COPPE
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IDENTIFICATION AND ASSESSMENT OF THE ECONOMIC OUTCOMES OF COMMERCIAL AIRCRAFT DECOMMISSIONING: A THEORETICAL AND MATHEMATICAL APPROACH TO SUPPORT DECISION-MAKING REGARDING END-OF-LIFE AIRCRAFT TREATMENT ISSUES

Flavio Soares de Oliveira Junior

Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia de Produção, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia de Produção.

Orientadores: Elton Fernandes
Laura Silvia Bahiense da Silva Leite

Rio de Janeiro
Fevereiro de 2019

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DISSERTAÇÃO SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE EM CIÊNCIAS EM ENGENHARIA DE PRODUÇÃO

Examinada por:

Prof. Elton Fernandes, Ph.D.

Prof. Laura Silvia Bahiense da Silva Leite, D.Sc.

Prof. Lino Guimarães Marujo, D.Sc.

Prof. Ronaldo Balassiano, Ph.D.

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DEDICATÓRIA

Esse trabalho é dedicado a todos os profissionais da indústria de transporte aéreo, dos órgãos governamentais da aviação civil, da academia, e das instituições de pesquisa e desenvolvimento, que devotam contínuos esforços e recursos ao desenvolvimento sustentável da aviação comercial, tendo em vista sua contribuição para a geração de conhecimento, inovações tecnológicas, emprego, renda e desenvolvimento sócio econômico em escala global.

"This work is dedicated to all professionals in the air transport industry, civil aviation government agencies, academia, and research and development institutions, who devote continuous efforts and resources to promote the sustainable development of commercial aviation in view of its contribution for the generation of knowledge, technological innovations, employment, income and socio-economic development on a global scale."

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Ao Pai, ao Filho e ao Espírito Santo, cujo amor excede a todo o conhecimento, para que sejamos preenchidos de toda plenitude de Deus. (cf. Efésios 3, 19)

Aos meus pais, Flávio e Amélia, que com seus sacrifícios sustentaram meus primeiros passos na busca de um rumo certo na vida.

À minha esposa, Cintia Aparecida, e aos meus filhos, Emanuelle Auxiliadora e David Gabriel, por perdoarem minhas ausências, incentivarem meus esforços, e me ajudarem a não desanimar nos momentos mais críticos da caminhada.

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Aos inúmeros amigos que me incentivaram ao longo dessa jornada, e celebram comigo a alegria por mais essa importante conquista humana e profissional.

“Há três caminhos para o fracasso:

Não ensinar o que se sabe,

Não praticar o que se ensina,

E não perguntar o que se ignora.”

"There are three paths to failure:
Do not teach what you know,
Do not practice what you teach,
And do not ask what is ignored. "

São Beda, monge inglês, séc. VII d.C.

Resumo da Dissertação apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Mestre em Ciências (M.Sc.)

IDENTIFICAÇÃO E AVALIAÇÃO DOS IMPACTOS ECONÔMICOS DO DESCOMISSIONAMENTO DE AERONAVES COMERCIAIS: UMA ABORDAGEM TEÓRICA E MATEMÁTICA PARA APOIO ÀS DECISÕES SOBRE AS QUESTÕES DE TRATAMENTO DE AERONAVES EM FIM DE VIDA ECONÔMICA

Flavio Soares de Oliveira Junior

Fevereiro/2019

Orientadores: Elton Fernandes
Laura Silvia Bahiense da Silva Leite

Programa: Engenharia de Produção

Este trabalho desenvolve a revisão da literatura acerca do problema do tratamento de fim de vida econômica das aeronaves utilizadas no transporte aéreo público de passageiros e cargas, no âmbito da aviação comercial internacional. As decisões de destinação final dessas aeronaves são analisadas sob a ótica dos aspectos técnicos e econômicos que orientam a tomada de decisão dos proprietários e operadores desses bens de produção. Além do arcabouço teórico desenvolvido, propõe-se ainda um modelo matemático para análise de custo-benefício financeira para auxiliar tal processo de tomada de decisão. O principal objetivo é determinar o tempo apropriado para tomar decisões de tratamento de fim de vida econômica dessas aeronaves, visando assegurar a recuperação de valor às partes interessadas no referido problema.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

IDENTIFICATION AND ASSESSMENT OF THE ECONOMIC OUTCOMES OF COMMERCIAL AIRCRAFT DECOMMISSIONING: A THEORETICAL AND MATHEMATICAL APPROACH TO SUPPORT DECISION-MAKING REGARDING END-OF-LIFE AIRCRAFT TREATMENT ISSUES

Flavio Soares de Oliveira Junior

February/2019

Advisors: Elton Fernandes
Laura Silvia Bahiense da Silva Leite

Department: Industrial Engineering

This work develops the literature review on the problem of the end-of-life treatment of aircraft used for public passenger and cargo air transport in the context of international commercial aviation. The final destination decisions of these aircraft are analyzed from the point of view of the technical and economic aspects that guide the decision-making of the owners and operators of these production assets. In addition to the developed theoretical framework, a mathematical model for financial cost-benefit analysis is also proposed to assist in this decision-making process. The main objective is to determine the appropriate moment to take end-of-life treatment decisions for these aircraft, in order to ensure the recovery of value to the stakeholders.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

DfE – Design for Environment

EOL – End-Of-Life

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

ISTAT – International Society of Transport Aircraft Trading

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCE – Life Cycle Engineering

PAMELA – Process for Advanced Management of End-of-Life of Aircraft

TCO – Total Cost of Ownership

1. Introduction

"*A long time ago in a galaxy far, far away Rey used to be a scavenger specialized in removing parts from abandoned aircraft and selling them for a living.*"

This previous sentence could be used to start talking about Rey's business, in "*Star Wars: Episode VII - The Force Awakens*". In a non-regulated galaxy, that could be an acceptable commercial practice because this society could not be aware of suspected unsafe aircraft crossing the skies. Considering the fictitious context of this famous epic space opera, one may suppose something about the types and magnitude of the losses if an unairworthy aircraft flying close to the speed of light suddenly crashes a populated space site due to the failure of a critical safety component. Fortunately, in real life, every society and their governments are both aware of safety concerns regarding safe aircraft operations.

Hence, they are only part of the network of stakeholders that shall keep in mind that retired aircraft can turn into significant social, environmental and economic problems if they are not appropriately treated when they reach the limits of their business life-cycle. The withdrawn of an aircraft from active service is a decision that belongs exclusively to its owner or operator, but the way they do that may give rise to the significant well known or emerging risks affecting the social welfare. These risks are the main reason that justifies the necessity of further researches to fully comprehend the challenges and opportunities facing the new business opportunities of end-of-life aircraft treatment.

However, it is not just a matter of doing what is right concerning social, environmental and economic externalities due to the end-of-life aircraft treatment. There is an important business question about how to do the right thing making profit or reducing the aircraft total cost of ownership, i.e., how to add value to all stakeholders. Sustainability involves social, environmental and economic aspects. Among the social aspects concerning end-of-life aircraft treatment, one may argue that safety concerns are in the cornerstone. Air transport turbulent business scenarios call for productive activities in all these aspects.

1.1 Problem statement and contributions

The aviation industry has been recently developing strategies to deal with commercial aircraft end-of-life problem appropriately. New standards and best practices are on development by the aircraft recovery industry to help coping with safety, environmental and economic concerns arising from this problem. Aircraft owners and operators are not well familiarized with these procedures. They can count on this novel and expanding industry to manage their aircraft end-of-life phase while reducing liability risks arising from improper retired aircraft's final disposal.

Before taking any decision about this issue, we need to analyze the aircraft end-of-life phase management considering one step behind, aiming to answer the following questions previously:

1. When one may say that an aircraft has reached the end of its business life-cycle?
2. What are the natures of the factors influencing how to determine that an aircraft has reached the end of its business life-cycle?
3. What is the dynamics of the costs and revenues to be considered when deciding that an aircraft has reached the end of its business life-cycle?

These three questions together are elected as the problem statement and guide our research efforts, looking for development of a systematic, technically feasible and cost-effective analytic tool to better support aircraft owners and operators decision-making processes regarding end-of-life aircraft treatment. The current literature does not offer clear and complete theoretical and mathematical approaches to analyze and solve these questions, which reinforce the need for exploratory research endeavor.

1.2 Research context and scope

When aircraft are withdrawn from the active service, they are sent to storage at specific sites in desert regions, where they remained parked and preserved from significant deteriorations affecting their fuselage, equipment, and systems. Parking and preservation routines implies in high costs to aircraft owners or operators. During this inactive phase, commercial aircraft represent safety, environment and economic concerns to owners, operators, regulators and the society. According to IATA (2016a), the rate of aircraft retirement is growing annually, while their age at retirement decreases. Aircraft manufactures also forecast increasing numbers of aircraft retirement due to fleet renewal policies and new deliveries in the long-term, to support the continuous growth of the air transport market. These circumstances tend to aggravate this new problem faced by the aviation industry, considering that more than 15,000 commercial aircraft are currently retired worldwide (IATA, 2016a). That increasing out-of-service fleet may be parked for an indefinite time, and can give rise to serious safety, an environmental and economic risk to different stakeholders involved in this problem.

Sometime after parking an aircraft, its owner or operator needs to take another strategic decision about its final disposal: (1) relocate the aircraft at another potentially profitable market condition; (2) resell the aircraft as an asset in the second-hand market; or (3) retire and decommission it. In this last option, the aircraft is said to have reached its end-of-life and is eligible to be submitted to the recovery process (Keivanpour *et al.*, 2015c). In this situation, the aircraft components are removed (disassembling) and recertified to be reused in the active fleet; the remaining structure is deconstructed (dismantling), when different materials are separated and pre-processed for recycling purposes; and both processes are aiming to reduce the amount of waste disposal (landfilling) (van Heerden and Curran, 2010). Although it may be deemed as a classical cost-benefit problem, the aircraft retirement decision involves many stakeholders' interests or requirements and gives rise to safety, environment, and economic concerns, as related by Towle *et al.* (2004), that put all together can turn it into a complex problem.

Considering this briefly described context we set the scope of this research focusing the aircraft parking, market relocation, retirement, and decommissioning decisions to identify and comprehend the main drivers behind this strategic decision, and also assess their impacts to all related stakeholders. The aircraft decommissioning decision and its implications will be analyzed under the concepts and scope of the recovery problem, as posed by Navin-Chandra (1994). Examining the motivations presented by the mentioned work, we may conclude that there are significant relationships between products early design decisions and the recovery solutions at their end-of-life phase. These relationships are not well known if we consider explicitly the aircraft early design decisions and the end-of-life aircraft recovery context, that will also be analyzed under the scope of this research.

An appropriated treatment of end-of-life aircraft can minimize or even prevent safety, environmental and economic adverse impacts, and potentially revert the parking, retirement and final disposal costs into revenues. All this dynamic also deserves an in-depth evaluation during this research to highlight the challenges and opportunities to all involved stakeholders. For that reason and considering the industrial engineering approach of this research, the relevant aircraft recovery problem will be theoretically discussed considering the intersections between the issues of Design for Environment (DfE), Reverse Logistics (RL), and Sustainability. This discussion will help to point out the main processes and drivers that support the implementation of eco-design solutions in the commercial aircraft manufacturing context. The eco-design solutions will then be the result of the adoptions of strategic decisions based on sound business sense, that turns these eco-design solutions into higher profits business practices (Srivastava, 2007).

1.3 Motivation

A recent study of the International Civil Aviation Organization highlighted the significant impacts of the air transport industry in the global economy (ICAO, 2016). This industry, directly and indirectly, supports the employment of 58.1 million people, contributes over $2.4 trillion to global Gross Domestic Product (GDP), and carries over 3.3 billion passengers and $6.4 trillion worth of cargo annually. According to the same study, since 1977 the global air traffic has doubled in size once every 15 years and will continue to do so. Simply put, the air transport industry plays a significant role in supporting sustainable development, even helping local economies overcoming recession periods, due to strategic investments to create and continuously operate the required infrastructure.

The most critical production assets that support this industry are the commercial aircraft engaged in the regular public transport of passengers and cargo. These aircraft must be submitted by their manufacturers to design, production and airworthiness approval procedures, in compliance with the requirements of the Title 14 CFR Part 21 [1], that establishes the aircraft certification procedures. These aircraft must also be designed and constructed in order to demonstrate compliance with the safety requirements of the Title 14 CFR Part 25 [2].

Technically, the commercial aircraft models are subdivided into three groups: (1) regional jets – single-aisle aircraft with capacity between 50 and 160 seats (extended range jets) ; (2) narrow bodies – single-aisle aircraft with more than 160 up to 290 seats (short and

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[1] and **[2]** The USA Aviation Regulations are enclosed in the Code of Federal Regulations (CFR), under the Title 14. This title encompasses all the aviation rules (called Parts), which contains the requirements related to each significant aviation concerns that needs to be regulated. Hence, the complete reference to these rules should be written as “Title 14 CFR Part XX”. For the sake of practicality, these references are generally written as FAR XX (Federal Aviation Regulation) or simply Part XX. Ex.: FAR 21 or Part 21.

medium-haul jets); and (3) wide bodies – twin-aisle aircraft with more than 290 seats (long-haul jets).

Under the macroeconomic point of view these aircraft are said to be non-ubiquitous production assets. Their project, development, and manufacturing are highly intensive in long-term investments, knowledge, workforce, leading-edge technological resources, and only a small caste of developed or developing countries can merge all these favorable conditions in a globally competitive manner. Between these countries are France, Germany, Spain and United Kingdom (Airbus), USA (Boeing), Brazil (EMBRAER), Canada (Bombardier), China (COMAC), Japan (Mitsubishi) and Russia (Irkut). Hence, commercial aircraft are high-cost and long-life assets, made of thousands of sophisticated components, and have a significant impact on the financial results of airlines.

The commercial aircraft long-term business life-cycle is also intensive in maintenance services, fuel consumption, high-qualified workforce demand (operating and managerial levels), requires sophisticated logistics, complex supply chain, infrastructure, and is subjected to several regulations concerning safety risk controls.

Ordering or leasing an aircraft demands complicated medium and long-term interactions between aircraft manufacturers and buyers (i.e., banks, leasing companies, and airlines), involving price negotiations, purchasing credits, anticipated payments mechanisms, and currency transactions. For those reasons, the accounting for aircraft acquisition and subsequent depreciation is complex. Although the airlines can count on the International Air Transport Association (IATA) standards on aircraft accounting (IAS 16 – *Property, Plant and Equipment*), this task requires judgements relating to useful business life-cycle and residual value, that must be revisited each reporting period. According to this reference, "*the high value of aircraft carried on balance sheet coupled with earnings volatility in the industry has historically exposed airlines to potential assets impairments.*"

Considering this complexity concerning to aircraft fleet purchasing, leasing and accounting procedures, aircraft owners and operators need to be aware that the initial purchase price is not to be regarded as the only individual variable influencing the purchase decision-making. Aircraft manufacturers, by their turn, must be aware that the aircraft buyers' behavior and purchasing decision may be affected by a broader assessment of the total cost of owning an aircraft, considering its whole business life-cycle ("cradle-to-grave" costs). Taking into account the high differentiation between products that characterizes the commercial aircraft trading, investments in research and development to significantly reduce the life-cycle cost can turn into a profitable, competitive advantage.

That context highlights the utility of the concept of total cost of ownership (TCO), which takes into account all the pre-transaction, transaction and post-transaction cost elements or cost drivers (Ellram, 1993). This concept, also known as Life Cycle Cost (LCC), involves identifying, quantifying and evaluating all the costs associated with ownership of a production asset, such as its initial price, operating, maintenance, service, overhaul, and disposal costs (end-of-life costs), and can be offset by the trade-in value (Jackson and Ostrom, 1980). It is an important concept to be considered by both aircraft manufacturers and buyers, because it is generally accepted that between 70 to 80% of the life-cycle cost of an aircraft configuration is locked in the early stages of the aircraft conceptual design and development, when very little actual money has been spent (Jonhson, 1990).

1.4 Research scope limitation

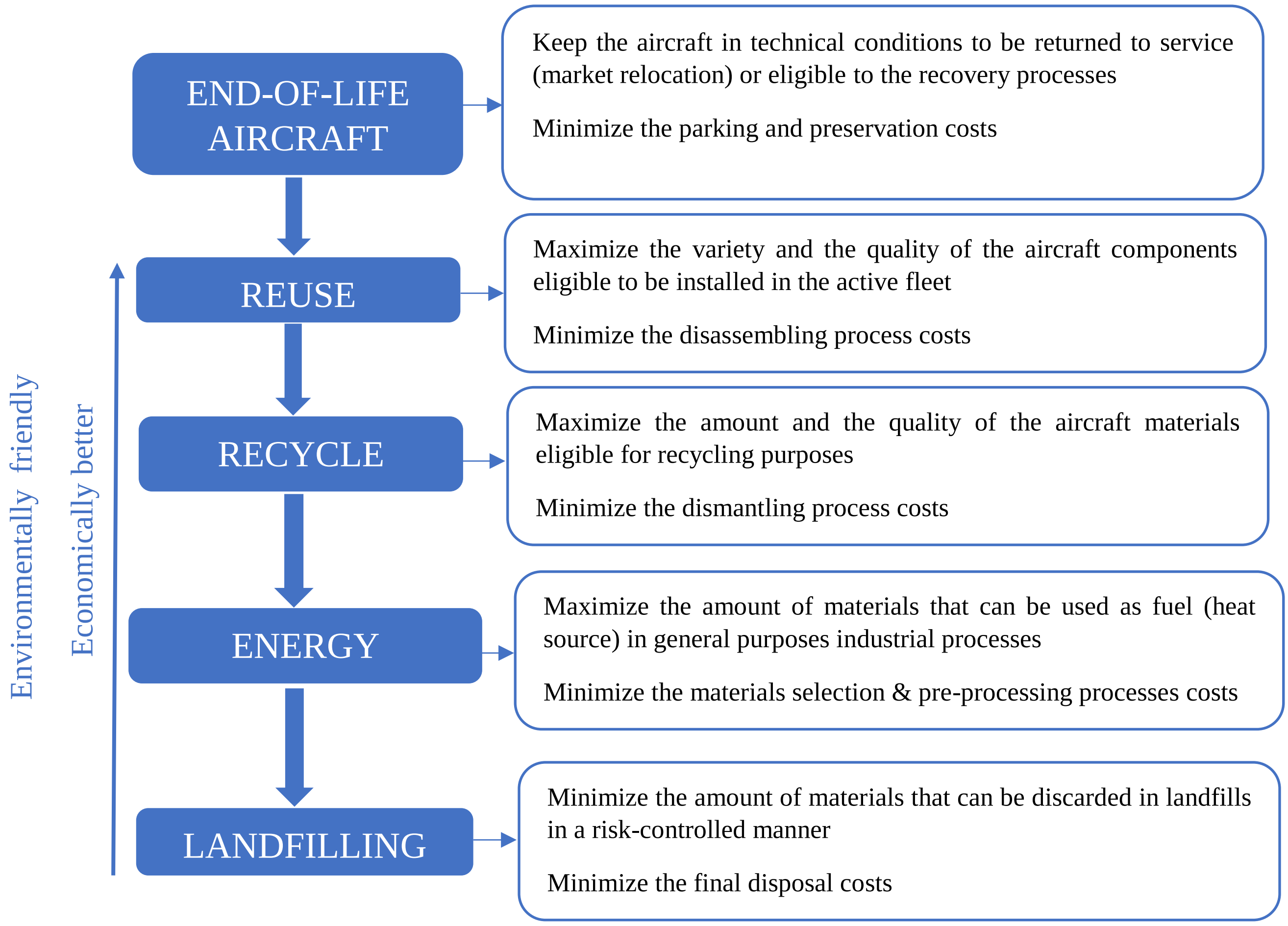
Taking into account the context and motivation previously described it is necessary to set the boundaries of this research scope. We are only interested in discussing the main issues regarding specific TCO pre-transaction costs incurred during the aircraft early design phase and the post-transaction costs due to the aircraft recovery processes at the end of their business life-cycle. This limitation is justifiable because the current literature covers the determination of the aircraft early design concept (i.e., research, development, testing, and evaluation) and direct operational costs exhaustively (Jonhson, 1990). Hence, it is silent about detailing the TCO components costs due to the aircraft green design implementation (DfE) and the aircraft end-of-life treatment costs, as discussed in the structured literature review section of this research.

1.5 Main deliverables

This research aims to highlight and comprehend the correlations between the implementation of the Design for Environment (DfE) in the aircraft design, development and manufacturing and its total cost of ownership (TCO), regarding the dynamics of the costs and revenues incurred at the early design phase and at the end of the business life-cycle, as well as best comprehend the retirement and decommissioning decision-making process itself. In other words, our main deliverable is the identification and evaluation of the outcomes of the implementation of the DfE methodology in the project, development, and manufacture of the aircraft, regarding the dynamics of the costs and revenues incurred during the aircraft end-of-life phase.

The analysis and comprehension of these correlations can subsidize the strategic decision-making about the aircraft parking, market relocation, retirement, and decommissioning considering the following objectives: (1) finding the optimal point to take the aircraft parking decision, considering its total time-in-service and maintenance condition; (2) finding business opportunities to return parked aircraft to the active service (market relocation); (3) finding the optimal point to decommission the aircraft (maximum parking time); (4) reducing the costs during the recovery processes (disassembling, dismantling and landfilling); and (5) maximizing the profits made up by the recovery processes (optimal point of disassembly or dismantling).

Taking into account this main research deliverable, the end-of-life aircraft recovery processes will be analyzed considering strategic objectives, as summarized in Figure 1.



Keep the aircraft in technical conditions to be returned to service (market relocation) or eligible to the recovery processes

Minimize the parking and preservation costs

Maximize the variety and the quality of the aircraft components eligible to be installed in the active fleet

Minimize the disassembling process costs

Maximize the amount and the quality of the aircraft materials eligible for recycling purposes

Minimize the dismantling process costs

Maximize the amount of materials that can be used as fuel (heat source) in general purposes industrial processes

Minimize the materials selection & pre-processing processes costs

Minimize the amount of materials that can be discarded in landfills in a risk-controlled manner

Minimize the final disposal costs

Figure 1 - Summarized view of the strategic objectives of the end-of-life aircraft recovery process. Source: The author

1.6 Specific deliverables

Considering the main deliverable of this research is focused in end-of-life aircraft costs and revenues dynamics, we set as specific deliverables the identification of the cost drivers that compose the initial and the final phases of the aircraft business life-cycle. They include the costs due to the implementation of Design for Environment in the aircraft early design phase, and the costs incurred during the recovery process at the of their end-of-life phase, both integrating the aircraft total costs of ownership (TCO). For this research, we consider as cost drivers the "*measure that is used to distribute the cost of activities to cost objects proportionally*" (Geiger, 1999; Ferrin and Plank, 2002). The recognition of these specific costs is considered as a relevant contribution to cover the detected lack of treatment of these issues in the literature dedicated to the determination of the aircraft TCO (Jonhson, 1990; Dhillon, 2010), as discussed in the structured literature review section of this research. Through the analysis of the cost components, it will be possible to assess how the early investments due to the implementation of Design for Environment in the aircraft early design phase can contribute to reduce the cost of the end-of-life aircraft recovery process and to optimize its profits, ensuring its leverage capability (Navin-Chandra, 1994).

