HIGH SCHOOL EDITION
Journal of Student Research

Towards Sustainable Management of End-of-Life Aircraft: Challenges, Innovations, and Circular Economy Perspectives

Yejun Park[1] and Nicholas Elefther[#]

[1]Bergen County Technical High Schools Teterboro, USA
[#]Advisor

ABSTRACT

The rapid growth of the aerospace industry, marked by a doubling of worldwide passenger and cargo traffic by 2030, causes concern for the management of end-of-life (EOL) aircraft. As population and demand increase, waste management is always a huge concern, and end-of-life materials of aircraft can have a significant impact on the environment without proper disposal, treatment, and processing. This study explores the stages of the EOL process and emerging strategies and technologies for addressing environmental and economic challenges within the aerospace sector. In addition, this study reveals the pivotal role of composite materials in modern aircraft design, which offers a higher performance edge but poses a recycling challenge. Current practices in aircraft recycling and recovery include the PAMELA project and "R" strategies. These practices were examined alongside emerging innovations such as pyrolysis and digital twin technology to examine the efficacy of the methods. In addition, the circular economy principle was explored, advocating for a shift towards sustainable resource utilization and waste reduction. In conclusion, numerous challenges still persist in managing EOL aircraft materials, therefore there is still a need for continuous research to create a more eco-friendly aerospace industry.

Introduction

Current studies show that worldwide passenger traffic will grow by approximately 5.1% and cargo traffic will grow by approximately 5.6% per year until 2030. Due to this increase in air transportation, the amount of aircraft around the world will nearly double over the following two decades. One issue that comes with this growth that cannot be ignored is the matter of managing end-of-life (EOL) aircraft in the aerospace industry. By 2050, the aviation sector is expected to generate about 500,000 tonnes of accumulated carbon fiber-reinforced plastic waste from the production and EOL phase (Meng et al., 2020). This phase is the last of seven in an aircraft's life cycle, the others being materials, design, supply chain, manufacturing, transport, and aircraft operations (Ribeiro & Gomes, 2015). The EOL process is where components will be allocated for reuse, recycling, disposal, and recovery profit (Cong et al., 2019). Although the rapid growth of the aerospace industry will lead to more efficient and sophisticated aircraft, there will also be detrimental social and environmental implications that follow. The end-of-life process has been given little to no attention in the past and the issue has been neglected for a long time. However, due to the severe environmental effects caused by this ignorance, more and more research has been done to bring awareness and development to the EOL stage.

Up until a few years ago, end-of-life aircraft were deposited in landfills around the world, contributing to immense amounts of environmental pollution. In the early 2000s, Airbus and Boeing, two of the largest aircraft manufacturers in the world, started the PAMELA project. This acronym stands for Process for Advanced Management of End-Of-Life Aircraft. Along with PAMELA, new ways of managing EOL aircraft began to emerge as awareness surrounding the importance of EOL management grew.

Composite Materials in Aerospace Engineering

During this age of rapidly growing technology, the modern aerospace industry has started to become increasingly sophisticated, majorly as a result of the use of composite materials. Composite materials have revolutionized the industry by providing several advantages such as greater strength and stability while also being relatively lighter than conventional uses of these raw materials. Essentially, composite materials are materials that are composed of both sturdy materials which can bear lots of weight, and weaker materials as shown in Figure 1. The stronger material is also known as the reinforcement while the weaker material is called the matrix. The reinforcement serves to give the composite material its stability and rigidness while the matrix contributes to the overall shape of the material and absorbs any initial force acted upon it (Mrázová, 2013).

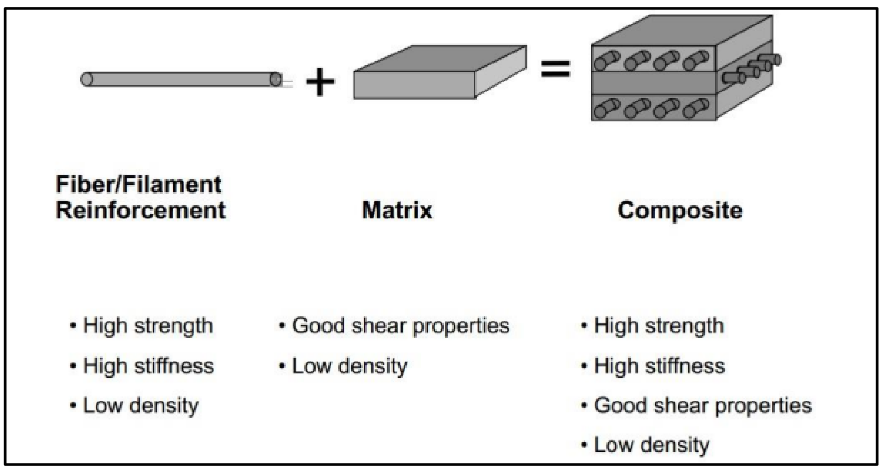

Figure 1. Parts of a Composite and their Attributes (Mrázová, 2013)

