as whole aircraft. This is the path to be taken in order to form a close loop. This will decrease the demand for virgin raw materials and hence achieving a lower environmental impact level. Under recovery, it is further split into formal and informal type. The informal type of recovery is reuse as this is mainly taking place within the usage stage among the consumers. The formal type is what the manufacturers are most concerned with. The three formal type of recovery are remanufacturing, reuse and recycling.

There are 4 options, other than the normal general disposal for EOL management; namely remanufacturing, recycling, reuse, and proper disposal. Table 2 states the definition of each option.
Table 2. Definition of EOL decisions

| Phase     | Effects                                                                 |
|-----------|-------------------------------------------------------------------------|
| Reuse     | On the highest level, there is reuse with sustaining of the same function. This happens within the usage stage. (A formal process that is being considered here). |
| Remanufacture | The aircraft are being dismantled to component level and these components being used in another aircraft. |
| Recycling | In most cases, the scrapped aircraft enters a shredder and is chopped into smaller pieces. During this process, the light material, so-called fluff, is sucked away from the waste stream. |
| Disposal  | The non-recovered part that are to be thrown away that does not harm the environment. The products may or may not go through additional treatment before disposal. |

5. Integration of alternative end-of-life in conceptual aircraft design

The priority of system is to reduce environmental burdens through a holistic life cycle approach of integrating all environmental information from all stages. As this paper is only concerned with the information from conceptual aircraft design and EOL stage, the information for the rest of the stage will not be discussed here. The method that will be discussed here in greater details is meant to assist the designers and EOL stakeholders to adopt and consider environmental information in their decisions and actions.

In the process of designing of aircraft, a designer should take in consideration of the EOL options of the aircraft and impute the environmental cost into the aircraft cost. This process of design considerations will bring the designers through round of EOL considerations before deciding on the final design.

5.1. Framework

The flowchart in Fig. 3 depicts the process of making design with environmental performance as the priority.

5.2. Design for environmental life cycle assessment

As shown in Fig 3, during the process of design, the designer will retrieved the design information from the system. These include the Design for End-of-Life (DfEOL) guidelines.

The designer will then design the aircraft and process based on these guidelines and the other traditional requirements. In event of conflicting decisions, the environmental considerations will take precedence. Once the design is done, the design will have to go through an environmental performance. Here the design will be checked for the usage of hazardous substances, recovery potential and energy efficiency.

The designer will go through the hierarchy of EOL options to decide the best way of designing the aircraft for lower environmental impacts.

Whenever possible, the designer should focus on design for service in the first place thinking about the service design in complement to the aircraft to fulfill the function required by the product. This will include incorporation of features for tracking usage, easy maintenance and upgrading, designing the service and payment system. The conceptual aircraft design of the service system is important to be included instead of leaving it to the marketing stakeholders is due to the fact that by considering the type of service that are to be provided, the designer can better design the aircraft to fit into the service system. This aspect of design is part of service engineering which is a new emerging field for after design for service; the next task of the designer is to look at design for EOL. Many of the current designers do not look beyond the operations stage of an aircraft when they do their design even in some of the DfE cases.

Fig. 3. Concept of EOL decision [19]

With the legislations, it is definitely a must to look at the implications of the design on the aircraft EOL and conceptual aircraft design to have an easier EOL management process and lower environmental impacts at the end-of-life. In conceptual aircraft design for EOL, there is a hierarchy for reference, generally one should always consider conceptual
aircraft design for refurbishing before remanufacturing, and then followed by recycling. For the designer to be able to consider all these criteria, they need to be provided with the information of these EOL options (reuse, remanufacturing and recycling) by the EOL stage stakeholders. This is the part of DfE that is currently not well managed and also an issue this system is trying to address. The provision of EOL information feedback to the conceptual aircraft design is defined and designed to facilitate DfE process.

Fig 4 illustrates the necessary considerations during conceptual aircraft design to achieve sustainable aircraft. Also, the integration of downstream issues into design is a complex task. The ambiguity attributed to a concept during the conceptual aircraft design creates grand challenges for the development of appropriate, accurate metrics related to sustainability.

Fig. 4. Concept of EOL decision

5.3. Life cycle assessment

A life cycle assessment will be carried out to study the totally environmental impact of this design through all the stages with some user input parameters. A simulation of the scenario with this design of the aircraft also is carried out to ensure that it is environmentally viable for the design. Once the design goes through both processes then it will be assessed to see if the design is approved for production. It will be assessed if it is overdesign or underdesign in term of environmental performance. In case design is acceptable for its environmental merits.

In case of overdesign, it is much easier as cost will then be placed at first priority since environmental performance is satisfying. The changes are to be considered in this order: cheaper suitable material, cheaper suitable process technology and cheaper modules. The idea here is to have a lower cost within acceptable environmental performance limit. In the event of no suitable alternatives, the original design will be acceptable for its environmental merits.

6. Summary

In this paper, a number of options and issues that aeronautical industry should consider when pursuing integration of environmental issues in aircraft design. During the conceptual aircraft design and end-of-life multiple dimensions of environment, economics, politics and operations come into play, and the differences among them create challenges in achieving an efficient balancing of environmental and economic trade-offs.

Our analysis uncovers a strong relationship between some of the issues identified and the characteristics of the aeronautical industry. Remanufacturing, reuse and recycling processes have been examined in detail previously, which provides a scientific basis for sustainability.

Therefore, a link between aircraft functions and requirements and an assessment of the end-of-life performance of a product has to be established.

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