Another import contribution of this research is the discussion of the legal and regulatory scenarios affecting the aircraft recovery industry, mainly concerning the definition of stakeholders' accountabilities for aviation safety and environmental impacts coming from the outcomes of the aircraft recovery processes. Many gaps can be found in the existing legal and regulatory framework, which need to be addressed through a broader rulemaking process. This process needs closer interactions between regulators, aircraft manufacturers, owners, operators, and the recovery industry, to set the standards regarding stakeholders' accountabilities, competences, prerogatives, and limitations.

1.7 Research framework

Considering the complexity of the context involving the end-of-life aircraft treatment, it is firstly necessary to establish a theoretical framework that will set the limits of the research scope and then decide the point of view to be adopted to analyze the referred context. The proposed framework is presented in Figure 2.

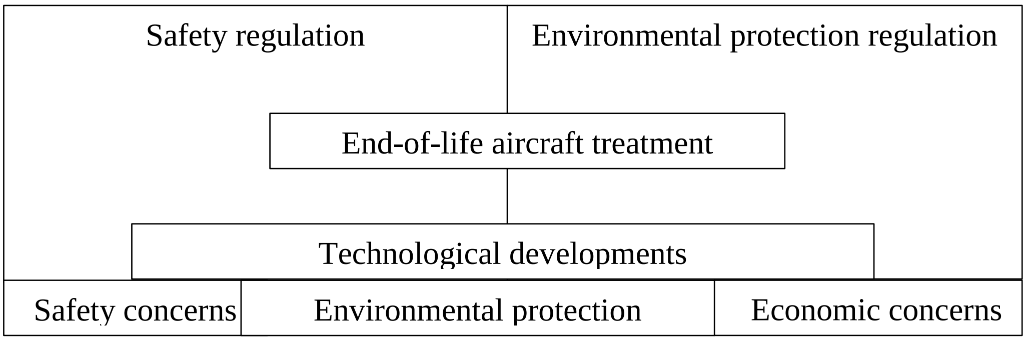


Figure 2 - Proposed theoretical framework to assess the end-of-life aircraft treatment process. Source: The author

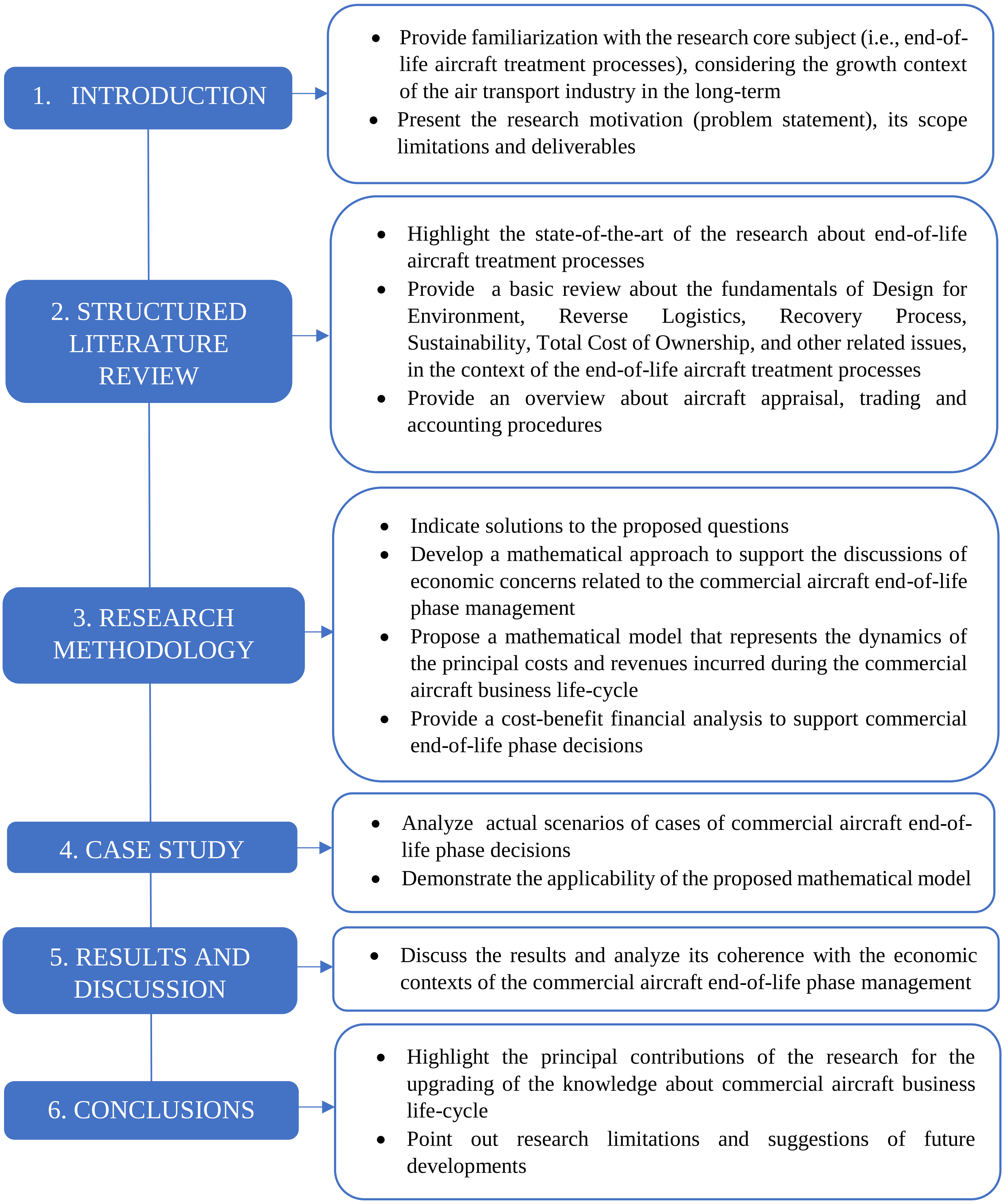
This framework intends to summarize the dynamic forces acting on the context: safety and environmental protection concerns together represent the social pressures for aircraft safe operations and social welfare due to the environment preservation. Economic concerns express the main interests of business organizations contracting, coordinating or performing end-of-life aircraft recovery activities (i.e., aircraft owners, aircraft operators, aircraft maintenance organizations, aircraft second-hand parts distributors and specialized recovery industries). All these pressures act as important drivers to the development of technological resources needed to support the end-of-life aircraft treatment processes to turn it into an attractive commercial activity, considering the total costs imposed by aviation safety and environmental protection current and upcoming regulatory restrictions. Hence, this framework helps to clarify about the infrastructure that gives support to the end-of-life aircraft treatment processes and assist in identifying the measurable outputs of this process, to assess its performance, regarding required efforts and valuable results. Table 1 sets out key features of each part of the proposed framework in more detail. It is essential to emphasize that this research is focused on an in-depth analysis of the economic concerns related to aircraft parking, market relocation, retirement, and decommissioning decisions.

Table 1 - Key features of the proposed framework.   Source: The author

Safety concerns: provide appropriate channels for disassembling and reprocessing aircraft parts and materials to be recertified and reused in the aerospace industry to minimize adverse safety impacts.
Environmental concerns: (1) provide appropriated channels for disassembling and reprocessing aircraft parts and materials to minimize adverse environmental impacts; (2) provide the achievement of sensitive decrease of the final disposal (landfills) to minimize adverse environmental impacts.
Economic concerns: create value to stakeholders by ensuring the minimization of the aircraft's total cost of ownership (TCO) and maximization of value extraction from second-hand aircraft parts and recyclable aerospace materials.
Technological developments: ensure higher quality and quantity of second-hand aircraft parts and recyclable aerospace materials, based on the fundamentals of green aviation design and manufacturing, green aviation supply chain, reverse logistics and end-of-life treatment channels (Design for Environment).
Safety regulation: establish directives and requirements to support the development, operation, and control (oversight) of channels dedicated to the recertification of second-hand aircraft parts and aerospace materials reentering the aviation industry supply chain
Environmental Protection Regulation: establish directives and requirements to support the development, operation, and control (oversight) of the channels reprocessing and disposing end-of-life aircraft parts and aerospace materials.
End-of-life aircraft processes: Decommissioning, Disassembling, Deconstruction/Dismantling ("3D Process" – As defined by AIRBUS PAMELA Project)

1.8 Research structure

This research is structured in six sections, as outlined in Figure 3, that also point out their specific purposes.



1. INTRODUCTION

- Provide familiarization with the research core subject (i.e., end-of-life aircraft treatment processes), considering the growth context of the air transport industry in the long-term
- Present the research motivation (problem statement), its scope limitations and deliverables

2. STRUCTURED LITERATURE REVIEW

- Highlight the state-of-the-art of the research about end-of-life aircraft treatment processes
- Provide a basic review about the fundamentals of Design for Environment, Reverse Logistics, Recovery Process, Sustainability, Total Cost of Ownership, and other related issues, in the context of the end-of-life aircraft treatment processes
- Provide an overview about aircraft appraisal, trading and accounting procedures

3. RESEARCH METHODOLOGY

- Indicate solutions to the proposed questions
- Develop a mathematical approach to support the discussions of economic concerns related to the commercial aircraft end-of-life phase management
- Propose a mathematical model that represents the dynamics of the principal costs and revenues incurred during the commercial aircraft business life-cycle
- Provide a cost-benefit financial analysis to support commercial end-of-life phase decisions

4. CASE STUDY

- Analyze actual scenarios of cases of commercial aircraft end-of-life phase decisions
- Demonstrate the applicability of the proposed mathematical model

5. RESULTS AND DISCUSSION

- Discuss the results and analyze its coherence with the economic contexts of the commercial aircraft end-of-life phase management

6. CONCLUSIONS

- Highlight the principal contributions of the research for the upgrading of the knowledge about commercial aircraft business life-cycle
- Point out research limitations and suggestions of future developments

Figure 3 - Structured view of the research. Source: The author

2. Structured literature review

2.1 Purpose

The primary purpose of this structured literature review is to identify, track and analyze the level of development of the research dedicated to the core subject of the end-of-life aircraft treatment processes, taking into consideration specific purposes, as shown in Figure 2. These purposes demand efforts aiming to: (1) consolidate the usage of specific terms and their definitions (taxonomy); (2) identify the mainstream research topics within the core subject; (3) identify the principal authors, their approaches and core contributions; (4) verify the evolution of the theoretical framework; (5) provide evidence of the applicability of the theoretical framework in scientific studies; (6) identify knowledge gaps; and (7) point out future research agendas.

2.2 Initial searching for relevant papers

The searching for papers related to the subject of end-of-life aircraft treatment was performed through the web platform “Portal CAPES” (for accessing the SCOPUS and WEB OF SCIENCE databases), and also the public web platforms “Google Scholar” and “Sci-Hub”. The keywords used during this searching were “*end-of-life aircraft*”, “*eol aircraft*”, “*aircraft retirement*”, “*retired aircraft*”, “*aircraft decommissioning*”, “*decommissioned aircraft*”, “*aircraft recycling*”, *and* “*aircraft recovery*”. That searching took place from February to April 2018 and resulted in a total of 69 publications, including technical reports, technical magazine articles, papers, dissertations, thesis and books’ chapters.

The collected papers were firstly analyzed considering their resume/abstract, introduction, findings, and conclusions contents. This analysis showed that the subject of end-of-life aircraft treatment requires a ground level of comprehension about other subjects, such as Design for Environment, Reverse Logistics, Recovery Process, Sustainability, Total Cost of Ownership, Aircraft production forecasts and Aircraft appraisal, trading and accounting procedures. Hence, it was necessary to look for seminal papers related to these subjects. Some of those papers were cited in the references of the papers related to aircraft end-of-life treatment, what made easier this second step of the searching for papers.

The reading of these papers was essential to have an overview of the fundamentals of each specific subject. They also contributed to essential findings that allowed us to better analyze and comprehend the end-of-life aircraft treatment, regarding its context, concerns, challenges, and opportunities. It was an essential step during the research that enables us to make useful correlations between these specific subjects and the end-of-life aircraft treatment issues. At the end of that searching for papers, we classified the collected paper in two categories: (1) entirely dedicated to the end-of-life aircraft treatment works; and (2) general purposes supporting works.

2.3 Mainstream research topics

During the initial research for papers it was possible to identify the following mainstream research topics: (1) Analysis of long-term air transport industry growth; (2) Analysis of the end-of-life products treatment / recovery industry; (3) Analysis of sustainable product development; (4) End-of-life aircraft recovery strategies - mathematical modeling and performance evaluation; (5) Total cost of ownership fundamentals; (6) Aircraft appraisal, trading and accounting procedures; and (7) Aircraft retirement and storage trends.

2.4 Principal authors and their research approaches

The principal authors and their research approaches are listed in Table 2, according to the mainstream research topics, as shown in subsection 2.3, following the chronological order of the paper or technical report publication. Their core contributions will be summarized in subsection 2.5.

Table 2 - Principal authors and their approaches, according to mainstream research topics. Source: The author

Mainstream research topics	**Authors**	**Research approach**		**Research focus**	
		theoretical	**mathematical**	**aviation/ aircraft related**	**general purposes**
Analysis of long-term air transport industry growth	Cunningham and de Haan (2006)	X	X	X	
	ICAO (2016)	X		X	
	Airbus (2018) CMO	X		X	
	Boeing (2018) CMO	X		X	
Analysis of the end-of-life products treatment / recovery industry and Analysis of product sustainable development	Navin-Chandra (1994)	X	X		X
	Dobler and Burt (1996)	X			X
	Doherty (1996)	X			X
	Tibben-Lembke (1998)	X			X
	Rogers and Tibben-Lembke (1999)	X			X
	Johansson (2002)	X			X
	Towle *et al.* (2004)	X		X	
	Srivastava and Srivastava (2006)	X			X
	Srivastava (2007)	X			X
	Das and Kaufman (2007)	X		X	
	Carberry (2008)	X		X	
	Airbus (2008a)	X		X	
	Airbus (2008b)	X		X	
	Fiksel (2009)	X			X
	Morimoto and Agouridas (2009)	X		X	
	van Heerden and Curran (2010)	X		X	
	Böckmann and Schmitt (2012)	X	X	X	
	Franz *et al*. (2012)	X		X	
	Asmatulu *et al.* (2013)	X		X	
	Keivanpour *et al.* (2013)	X		X	
	Johanning and Scholz (2013)	X	X	X	
	Mascle (2013)	X	X	X	
	Keivanpour *et al*. (2014a)	X	X	X	
	Keivanpour *et al*. (2014b)	X		X	
	Ribeiro e Gomes (2014)	X		X	
	TeamSAI (2014)	X		X	
	Ribeiro e Gomes (2015)	X		X	
	Keivanpour *et al.* (2015c)	X		X	

	Zahedi et al. (2015)	X		X	
	Keivanpour and Ait-Kadi (2016)	X		X	
	Sabaghi *et al.* (2016a)	X	X	X	
	Sabaghi *et al.* (2016b)	X	X	X	
	Spoors (2016)	X		X	
	Zahedi et al. (2016)	X		X	
	Keivanpour and Ait-Kadi (2017a)	X	X	X	
	Keivanpour *et al.* (2017b)	X	X	X	
End-of-life aircraft recovery strategies -mathematical modeling and performance evaluation	Latremouille-Viau *et al*. (2010)	X	X	X	
	Siles (2011)	X	X	X	
	Camelot *et al*. (2013)	X	X	X	
	Mascle *et al*. (2015)	X	X	X	
	Sabaghi *et al*. (2015)	X	X	X	
	Dayi *et al*. (2016)	X	X	X	
The total cost of ownership fundamentals	Jackson and Ostrom (1980)	X			X
	Johnson (1990)	X	X	X	
	Cavinato (1991)	X			X
	Cavinato (1992)	X			X
	Ellram (1993)	X			X
	Ellram and Siferd (1993)	X			X
	Ellram (1994)	X			X
	Ellram (1995)	X			X
	Ellram and Siferd (1998)	X			X
	Asiedu e Gu (1998)	X			X
	Geiger (1999)	X			X
	Ferrin and Plank (2002)	X			X
	Castagne *et al*. (2004)	X	X	X	
	Curran *et al*. (2005)	X	X	X	
	Thokala (2009)	X	X	X	
	Dhillon (2010)	X	X	X	
Aircraft appraisal, trading and accounting procedures	Clark (2007)	X		X	
	Ackert (2011)	X		X	
	Ackert (2012)	X		X	
	IATA (2016b)	X		X	
Aircraft retirement and storage trends	Forsberg (2015)	X		X	
	IATA (2016a)	X			
	IATA (2018)	X			

2.5 Principal authors and their core contributions

A detailed reading and analysis of the selected publications made it possible to highlight the most relevant findings and conclusions that are briefly exposed below, according to mainstream research topics.

2.5.1 Analysis of long-term air transport industry growth

According to ICAO (2016), since 1977 the global air traffic has doubled in size once every 15 years and will continue to do so. Considering these growth trends, it is essential to assess whether the current safety and environmental standards and their related risk control procedures will be enough and adequate to manage the adverse outcomes of that growth. Considering the similar context, Cunningham and de Haan (2006) made long-term forecasting for the sustainable development of the air travel demand for 2050. Adopting two different approaches (i.e., ideal scenario and empirical modeling), they concluded that a 5.4% yearly rate of air travel demand is expected during that period.

This result calls our attention to the central question posed by these authors at the very beginning of their problem statement: "*How can we keep the positive effects (from flying) while at the same time reduce the negative ones?*" The authors consider that the concept of Sustainable Development is promising in solving this dilemma, but unfortunately, it does not give us many practical solutions. They say that, at best, it gives us the criteria to which we can compare our long-lasting solutions to see whether they are actually contributing to sustainable development.

The leading commercial aircraft manufacturers, Airbus, Boeing, Bombardier, and EMBRAER disclose their global market forecast annually, considering a 20-year threshold. These reports are import sources of global and regional air travel future demands, based on the forecasted economic growth rates. For instance, according to Boeing (2018), the traffic growth will reach 4.7% yearly rate, followed by a fleet growth of 3.5% yearly rate. All this growth will demand 41,030 new aircraft deliveries, representing a business of USD 6.1 trillion. Airbus (2018) and Boeing (2018) forecast that something between 10,000 and 18,000 aircraft, respectively, will be retired and decommissioned between 2017 and 2037.

Considering this research scope, we can say that the increasing global number of decommissioned commercial aircraft is one the most significant indirect adverse effects. According to IATA (2016a), 700-900 commercial aircraft were parked annually between 2008-2014, resulting in more than 15,000 parked assets by the end of 2015, with an average age of around 27 years in-service. This amount represents around 55% of the existing active fleet, that reached more than 27,000 aircraft by the end of 2015, what remains relatively stable. The author also highlights that a slight decrease in the aircraft total time in-service in the period 2008-2014, such that in 2015 the average age reached around 22 years at the parking time, as consequence of the increase of the aircraft production rates and the earlier aircraft parking decision. The primary drivers of the aircraft parking and decommissioning decision-making are: (i) the aircraft fleet renewal policies (i.e., operators looking for fleet right-sizing or more efficient aircraft to reduce their direct operational costs and enhance competitiveness between them); and (ii) seasonal or local decreases in air transport demands around the globe (i.e., an effect of adverse economic conditions to the operations profitability operations).

Coming back to the question posed by Cunningham and de Haan (2006), we can conclude that the implementation of a worldwide aircraft recovery industry is a feasible and sustainable solution to deal with the safety, environmental and economic risk concerns related to the aircraft parking and decommissioning decisions, considered as an adverse outcome from the growth context of commercial aviation operations. As highlighted by the referred authors, we can consider that the next important step is the establishment of sustainability indicators to assess the performance of the aircraft recovery industry accurately.

It is important to consider that this newly established industry faces a low level of safety and environmental regulatory burdens. It is a particular case where the economic activity is following a developing rate while regulations are not yet well established to set accountabilities, competences, prerogatives, limitations, quality and risk controls standards. These standards are essential to help to promote the balance between the interests and objectives of all the stakeholders affecting or affected by the positive and negative outcomes from this economic growth scenario of the air travel demand, considering specifically the development of a sustainable aircraft recovery industry.

2.5.2 Analysis of the end-of-life products treatment / recovery industry

The first known work dedicated to outlining the initial development of the aircraft recovery industry was issued by Towle *et al.* (2004), from the Department of Materials, Oxford University. It is a technical report based on the collection of a wide range of public domain information from websites dedicated to this subject. It was an initiative of the network called WINGNet (Waste reduction IN aircraft-related Groups), funded by the UK Engineering and Physical Science Research Council (EPSRC). WINGNet is focused on the development of technologies and infrastructure required to meet the challenges in the sustainable use and reuse of aircraft materials, considering the UK aerospace industry context.

The main discussion raised by the referred authors is about product stewardship, also known as extended product responsibility (EPR). According to Towle *et al.* (2004), manufacturers can and must retain new responsibilities to reduce the environmental footprint of their products. Product stewardship calls on manufacturers, retailers, users, and disposers to share responsibilities for reducing the environmental impacts of products.

The authors also argue that product stewardship can represent a business opportunity: manufacturers can increase productivity, reduce costs, foster product, and market innovation, and provide customers with more value at less environmental impact, by rethinking their product, their relationship with supply chain and the end customers. They also stress that in a competitive market like the aviation industry, where corporate identity and brand awareness have significant value, there is a growing reluctance for the original equipment manufacturer (OEM) to be associated with decaying structures.

Besides to this discussion, Towle *et al.* (2004) also provide a ground level description of the leading industrial processes that support the end-of-life aircraft treatment, such as parting-out, parts control and distribution, and valuable materials selection, identification, separation, and recycling. Finally, it is important to highlight that these authors affirm that "*in the absence of legislative drivers, projects and expenditure in this area have to be justified by economic benefit*." Therefore, this sentence is in alignment with our research motivation (problem statement) and the establishment of its deliverables.

Das and Kaufman (2007) are concerned about the context of thousands of old aircraft that have been sitting in "graveyards" while the demand for recycled aluminum continues to increase. They argue that the recycled aluminum alloys coming from obsolete aircraft could just be reused in the aerospace industry with additional processing, because of the strict controls on impurities and performance requires. However, this “secondary metal” can be reused by other industries for general purposes. The authors highlight that are two main driving forces to enable large-scale recycling aluminum aircraft alloys: (i) economic incentive: the production of aluminum as “secondary metal” permits energy savings of 95% compared with the energy consumption required to produce primary aluminum; and (ii) environmental benefit: recycling results in the emission of only about 4% as much CO_2 as does primary production.