The integration of composite materials in the aerospace industry introduces several significant benefits. For instance, the use of composite materials results in cost reduction and weight reduction. According to a Federal Aviation Administration Advanced Materials Research Program report, approximately $100-300 of service life fees is saved for every pound of weight saved on a commercial aircraft (Mrázová, 2013). Moreover, the use of composites yields greater strength and the prolonged lifespan of aircrafts. This extension in lifespan also cuts down on the amount of costly inspections needed for aircraft. For example, through the use of composites, Airbus has increased the service intervals of their A350XWB by six years, immensely decreasing the amount of maintenance required for the aircraft. Furthermore, composites are more resistant to fatigue and corrosion than metals.

The three most prominent composite reinforcements are fiberglass, carbon fiber, and aramid fiber. Fiberglass is a material made of a plastic matrix which is stabilized by high-quality fibres of glass. In comparison to carbon fiber, it lacks strength and stability but is much more resilient and cost-friendly (Joustra et al., 2021). On the other hand, carbon fiber-reinforced polymers are extremely strong and lightweight. Lastly, aramid fibers are sturdy synthetic fibers that are utilized in the aerospace industry, sometimes as a replacement for asbestos (Mrázová, 2013). Every composite serves different functions and possesses different properties that may apply to certain aspects of an aircraft as opposed to other composites. Therefore, the research that delves into creating the proper combination of materials is crucial for the advancement of the aerospace industry.

Despite these advantages, composites also have disadvantages and challenges in implementation. For instance, many composite materials are extremely expensive compared to raw materials. Furthermore, damaged composites are hard to distinguish from pristine ones (Zimmermann & Wang, 2020). Due to the rapidly increasing need for new composite materials for high-performance aircraft, more research is needed to identify which composites should be used for certain components and how different materials will be integrated to create high-quality composite materials.

Current Practices in Aircraft Recycling and Recovery

There are several practices that are currently being used for aircraft recycling and recovery, one of which is PAMELA. PAMELA incorporates the use of a three-step process approach that is concerned with EOL aircraft. This process is also referred to as the 3D approach. The first step of this practice is to decommission the aircraft. The materials would be cleaned and decontaminated, tanks would be drained, and safety procedures would be implemented. Then, individual equipment would be disassembled and parts would be isolated. Finally, the last step is to carefully dismantle the aircraft by draining the system once again, removing all valuable components, categorizing materials, and shipping certain extraneous materials to waste treatment channels (Ribeiro & Gomes, 2015).

Other effective techniques used for disassembling and recovering materials from EOL aircraft include the R method. The "R" strategies consist of reusing, repairing, recovering, remanufacturing, refurbishing, replacing, and ultimately recycling valuable materials used in the aerospace industry, as shown in figure 2 (Chatziparaskeva et al., 2022). By reusing certain components, the lifetime of the material is extended. By repairing materials, existing materials are sustained and its EOL process is delayed. Recovering materials increases the amount of times that certain parts can be used. Remanufacturing components allows for the reinforcement of composite materials to be reused. Refurbishing parts of an aircraft helps repurpose certain materials in new ways where they can find value. Replacing components with other sustainable options such as recyclable biocomposites ultimately minimizes environmental impact. Finally, recycling materials helps create an overall sustainable cycle for aircraft which inspires the development of a circular economy within the aerospace industry (Chatziparaskeva et al., 2022).