Das and Kaufman (2007) also describe the ideal process for aluminum alloys recycling and point out the related challenges to do so, aiming to have a feasible and cost-effective industrial process in place. Finally, they propose a strategic program to overcome those technical and logistic challenges.

Carberry (2008) describes Boeing efforts and targets related to the development of aircraft recycling procedures, aiming to benefit Boeing aircraft owners and operators to manage the safety and environmental outcomes form their end-of-life assets. Boeing has been working in partnership with other companies to develop retired aircraft recycling standards in order to improve the performance of this new industry. This partnership was enhanced by the foundation of the Aircraft Fleet Recycling Association (AFRA), in 2006. It is a non-profit industry association whose mission is to enable airlines to manage their retired aircraft while maximizing value creation responsibly. AFRA’s primary goal is to achieve the highest possible commercial value for recovered components and materials, which would reduce the total cost of recycling aircraft for commercial airlines.

The author notes that Boeing is particularly interested in the development of technologies for carbon fiber recycling, taking into account economic and performance drivers. Recycled chopped carbon fiber costs up to 70% less to produce and requires up to 98% less energy to manufacture than virgin chopped fiber, and the performance of the two materials are comparable. Boeing has already started testing the use of recycled carbon fiber to produce non-structural parts of commercial and military aircraft.

The very first known systematic approach to end-of-life aircraft treatment was a technical report that summarizes the outcomes of a significant project from Airbus, during which the company gained experience of managing the parting-out of a retired model A300-B4 (Airbus, 2008a). Airbus joined efforts with key partners to draw up and disseminate a systematic process for parting-out an aircraft managing safety and environmental concerns. This project was called PAMELA (Process for Advanced Management of End-of-Life of Aircraft) This initiative demonstrated that 85% of the weight of an aircraft could be reused or recycled, reducing the final disposal significantly in landfills (down by 66%). The main contribution of the PAMELA project is the systematization of an appropriate end-of-life aircraft recovery process, also called “3D process”, as outlined in Figure 4.

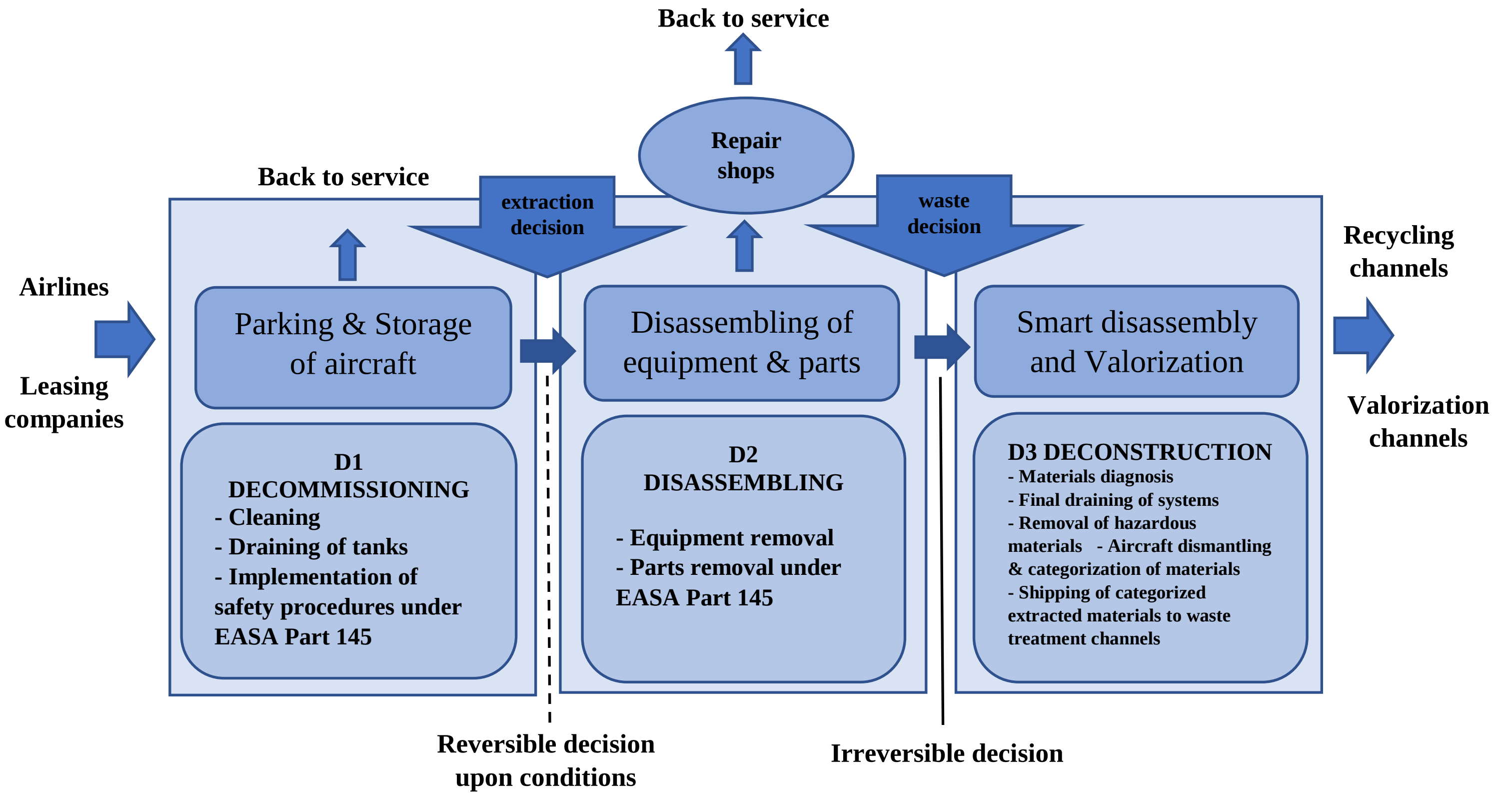


Figure 4 - Systematics overview of the PAMELA “3D Process”.
Source: Airbus (2008a)

Considering the safety concerns related to the end-of-life aircraft recovery processes, Airbus deems as necessary that all the technical work during the phases D1 and D2 must be performed by aircraft maintenance organizations (AMO), certified under EASA Part 145 or other similar regulation of countries outside the EU. The significant contribution of the PAMELA technical report is the evidence that the end-of-life aircraft treatment processes can be expertly planned, performed and managed, in compliance with the current aviation safety and environmental regulations, and also turn into an attractive business.

After analyzing the full picture of the end-of-life aircraft treatment, Airbus (2008a) concludes it is a tiny niche in the overall business of treating materials and cannot generate its dedicated reverse logistics and related treatment channels. This context, together with the aerospace industry specificities, makes difficult to directly apply the current end-of-life treatment policies and procedures to the retired and decommissioned commercial aircraft, such as those established by the End-of-Life Vehicle Directive 2000/53/EC.

Another valuable contribution to this subject comes from van Heerden and Curran (2010). They discuss “*What can be done with these end-of-life aircraft, concerning the 5 W’s: the why, when, what, who and where?*” The major difficult to effectively respond to these questions is the fact that there are no legislation nor aviation regulations setting rules and requirements, respectively, that obligates aircraft manufacturers or aircraft owners and operators how to design or deal with their end-of-life aircraft, respectively, or precisely how to design an aircraft that meets proper and due end-of-life requirements.

The referred authors also present a complete set of terms and definitions to be used in structuring the end-of-life aircraft treatment processes. The definitions are in alignment with other specific aviation terms and its usage. They propose clear and useful definitions to “*reuse*”, “*recycle*”, “*recovery*”, “*disposal*”, “*primary recycling*”, “*secondary recycling*”, “*down-cycling*”, “*disassembly*”, *and* “*dismantling*”. At this point, it is important to highlight that the term “*recovery*” is used by van Heerden and Curran (2010) to designate the *energy recovery process* solely (i.e., burning rejected materials as fuel/heat source). In the context of this research, the term “*recovery*” is used to lump the terms “*decommissioning*”, “*disassembly*”, “*dismantling*”, “*reuse*”, “*recycle*”, “*energy recovery*”, *and* “*landfilling*” into a single word, similarly to the usage proposed by Navin-Chandra (1994). That is why we prefer the term “*end-of-life aircraft recovery processes*” to designate the main subject of this research. Additionally, the term “*parting-out*” is also frequently used in the literature referring to “*disassembly*”, “*dismantling*” or both.

The referred authors also describe in detail all the phases of the end-of-life aircraft recovery processes, in alignment with the PAMELA “3D process”. Thus, they propose a closed loop representation of these processes, as shown in Figure 5.

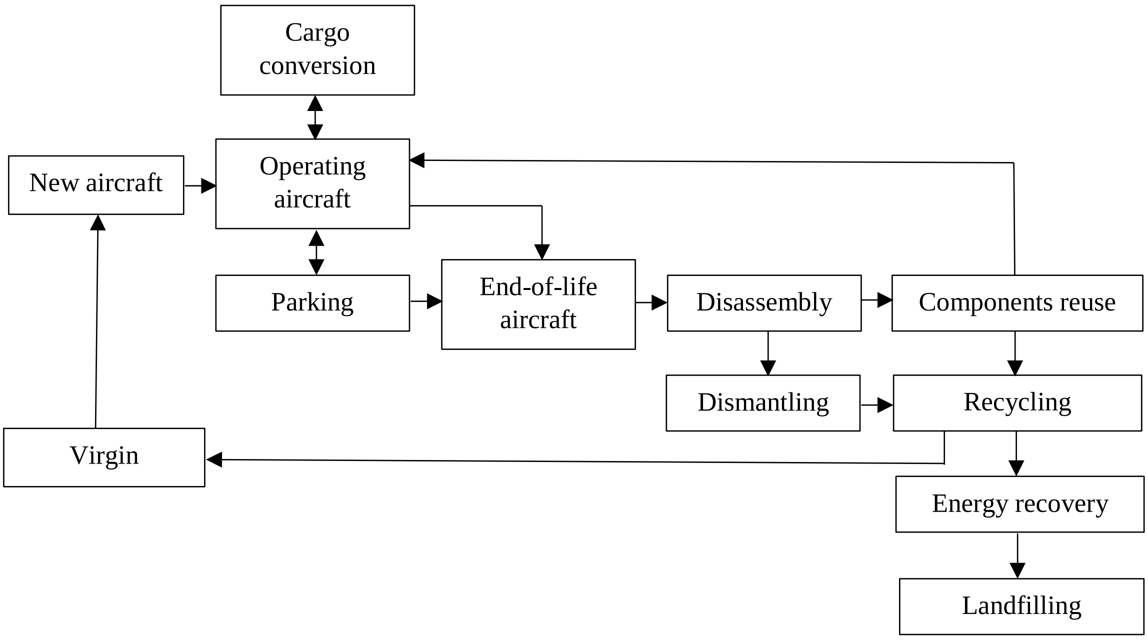


Figure 5 - Flow of an end-of-life aircraft. Source: van Heerden and Curran (2010)

Additionally, van Heerden and Curran (2010) discuss the recovery process performance adopting a modified set of two equations, initially used to measure the performance of road vehicles recovery processes, as established by ISO reference 22628:2002(E). The authors argue that the main limitation of this method is that components that are removed are considered to be reused 100%, which of course is not always the case because some parts will never be reinstalled in another aircraft. One may also consider that the replaced component needs to be disposed of. These two factors affect the end-of-life aircraft recovery process performance measurement in such a manner that maybe not feasible to track and quantify.

The economic aspects of the end-of-life aircraft were also discussed by van Heerden and Curran (2010). Taking into account their arguments, we may conclude that the decision of parking and decommissioning an aircraft is influenced by three factors: (i) aircraft economics: the comparison between its value in the second-hand aircraft market and the total value of its used parts in the second-hand parts market; (ii) company economics: the discrepancy between its book value or net present value (usually higher) and its market value, due to depreciation; and (iii) global economics: its market value and total value of used parts is strongly affected by the laws of supply and demand for used aircraft or used parts, due to fluctuations in the air travel demands around the globe and the size of the remaining active fleet, respectively.

Finally, van Heerden and Curran (2010) emphasize the needs of the aviation sector to resolve the problem of the long-lasting parked aircraft and to develop industry standards for end-of-life aircraft treatment. They argue that the first steps were made by the founding of AFRA (Aircraft Fleet Recycling Association). This aviation industry association developed the Best Management Practices manual (BMP), aiming to set the first standards. Many parting-out companies around the world have been accredited in compliance with the AFRA BMP standards, that requires the implementation of some quality and safety risks control to perform end-of-life aircraft recovery processes appropriately.

Asmatulu *et al.* (2013) provide an overview of the state of technological development in the aircraft recovery industry by 2011, focusing on materials recycling technologies. Advances in this area contribute to the reduction of virgin materials consumption, air, water and soil contaminations, as well as energy demand. New procedures and tools dedicated to aircraft recycling are developed by this industry aiming to improve environmental efficiency and profitability. The authors also argue that the recycling industry promotes social benefits, such as employment creation, development of communities and a cleaner environment.

Keivanpour *et al.* (2013) note the transdisciplinarity aspects of the end-of-life aircraft recycling projects, and then propose a conceptual framework to analyze this context and provide theoretical support to the implementation of these projects. The proposed framework has four essential elements: (i) business model; (ii) knowledge management; (iii) market and industrial context; and (iv) performance management. We may conclude that this framework can be useful to help all the stakeholders involved in aircraft recycling projects identifying and addressing the main challenges and risks facing these business opportunities, and hence, planning strategies to overcome them. Finally, the authors propose a research agenda pointing out many research highlights (topics) for each framework element, such as *a value from owner perspective*; *the revenue from different recovered parts and materials; value-added operations; the act of aircraft manufacturers,* and so on, that will be discussed during this research.

Another significant contribution comes from TeamSAI (2014) technical report, showing the state of the aircraft dismantling and recycling industry. TeamSAI is a consulting services enterprise to the aviation industry that worked in partnership with the AFRA surveying, measuring and assessing the global aircraft dismantling and recycling market. This survey made possible to have a better estimating of the following outcomes: (i) the impacts that dismantling firms are having on the maintenance, repair and overhaul (MRO) and aerospace market; (ii) the impacts on the second-hand parts market; (iii) the total market size; and (iv) future trends and technical challenges of the market.

For this research, we will only take into consideration the technical challenges pointed out by the referred survey: (i) development of recycling solutions for new aeronautical materials (i.e., carbon fiber and other composites); (ii) finding qualified personnel; (iii) environmental regulations; (iv) better planning of the end-of-life phase by operators/lessors; and (v) falling value of aircraft second-hand parts. Despite these challenges, the survey demonstrates that it is a small market, if compared to the vehicle recovery industry, for instance, but is a quickly growing business sector, considering the rapid increase in the commercial aircraft parking and retirement trends for the next decades.

Ribeiro and Gomes (2015) analyze the end-of-life aircraft recovery processes and its current context. They note that no legislation regulates the end-of-life aircraft treatment, and all the developments and efforts in this area are voluntary. In order words, we may consider that the end-of-life aircraft recovery industry is profit-driven because the involved stakeholders are motivated by value creation opportunities from this new business. However, the authors argue that this situation may change, and this industry can be affected by future legislation concerning an extended product responsibility (product stewardship), as also mentioned by Towle *et al.* (2004). Hence, the aviation industry could also face legislation similar to the regulations in the automotive industry. This opinion is contrary to Airbus’ conclusions, as stated in the PAMELA project report (Airbus, 2008a), which consider that the end-of-life vehicles European Directive (Directive 2000/53/EC) cannot be directly applied to commercial aircraft.

The referred authors also note that much attention has been paid to Design for Environment (DfE) and Design for Disassembly (DfD). Aircraft manufacturers are interested in these design methodologies because they contribute to the reduction of production and maintenance costs, during the aircraft manufacturing and operational life phases, respectively. DfE and DfD also increase value extraction at the end-of-life phase because they improved the recoverability of parts and materials and made disassembly process more manageable and cheaper.

Finally, the authors revised the PAMELA “3D process” (Airbus, 2008a) and proposed a closed loop configuration for it, which agrees with van Heerden and Curran (2010) approach for the end-of-life aircraft recovery processes. The main advantage of this approach is that it helps track and quantify the recovery process sustainability outcomes. Their main conclusion is that understanding and controlling end-of-life aircraft decision supporting models is essential to facilitating economic growth and improving health and societal well-being.

Keivanpour *et al.* (2015c) are interest in discussing the challenges and opportunities to be faced by the aircraft manufacturers during their interactions with the end-of-life aircraft recovery processes and its stakeholders. Considering this context, the authors pose the following research questions: (i) “*What is the role of the manufacturers in the end-of-life aircraft problem?*”; and (ii) “*What are the different opportunities and challenges of aircraft manufacturers concerning retired aircraft as a part of product responsibility?*” The authors describe the end-of-life aircraft context as different from other end-of-life products’ recovery solutions due to the following aspects: (i) the small volume of the recovered materials; (ii) the condition and reliability required for the disassembled parts; (iii) the recertification procedures required for reusing recovered parts and materials; (iv) the second-hand parts market structure and procedures; (v) the complexity of treatment processes; and (vi) the specific supply chain contextual relationship in the aerospace industry.

In order to analyze this context and respond to these questions the referred authors propose a conceptual framework to support the discussion on a theoretical basis, considering the following elements: (i) supply chain competency; (ii) governance policy; (iii) aerospace industry context; and (iv) relationship in supply chain.

The authors argue that the primary challenge in this context is the implementation of a green supply chain and a reverse logistics infrastructure in the aerospace industry to support the end-of-life aircraft recovery industry development. The current aviation regulations do not impose any responsibility to aircraft manufacturers for dealing with end-of-life aircraft in routine. Hence, their motivation to interact with that problem is based on corporate social responsibility image and extended product responsibility. At the end of this analysis, the authors propose a list of opportunities and challenges to be faced by the aircraft manufacturers to implement green supply chain and reverse logistics solutions in their operations and business models.

Analyzing this contribution, we can conclude that the aviation industry complexity and particularities, in terms of: (i) worldwide operations; (ii) regulatory frameworks diversity, gaps and conflicts; (iii) airlines business model alternatives; and (iv) safety and performance requirements for recovered aircraft parts and materials are some of the barriers that make challenging to implement classical solutions to the aircraft recovery problem, similar to the ones adopted in the automotive and electronics industries, for instance.

Spoors (2016) provides a technically detailed description of the end-of-life aircraft recovery processes, from after the last landing to the parting-out procedures, considering peculiarities regarding aircraft parts removal and recertification, depollution and recycling challenges. The author notes that in the past the aircraft used to be retired on average at 30-plus years old, but nowadays the retirement age is about 20 years, and it has been reducing. She comments that industry average for aircraft recycling is achieving a rate of 80-85%, but GJD Services Ltd (a UK based aircraft recovery company) currently aim to achieve a recycling rate of at least 95%. That company achieved a 99% recycle rate for an airline. She notes that it is "*an additional cost element, but larger airlines are willing to pay to reduce their carbon footprint as part of their corporate environmental responsibility*."

Spoors (2016) also notes that due to the EU Waste Framework Directive 2008/98/EC, decommissioned aircraft have to comply with the end of life vehicle (ELV) legislation. However, she argues it is a challenging process because currently working practices employed in the vehicle recovery industry did not fit to the aircraft recovery industry, and it is hard to determine when an aircraft becomes "waste".

2.5.3 Analysis of product sustainable development

The end-of-life aircraft recovery process is recognized as a transdisciplinary problem (Keivanpour *et al.*, 2013) that needs to be analyzed and solved considering the sustainability principles putting the screws on profit-driven activities, aiming to keep their outcomes under evaluation and control. Social interests, such as safety, environment preservation, welfare, and social development need to be sheltered by legal and regulatory frameworks and balanced with profitability targets. For this reason, enterprises have been embodying sustainability principles and practices in their policies and business models, respectively. The technical report named "*Our common future*" (also known as

Brundtland Report) set the sustainability principles, summarized in the following sentence: "*Sustainable development is a development that meets the needs of the present generation, without compromising the ability of future generations to meet their needs*."
Considering the application of these principles and practices in the transportation industry, the European Commission established the definition of sustainable transport. For the purposes of this research, we will focus our attention on the part of its definition that talks about the "*need of limiting the emissions and waste within the planet's ability to absorb them, using renewable resources at or below their rates of generation, and, uses the non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise*".

That is the context of the end-of-life aircraft recovery problem: it is necessary to solve the dilemma of supporting the increasing global demand of air travel and keep its positive effects while reducing the negative ones (Cunningham and de Haan, 2010). Between the adverse effects we can highlight the increasing annual rate of parked and decommissioned commercial aircraft, with little perspectives of returning to service, also susceptible to turn into serious safety, environmental and economic concerns.

Aiming to have a broader view of the complexity of the end-of-life aircraft recovery problem it is useful to set a theoretical basis to discuss that problem, considering the contributions from other research areas, namely: Design for Environment, Reverse Logistics, and Recovery Processes. Firstly, a ground level approach about these issues will be presented. Afterward, it will be possible to recognize some intersections between these issues, that will enable us to correctly place the problem in the context of the sustainable development, considering social (people) environmental (planet) and economic (profit) outcomes, also known as the "sustainability 3P axis".

(a) *Design for Environment*

Fiksel (2009) defines Design for Environment (DfE) **[3]** as "*the systematic consideration of design performance concerning environmental, health, safety, and sustainability objectives over the full product and process life-cycle.*" Taking into account that the product life-cycle encloses its decommissioning and end-of-life phase, which justify efforts to design products for recovery, i.e., to develop products that are both environmentally compatible and commercially viable (Navin-Chandra, 1994).

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[3] Design for Environment is also referred to as Eco-Design, Life-Cycle Design, and Design for Eco-efficiency. (Fiksel, 2009)

Complementing these understandings, Johansson (2002) highlights that DfE "*is aimed at minimizing a product's environmental impacts during its whole life-cycle, without compromising other essential product criteria, such as performance and cost*." This same author also notes that environmental issues in product development deem to be considered as an essential part of environmental concerns of the enterprises, since product development merges current markets, technology trends and regulatory demands into product characteristics.

Airbus was the first commercial aircraft manufacturer to issue a technical report dedicated to show its DfE approach to be implemented in the aerospace industry (Airbus, 2008b). According to this report, the main drivers behind DfE implementation are: (i) compliance with legislation; (ii) satisfaction of stakeholders' expectations; (iii) search for competitive advantage; and (iv) opportunities to reduce costs and increase values. In order words, DfE practices are intended to develop compatible environmental products, while maintaining or improving price, performance and quality standards. This report starts briefly discussing the main parameters of a successful DfE implementation.