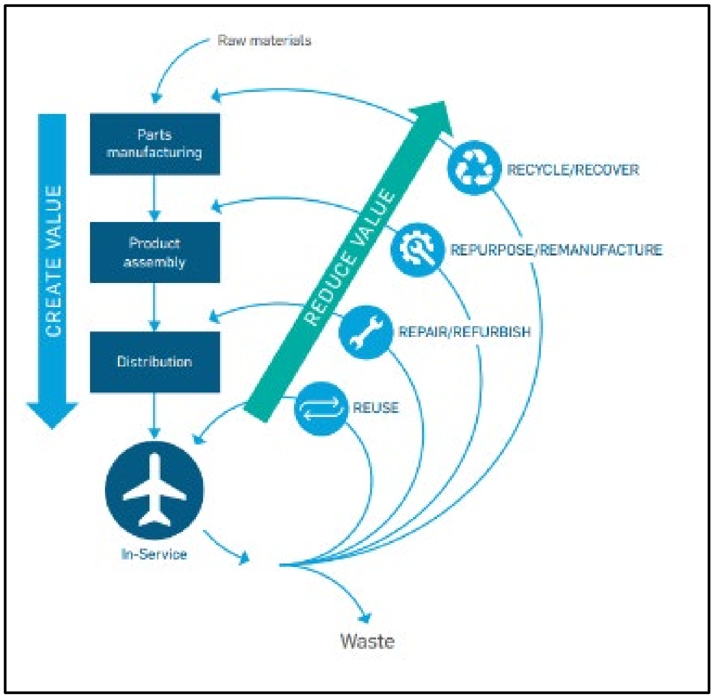

Figure 2. The Circular Economy and the "R" Strategies (Domone et al., 2021)

Challenges and Opportunities in Sustainable Aircraft Recovery

There are many challenges that come with trying to create a sustainable way of recovering aircraft. For instance, many materials cannot be reused due to concerns relating to quality drop-offs. Specifically in regard to composite materials, many fibers lose strength and the quality of their recyclate is very low in comparison to their pristine state (Domone et al., 2021). Furthermore, balancing high material reuse and low environmental implications is hard to manage as there are many factors that have to go into consideration with respect to the recovery process. However, there are opportunities and promising ways of recycling aircraft such as the use of heuristics to recover as much economic and ecological value as reasonably possible. For example, the United Kingdom and the European Commission recommend the EOL pyramid, a heuristic approach intended to pose several EOL treatments (Ribeiro & Gomes, 2015). Unfortunately, the approach lacks a quantitative backbone on which it is based, leaving room for further research and development.

Emerging Technologies and Innovations

There are many promising new technologies and innovations that could lead to a more sustainable supply chain and recovery process within the aerospace industry. Approaches such as pyrolysis, chemical treatments, and mechanical grinding are posed as some of the new possible methods of recycling valuable materials. However, there are still many limitations as much research is yet to be done on these processes. Furthermore, retaining the integrity of fibers in composite materials is still a dilemma at hand with these approaches. Another possible solution for material recycling is the cement kiln method, also known as cement co-processing. This process offers complete recovery of composite waste as energy and raw materials, with no ash residue (Bachmann et al., 2021). Several case studies have shown the cost-effectiveness and environmental benefits of the approach in industrial-scale implementations. This is a promising solution for material repurposing as lower Technology

Readiness Level (TRL) methods such as the Vitrimer method can be further researched and adopted within the industry (Krauklis et al., 2021).

A huge part of being able to optimize the recycling process is evaluating which parts of a material can be implemented into a sustainable cycle or turned into other forms of value at the end of its life. Therefore, by determining this before creating materials, manufacturers can consciously design their products to make it easier to reuse these parts or extract them for other purposes. This holds tremendous potential as the EOL stage of the recovery process would be greatly facilitated. Furthermore, new research surrounding certain materials and their overall recyclability/reusability could be extremely beneficial in advancing the recovery process as manufacturers will be able to determine which parts of a component can be repurposed without quality degradation.

Integration of Digitalization and AI in Recovery Processes

The use of digitalization and AI in recovery processes is a promising outlook for the future of the aerospace industry. Much research has yet to be done on this topic. However, certain applications have been put to use in recent times. One of these processes is called digital twin (DT). A digital twin is essentially a virtual copy of any physical product that can be used to aid product development, design optimization, performance improvement, and predictive maintenance. However, utilizing the digital twin technology without giving it detailed inputs and information needed can result in faulty simulative versions of what is being recreated. Therefore, manufacturers place DT sensors inside of a given physical system during operation so that they can gather the data needed to create an accurate model (Li et al., 2021).