Airbus (2008b) considers that DfE encompasses a range of improved practices, such as: (i) Design for disassembly; (ii) Design for recycling; (iii) Design for remanufacture; (iv) Design for energy efficiency; (v) Hazardous materials minimization; and (vi) Compliance with regulations and standards. All these practices together made it possible to reach the following objectives: (i) optimizing consumption of materials and resources across the product life-cycle; (ii) reducing emissions across the product life-cycle; (iii) reducing energy consumption; (iv) enhancing re-usability and recycling potential; (v) minimizing hazardous materials consumption and final disposal; (vi) facilitating dismantling or recovery at the product end-of-life. Thus, the analytical tool supporting DfE is Life Cycle Assessment and its streamlined versions.

Airbus (2008b) highlights the main barriers for implementing DfE in the aerospace industry: "*The structural inertia inherent to a large and complex organization designing safety-critical systems will almost inevitably lead to a lengthy process of change. This process can only be accelerated by tougher regulations and more clear financial incentives for environmental actions.*" They consider it can be an effective manner to strengthen the business commitment, as happened to other industries, such as the automotive industry. These incentives may come from the regulation, derived from customer requirements or the results of the company policy or commitments, but they must be part of the design requirements at the beginning of the aircraft program. Finally, they consider the application of life-cycle thinking in decision-making needs to be guided by appropriate tools and methods. Due to the complexity of a commercial aircraft and the massive supply chain demanded, the full data requirements of standard Life Cycle Assessment methods may not be feasible and manageable.

Also considering specifically the context the aerospace industry, Morimoto and Agouridas (2009) argue that the implementation of life-cycle approaches, such as DfE, enable aircraft manufactures to assess and control not only the environmental impacts but also costs systematically, from research and development to aircraft retirement. In other words, it means development efforts to improve lifecycle efficiency, because the end-of-life costs can be reduced or overcome by revenues, due to aircraft parts reuse and materials recycling. Finally, these authors highlight that implementing life-cycle approaches in the aerospace industry depends on facing many challenges and resistances, that is thoroughly analyzed through their article. However, they can be all surpassed "*getting the right products to the right market, at the right time, for the right cost.*"

(b) *Reverse Logistics*

According to Rogers and Tibben-Lembke (1999), Reverse Logistics (RL) is the process of moving a product from its point of consumption to the point of origin to recapture value or for proper disposal. Srivastava and Srivastava (2006) propose a more technically detailed definition to RL, as "*the process of planning, implementing, and controlling the efficient and effective inbound flow, inspection, and disposition, returned products and related information to recover value.*" They also note that three drivers – economic, regulatory and customer pressure – drive product returns worldwide, where the volume of returns drive the decisions ("push" system). The referred authors also argue that Reverse Logistics in regulatory-driven in EU, profit-driven in the USA, and is at an incipient stage in other parts of the world. Thus, considering the increasing disposal costs and current environmental regulation, experts predict that shortly RL will play an important role in strategic business planning (Doherty, 1996).

Talking about this scenario, Tibben-Lembke (1998) notes that although the regulatory pressure for RL may increase, the factor that will continue to motivate RL systems is the economic benefit that can be gained. The author also raises an interesting discussion about the relations between Reverse Logistics (RL) and Total Cost of Ownership (TCO). As explained previously, TCO is a purchasing methodology in which the goal is an understanding of the actual cost of buying a particular good or service from a particular supplier (Dobler and Burt, 1996), which considers the analysis and accounting of the end-of-life phase costs, as well. According to Tibben-Lembke (1998), RL is the process of moving products the “wrong way”, and the incurred costs should be taken into account in the calculation of the TCO. Therefore, these product return costs may influence the purchasing decision-making. Managing product returns in an effective and cost-efficient manner are of increasing interest in the business. It leads to profits and at the same time increased customer service levels and higher customer retention (Srivastava and Srivastava, 2006).

Considering the aerospace industry context, this does not mean that the retired aircraft will be returned to its manufacturer because this industry is not currently subjected to “take back” directives, as is the case of the automotive and electronics industries. The end-of-life aircraft recovery industry is essentially a profit-driven business, which counts on a well-established network for disassembly, dismantling, materials recycling and second-hand parts distribution. The aerospace industry supply chain is fully dedicated to supporting the production parts and materials for new aircraft and is not currently prepared to manage “take back” products for reconditioning and recertification, without compromising the production schedules established by the aircraft manufacturers. Under this point of view, we may cite Keivanpour *et al.* (2015c), when they argue that the aerospace industry cannot merely apply practices and solutions of reverse logistics in place in other industries, considering its contextual challenges.

Within this context, the end-of-life aircraft recovery industry demands a reverse logistics system that has been operated by third-party enterprises with little or no support from the original equipment manufacturers (OEM), whose current business models are not fitted to face these business opportunities without significant strategic and operational changes. From the customer's perspective, as noted by Tibben-Lembke (1998), we can assume that aircraft owners and operators can see a potential benefit in using this reverse logistics system, even bearing the costs of disposal to manage their end-of-life assets appropriately. It can turn into a significant competitive advantage, that deems to be considered by aircraft manufacturers and their supply chain partners.

(c) *Recovery Processes*

Based on Navin-Chandra (1994), we assume that the recovery processes enclose all the operations to parting-out a retired commercial aircraft (see PAMELA project “3D process”), the reuse or recycling of the harvested parts and materials, and the corresponding safety, environmental and economic gains coming from these processes. This author stresses that the recovery process is a complex and defiant problem, that requires mathematical modeling to improve its efficiency, which also helps to find environmentally better product design alternatives. Anecdotally, the author affirms that the recovery process is like chess game: one has to be willing to lose some pieces along the way to reach the objective. Its optimal solution is a trade-off between cost, time and environmental concerns.

Navin-Chandra (1994) poses the recovery problem as the following statement: For a given product or design, find a recovery plan that balances the amount of effort that is put in recovery and the amount of effort that is saved reusing parts and recycling materials. “*In this way, recovery is a leverage process – one gets back or saves more than one puts in*.” Hence, the recovery problem can also be viewed in graphical terms, where costs and revenues can be plotted and compared, in order to estimate the profits. During the time of this initial searching for publications, no articles were found discussing this subject of costs and revenues, in the context of the end-of-life aircraft recovery processes. The recovery problem, as posed by Navin-Chandra (1994), is the cornerstone to support all the discussions about the performance of the end-of-life recovery industry.

(d) *Recovery problem statement*

After this necessary review concerning Design for Environment (DfE), Reverse Logistics (RL) and Recovery Processes (RP), it is possible to outline intersections between them, and identify the main drivers, resources and variables within each intersection, which made possible to track and quantify their contribution to the end-of-life recovery problem statement. Figure 6 and the following explanation illustrate a tentative of representing this complexity using a more straightforward approach.

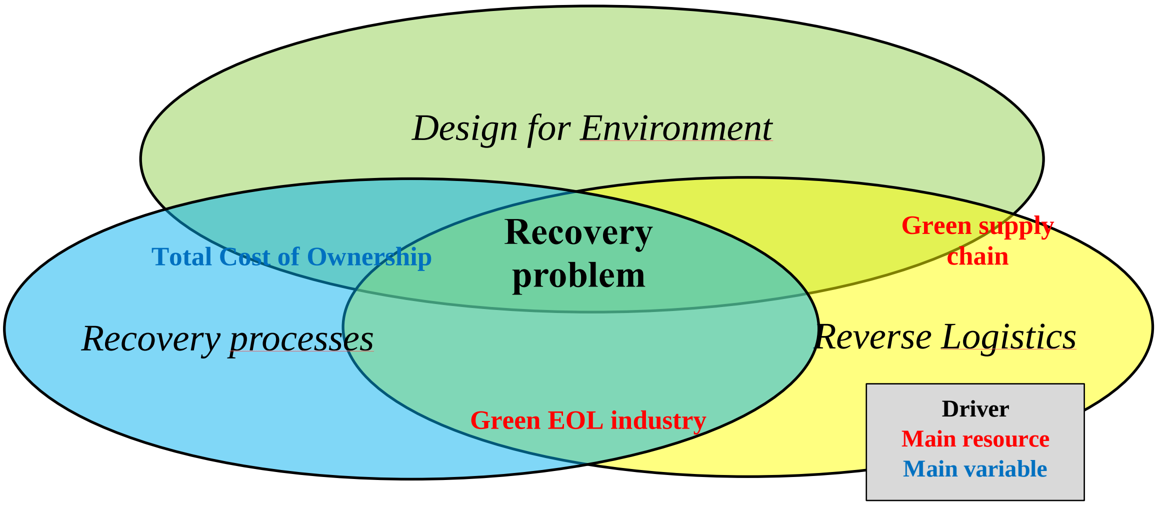

Figure 6 - Intersections between Design for Environment, Reverse Logistics, and Recovery Processes. Source: The author

The Design for Environment methodology is dedicated to the concept of a product taking into consideration materials, energy and labor savings at or below of the minimum amounts required (green design and manufacturing) to ensure that the final product in compliance with the applicable requirements (i.e., safety, operational performance, environmental and costs). The DfE is linked to the Reverse Logistics aiming to effectively plan and manage the logistics pathway of the product's "take back". These objectives are only possible through a green supply chain dedicated to supporting the manufacturer meeting the green product requirements.

All the decisions during the DfE phase will significantly influence the TCO during the product business life-cycle, which is planned to consume renewable resources at or below their rates of regeneration and non-renewable resources at or below the rate of development of renewable substitutes while minimizing impacts on the environment (green product). Reaching these objects depends on the level of technological development embodied in the green design and manufacturing process and the accuracy of the Total Cost of Ownership. These costs will also influence the customer's decision regarding the product treatment at its end-of-life phase, i.e., when and how to plan and perform the product recovery processes.

The reverse logistics and the recovery processes are linked to help to deal with the adverse outcomes of an unappropriated product end-of-life treatment, preventing or reducing undesirable outcomes to all the involved stakeholders (green end-of-life treatment). These objectives are made possible only with the support of an efficient green end-of-life industry, with technical capabilities to perform the recovery processes.

Thus, the recovery problem poses in the triple intersection of these sets, showing that it will only be a leverage process if all these conditions mentioned above are satisfied. That is an optimization problem, whose solution represents a trade-off between cost, time and environmental concerns (Navin-Chandra, 1994). It also shows the importance of alignment of business strategies between the major stakeholders and rethinking of their business models concerning sustainable development and competitiveness. That it is probably one of the main challenges to be faced by the aerospace and the air travel industries, but the analysis and treatment of these concerns are scarce in the current aviation literature.

Additionally, Tibben-Lembke (1998) concludes that "*although the literature agrees that costs of disposal must be considered in TCO, more consideration of the impacts of the end-of-life issues on TCO is needed.*" His conclusion can be extended to say that more discussion is deemed to fully comprehend the effects of the implementation of the Design for Environment, Reverse Logistics and Recovery Processes on the commercial aircraft TCO analysis and accounting procedures. That is precisely the core discussion topic of this research effort.

(e) *Green supply chain management and the recovery problem*

Srivastava (2007) defines Green Supply Chain Management (GrSCM) as "*integrating environmental thinking into supply chain management, including product design, material sourcing, delivery of final product to the customers, as well as end-of-life management of the product after its useful life*." He notes that GrSCM literature is divided into three streams: (i) the importance of GrSCM; (ii) Green Design (DfE); and (iii) Green Operations. The recovery problem is within the green operations stream and is analyzed considering the reverse logistics angle. The author argues that the establishment of efficient and effective reverse logistics is a pre-requisite for the efficient and profitable product recovery process. Thus, considering this research point of view, we can analyze the end-of-life aircraft recovery problem from green design and green operations.

(f) *Green design and green operations in the context of the aerospace industry*

The aerospace industry operates in a heavily regulated environment, concerning safety, operational performance and environmental (i.e., noise and emissions) requirements. Besides that, aircraft buyers pressure aircraft manufacturers to design and develop aircraft which meet their operational standards, concerning load capacity, engine thrust, fuel consumption, cabin, and interior configurations, and operating costs. Meeting all these regulations and customers standards demands the establishment of long-term projects, aiming at the development of sophisticated and complex equipment and systems. The success of these projects demands the contracting of many specialized partners to design, manufacture and integrate all equipment and systems. In this context, the aircraft manufactures act as the main technology integrator, remaining responsible for ensuring that the final product complies with the applicable regulations and customers standards.

Thus, aircraft manufacturers must establish documented quality system procedures, which ensure that each supplier-provided product, article, or service conforms to the production approval holder's requirements, as required by FAR § 21.137(c)(1). This requirement imposes aircraft manufacturers the obligations of managing and assessing their supply chain. However, in practice, this does not mean that the aircraft manufacturers have direct and full control of each development decisions made by their partners. It shows a critical limitation to the development of the "totally green" aircraft design and operating concepts. Each technology developer within the aerospace supply chain takes its own decisions on how the applicable requirements will be met, and the cost-benefit of adopting green solutions. Gaps in the current regulations regarding these issues can be considered as "degrees of freedom", to be appropriately used and managed by the industry to find the equilibrium point between meeting requirements and meeting production and operating costs savings, in order to satisfy both the aerospace and the air travel industry needs.

All the decisions taken during these phases of design, development, integration, and manufacturing will set the boundary conditions for the management of the aerospace green supply chain, which in turn, provides support to the end-of-life aircraft recovery processes.

(g) *Green design and end-of-life research developments in the aerospace area*

Franz *et al.* (2012) present an interdisciplinary approach for Life Cycle Engineering (LCE) during the preliminary aircraft design, enabling the evaluation of costs and environmental impacts of the entire aircraft life-cycle. According to them, the existing methods for assessing the aircraft life-cycle are focused on life-cycle costing or on sustainability assessment of only certain life-cycle phases, mainly the operating phase. Thus, they are insufficient to provide an assessment of the whole aircraft life-cycle from “cradle-to-grave”, concerning sustainability already in the design stage. This new approach was developed within the scope of the project named “Air Transport Vehicle Life Cycle Analysis” (ATLA).

The LCE approach developed by Franz *et al.* (2012) combines the design for cost and the design for the environment under the consideration of technological restrains. They argue that the primary challenge of LCE in the preliminary aircraft design is the lack of data. The complexity of the processes within each life-cycle phase, the large number of stakeholders and the complexity of the aircraft itself with its thousands of components are additional challenges to be overcome to fully assess the economic, social and environmental impacts of the aircraft through its entire life-cycle. However, this approach enables to assess and compare different aircraft designs based on their impacts on sustainability and optimize it during the early design phase.

Böckmann and Schmitt (2012) both belong to the research team of ATLA project and present a practical application of the LCE approach developed by Franz *et al.* (2012). They used the referred approach to assess the production process of a civil aircraft fuselage, concerning economic and environmental impacts. The results showed that choosing composite materials instead of aluminum for a fuselage is preferable in economic and environmental terms, based on the assumptions and available data. The authors highlight that other results are possible because the approach is sensible to database and assumptions. However, the approach can be applied to other aircraft components. The main advantage is that it enables to detail and model aircraft design and manufacturing decisions on a detailed technical level.

Johanning and Scholz (2013) develop a Life Cycle Assessment (LCA), based on ISO 14040 standards, in order to evaluate the environmental impacts of each aircraft life-cycle phase during its early design. They concluded that the processes occurring once in the life-cycle of an entire aircraft fleet have a minor influence on the environmental impacts, as they are distributed over all passenger-kilometers traveled by the whole fleet. In a first analysis, we argue that this conclusion should not be applied to the end-of-life phase, although the recovery processes occur only once in the aircraft life-cycle. It is a reasonable result for events occurring once during the operating cycle, which is not the case of the aircraft recovery processes. For this reason, we also argue that the total fleet must multiply the environmental effects from each end-of-life aircraft.

Mascle (2013) proposes a methodology and a mathematical model to assess how aircraft manufacturers could manage design for rebirth and green supply chain decisions, addressing the following issues related to the end-of-life aircraft treatment: (i) incomes generated from spare parts and materials sales; (ii) treatment costs; (iii) compliance with regulations; and (iv) environmental performance. It enables manufacturers to design aircraft considering objectives defined by its end-of-life and its general engineering requirements during its early design phase. This effort results in a design approach focused on reducing the environmental impacts of the aircraft at its end-of-life phase. However, the author argues that this approach does not explicitly address the influences of costs and the market in the design decision-making.

Mascle (2013) notes that Design for Rebirth aims to ease of disassembly, reuse, remanufacturing, upgradability and recovery, increasing the possibilities to recover higher values at its end-of-life phase. However, the author argues that maximizing the net profit of the recovered parts and materials is not always the same as minimizing the disassembly costs. Some low-value non-functioning parts need to be removed first, in order to provide access to the high-value functioning parts, and these operations may affect the disassembly costs.

The author highlights that cost-benefits considerations impose a significant constraint on the achievability of a higher level of sustainability in the design. Using this model, the designer can only have a quick evaluation of the aircraft environmental performance to modify the project to satisfy the design requirements.

Keivanpour *et al.* (2014a) develop a decision tool framework to support aircraft manufacturers in the early stage of design to select a portfolio of eco-design techniques to maximize the value perceived by all stakeholders during the aircraft physical and busines life-cycles. That is a conceptual work that needs further developments and application to actual cases of aircraft design considering economic and environmental performances.

Ribeiro and Gomes (2015) propose a conceptual framework to integrate the end-of-life treatment into the aircraft early design stage. This concept is based on LCA principles, and aims to close the aircraft life-cycle loop, concerning physical product and its information from the end-of-life phase to the preliminary design phase. It enables the management of every phase and activities through the whole manufacturing and end-of-life phases concerning the environmental impacts. The authors note that current designers do not look beyond the operating phase of an aircraft when they take design decisions, even when adopting DfE methodologies.

Keivanpour and Ait-Kadi (2016) propose a conceptual framework for modeling the end-of-life phase of complex products, such as commercial aircraft, also a closed-loop approach based on LCA principles. It aims to contribute to the selection of the appropriate model for the end-of-life phase, in order to improve the recovery problem analysis and its solution. The framework takes into consideration the following elements or boundary conditions to model a complex product end-of-life phase: (i) product characteristics; (ii) modern context and regulations; (iii) sustainability principles and tools; and (iv) end-of-life models defined by product experts. That framework was then enhanced and adopted as the basis of a mathematical model developed by Keivanpour and Ait-Kadi (2017), to be applied to the end-of-life aircraft recovery problem. The authors established an expert panel to propose end-of-life aircraft models. The experts' opinions were collected and treated using fuzzy approaches, aiming to make possible the comparison between different end-of-life aircraft models, considering strategical, operational, tactical and sustainability aspects of end-of-life management. The authors recognize that further researches in this area are needed to test the proposed model in the context of other industries.

Sabaghi *et al.* (2016b) note that every year, hundreds of aircraft remain parked in airfields with no appropriate treatment, mainly due to the lack of proper design for end-of-life. This context highlights the importance of considering disassembly aspects at the time of retirement during the early design phase. Considering disassembly as a multi-criteria decision-making problem, the authors developed a mathematical model to determine which disassembly criteria are more critical and need to be primarily during the early design. Five technical disassembly parameters were initially considered: (i) accessibility; (ii) mating faces; (iii) tools types; (iv) connections types; and (v) quantity and variety of connections. The results showed that "accessibility" and "quantity and variety of connections" are the most significant ones who can profoundly influence the disassembly tasks. Paying attention to these findings, aircraft designer can design more natural disassembly hierarchies and tasks, at lower costs, improving the recovery processes performance.

Keivanpour *et al.* (2017b) propose a holistic approach to end-of-life aircraft treatment, considering lean management, sustainable development, and the global business environment. According to the authors, three significant challenges must be faced by the aerospace industry to deal with the economic, environmental and social concerns coming from the retired aircraft problem: (i) the literature on end-of-life aircraft treatment is not productive and well developed; (ii) the classical frameworks for logistics networks of product recovery are not entirely applicable to the aerospace industry context; and (iii) low availability of costs and technical data.

The authors also develop a multiple objective mixed-integer a nonlinear programming model to simulate feasible solutions for the end-of-life recovery problem. Running this model with the support of a user-friendly interface, the end-of-life aircraft problem owner and other stakeholders can have access to useful information about costs, environmental impacts, and social benefits, in order to support its decision-making process regarding the most cost-effective solution for the end-of-life aircraft recovery problem.

2.5.4 End-of-life aircraft recovery strategies – mathematical modeling and performance evaluation

The following studies were summarized to show that the current researches involving mathematical models are dedicated to developing algorithms aiming to improve planning and efficiency of the disassembly process, i.e., to reduce its time-consume, labor demand and related costs. Neither of these models takes into consideration DfE or DfD methodologies because they are not yet fully embodied in the existing aircraft disassembly and dismantling procedures. They analyze the disassembly procedures, as established by the aircraft maintenance manuals, to generate the most efficient disassembly strategy.

Latremouille-Viau *et al*. (2010) develop a mathematical model to optimize the profitability of the end-of-life aircraft dismantling process. The model is focused on determining which airframe part must be sheared and sorted before shredding it and the airframe parts that must be directly shredded, aiming to get a higher valorization from the aluminum recycling. This model does not depend on disassembly sequence generations and disassembly planning methods, which reduces the time consuming to run the model and makes more natural its alteration to a specific aircraft.

Siles (2011) also develop a mathematical model to assist aircraft dismantling enterprises in organizing their operations considering different dismantling scenarios, depending on the aircraft delivery date, know-how, tools, available technologies, costs and revenues related to the disassembly and sell off parts and materials. The objective is maximizing the profits while respecting the selected constraints. Thus, the model proposes for each aircraft the dismantling scenario to be performed, as well as the aircraft to be scrapped to free up space at each date.

Camelot *et al.* (2013) develop a mathematical model dedicated to obtaining an optimized and rational disassembly approach. The model analyzes all the maintenance tasks within the Aircraft Maintenance Manual (AMM) that are required to disassembly reusable parts and arrange them together, considering execution zone and tasks preparation criteria, in order to produce a structured and organized parts disassembly strategy. Organizing the disassembly operations using these model outputs can result in reducing workforce, time-consuming and costs of disassembly. Mascle *et al.* (2015) applied this model to a case study to provide the optimized disassembly approach to the aircraft Bombardier model CRJ100.

Sabaghi *et al.* (2015) argue that a full disassembly, dismantling and shredding an aircraft is not economically or environmentally feasible. Considering this constrains, the authors develop a mathematical model to select the best disassembly and dismantling strategies, concerning sustainability parameters and scores. A total of eight strategies currently used by Bombardier to disassembly and dismantling its regional jets were analyzed, considering ten different risk scenarios. The results showed that in risky environmental scenarios, “systematic disassembly” and “smart disassembly” are preferable, while in economic and social risky scenarios “shredding” and “smart shredding” are the ones preferable, respectively.