The implications of DT are extremely beneficial to the aerospace industry. By using AI or algorithms to analyze the input data given to a rendered virtual model, engineers can test and apply new ways of developing and maintaining different components. Furthermore, since many products, such as aircraft and rovers, from the aeronautical sector are expensive, creating digital twins of them and simulating possible dangers or hindrances at low stakes can help optimize their real usage when the actual model is at risk. Digital twins also help facilitate the process of testing new products. While creating real-life prototypes can be costly and lead to failure, simulating certain components can help run quality checks and other physical tests at higher rates with a greater variety of design choices.

Despite these benefits, the use of digitalization in the aerospace industry comes with several limitations. For instance, the integration of DTs generally comes at high costs. The U.S. Air Force system DT budget is projected to reach between $1 and $2 trillion and further development of the technology can take up to a century or longer (Li et al., 2021). Furthermore, information technology (IT) comes with environmental costs and contributes to pollution as it is a high energy consumption practice. However, new methods such as green information technology (green IT) are emerging in order to help combat these environmental implications (Dias et al., 2022). Overall, more research is needed to discover environmentally and financially optimal ways of incorporating and reaping the benefits of digitalization and AI in a sustainable manner.

Circular Economy Principles and their Application in Aerospace Industry

A circular economy (CE) is essentially an industrial economic model that is centered around maintaining materials and other valuable resources in circulation. For instance, materials that would otherwise be put to waste in a linear business model would be reused and repurposed in CE. In other industries, circular business models have several commonalities: they advocate for the use of renewable energy sources and bio-based fuels, sustainable management of waste products, the sharing of materials between companies, the lengthening of the lifespan of products, and the optimization of maintenance, renovation, reuse, remanufacturing, and remarketing. In the context of the aerospace industry, applying a circular economy would improve environmental sustainability as well as EOL products' abilities to retain as much value as possible, as shown in Figure 3. In recent years, circular economy practices have been posed as an alternative to the linear model as prior usage of the linear model has led to repercussions such as increased pollution and deforestation, reduction of natural resources, and loss of biodiversity, among others (Dias et al., 2022).

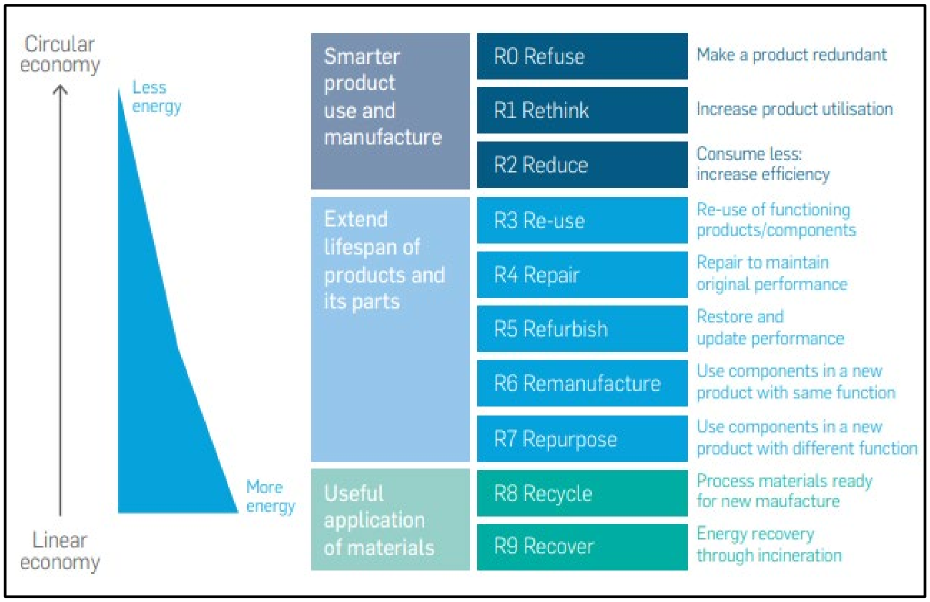

Figure 3. Steps of a Circular Economy and its Energy Consumption v. Linear Economy (Domone et al., 2021)

Components and materials generally are expensive and there are up to half a million individual parts needed to construct a large aircraft. Furthermore, many processes used within the industry itself contribute to global warming and other forms of environmental pollution. A specific cause for these high levels of pollution is the amount of carbon emissions that are generated from the aeronautical sector. Currently, only 1% of the energy consumed by the industry is renewable, indicating that most of the energy used within the sector comes from the practice of burning fossil fuels. Due to this, awareness has been growing around improving the overall sustainability and efficiency of aircraft. However, since the use of advanced materials affects the cost of manufacturing and consumes a lot of energy, the recovery of these materials is crucial. By implementing coherent ways of recovering raw materials and components, many advantages emerge such as less use of natural resources, a decrease in net pollution, an increase in job opportunities, the improvement of energy efficiency, and the stimulation of the recycled material market (Dias et al., 2022). Establishing sustainable approaches such as the circular economy can help remedy problems that pertain to the aerospace industry while simultaneously increasing the life cycle of products and optimizing the use of cost-heavy materials.