Dayi *et al.* (2016) propose a lean-based process planning for aircraft disassembly aiming to improve the recovery of parts. The mathematical model was conceived to establish a sequence of disassembly tasks minimizing changing the working zone and displacements while maximizing the number of tasks per working zone. This model resulted in the reduction of delays and time-consuming, provided a continuous stream of the sequence of disassembly tasks, and improved efficiency and quality.

2.5.5 Total cost of ownership fundamentals

(a) *Total cost of ownership in the purchasing literature*

Based on the discussions about the recovery problem statement, as presented in subsection 2.5.3(d), we can argue that its solution will influence the dynamics of the costs incurred during the end-of-life phase of a specific product. This solution must be: (i) feasible and affordable, concerning the available technological resources; (ii) admissible and controllable, regarding the environmental and social impacts; and (iii) value extractable or profitable for its stakeholders. Such a context points out the importance of improving products design during its early phase, considering all measurable and controllable impacts coming from their development, production, operating and retirement phases (i.e., total life-cycle).

According to Asiedu and Gu (1998), over 70% of the total life-cycle cost (or TCO) of a product is committed at the early design phase, what put designers in a favorable position to make efforts to reduce the total life-cycle cost. They note that the increasing recognition of cost competition has pushed the development of a wide variety of methodologies in the Design for "X" realm, among which we can include the Design for Environment (Fiksel, 2009) and Design for Rebirth (Mascle, 2013). However, Asiedu and Gu (1998) argue that these methodologies are not cost-driven, although most of them are successful in reducing costs. Thus, the authors highlight that methodologies and tools are needed to provide cost information to designers. They argue that Life Cycle Costing (LCC) analysis provides a framework to estimate the costs of developing, producing, operating and retiring a specific product.

The concept of Life Cycle Costing receives many names in the current literature, such as: Life Cycle Costing (Kaufman, 1969; Jackson and Ostrom, 1980; Dhillon, 2010); Cost-based supplier performance evaluation (Monckza and Trecha, 1988); All-in-costs (Burt *et al*., 1990); Product life-cycle costs (Shields and Young, 1991; Asiedu and Gu, 1998); Total Cost (Cavinato, 1991, 1992); and Total Cost of Ownership (Ellram, 1993, 1994, 1995; Ellram and Siferd, 1993, 1998; Ferrin and Plank, 2002). According to Ferrin and Plank (2002), all these concepts are related. For this research, we adopted the term Total Cost of Ownership (TCO) because it is a border concept than Life Cycle Costing, which is a subset of TCO activity and generally neglects the pre-transaction costs (Ellram, 1995). Considering Dhillon (2010) valuable contributions to this issue, we can conclude that Life

Cycle Costing also neglects the end-of-life phase costs. Thus, our choice is also justified by our interest in having a clear picture of the: (i) pre-transaction costs components incurred during the aircraft early design phase, due to the embodiment of Design for Environment methodologies; and (ii) post-transaction costs components incurred during the aircraft retirement phase, due to the end-of-life aircraft recovery processes.

Although our focus in this research is limited to these two above mentioned cost components, it is important to highlight that the TCO of a commercial aircraft encompasses the costs incurred during all the aircraft life-cycle phases. This issue will be further discussed in the Research Methodology section of this research.

Jackson and Ostrom (1980) note that only minimal attention is dedicated to LCC in the purchasing literature, although it is an important concept, which allows the purchaser to identify, quantifying and evaluating all the costs associated with the ownership of a product. According to them, "*it attempts to overcome the fallacy of considering only the initial costs and ignoring other costs which may account for a substantial proportion of the total costs of a product throughout its useful life*." The authors also present a useful and simplified eight steps procedure to calculate the TCO, that could be used as a primary approach for the TCO calculation of a complex product, such as a commercial aircraft.

Ellram (1994) presents many benefits of implementing TCO analysis in the purchasing decision-making process. Some of these benefits can be analyzed considering the context of the commercial aircraft buyers, as follows: (i) it provides an excellent framework to evaluate aircraft manufacturers; (ii) it provides excellent data for comparing aircraft manufacturers performance; (iii) it requires purchasing decision-makers to develop an awareness of the most significant non-price factors that contribute to an aircraft TCO; (iv) it identifies where aircraft manufacturers should focus their product's efficiency improvement efforts; (v) it helps identifying cost savings opportunities; and (vi) forces commercial aircraft buyers to look at internal issues, how their requirements/specifications may actually increase costs.

Ellram (1994) also presents many barriers to TCO implementation. The most significant ones are related to resource issues, such as: (i) lack of readily accessible data to support efforts/lack of systems; (ii) labor-intensive to develop and support; (iii) lack of resources to develop, implement and maintain. Considering the context of the commercial aircraft buyers again, the lack of readily accessible data to support efforts for implementing aircraft TCO analysis can be assumed as the primary challenge, because they depend on the aircraft manufacturers or on their operating expertise to gather input data to feed their analysis.

Considering also the increasing pressures of the public interest and regulations on the environmental and social impacts coming from the end-of-life treatment of complex assets, such as vehicles and aircraft, commercial aircraft owners and operators need to take into account the dynamics of the costs incurred during the end-of-life aircraft treatment and include them in their TCO analysis. Knowing these end-of-life costs, aircraft owners and operators can plan and profitably manage this phase, throughout an appropriated recovery process. Revenues coming from the resale of the aircraft second-hand parts and materials can overcome disassembly and dismantling marginal costs (van Heerden and Curran, 2010), making the recovery process a leverage process (Navin-Chandra, 1994).

Ferrin and Plank (2002) present an exploratory study about TCO models. After analyzing the current literature on TCO models and point out their limitations, the authors propose a TCO model based on a core set of cost drivers, along with an auxiliary set of cost drivers. They adopted the concept of cost driver as proposed by Geiger (1999): "… *another measure that is used to distribute the cost of activities to cost objectives* proportionally." Considering the purposes of this research, we can highlight that the following set of cost drives are of interest: (i) product design costs; (ii) out-of-service costs; (iii) depreciation; (iv) final disposal value; (v) final disposal costs; (vi) scrap; and (vii) obsolescence costs.

Another cost driver that can be included in this list are the reverse logistics costs, as noted by Timbe-Lembke (1998) because it also has a significant impact on the TCO calculation. With the increasing disposal costs and environmental regulations, manufacturers are interested in what happens to their products at the end of their business life-cycle. Investing in reverse logistics can improve the value extraction of the end-of-life products in many ways, considering the second-market opportunities for remanufactured products, parts, and materials. Considering this context, the author cites Doherty (1996), highlighting that "… *in a near future reverse logistics will play an important role in the strategic business planning*".

(b) *Aircraft total cost of ownership*

Dhillon (2010) argues that in the global economy and due to various market pressures, the acquisition decision-making of many engineering systems cannot be based solely on the procurement cost, but in their life-cycle costs, which can range from 10 to 100 times the original acquisition cost. The author gives essential contributions to the calculation of the total cost of ownership (TCO) of many types of engineering systems and complex assets, including aircraft, but his approach does not consider the end-of-life phase costs. This gap will be analyzed and fulfilled during the Research Methodology section of this research. At this point, it is important to highlight that the literature regarding aircraft TCO is scarce.

Johnson (1990) notes that between 70 to 80% of the LCC of a commercial aircraft is committed during its early design phase, when very little money has been spent. For this reason, the author notes that is necessary to weigh the merit of decreases in the operating costs against the increase in the acquisition cost and vice versa. He proposes a methodology that makes it possible to identify an aircraft concept that will meet the mission requirements and have the lowest TCO. His mathematical model is focused on the acquisition and operating costs, which are the principal components of the TCO, and no consideration of end-of-life treatment costs is made.

Castagne *et al*. (2004) develop a methodology to estimate the TCO of the early design of the fuselage panels that comprise the main fuselage structure of a typical regional jet. The mathematical model is also limited to consider performance requirements, design configuration, and manufacturing cost, in order to generate a solution that minimizes the direct operating costs to the airline operator. Thus, the mentioned model does not consider end-of-life treatment costs.

Curran *et al*. (2005) also develop a methodology to apply design for manufacturing and assembly principles to the early design of airframe structures. Its mathematical model is dedicated to achieving the simplest structural configuration that meets the system requirements, concerning structural integrity, aerodynamic performance or additional functionality. The main contribution of this model is identifying and modeling key drivers that can be related to the costs of design, production, and operation. Once again, end-of-life treatment costs are out of the model decision scope.

Thokala (2009) proposes an aircraft TCO model to estimate based on the total product costs breakdown structure proposed by Asiedu and Gu (1998), which considers: (i) research and development costs; (ii) production and construction costs; (iii) operating and maintenance costs; and (iv) retirement and disposal costs. However, the model is applied only to the case study of a generic unmanned air vehicle.

Based on this brief literature review about aircraft TCO we can conclude that the current literature has a gap of detailing the end-of-life treatment costs, which is the focus of this research.

2.5.6 Aircraft appraisal, trading and accounting procedures

Commercial aircraft are considered a production asset whose valuation process is quite complex, due to a broad scope of technical, economic, financial, and market factors which affect its market value during each phase of its life-cycle. This valuation is performed by skilled and experienced appraisal companies and professionals, entirely dedicated to commercial aircraft appraisal and trading. These companies also provide consulting to aircraft owners and operators regarding aircraft pricing, depreciation and accounting procedures.

These are essential activities for the air travel industry because they set parameters for pricing both new and second-hand aircraft markets, influencing the aircraft buyers' behavior and decisions. The air travel industry cyclic demand also influences these stakeholders' timing decisions of investing or divesting in fleet capacity, in order to respond to current and anticipated demands. These cycles are the driving forces behind the airlines and investors decisions regarding decommissioning or recommissioning their aircraft, which in turn affect the aircraft appraisal and trading trends.

(a) *Aircraft appraisal and trading*

Before discussing the procedures regarding commercial aircraft valuation, it is essential to consider its life-cycle program, as shown in Figure 7.

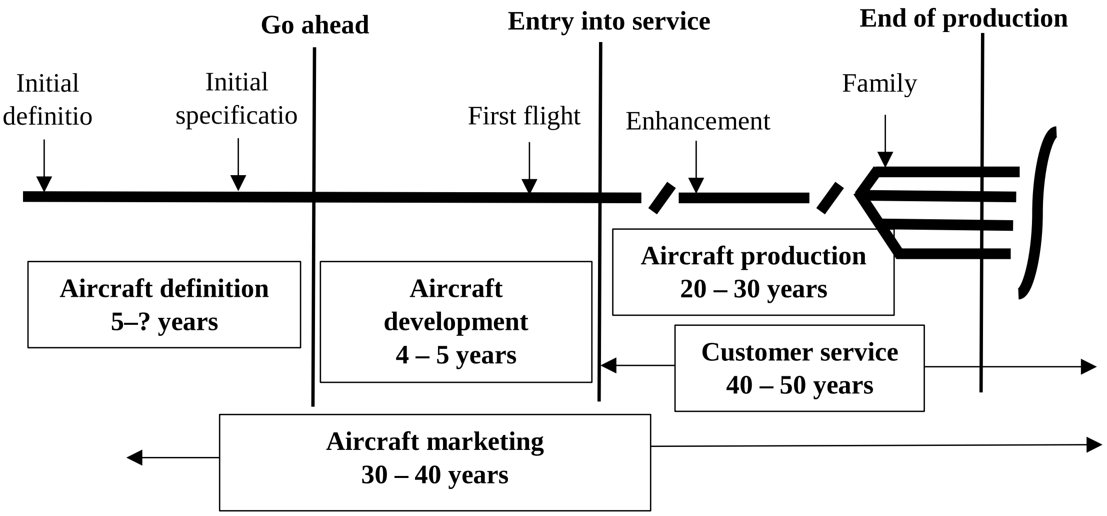

Figure 7 - Typical commercial aircraft life-cycle program. Source: Clark (2007)

Based on both Clark (2007) and Fiksel (2010) interpretations regarding commercial aircraft projects and products life-cycle, respectively, we may claim that commercial aircraft are subjected to a dual life-cycle: (i) physical life-cycle: period during which the aircraft can be airworthy, but beyond a certain point the investment required to extend its physical life is no longer justified (i.e., end of physical life-cycle); and (ii) business life-cycle: period during which the aircraft is expected to be profitably operated, but beyond a certain point the total cost of ownership (mainly the direct operating costs) is higher than the expected profits (i.e., end of business life-cycle), where is our primary interest in this research.

As well as any other production asset, the market value of a commercial aircraft varies through its life-cycle, influenced by many factors that will be discussed here. However, it is generally accepted in the air travel industry that aircraft value means different things to different people. Airlines analyze an aircraft based on the present value of its operating profits expected over its life-cycle. By their turn, aircraft investors analyze an aircraft considering the present value of the lease income and the capital gains from the sales of the aircraft (Ackert, 2012). An account will think of the aircraft regarding its “book value". An aircraft trader will consider its "fair market value" under prevailing market conditions (Clark, 2007).

Ackert (2011) presents a detailed discussion of the technical terminology standardized by International Society of Transport Aircraft Trading (ISTAT) and used by the majority of the aircraft appraisers, aiming to establish different nuances of an aircraft market value, which depends on the purpose of the aircraft appraisal. However, we will focus our attention on the residual value that a commercial aircraft retains at the end of its business life-cycle, which means its market value as an "as is" flying transport vehicle.

Generally, the first option is trying to remarket the parked aircraft, either as a passenger aircraft for second or third tier operators or converting it into a cargo configuration. In some circumstances, the used aircraft remarketing may not be cost-effective, and its market value can be lower than the total value of its main marketable second-hand parts for reuse in the active fleet, such as engines, landing gears, and other equipment, and also as a source of valuable materials for the recycling industries. At this point, the aircraft is said to have reached its salvage or parting-out value, when its owner or operator decides to decommission and parting the aircraft out to resell its parts and materials. In the end, it can be considered a value retention issue that drives the stakeholders' decision.

Clark (2007) establishes a set of fourteen factors influencing the aircraft residual value, after what the author comments that "*a good knowledge of residual value can help an airline determine the optimum time to introduce an aircraft into the fleet and can help in the construction of a financing package.*" Something similar can be said of the airline decision about withdrawing an aircraft from the active service to extract the maximum value from its remarketing or parting-out. Ackert (2011) claims that aircraft market values can be affected by manufacturer, aircraft and market determinant factors. Ackert (2012) notes the aircraft value retention factors can be divided in market-driven and performance-driven factors.

Considering both Clark (2007) and Ackert (2011, 2012) contributions, we can argue that there are four categories of factors influencing the aircraft residual value:

(1) Technical

(i) *Aircraft age*: It can explain something like 50% or more of the value of an aircraft. However, similarly, aged aircraft can have very different prices, considering their maintenance status, for example.

(ii) *Production line position*: early production and tail end units tend to have reduced values, comparing to mid-to-late units, due to higher operational costs and competition against newer technology aircraft, respectively.

(iii) *Production status* or *production runs*: As soon as an aircraft production line closes, due to newer models launching or manufacturer demise, then the residual value is impaired. Long production runs tend to enhance the aircraft residual value.

(iv) *Aircraft specification:* Gross weight configuration, engine configuration, cabin and flight deck configurations. Usually, generic configurations have higher prices than specific configurations.

(v) *Aircraft commonality:* Aircraft belonging to a family with similar technology hold their value better than specific or customized units.

(vi) *Flexibility:* Aircraft which can be more easily deployed in alternative regions and markets are more attractive if conditions change.

(vii) *Aircraft technical condition:* low mileage or less cycled and well-maintained aircraft, with appropriate maintenance records (airworthy condition), usually reach higher prices in the market.

(viii) *Stability of the manufacturer:* It ensures long-term support to the aircraft operation, which brings stability to its market value.

(2) Economic

(i) *Inflation:* Trends in residual values are more apparent with inflation removed from the context. Keeping inflation in the residual value forecast means that the value of inflation also needs to be forecasted.

(ii) *Interest rates:* When the interest rates are high the pricing of second-hand aircraft usually rises, as well to help recover the higher costs of financing or leasing incurred.

(iii) *Economic growth*: The demand for new aircraft tends to be higher during economic booms, and the second-hand aircraft have higher demands during economic downturns.

(iv) *Aircraft economic performance*: Efficient aircraft tend to reach higher values in the market than less efficient aircraft. Aircraft efficiency primarily depends on extraneous factors, such as maintenance costs and fuel prices.

(v) *Aircraft operating history*: The kind of operations will determine its wear level suffered by the aircraft, which impacts its residual value.

(vi) *Aircraft profits margins*: Each airline operates the aircraft according to its business model, and the kind of operations will determine how much profit can be done, taking into account its past usage and current technical condition.

(vii) *Air traffic growth*: It will determine the level of utilization of the aircraft fleet, and aircraft market values usually increase during high demand periods.

(3) Financial

(i) *Pricing strategy:* If the aircraft manufacturer deep discounts strategy persist the residual values will not return to their historical levels relative to the appraised base values.

(ii) *Depreciation, base value and loan payments:* An aircraft base value and the depreciated book value can be entirely different. Most of the air travel industry adopts the straight-line method depreciation. Also, the market value of an aircraft may be either below or above the repayments owed on the aircraft, depending on the type of repayment scheme adopted.

(iii) *Aircraft financing environment:* The aircraft manufacturers and airlines both depends on credit markets to finance their production activities. During economic downturn periods, these credits can be reduced, denied or reach higher costs, due to the increased risks. These conditions may impair the balance between the market value of new and used aircraft.

(4) Market

(i) *Price of new aircraft:* New aircraft generally set the ceiling on market value, especially if the prices are stable.

(ii) *Significant fleet re-equipment policies:* If a large airline implements a major re-equipment program, this could result in the sudden increase of an individual aircraft model availability, depressing its market value.

(iii) *Aircraft secondary market prospects:* Conversion to cargo configuration is the largest market for used passenger aircraft. Another valuable alternative is parting the aircraft out, in order to resell its parts and materials.

(iv) *Market conditions*: Actual residual values will be closer to the base value in normal market conditions.

(v) *Market liquidity or market penetration*: Appraisers will consider the number of active aircraft and on order (backlog), the number and type of operators and its geographical distribution, and also the breadth of the manufacturer's product line, in order to set aircraft market values.

(vi) *Surplus/Shortage*: In valuation terms, shortages of aircraft (i.e., strong market conditions) drive values up, and surplus (i.e., weak market conditions) push values down.

Considering all the above mentioned technological, economic, financial and marketing factors influencing the aircraft residual value we can assume that aircraft parking, market relocation, retirement and decommissioning decisions can quickly turn into a multi-criteria problem. Many of these factors, such as commonality and flexibility are difficult to quantify, in order to turn into an input of the mathematical model, which suggest the adoption of a fuzzy modeling approach as a trial to overcome this limitation. For this research, we will establish a mathematical model for the end-of-life aircraft treatment decision-making process considering only the aircraft age and its maintenance conditions, concerning engines and landing gear "green time", as will be detailed in the Research Methodology section.

(b) *Aircraft accounting procedures*

According to IATA (2016b), "*the high value of aircraft assets carried on the balance sheet coupled with the earnings volatility in the air travel industry has historically exposed airlines to potential asset impairments. That creates further accounting complexity and requires judgment in estimating the recoverable value of assets*." For this reason, IATA establishes the International Accounting Standards, called IAS 16 – Property, Plant and Equipment, aiming to support airlines with clear accounting principles. Applying them also demand judgments regarding the aircraft economic life and its residual value, to be revisited each reporting period.

IAS 16 requires an asset to be decomposed into components. The level to each component should be decomposed on the extent to which they have similar economic life or consumption profiles. Each airline set its criteria for doing this, such as adopted by Lufthansa Group 2014 Annual Report: "*Reparable spare parts for aircraft are held at continually adjusted prices based on the average acquisition costs. For measurement purposes, spare parts are assigned to individual aircraft models and depreciated on a straight-line basis depending on the life phase of the fleet models for each they can be used*." Thus, depreciation rates for individual components are determined by estimating economic life and residual value, and this rate depends on a number of factors, such as: (i) intended life of the fleet type being operated; (ii) estimate of the economic life from the manufacturer; (iii) fleet deployments including timing to fleet replacements; (iv) changes in technology; (v) repairs and maintenance policies; (vi) aircraft operating cycles; (vii) prevailing market prices and trend in price of second-hand and replacement aircraft; (viii) aircraft-related fixed assets depreciation rates; (ix) treatment of idle assets; and (x) distinction between fleet types.

IATA (2016b) also notes that business life-cycle and residual values of the existing aircraft fleets have been increasingly impacted by the “new generation” aircraft, which have reduced operating costs. That is causing older aircraft earlier retirement, accelerating their depreciation rates to the residual value over a shorter remaining business life-cycle. There is a sensible divergence in business life-cycle and residual value assumptions adopted by different airlines, depending on their fleet utilization plans and business models. Typically, aircraft are depreciated over 15 to 25 years with the residual value ranging from 0 to 20%. The straight-line depreciation method is mostly used. Small changes in business life-cycle and residual value can have significant impacts on the profits or loss during a specified period. Some airlines are used to assign a zero-residual value at the initial capitalization and then adjust his rate accordingly when a reasonable scrap value can be estimated.

In practice, we can have an idea of the financial impacts of the aircraft depreciation for an airline, considering Lufthansa Group 2014 Annual Report: “*Impairment losses of EUR 137m were recognized the previous year. EUR 124m of the total was recognized for a total of 44 aircraft either available for sale or to be decommissioned successively in line with current corporate plans and which were written down to fair value fewer costs to sell*.”

This brief discussion about aircraft accounting procedures is useful to highlight the importance and magnitude of the aircraft parking, market relocation, retirement and decommissioning policies and practices into the airline financial results. An appropriated fleet management, which includes depreciation procedures effectiveness, can turn end-of-life fixed costs and financial losses into attractive revenues, if the airline takes the parking , market relocation, retirement and decommissioning decision in a timely manner, aiming to extract value from the end-of-life aircraft through the recovery process (Navin-Chandra, 1994; van Heerden and Curran, 2010; and Keivanpour *et al.* 2015c).

2.5.7 Aircraft retirement and storage trends

Forsberg (2015) notes that historical patterns show that the ability of owners and operators to return stored aircraft to the active service is significantly reducing as time passes. That can be explained by the increasing technical costs of recommissioning a retired aircraft beyond a stored period of two years, which can reach USD 1.5m for narrow bodies and USD 3.5m for wide bodies. Over the past 20 years, only 1,200 aircraft out of 18,000 were returned to service after more than two years of being parked. According to the referred author, a wide range of factors continues to influence the pattern of aircraft retirement and fleet replacement, raising essential questions to the air travel industry: (i) "*Have the approaching technology transitions in all three aircraft size categories started to impact retirement patterns*?"; (ii) *"Is the business life-cycle of the current aircraft generation types getting shorter* than before?"; (iii) "*Will the current lower oil price environment result in more aircraft being brought out of storage*?"; and (iv) "*Will retirements of older fleets be deferred at the expense of new deliveries?*"

Analyzing aircraft retirement trends in 2014, Forsberg (2015) presents the following results for the three aircraft size categories, as shown in Table 3.

Table 3 - Aircraft average age at retirement for the three aircraft size categories. Source: Forsberg (2015)

Aircraft size category	**Average age at retirement (years)**
Regional jets	12,2
Narrow-body jets	26,6
Wide-body jets	24,6

Their specific operational profile can explain this significant difference in the average age at retirement between regional jets and narrow or wide-body jets. While a wide-body is typically submitted to one or two cycles during 16 flight hours per day, considering its long-haul operations, a regional jet can usually perform from three to six cycles, considering its short-haul operations. Thus, a high-cycled regional jet tends to be retired earlier than the narrow body and wide-body jets, due to the increasing costs of aging inspections and maintenance procedures affecting the aircraft structure, engine performance restoration, and landing gear overhaul procedures.

Forsberg (2015) analyzes the aircraft fleet retirement trends considering what he calls the “retirement waves”, just as follows:

(1) ***First wave fleet retirement*** – They are the oldest remaining fleet populations, composed by the narrow bodies Boeing 727, DC-9, Fokker F28, Boeing 737-100/200, and the wide bodies Lockheed L-1011, Boeing 747-100/200/300, and DC-10. We may argue that they are not economically attractive for the recovery processes because their entire inactive fleets correspond to 86% of the delivered units, which reduces the size of the second-hand market for their reusable parts significantly. Two-thirds of the active fleet has an average age of 36 years and are cargo configuration converted (freighters).

(2) ***Second wave fleet retirement*** – They correspond to the most recently out of production models or long-lived programs, composed by the narrow bodies BAe 146, MD-80, Boeing 737 Classic, Fokker 70/100, MD-90, BAe Avro RJ, Boeing 757, Boing 717, and the wide bodies Airbus 300, Airbus 310, Boeing 747-400, Boeing 767, MD-11. We can assume that they are economically attractive for the recovery processes because their entire inactive fleets correspond to only 27% of the delivery units, what represents a broader second-hand market for their reusable parts and valuable materials for recycling purpose. Their average age is about 21.7 years at the retirement.

(3) ***Third wave fleet retirement*** – They are the currently in production models. They are composed by the narrow bodies A320 family and Boeing 737NG, and the wide bodies Airbus A330, Airbus A340 and Boeing 777. We can argue that they represent a massive potential for the recovery processes for the next decades because only 3% of the delivered units are currently retired. Their average age is about 7.6 years at the retirement. We can also include the EMBRAER E-jets E1 family and the Airbus A380 in this list because some of their operators (i.e., JetBlue Airways and Singapore Airlines, respectively) have just announced the retirement of these models between 2018 and 2020, just ten years after their entry into service.

Finally, Forsberg (2015) analyzes in detail the context of the Airbus A320 family and Boeing 737NG family retirement trends, due to their worldwide market penetration and liquidity advantages. At the end of his report, the referred author presents important conclusions about aircraft retirement trends, which are useful guidelines for aircraft owners, operators, and aircraft recovery industry companies.

The primary commercial aircraft manufactures also publish their global market forecasts considering new aircraft deliveries and retirements for the period 2017-2037, as outlined in Table 4.

Table 4 - Commercial aircraft projected deliveries and retirements 2017-2037.

Current fleet (2017)	**New aircraft deliveries (2017-2037)**	**Retirement (2017-2037)**	**Retained (2017-2037)**	**Growth (2017-2037)**	**Total fleet (2037)**	**Source**
24,400	42,730	18,590	5,810	24,140	48,540	Boeing (2018)
21,453	37,389	12,415	9,038	26,534	47,987	Airbus (2018)

2.6 Synthesis

2.6.1 Principal contributions and gaps

The primary purposes of this structured literature review were: (1) identify the principal contributions to the analysis and solutions of the end-of-life aircraft recovery problem, showing its relevance as a research theme; and (2) highlight the research gaps which justify further investigations and solutions. Considering these purposes, we can summarize our initial findings as presented in Tables 5 and 6.

Table 5 - Literature review principal contributions. Source: The author

Principal contributions	Reference subsection
The increasing worldwide number of retires aircraft is dne of the primary adverse outcomes from the air travel industry growth, considering its forecast rates for the next decades.	2.5.1
The implementation of a worldwide aircraft recovery industry is a feasible and sustainable solution to cope with the safety, environmental and economic risks related to end-of-life aircraft problem.	2.5.1
The significant energy savings and emission reductions are, respectively, the main economic and environmental drivers of the efforts and investments in R&D in aerospace aluminum alloys and carbon fiber recycling processes.	2.5.2
The end-of-life aircraft recovery problem requires a closed loop approach to be appropriately managed, aiming to deal with its safety, environmental and economic outcomes.	2.5.2
The current end-of-life treatment policies and procedures, such as those established by Directive 2000/53/EC (End-of-Life Vehicles) cannot be directly applied to the treatment of the retired commercial aircraft.	2.5.2
There are important processes and drivers in the intersections between Design for Environment, Reverse Logistics, and Recovery Processes, which need to be identified and analyzed, in order to appropriately pose and treat the aircraft recovery problem.	2.5.3
The end-of-life aircraft recovery is a leverage process, i.e., it generates more value to its stakeholders than they need to invest in operating and managing these processes, considering the revenues from the second-hand parts and the valuable recycling materials remarketing.	2.5.3
Gaps in the current aviation regulations regarding end-of-life aircraft and Design for Environment can be considered as "degrees of freedom", to be appropriately used and managed by the industry to find the equilibrium point between meeting requirements and meeting production and operational costs savings, in order to satisfy both the aerospace and the air travel industry needs.	2.5.3
The current researches involving end-of-life aircraft problem mathematical models are dedicated to developing algorithms aiming to improve planning and efficiency of the disassembly process, i.e., to reduce its time-consume, labor demand and related costs. Neither of these models takes into consideration Design for Environment or Design for Disassembly methodologies, because they are not yet fully embodied in the existing aircraft disassembly and dismantling procedures.	2.5.4
The Total Cost of Ownership (TCO) was adopted to consider all the costs incurred during the whole aircraft business life-cycle, but we are specifically interested in having a clear picture of the: (1) pre-transaction costs components incurred during the aircraft early design phase, due to the embodiment of Design for Environment methodologies; and (2) post-transaction costs components incurred during the aircraft retirement phase, due to the aircraft recovery processes.	2.5.5
The reverse logistics costs (i.e., infrastructure and processes) have an essential impact on the TCO of a product that reaches the end of its business life-cycle.	2.5.5
The commercial aircraft appraisal, trading and accounting procedures are quite complex, affected by many technical, economic, financial and market factors. Its market value at retirement decision time and during the parking period will be decisive to the owner or operator, influencing their decision about remarketing the aircraft or sending it to the parting-out processes.	2.5.6
There are three waves of aircraft fleet retirement: (1) the oldest aircraft models; (2) the recent out-of-production or long-lived aircraft models; and (3) the currently in production aircraft models. This last group, which include the Boeing 737 and Airbus A320 families, is the most promising one, concerning value extraction at the end of the business life-cycle, due to their market penetration and liquidity advantages.	2.5.7

Table 6 - Literature review principal gaps. Source: The author

Principal research gaps	**Reference subsection**
There is a lack of performance indicators developed to measure the efficiency and the effectiveness of a feasible and sustainable end-of-life aircraft recovery industry.	2.5.1 2.5.2
There is a lack of R&D development efforts dedicated to the aerospace aluminum alloys and carbon fiber recycling processes.	2.5.2
There is a lack of directives/regulations (i.e., policies and procedures) dedicated to organizing and framing the end-of-life aircraft treatment context, aiming to establish the aircraft manufacturers, owners, operators, and the other stakeholders' responsibilities.	2.5.2
There is a lack in the literature regarding an appropriate dialogue between the recovery problem and existing related methodologies as green design, green manufacturing, and complex products final disposal treatment.	2.5.3
There is a lack of conceptual approaches and mathematical models dedicated to analyzing and treating the complexity of the embodiment of Design for Environment to the commercial aircraft early design, aiming to maximize the value extraction at the end of its economic life- cycle.	2.5.4
There is a lack of comprehension about the Total Cost of Ownership components relating to the costs of the embodiment of the Design for Environment in the commercial aircraft early design phase and the costs at the aircraft end of business life-cycle.	2.5.5

For the purposes of this research we direct our efforts to: (1) present a conceptual approach to discussing the complexity of the embodiment of Design for Environment to the commercial aircraft early design; and (2) provide detailed comprehension about the Total Cost of Ownership components relating to the embodiment of the Design for Environment in the commercial aircraft early design phase and to the end-of-life aircraft phase. We consider that these contributions will be useful to best support aircraft owners and operators in their decision-making regarding the aircraft fleet planning and the valuable management of its end-of-life phase.

2.6.2 Green aviation concept

Although the research focus being the study of the economic outcomes of the embodiment of the Design for Environment in the commercial aircraft early design phase and its end-of-life phase, it is important to highlight that all the discussions are based in the green aviation concept, as outlined by the following expression (Fig. 8).

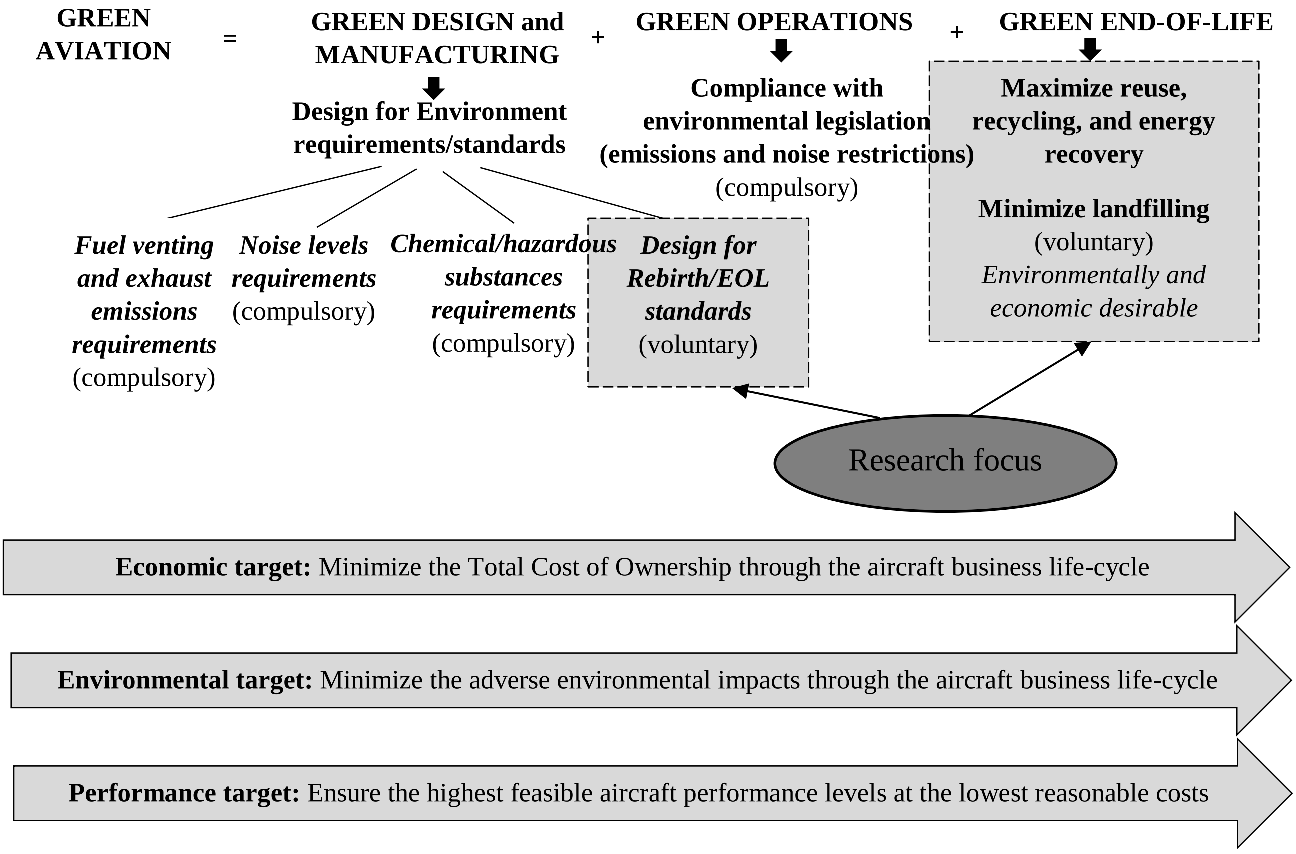

Figure 8 - Revisited green aviation concept. Source: The author

2.6.3 Research question

Considering all these previous contributions and gaps derived from the structured literature review we present the core research question: "***What are the principal cost drivers influencing the aircraft owners and operators decision-making process regarding commercial aircraft end-of-life phase*?**" During this research we propose a theoretical approach to answer to this question, and a mathematic model that can provide a cost-benefit analysis to best support the aircraft parking, market relocation, retirement and decommissioning strategic decisions.

3. Research methodology

This section is dedicated to study the problem of the end-of-life aircraft treatment, considering the principal costs and revenues incurred during its whole business life-cycle. The primary objective is proposing a mathematical model to support commercial aircraft owners and operators decision-making process, concerning aircraft parking, market relocation, retirement, and decommissioning. The dynamics of these costs and revenues will be outlined and analyzed, considering the scarce available data. The total cost of ownership is embedded in the proposed approach because the end-of-life phase costs can influence the procurement and the long-term fleet planning decisions by aircraft owners and operators.

The aircraft total cost of ownership encompasses the costs drivers incurred during its business life-cycle phases: (i) design and development; (ii) production and testing; (iii) operations; (iv) maintenance, repair and overhaul; (v) airworthiness directives embodiment; (vi) aircraft alterations embodiment; (vii) aircraft systems upgrades; (viii) parking and preservation; and (ix) end-of-life treatment (recovery processes). Taking into account that these are well-known costs by aircraft owners and operators, we will focus our attention only on parking and preservation costs, aiming to understand how much it can affect the aircraft end-of-life phase decisions.

The aircraft parking, market relocation, retirement and decommissioning decision-making processes are generally made on an *ad-hoc* basis. Generally, once the aircraft operating costs overcome the operating revenues its owner or operator decides to withdraw it from active service. Then, the aircraft is parked at graveyards. Usually, the aircraft returns to operation if favorable scenarios of expected reduced operating costs or improved revenues take place. If this does not happen, the aircraft may be parked indefinitely or decommissioned and sent to parting-out (disassembly and dismantling), aiming to make profits or to reduce losses trading its reusable second-hand parts and recyclable materials.

Aiming to best comprehend the aircraft parking, market relocation, retirement and decommissioning decision-making processes, we propose a cost-benefit financial model taking into account the dynamics of the expected costs and revenues incurred during the whole aircraft business life-cycle, as shown in Figure 9. This is a conceptual structure of the model based on a hypothesis on these costs and revenues. Points *a*, *b* and *c* are decision-making marks. The hypothesis of this model is detailed as follows:

1. Total operating cost (C_{opr}) grows continuously as the aircraft ages, due to increased fuel consumption rates, airframe heavy checks, engines and landing gear overhauls, engine performance restoration, repairs, airworthiness directives compliance, and updating aircraft systems;

2. Operating revenue (R_{opr}) decreases over time because newer and more efficient aircraft enter into operations, causing load factor reductions to older aircraft. When the $C_{opr} = R_{opr}$, at $t = t_a$, the airline may decide to park the aircraft;

3. Considering the operating revenue losses over time, as described above, the aircraft owner or operator should look for better business opportunities to keep it profitably flying. At this time, they need to find a market condition where an opportunity revenue (R_{opp}) higher than the current operating revenue (R_{opr}) may be achievable. In the best scenario, R_{opp} will be equal to the R_{opr} when the aircraft was new. Some aircraft cabin configuration alteration or engine replacement, for instance, can be demanded to make it possible. Its incurred costs must also be taken into account to support the decision of relocating the aircraft into another market environment or parking it;

4. Aircraft parking, retirement and decommissioning can be postponed if, for instance, an opportunity revenue $R_{opp} \geq R_{opr}$ can be expected. If $R_{opp} = R_{opr}$, generally the aircraft will be parked but not retired and decommissioned, while its owner or operator waits for a more attractive market condition to return the aircraft to service, i.e., $R_{opp} > R_{opr}$. Once $C_{opr} = R_{opp}$, at $t = t_b$, the aircraft is finally parked, and its decommissioning arises as the last opportunity to make the profits sending the aircraft to parting-out;

5. If the aircraft is not returned to operations (i.e., if $R_{opp} \geq R_{opr}$ is not satisfied), parking and preservation cost (C_{pp}) must be considered during the inactive period (i.e., between $t_a \leq t \leq t_b$) due to maintenance routines to reduce the efforts of returning the aircraft to operations. This cost needs to be deduced from the recovery revenue, aiming to determine the recovery process profitability;

6. Aircraft parting-out results in a recovery revenue (R_{rec}) due to reusable parts and recyclable materials trading;

7. Disassembly and dismantling costs (C_{dd}) are considered marginal concerning to the recovery revenues ($R_{rec} >> C_{dd}$);

8. The core decision of postponing aircraft parking, retirement and decommissioning will be worthwhile only while the cumulative operating profit overcomes the recovery profit losses, both considered between the instants $t_a \leq t \leq t_b$, i.e., $\Sigma_t (R_{opp}(t) - C_{opr}(t)) \geq | (R_{rec}(t_b) - C_{pp}(t_b)) - (R_{rec}(t_a) - C_{pp}(t_a)) |$;
9. The aircraft residual value (V_r) or book value is assumed as linear decreasing over time, and is considered only for accounting purposes; and
10. This decision-making process rationale only makes sense if the leverage potential of the aircraft recovery process is considered, i.e., at the instant $t = t_c$, the aircraft market value (V_m) becomes lower than the aircraft recovery revenue ($V_m < R_{rec}$).

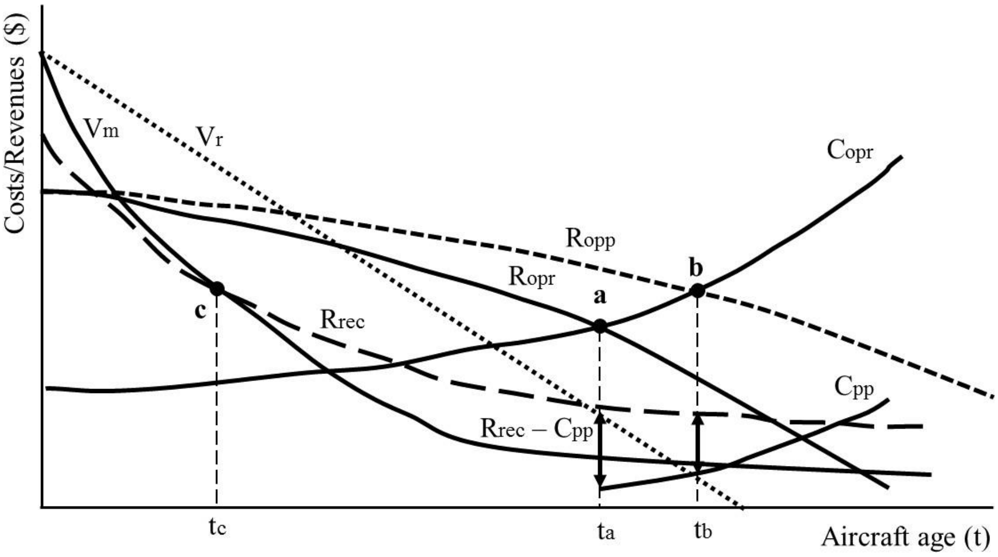

Figure 9 - Dynamics of expected costs and revenues during the aircraft business life-cycle.
Source: The author

4. Case study

Cost and revenue data for a specific aircraft model are scarce in the current literature because this kind of information is considered strategic by air carriers, aircraft leasing companies and aircraft manufacturers for competitiveness purposes. The U.S. Department of Transportation (DOT) discloses the quarterly financial review for the large certified air carriers. This report is based on data reported to DOT by all the air carries on DOT Form 41. It presents the air carriers financial condition, concerning operating costs, operating revenues and operating profit or loss, considering their whole fleets. That is an interesting information for those studying the air carriers' financial performance. However, we are focused on getting this kind of information for specific aircraft models. Our primary purpose is to obtain an estimate of the costs and revenues, as presented in Figure 10, to best comprehend an aircraft parking, market relocation, retirement and decommissioning decision-making rationale.

Due to these data limitations, this case study presents a cost-benefit financial analysis for the aircraft Boeing model 747-400, taking into account the main costs and revenues incurred during its approx. 30-year business life-cycle, aiming to support its parking, market relocation, retirement and decommissioning decision-making processes. The resulting cost-benefit financial analysis is shown in Figure 10.