Unfortunately, there are many obstacles that currently exist with the application of a circular economy within the aerospace industry. For instance, there are technological limitations in regard to the ability to recycle composite materials and other raw materials in an efficient manner. Due to the fragile nature of many components used in the aeronautical sector, there are concerns and issues related to quality control and the materials' overall structural integrity once they have reached the EOL stage. Although the use of a circular business model would help to create a more sustainable supply chain and minimize negative effects on the environment, the incorporation of CE in other industries has proven to be a challenge. Therefore, it is imperative that further research is done on how to properly implement a circular economy within the aerospace industry.

Global Market Trends and Forecast

The total composite market is expected to grow at a compound annual growth rate of 7.3%, reaching a value of US $30 billion by 2026. The global aircraft recycling market was valued at $4 billion in 2022 and is expected to grow up to $9.7 billion by 2028, growing at a rate of approximately 15.8% per year from 2023 to 2028. According to the International Civil Aviation Organization (ICAO), the annual world air traffic is estimated to double in the next 15 years (as of 2015) with an annual growth rate of approximately 4.6%. Furthermore, by 2034, Airbus and Boeing expect to manufacture 70,635 new aircraft combined. With the increase in aircraft in the air, carbon emissions are bound to increase. To combat this, aircraft manufacturers are endeavoring to decrease the weight of the aircraft which decreases the amount of carbon dioxide that is emitted. Carbon fiber reinforced plastic (CFRP) allows for aircrafts to become extremely lightweight compared to an aircraft made of conventional metals. To put into perspective, components within the aerospace industry that incorporate CFRP into the build are usually 25-30% lighter than the same components made of conventional metals. Unfortunately, CFRP is difficult to recycle and retains a high cost to manufacture. Implementing ways to recycle CFRP is extremely crucial to the future of the aerospace industry as new CFRP costs around $33-66/kg while recycled/reused CFRP drops to around $13-19/kg (Lefeuvre et al., 2017). Since companies started to incorporate CFRP in their products, the average proportion of CFRP by aircraft in the world has grown, recently around 1% per year. Assuming that the average lifespan of an aircraft is 25 years, around 527,374 tons of CFRP waste will have been generated around the world by 2050 without the utilization of any recycling methods. Furthermore, the rate at which CFRP waste grows is projected to increase over time, highlighting the importance of creating an efficient and sustainable recycling system. In 2016, CFRP was mostly either incinerated or landfilled and rarely ever recycled. Depositing CFRP waste into landfills completely rejects the possibility of recovering any value from the materials themselves and also damages the environment. Similarly, incinerating CFRP is inefficient for recovering value and contributes to worldwide pollution. Therefore, with the projected increases in aircraft and composite material usage, it is extremely vital to find efficient techniques to recycle or recover raw materials in order to create a circular economy and sustainable supply chain within the aerospace industry.

Conclusion

As the world population continues to grow and demands for new aircraft increase, the need to address environmental damage caused by factors such as carbon emission and waste allocation steadily grows. Therefore, finding different means of relieving these issues with new technologies like composite materials and AI is very important. Furthermore, the aeronautical sector must slowly rid itself of its linear model and apply a circular economy business model in order to create a sustainable supply chain. A crucial component of the circular economy involves finding and utilizing an efficient recovery method for valuable raw materials at their EOL stage. Although many of these new promising approaches have yet to be implemented, this leaves room for further research and development to be done for the underlying objective of creating a sophisticated, eco-friendly, and innovative environment within the aerospace industry.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

Altıparmak, S. C., & Xiao, B. (2021). A market assessment of additive manufacturing potential for the aerospace industry. *Journal of Manufacturing Processes*, *68*, 728–738. https://doi.org/10.1016/j.jmapro.2021.05.072

Chatziparaskeva, G., Papamichael, I., Voukkali, I., Loizia, P., Sourkouni, G., Argirusis, C., & Zorpas, A. A. (2022). End-of-life of composite materials in the framework of the circular economy. *Microplastics*, *1*(3), 377–392. https://doi.org/10.3390/microplastics1030028

Cong, L., Zhao, F., & Sutherland, J. W. (2019). A design method to improve end-of-use product value recovery for circular economy. *Journal of Mechanical Design*, *141*(4). https://doi.org/10.1115/1.4041574

Domone, James & Bliss, Philippa & Copus, Matt. (2021). A Circular Economy for Civil Aerospace. 10.13140/RG.2.2.15380.01927.

Ibn-Mohammed, T., Mustapha, K. B., Godsell, J., Adamu, Z., Babatunde, K. A., Akintade, D. D., Acquaye, A., Fujii, H., Ndiaye, M. M., Yamoah, F. A., & Koh, S. C. L. (2021). A critical analysis of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. *Resources, Conservation and Recycling*, *164*, 105169. https://doi.org/10.1016/j.resconrec.2020.105169

Joustra, J., Flipsen, B., & Balkenende, R. (2021). Circular design of composite products: A framework based on insights from literature and industry. *Sustainability*, *13*(13), 7223. https://doi.org/10.3390/su13137223

Krauklis, A. E., Karl, C. W., Gagani, A. I., & Jørgensen, J. K. (2021). Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. *Journal of Composites Science*, *5*(1), 28. https://doi.org/10.3390/jcs5010028

Li, L., Aslam, S., Wileman, A., & Perinpanayagam, S. (2022). Digital Twin in aerospace industry: A gentle introduction. *IEEE Access*, *10*, 9543–9562. https://doi.org/10.1109/access.2021.3136458

Lefeuvre, A., Garnier, S., Jacquemin, L., Pillain, B., & Sonnemann, G. (2017). Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050. *Resources, Conservation and Recycling*, *125*, 264–272. https://doi.org/10.1016/j.resconrec.2017.06.023

Maria, M. (2013). Advanced composite materials of the future in aerospace industry. *INCAS BULLETIN*, *5*(3), 139–150. https://doi.org/10.13111/2066-8201.2013.5.3.14

Markatos, D. N., & Pantelakis, S. G. (2022). Assessment of the impact of material selection on aviation sustainability, from a circular economy perspective. *Aerospace*, *9*(2), 52. https://doi.org/10.3390/aerospace9020052

Mascle, C., Baptiste, P., Beuve, D. S., & Camelot, A. (2015). Process for advanced management and technologies of aircraft EOL. *Procedia CIRP*, *26*, 299–304. https://doi.org/10.1016/j.procir.2014.07.077

Meng, F., Cui, Y., Pickering, S., & McKechnie, J. (2020). From aviation to aviation: Environmental and financial viability of closed-loop recycling of carbon fibre composite. *Composites Part B: Engineering*, *200*, 108362. https://doi.org/10.1016/j.compositesb.2020.108362

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability*, *8*(9), 937. https://doi.org/10.3390/su8090937

Naqvi, S. R., Prabhakara, H. M., Bramer, E. A., Dierkes, W., Akkerman, R., & Brem, G. (2018). A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resources, Conservation and Recycling*, *136*, 118–129. https://doi.org/10.1016/j.resconrec.2018.04.013

Parveez, B., Kittur, M. I., Badruddin, I. A., Kamangar, S., Hussien, M., & Umarfarooq, M. A. (2022b). Scientific advancements in composite materials for aircraft applications: A Review. *Polymers*, *14*(22), 5007. https://doi.org/10.3390/polym14225007

Ribeiro, J. S., & Gomes, J. de. (2015). Proposed framework for end-of-life aircraft recycling. *Procedia CIRP*, *26*, 311–316. https://doi.org/10.1016/j.procir.2014.07.048

Rodrigues Dias, V. M., Jugend, D., de Camargo Fiorini, P., Razzino, C. do, & Paula Pinheiro, M. A. (2022). Possibilities for applying the circular economy in the aerospace industry: Practices, opportunities and challenges. *Journal of Air Transport Management*, *102*, 102227. https://doi.org/10.1016/j.jairtraman.2022.102227

Zimmermann, N., & Wang, P. H. (2020). A review of failure modes and fracture analysis of aircraft composite materials. *Engineering Failure Analysis*, *115*, 104692. https://doi.org/10.1016/j.engfailanal.2020.104692