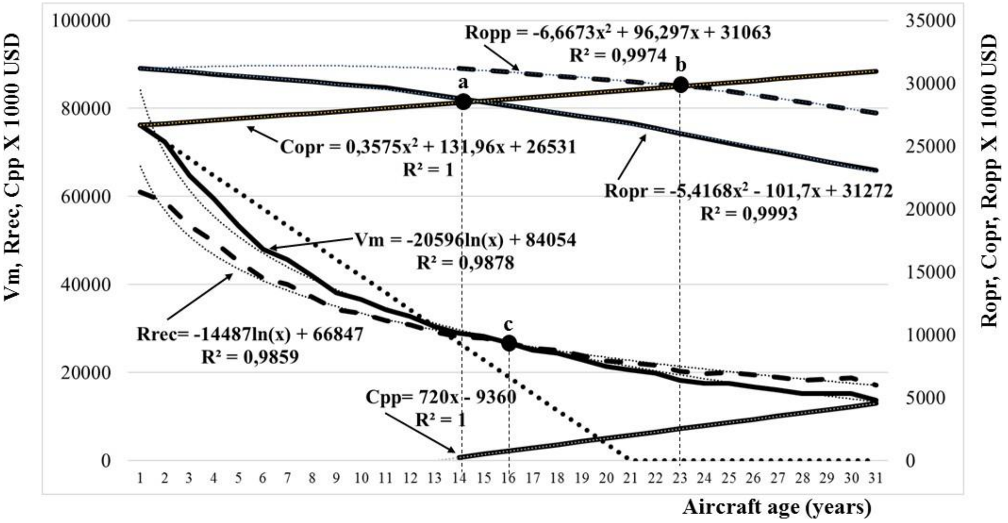

Figure 1290 - Principal costs and revenues incurred during the business life-cycle of a Boeing aircraft model 747-400 to support end-of-life decisions. Source: The author

4.1 Data and results

The current literature about commercial aircraft costs and revenues is scarce. Most of the cost and revenue data used as inputs in this mathematical model were obtained searching through websites or newsletters dedicated to discussing commercial aircraft financial aspects. In the absence of some specific data, such as recovery revenue (R_{rec}), estimations based on reasonable assumptions were made, as detailed below:

1. A Boeing aircraft model 747-400, delivered in 1992, 347 seats, 66,000 flight hours (TTSN) and engines model PW4056 was selected from an aircraft trading website advertisement. Its current aircraft market value is 16 million USD (2018). Its market value (V_m) from new condition until thirty years in service was obtained considering the wide-body transaction value curve proposed by Hallerstrom and Melgaard, apud from Clark (2007);
2. The aircraft recovery revenue (R_{rec}) was not available in the literature. This value was estimated considering $R_{rec} = 0.80 \times V_m$ when the aircraft was new, and $R_{rec} = 1.25 \times V_m$, for a 30-year-old aircraft. R_{rec} initial value is lower than its final value because although low cycled aircraft parts being more valuable than high cycled aircraft parts, it is an unusual practice sending low cycled aircraft to parting-out. Besides that, if newer aircraft composes the major part of an active fleet its second-hand parts market maybe not fully developed to become an attractive business. Finally, adjustment factors were arbitrarily tested to provide an intersection between R_{rec} and V_m curves when the aircraft was around 16 years in service;
3. The aircraft operating cost (C_{opr}) was taken from an ICAO report (ICAO, 2017), considering a similar 375-seat aircraft. This value was adapted to fit a 347-seat aircraft;
4. The operating revenue (R_{opr}) was taken from an IATA report (IATA, 2015), considering USA air carriers' average profitability per seat;
5. The operating profit P_{opr} comes from the difference $R_{opr} - C_{opr}$;
6. The opportunity revenue (R_{opp}) was estimated considering an attempt to obtain at $t = t_a$ the same operating revenue at $t = t_0$, i.e., $R_{opp}(t = t_a) = R_{opr}(t = t_0)$;

7. The parking and preservation cost (C_{pp}) was taken from Lyte (2016);
8. The aircraft book value or residual value (V_r) was a depreciation from 100% to none of its initial value, considering a 20-year business life-cycle; and

9. The disassembly and dismantling cost (C_{dd}) was considered neglectable, based on van Heerden and Curran (2010).

Table 7 shows the aircraft life-cycle costs and revenues used as input data for this case study.

Table 7 - Data sampling supporting the case study (value X 1000 USD).
Source: The author

Years	**V_m**	**V_r**	**C_{pp}**	**C_{opr}**	**R_{opr}**	**R_{opp}**	**R_{rec}**
1992	76190	76190	0	26663	31190	0	60952
1993	72381	72381	0	26796	31034	0	58773
1994	64762	68571	0	26930	30879	0	53375
1995	59428	64762	0	27065	30724	0	49714
1996	53333	60952	0	27200	30571	0	45285
1997	48000	57143	0	27336	30418	0	41367
1998	45714	53333	0	27473	30266	0	39989
1999	41905	49524	0	27610	30115	0	37206
2000	38095	45714	0	27748	29964	0	34331
2001	36571	41905	0	27887	29814	0	33452
2002	34286	38095	0	28027	29665	0	31832
2003	32762	34286	0	28167	29368	0	30873
2004	30476	30476	0	28308	29075	0	29150
2005	28952	26667	720	28449	28784	31190	28108
2006	28190	22857	1440	28591	28496	31034	27779
2007	26667	19048	2160	28734	28211	30879	26671
2008	25143	15238	2880	28878	27929	30724	25525
2009	24381	11429	3600	29022	27650	30571	25122
2010	22857	7619	4320	29167	27373	30418	23906
2011	21333	3810	5040	29313	27100	30266	22646

Years	V_m	V_r	C_{pp}	C_{opr}	R_{opr}	R_{opp}	R_{rec}
2012	20571	0	5760	29460	26829	30115	22165
2013	19809	0	6480	29607	26426	29964	21664
2014	18286	0	7200	29755	26030	29814	20298
2015	17524	0	7920	29904	25639	29665	19744
2016	17524	0	8640	30053	25255	29368	20040
2017	16762	0	9360	30204	24876	29075	19456
2018	16000	0	10080	30355	24503	28784	18851
2019	15238	0	10800	30507	24135	28496	18222
2020	15238	0	11520	30659	23773	28211	18496
2021	15238	0	12240	30812	23417	27929	18773

5. Discussion

5.1 Spot analysis

Considering the estimated operating cost and operating revenue, this aircraft should be parked fourteen years after entering in operation, at $t = t_a$ (Fig.5), because at this time $C_{opr} = R_{opr}$. This first parking decision could be postponed if a new revenue opportunity (R_{opp}) takes place, estimating its initial value should be the same as the operating revenue when the aircraft was just delivered, considering the most favorable scenario. If this financial condition happens, the aircraft could remain active or be returned to operations for nine years more, until $t = t_b$, when $C_{opr} = R_{opp}$, and the aircraft should be parked for a second time (Fig.5, point *b*). At this time, another (R_{opp}) higher than the previous one can be considered, aiming to relocate the aircraft to healthier market conditions. However, every time an aircraft owner or operator tries to relocate the aircraft to efficiently cope with operating revenue losses or growing operating cost conditions, this scenario may not happen. That means that the risks of financial losses at the aircraft end-of-life phase tend to increase continuously, as the aircraft decommissioning decision is postponed.

After sixteen years in operation, the aircraft market value becomes lower than the aircraft recovery revenue, at $t = t_c$ (Fig. 5). At this time, aircraft decommissioning turns into a more attractive business than selling the aircraft as a “flyer” in the second-hand market.

After $t = t_b$, the cumulative operating profit becomes lower than the profit losses for not decommissioning the aircraft and sending it to parting-out, indicating that aircraft decommissioning should be compulsory. After this point the aircraft may remain in service, making no profit, for other reasons, such as keeping the air carrier service level.

5.2 Global analysis

This case study shown in Table 2 confirmed that as the aircraft reaches closer to its mid-life, around fourteen years, the increasing operating costs and the decreasing operating revenues would both determine the appropriate moment to park the aircraft or to relocate it at another business condition, expecting higher operating revenues or lower operating costs. Aircraft parking and preservation costs influence how much time an aircraft can remain inactive before deciding between returning the aircraft to active service or decommissioning it. If the aircraft is decommissioned, this parking and preservation cost should be deduced from the aircraft recovery revenues, which determines the aircraft recovery process profitability. The dynamics of these costs and revenues drive the aircraft parking, market relocation, retirement and decommissioning decision-making processes. Thus, they should be continuously monitored and assessed by commercial aircraft owners and operators in order to ensure value creation at the aircraft end-of-life phase.

Besides the increasing costs incurred while an aircraft remains parked and preserved, its current market value is strongly affected by the air travel demand fluctuations and macroeconomic conditions, being susceptible to appreciation and depreciation trends. These internal and external contexts should also be monitored by aircraft owners and operators, aiming to support the decision of when is the “best” moment to decide to decommission an aircraft and submit it to the recovery process, if its return to active service does not become a profitable alternative. Unplanned decommissioning decision-making may lead to significant risks of financial losses due to commercial aircraft retirement increasing trends and fleet renewal policies. While the active fleet of a specific aircraft model decreases, two significant outcomes are usually expected: (1) the depreciation of the aircraft market value of the remaining active fleet, because newer and more efficient aircraft models are available; and (2) the decreasing of business opportunities and value creation possibilities, because of the decreasing demand for second-hand reusable aircraft parts, such as engines, landing gear, auxiliary power unit (APU), avionics, and the market value of these second- hand parts also face depreciation effects.

Taking into account all these results and the previously described boundary conditions, we may argue that appropriate aircraft end-of-life phase management can be seen as a complementary strategy to keep an efficient, competitive and profitable long-term fleet capacity planning.

5.3 Sensitivity analysis

The mathematical model proposed in Section 3 was tested to demonstrate how changes in the input parameters may affect the stakeholders' decision-making concerning the appropriated time to park the aircraft, relocate it in another market condition, and finally decommissioning the aircraft and sending it to the parting-out process.

The first scenario was simulated estimating new operating costs 20% higher and lower than the base value used in the case study (C_{opr}' = 1.20 x C_{opr} and C_{opr}'' = 0.80 x C_{opr}), while keeping its same operating profit (P_{opr}' = P_{opr}'' = P_{opr} = R_{opr} – C_{opr}), as seen in Figure 10. The results are show in Figures 11 and 12, respectively.

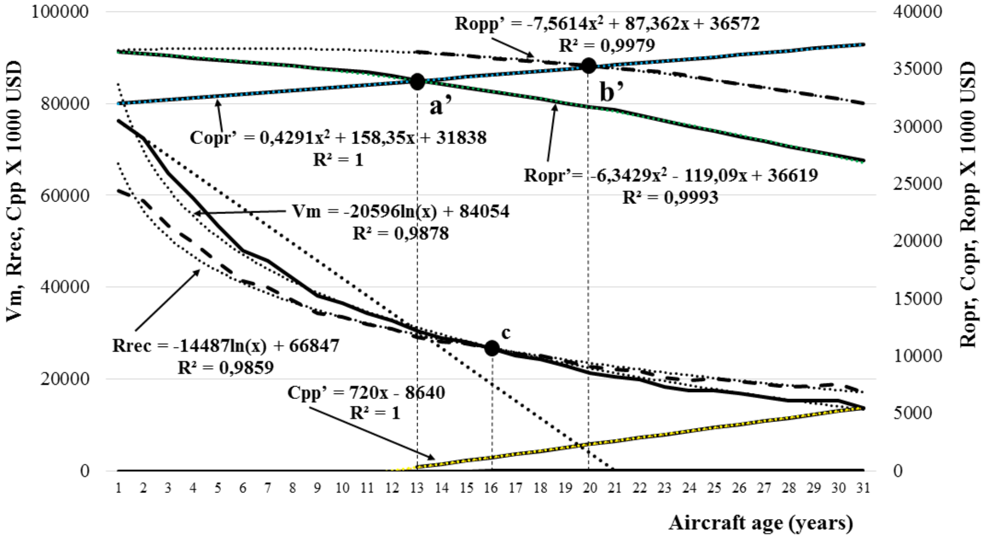

Figure 11 - Dynamics of costs and revenues affected by a 20% increase in the operating cost and steady operating profit. Source: The author

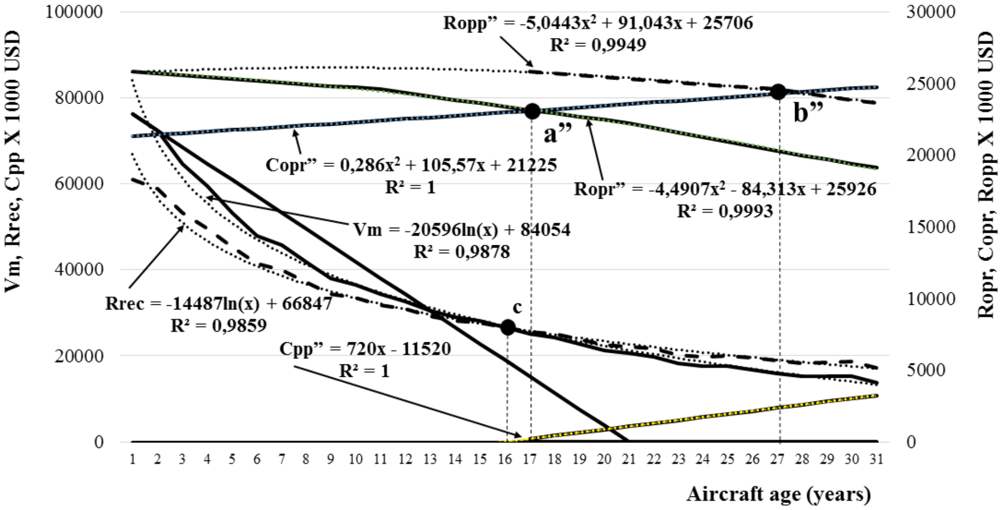

Figure 12 - Dynamics of costs and revenues affected by a 20% decrease in the operating cost and steady operating profit. Source: The author

The second scenario was also based in the case study estimating two decreasing steps in the operating profit (P_{opr}' = 0.75 x P_{opr} and P_{opr}" = 0.50 x P_{opr}), while keeping its same operating cost (C_{opr}' = C_{opr}" = C_{opr}), as seen in Figure 10. No increasing steps for the operating profit was considered because the base case study was built considering the U.S. carriers' average operating profitability, which is the highest in the globe. The results are show in Figures 13 and 14, respectively.

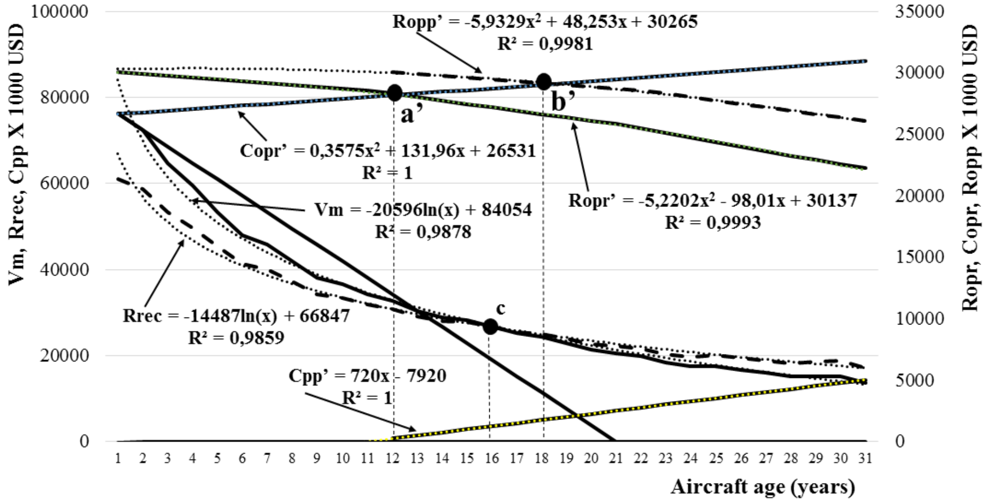

Figure 13 - Dynamics of costs and revenues affected by a 25 % decrease in the operating profits and steady operating cost. Source: The author

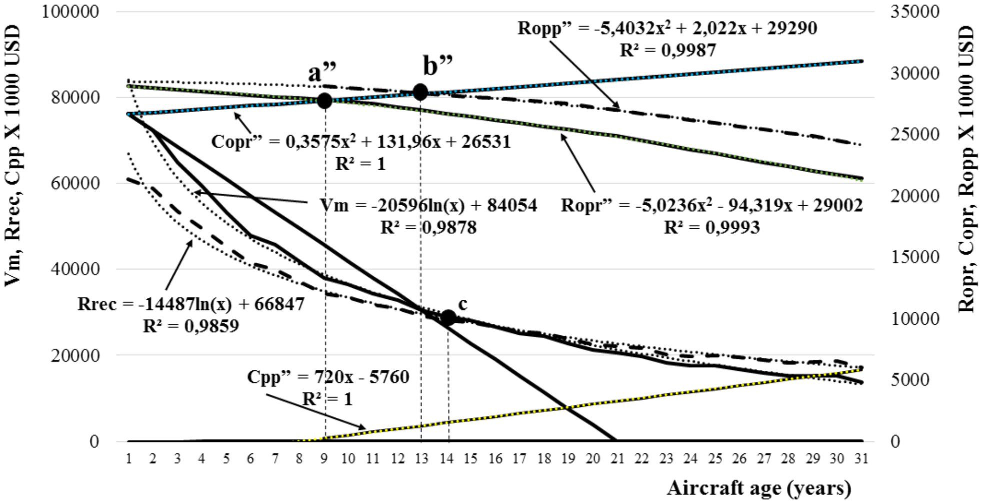

Figure 14 - Dynamics of costs and revenues affected by a 50% decrease in the operating profits and steady operating cost. Source: The author

Taking into account these two scenarios previously described we can note that C_{opr}, R_{opr} and R_{opp} are the only input variables affecting the decision-making problem. For this reason, the sensitivity analysis was done neglecting the input variables R_{rec}, C_{pp} and V_m. Considering the first scenario (Fig. 11 and 12), one may note that the decision-making points **a** (aircraft's first parking time) and **b** (aircraft's second parking time) both move forward to points **a**' and **b**', respectively, as the operating cost increases ($C_{opr}' > C_{opr}$), and the operating profits still the same from the case study ($P_{opr}'' = P_{opr}' = P_{opr}$). Contrarily, points **a** and **b** points move backward to **a**" and **b**", respectively, as the operating cost decreases ($C_{opr}'' < C_{opr}$), and the operating profits remain the same from the case study. These behaviors are shown in Figure 15.

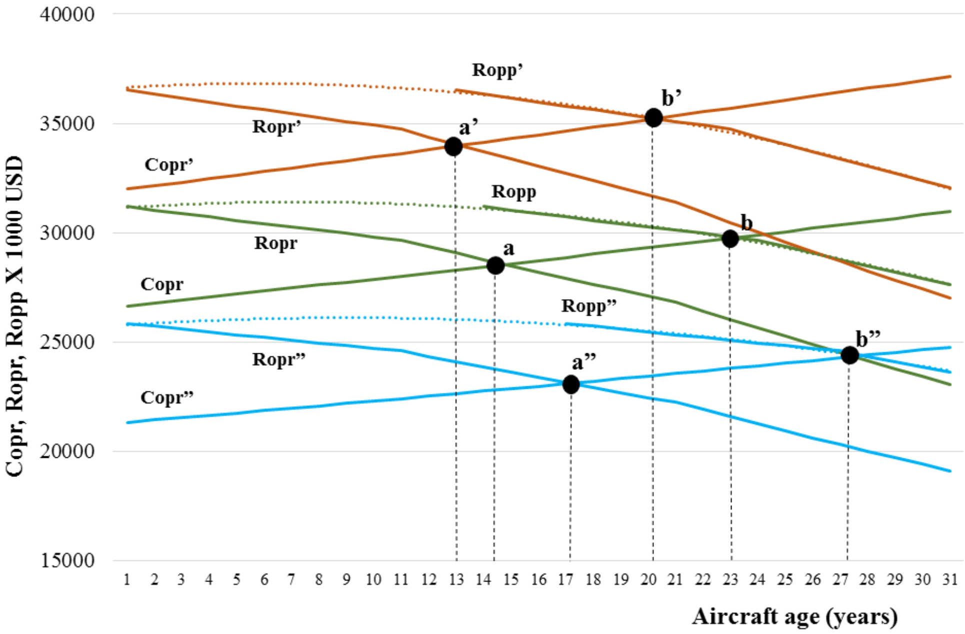

Figure 15 - Sensitivity analysis for both increasing and decreasing operating costs against steady operating profits. Source: The author

Analyzing Fig. 15, it is possible to conclude that increasing operating cost causes the aircraft’s first and second parking times (points **a**’ and **b**’) being both anticipated, and the aircraft business life-cycle is reduced by two years in relation to the case study. In the other hand, decreasing operating cost results in postponing the aircraft’s first parking time (point **a**”) by three years, and extends the gap until the aircraft’s second parking time (point **b**”), increasing the aircraft business life-cycle by one year in relation to the case study.

Based on the second scenario results (Fig. 13 and 14), it is possible to note that the decision-making points **a** (aircraft’s first parking time) and **b** (aircraft’s second parking time) both move backward to points **a**’ and **b**’ or **a**” and **b**”, as the operating profit successively decreases ($P_{opr}'' < P_{opr}' < P_{opr}$), and the operating costs still the same from the case study ($C_{opr}'' = C_{opr}' = C_{opr}$). These behaviors can be seen in Figure 16.

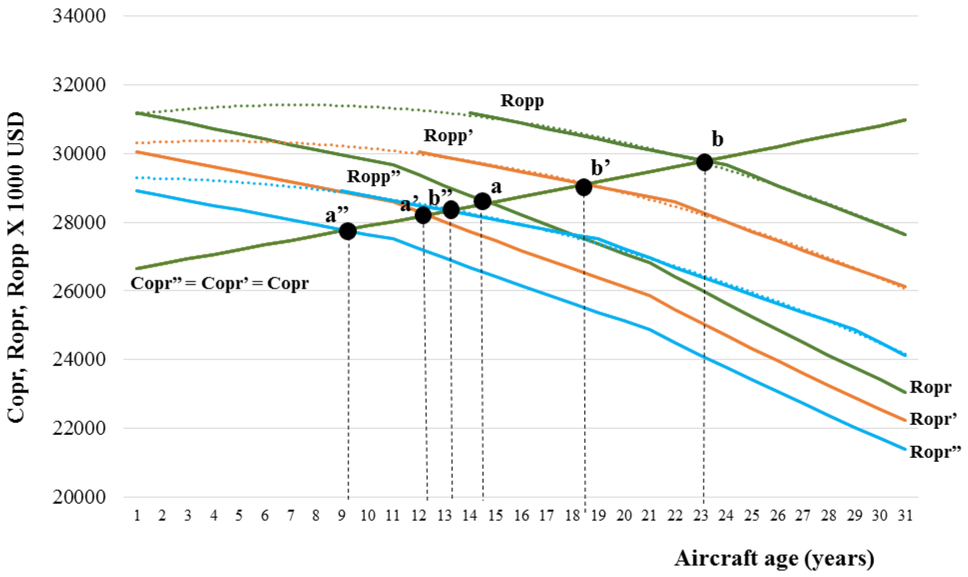

Figure 16 - Sensitivity analysis for decreasing operating profits against steady operating costs. Source: The author

Analyzing Fig.16, one may conclude that decreasing operating profit causes the aircraft’s first and second parking times (points **a**’ and **b**’ or **a**” and **b**”) being both anticipated, and the aircraft business life-cycle is reduced by three or five years, respectively, as the operating cost remains constant in relation to the case study ($C_{opr}'' = C_{opr}' = C_{opr}$).

Summarizing all these previous observations, it is possible to conclude that the appropriated time to take the decision of parking an aircraft, relocating it in more profitable market condition, decommissioning it, and sending it to the parting-out process is influenced by the feasible estimations of C_{opr}, R_{opr}, R_{opp} and C_{pp}, and by the dynamics changes these input variables suffer along the aircraft business life-cycle.

Finally, one may observe that the linear regression used to generate all the functions representing the dynamics of costs and revenues along the time returned very high R^2 values (close or equal to 1), as can be seen in Figs. 10, 11, 12, 13 and 14. The main reason for that is the reduced data sampling available to each input variables. These results can be enhanced once larger sampling becomes available.

6. Concluding remarks and suggestions for future research agenda

Aircraft end-of-life phase management is a novel research area, which can explain the low number of publications dedicated to it. The current researchers and practitioners are focused on: (1) providing literature reviews; (2) developing aerospace material recycling technologies; (3) developing aircraft parting-out efficient strategies; (4) discussing and planning aircraft end-of-life phase at its early design phase; and (5) disclosing best practices in aircraft end-of-life phase management. Thus, there is a significant research gap regarding end-of-life aircraft cost-benefit financial analysis in order to better support commercial aircraft parking, market relocation, retirement, and decommissioning decisions. The present study aims to fulfill this gap by proposing a mathematical model to assist commercial aircraft owners and operators improving their decision-making process, taking into consideration the end-of-life aircraft financial concerns.

The proposed model was applied to the case study of the Boeing aircraft model 747-400. This case study is considered by the authors as a first trial to simulate the dynamics of the main expected costs and revenues incurred during the entire business life-cycle of a commercial aircraft, which includes its end-of-life phase. It was based on a single sample aircraft model, considering the limitations of access to publicly disclosed data. This first simulation produced output data that actually confirms that the commercial aircraft age at retirement is around 27 years, as disclosed by IATA(2016).

The referred model was submitted to a sensitivity analysis to simulate how the end-of-life decision-making process is affected when changes in the principal costs and revenues are considered. The first scenario revealed that increasing operating costs against steady operating profits results in anticipated aircraft's first parking time and reduces the aircraft business life-cycle. In the other hand, decreasing operation costs against steady operating profits causes postponing the aircraft's first parking time and extends its business life-cycle. The second scenario showed that reducing operating profits below its maximum value against steady operating costs also anticipates the aircraft's first parking time and reduces its business life-cycle.

A dedicated case study can be simulated in the future to represent airlines' actual cost-benefit financial analysis regarding aircraft parking, market relocation, retirement and decommissioning decision-making. It would be possible because these companies have full records of these costs and revenues. If historical data of recovery revenues of specific aircraft model fleets are also available, it can be used to measure the productive efficiency of this recovery process using data envelopment analysis.

This model can be used by aircraft fleet lessors to analyze their strategies regarding fleet planning during the aircraft business life-cycle. Just like the operating revenues, leasing revenues reduce significantly while the aircraft ages. This behavior should be monitored by these companies, in order to support the decision-making regarding relocating a specific aircraft into another market condition that could result in higher leasing profit margins. If no profitable market relocation is feasible, then leasing companies should be aware of aircraft market value depreciation and value recovery losses, as they postpone the aircraft retirement and decommissioning decision.

This proposed model can also be adapted to analyze the aircraft manufacturer's strategies affecting their aircraft business life-cycle. Instead of considering operating revenues, they can take into account the after-market technical support revenues (i.e., maintenance, spare parts supply, and personal training). These are fixed costs to airlines but represent the primary revenue sources for aircraft manufacturers, considering the aircraft business life-cycle as a whole. This kind of revenue tends to increase as the aircraft ages but can be optimized by the aircraft manufacturer during the aircraft early design, aiming to reduce its total cost of ownership for airlines and other aircraft owners. Besides all the efforts to reduce fuel consumption, fuel venting, exhaust emissions, and aircraft noise, the reduction of end-of-life management cost may turn into the newest frontier for competitiveness between the aircraft manufacturers for the next decades.

Among the recommended strategies to increase value extraction at the commercial aircraft end-of-life phase, the aircraft manufacturers may invest in developing Design for Environment solutions, aiming to: (1) reduce aircraft parking and preservation costs; (2) reduce aircraft disassembly and dismantling costs; (3) reduce aircraft parts and systems' upgrading costs, aiming to enhance its reuse rates; and (4) increase high-value aerospace materials recyclability rates. These strategies should be planned during the aircraft early design phase, and together they may contribute to significantly reduce the aircraft total cost of ownership. Finally, this can lead aircraft owners and operators to revisit the technical and financial criteria affecting their long-term aircraft fleet planning, considering not only its procurement, operating and maintenance costs, but also value creation possibilities during aircraft end-of-life phase.

During this research efforts it was not possible take conclusions about the cost drivers influencing the aircraft early design phase decisions. The embodiment of Design for Environment methodologies is novel challenge faced by the aerospace industry, and there are no costs estimation available that could be used to develop a systematic cost-benefit analysis, similar to that one proposed for aircraft end-of-life phase. Once available, this kind of data will made possible to compare the costs and benefits of the commercial aircraft green design, considering the possibilities of value creation to aircraft manufacturers, owners and operators. Design for Environment solutions aiming to reduce the aircraft end-of-life phase costs, rather than direct operating costs, can turn into a new cornerstone for the global aerospace industry, considering its fierce and long-lasting competition for aircraft efficiency improvements.

The present research is a first attempt to propose both theoretical and mathematical backgrounds to discuss the commercial aircraft business life-cycle management problems, from a cost-benefit financial analysis basic approach. Notwithstanding the core limitation of having access to field data regarding the principal costs and revenues affecting the aircraft end-of-life phase management, the proposed model produced results that are consistent with the current practices and aircraft retirement trends, considering the analysis from Forsberg (2015) and IATA (2016). This basic approach can be enhanced to provide more detailed and accurate analysis, depending on the decision maker’s specific interests.

During this research was not possible to fully study the aircraft recovery process due the lack of actual data regarding its costs and revenues of this process. It was necessary to take some reasonable assumptions about these data, based on the aircraft market value, and considering the recovery process’ leverage potential (Navin-Chandra, 1994).

Additionally, it was not feasible to provide a complete analysis of the financial impacts of the implementation of Design for Environment methodologies in the aircraft early design phase on the profitability of the aircraft end-of-life phase management. The aerospace industry is not yet experienced in this implementation, which makes more difficult generating and having access to actual costs and revenues data to develop a mathematical model. Under these conditions the present research effort did not reach the initial purpose of identifying and discussing the core correlations between the costs of implementation Design for Environment methodologies in commercial aircraft early design and its potential benefits of Total Cost of Ownership reduction during its whole business life-cycle and value extraction opportunities at the aircraft end-of-life phase management.

Considering all these research contributions and limitations, it worths to propose the following future works:

(1) Once available, costs and revenues field data coming from airlines, leasing companies, and aircraft manufacturers' business operations will make possible enhancing the mathematical model to have more accurate information to develop profit-driven strategies for the aircraft end-of-life phase management. These enhanced models can be adopted as a complementary supporting tool for a more efficient long-term fleet planning, considering peculiarities of each aircraft owner or operator and the varying contexts of the air travel global market.

(2) More time, investing, and R&D are needed to develop Life Cycle Assessment and Design for Environment methodologies in the aerospace industry, both taking into account cost-benefit financial analysis of the aircraft business life-cycle management, besides aiming to reach the legal targets of environmental footprint reduction and safety requirement compliance. Accurate estimates of the aircraft Total Cost of Ownership during its early design phase (including its end-of-life value extraction opportunities), may become another decisive parameter for decision makers when purchasing, leasing and retiring commercial aircraft that "best" fits to their long-term fleet planning and business model.

(3) Addition investigation is necessary to comprehend better the influence of the size of retired fleets on the aircraft recovery revenue (R_{rec}) along the time. Considering the retirement trends for a specific aircraft model, one may suppose that there will be a minimum size of the remaining active fleet, below which the business opportunities for the second-hand parts remarketing will not be attractive. Once this minimum is achieved, the leverage potential of the aircraft recovery process declines according to an ignored manner. We consider it rash to arbitrate this number to run the proposed model. Taking this limitation into account, the proposed mathematical model does not consider this decreasing effect on R_{rec} along the time when running the model, preventing additional unknown bias affecting the results.

(4) The sensitivity analysis can be also applied to better comprehend how much the aircraft end-of-life phase management decisions are affected by the available costs and revenues data. It can make evident several possibilities for better

planning where, how and for how long an aircraft can be profitably operated. The aircraft business life-cycle can be appropriately planned, aiming to extract considerable value from it at its end-of-life. Aircraft early decommissioning decision of in-production models can be trigged by operating costs reduction, fleet renewal or right-sizing fleet capacity policies from aircraft owners and operators, such as those currently affecting Airbus A320 (former models) and A380 (former and new models), Boeing 737 (former and new models) and Embraer ERJ 170, 175, 190 and 195 (former and new E1 jets). These cases can also be submitted to a sensitivity analysis aiming to better support the aircraft end-of-life phase decisions.

REFERENCES

Ackert, S., 2011. The relationship between an aircraft value and its maintenance status. URL: http://www.aircraftmonitor.com/industry-reports.html. Online; accessed February 2018.

Ackert, S., 2012. Basics of Aircraft Market Analysis. URL: http://www.aircraftmonitor.com/industry-reports.html. Online; accessed February 2018.

Airbus, 2008a. Process for advanced management of end-of-life of aircraft. URL: http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=ACADEMY_PAMELA.pdf

Airbus, 2008b. Design for environment. URL: http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=ACADEMY_DesignforEnvironment.pdf. Online; accessed February 2018.

Asiedu, Y., Gu, P., 1998, "Product life cycle cost analysis: state of the art review, *International Journal of Production Research*, 36, 4, pp. 883-908.

Asmatulu, E., Overcash, M., Twomey, J., 2013, "Recycling of aircraft: State of the art in 2011", *Journal of Industrial Engineering*, ID 960581.

Böckmann, M.G., Schmitt, R., 2012, Methodology for ecological and economical aircraft life cycle analysis", *19th CIRP International Conference on Life Cycle Engineering*, Berkeley.

Boeing, 2018. Current Market Outlook – 2017-2036. URL: http://www.boeing.com/resources/boeingdotcom/commercial/market/current-market-outlook-2017/assets/downloads/cmo-2018-2-22.pdf. Online; accessed February 2018.

Brundtland, G.H., 1987. Our Common Future, *Report of the UN Commission on Sustainable Development*, Oxford University Press.

Burt, D.N., Norquist, W.E., Anklesaria, J., 1990. Zero base pricing: achieving world class competitiveness through reduced all-in-costs, Chicago, Probus Publishing Co.

Camelot, A., Baptiste, P., Mascle, C., 2013, "Decision support tool for the disassembly of reusable parts on an end-of-life aircraft", *5th Industrial Engineering and Systems Management Conference*, Morocco, IESM.

Carberry, W., 2008, Airplane recycling efforts benefit Boeing operators, *Boeing AERO Magazine QRT, 4, (8), pp. 6-13.*

Castagne, S., Curran, R., Rothwell, A., Price, M., Bernard, E., Raughunathan, S., 2004, "A generic toll for cost estimating in aircraft design", *AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum*, Chicago, Illinois.

Cavinato, J.L., 1992, "A total cost/value model for supply chain competitiveness", Journal of Business Logistics, 13, 2, pp. 285-301.

Cavinato, J.L., 1991, "Identifying interfirm total cost advantages for supply chain competitiveness", *International Journal of Purchasing and Materials Management*, Fall, pp.10-15.

Clark, P., 2007, Buying the Big Jets – Fleet Planning for Airlines, 2nd ed., Ashgate.

Cunningham, S.W., de Haan, A.R.C., 2006, "Long-term forecasting for Sustainable Development: air travel demand for 2050", *International Journal Environment and Sustainable Development*, 5 (3), pp. 297-314.

Curran, R., Price, M., Raghunathan, S., Benard, E., Crosby, S., Castagne, S., Mawhinney, P., 2005, "Integrating aircraft cost modeling into conceptual design", *Concurrent Engineering: Research and Applications*, 13, 4, pp. 321-330.

Das, S.K., Kaufman, J.G., 2008, "Recycling aluminum aerospace alloys", *Advanced Materials and Processes*, 166 (3), pp. 34.

Dayi, O., Afsharzadeh, A., Mascle, C., 2016, "A lean based process planning for aircraft disassembly", *International Federation of Automatic Control*, IFAC-PapersOnLine 49 (2), 54–59.

Dhillon, B.S., 2010, Life Cycle Costing for Engineers, CRC Press.

Dobler, D.W., Burt, D. N., 1996. Purchasing and Supply Chain Management, sixth edition, McGraw-Hill.

Doherty, K., 1996. "What goes around … comes back" (Reverse Logistics), *U.S. Distribution Journal*, October, 223 (10).

Ellram, L., 1993, "Total Cost of Ownership: Elements and Implementation", *International Journal of Purchasing and Materials Management*, Fall, pp. 3-11.

Ellram, L., 1994 "A taxonomy of total cost of ownership models", *Journal of Business Logistics*, 15, 1, pp. 171-191.

Ellram, L., 1995, "Total cost of ownership – An analysis approach for purchasing", *International Journal of Physical Distribution and Logistics Management*, 25 (8), 4–23.

Ellram, L., Siferd, S.P., 1993, "Purchasing: the cornerstone of the total cost of ownership concept", *Journal of Business Logistics*, 14, 1, pp. 163-184.

Ellram, L., Siferd, S.P., 1998, "Total cost of ownership: a key concept in strategic cost management decisions", *Journal of Business Logistics*, 19, 1, pp. 55-84.

Ferrin, B.G., Plank, R.E., 2002, "Total cost of ownership models: an exploratory study", *The Journal of Supply Chain Management*, Summer, pp. 18-29.

Fiksel, J., 2009. Design for Environment – a guide to sustainable product development, second edition, McGraw Hill.

Forsberg, D., 2015. "Aircraft retirement and storage trends – economic life analysis reprised and expanded". URL:http://alljets.ch/wp-content/uploads/2015/08/Avolon-White-Paper-FInal-30-March-

2015.pdf. Online; accessed 26 November 2018.

Franz, K., Hörnschemeyer, R., Ewert, A., Fromhold-Eisebith, M., Böckmann, M. G., Schmitt, R., Petzoldt, K., Schneider, C., Heller, J. E., Feldhusen, J., Bücker, K., Reichmuth, J., 2012, “Life cycle engineering in preliminary aircraft design”, *19th CIRP International Conference on Life Cycle Engineering,* Berkeley.

Geiger, D.R., 1999, “Practical issues in cost driver selection for managerial costing systems”, *The Government Accountants Journal*, (48:3), pp. 32-39.

IATA, 2015. Airline Profitability Strengthens Further – IATA Press Release No. 26, 8 June 2015. URL: https://www.iata.org/pressroom/pr/Pages/2015-06-08-03.aspx.. Online; accessed 26 November 2018.

IATA, 2016a. IATA & Aircraft Decommissioning, *Aircraft Fleet Recycling Association Annual Meeting & Aviation Suppliers Association Annual Conference,* Las Vegas, Nevada, USA, June 26–28.

IATA, 2016b. Aircraft acquisition cost and depreciation. URL: https://www.iata.org/publications/Documents/Airline-Disclosure-Guide-aircraft-acquisition.pdf; Online, accessed February 2018.

IATA, 2018. Best Industry Practices for Aircraft Decommissioning (BIPAD), Montreal–Geneva - 1st edition. URL: https://www.iata.org/publications/Documents/BIPAD.pdf. Online; accessed 19 December 2018.

ICAO, 2016. ICAO DOC 9750 - 2013 – 2028 Global Air Navigation Capacity and Efficiency Plan, Montreal, Quebec, Canada. URL: https://www.icao.int/Meetings/anconf12/Documents/Draft%20Doc%209750.GANP.en.pdf. Online; accessed 26 November 2018.

ICAO, 2017. Airlines Operating Costs and Profitability – *ICAO Seminar on Airline Economics*, Tehran, Iran, February 20–23. URL: https://www.icao.int/MID/Documents/2017/Aviation%20Data%20and%20Analysis%20Seminar/PPT3%20-20Airlines%20Operating%20costs%20and%20productivity.pdf. Online; accessed 26 November 2018.

Jackson-Jr., D. W., Ostrom, L.L., 1980, “Life cycle costing in industrial purchasing”, *Journal of Purchasing and Materials Management*, Winter, 8-12.

Johanning, A., Scholz, D., 2013. “A first step towards the integration of life cycle assessment into conceptual aircraft design”, *Deutscher Luft- und Raumfahrtkongress,* DocumentID: 301347.

Johansson, G., 2002, “Success factors for integration of ecodesign in product development: a review of state of the art”, *Environmental Management and Health,* 13, 1, pp. 98-107.

Johnson, V.S., 1990, “Minimizing life cycle cost for subsonic commercial aircraft”, *Journal of Aircraft*, 27 (2), 139-145.

Kaufman, R., 1969, “Life Cycle Costing: Decision making tool for capital equipment acquisitions", *Journal of Purchasing*, 5, pp. 16-31.

Keivanpour, S., Ait-Kadi, D., 2016, "An integrated approach to analysis and modeling of end of life phase of the complex products", *International Federation of Automatic Contro*l – IFAC–PapersOnLine 49 (12), 1892–1897.

Keivanpour, S., Ait-Kadi, D., 2017a, "Modelling end of life phase of the complex products: the case of the end of life aircraft", *International Journal of Production Research*, 55 (12), 3577–3595.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2013, "Toward a strategic approach to end-of-life aircraft recycling projects a research agenda in transdisciplinary context", *Journal of Management and Sustainability*, 3 (3), 76–94.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2014a, "Toward a decision tool for eco-design strategy selection for aircraft manufacturers considering stakeholders value network", *SAE International Journal of Materials and Manufacturing*, 7 (1), 73-83.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2014b, "A conceptual framework for value chain analysis of end of life aircraft treatment in the context of sustainable development", *Society of Automotive Engineers - SAE technical paper* 2014-01-2232.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2015a, "Towards a projection model for estimation of end of life aircrafts", *Industrial Engineering and Operations Management* (IEOM), *Proceedings of the International Conference*, Dubai, IEEE , pp. 1-7.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2015b, "The critical success factors for end of life aircraft treatment projects", *The Journal of Modern Project Management*, 2 (3).

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2015c, "End of life aircrafts recovery and green supply chain (a conceptual framework for addressing opportunities and challenges)", *Management Research Review*, 38 (10), 1098–1124.

Keivanpour, S., At-Kadi, D., Mascle, C., 2017b, "End-of-life aircraft treatment in the context of sustainable development, lean management, and global business", *International Journal of Sustainable Transportation*, 11(5), 357-380.

Latremouille-Viau, J., Baptiste, P., Mascle, C., 2010, "Airframe dismantling optimization for aerospace aluminum valorization", *Frontiers of Assembly and Manufacturing*, Springer Berlin Heidelberg, pp. 157-169.

Lyte, B., 2016. How are planes decommissioned, and how much value can be salvaged from their parts? URL: https://www.flexport.com/blog/decommissioned-planes-salvage-value/. Online; accessed 26 November 2018.

Mascle, C., 2013, "Product design for rebirth: Application to aircraft life cycle modeling", *Supply Chain Forum: An International Journal*, 14 (2), 70-83.

Mascle, C., Baptiste, P., Sainte Beuve, D., Camelot, A., 2015, "Process of advanced management and technologies of aircraft EOL", *Procedia CIRP* 26, 299-304.

Monczka, R.M., Trecha, S.H., 1988. “Cost-Based Supplier Performance Evaluation,” *Journal of Purchasing and Materials Management*, 24, 1, pp. 2-8.

Morimoto, R., Agouridas, V., 2009, “Supporting aircraft manufacturers to formulate and implement sustainable development strategies systematically”, *Transportation Research Record: Journal of the Transportation Research Board*, 2106, pp. 12-19.

Navin-Chandra, D., 1994, “The recovery problem in production design”, *Journal of Engineering Design*, 5 (1), 65-86.

Ribeiro, J.S., Gomes, J.O. 2014, “A framework to integrate the end-of-life aircraft in preliminary design”, *Procedia CIRP* 15, 508-513.

Ribeiro, J., Gomes, J., 2015, “Proposed framework for end-of-life aircraft recycling”, *Procedia CIRP* 26, 311-316.

Rogers, D., Tibben-Lembke, R.S., 1999. Going backwards: Reverse Logistics Trends and Practices, Pittsburg, PA, Reverse Logistics Executive Council.

Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., 2015, “Sustainability assessment of dismantling strategies for end-of-life aircraft recycling”, *Resources, Conservation and Recycling*, 102, 163–169.

Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., 2016a, “Towards a sustainable disassembly/dismantling in aerospace industry”, *Procedia CIRP* 40, 156-161.

Sabaghi, M., Mascle, C., Baptiste, P., 2016b, “Evaluation of products at design phase for an efficient disassembly at end-of-life”, *Journal of Cleaner Production*, 116, 177-186.

Shields, M.D., Young, S.M., “Managing product life cycle costs: an organizational model”, *Journal of Cost Management*, 5, 3, pp. 39-52.

Siles, C., 2011. “Aide à la décision pour la gestion d’un parc d’avions en fin de vie”. Master dissertation, École Polytechnique de Montréal.

Spoors, A., 2016, Plane & Simple, *Materials Handling and Recycling*, CIWM, September, pp. 48-50.

Srivastava, S. K., Srivastava, R. K., 2006, “Managing product returns for reverse logistics”, *International Journal of Physical Distribution & Logistics Management*, 36, 7, pp. 524- 546.

Srivastava, S. K., 2007, “Green supply-chain management: A state-of-the-art literature review”, *International Journal of Management Reviews*, 9, 1, 53-80.

TeamSAI Consulting, 2014. State of the aircraft dismantling and recycling business.

Towle, I., Johnston, C., Lingwood, R., Grant, P.S., 2004. The aircraft at end of life sector: a preliminary study. URL: http://users.ox.ac.uk/~pgrant/Airplane_end_of_life.pdf. Online; accessed 26 November 2018.

Tibben-Lembke, R.S., 1998, “The impact of Reverse Logistics on the Total Cost of Ownership”, *Journal of Marketing Theory and Practice*, 6:4, 51-60.

Thokala, P., 2009. “Life cycle cost modelling as an aircraft design decision support tool”. *University of Southampton, School of Engineering Sciences, Doctoral Thesis.*

van Heerden, D., Curran, R., 2010. Encyclopedia of Aerospace Engineering, Eds. Blockley, R. and Shyy, W. John Wiley & Sons, Ltd. chapter 306 - Value extraction from end-of-life aircraft. pp. 3715-3726.

Zahedi, H., Mascle, C., Baptiste, P., 2015, “A conceptual framework toward advanced aircraft end-of-life treatment using product and process features”, *International Federation of Automatic Control* - IFAC- PapersOnLine 48 (3), 767-772.

Zahedi, H., Mascle, C., Baptiste, P., 2016, “Advanced airframe disassembly alternatives an attempt to increase the afterlife value”, *Procedia CIRP* 40, 168-173.