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LCA AS A TOOL TO COMPARE SUSTAINABLE ALTERNATIVES FOR STRUCTURAL AEROSPACE COMPOSITE MATERIALS

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Abstract

The aim of this study is to investigate sustainable alternatives to traditional aerospace composite materials comparing traditional thermoset resins with high-performance thermoplastics and covalent adaptable networks (CANs). Using Life Cycle Assessment (LCA) on an eVTOL structure, the study assesses production and end-of-life impacts. Results show that CANs can cut Global Warming Potential by 20% through material reshaping and reuse. Sensitivity analysis reveals thermoplastics become more sustainable than epoxy resins when over 50% of the material is reused. While promising in terms of emissions, further research is needed to optimize reshaping processes and evaluate long-term performance of reshaped composites.

1. Introduction

Sustainability is one of the biggest challenges for the aerospace sector. In 2017, aviation was responsible for the 3.8% of the total EU CO_2 emissions. The goal set by the European Green Deal to achieve climate neutrality, is to reduce by 90% transport-related emissions, compared to 1990s level. Yet, according to ICAO forecasts, in the next years emissions could triplicate in the worst-case scenario, unless technology advancements can balance demand growth [1].

In addition to the expected volume increase in general aviation flights, Advanced Air Mobility (AAM) market is expected to grow drastically. AAM can be split in two main concepts: (i) Urban Air Mobility (UAM) covers passengers' aerial transportation within cities and their surroundings, typical services are air taxi and airport shuttles; (ii) Urban Air Delivery (UAD) refers to the transportation of goods. It is being already implemented for critical applications, such as delivering medicines or organs in areas with poor road infrastructures.

According to a study performed by NASA [2], in 2018 the possible market size for the air taxi and airport shuttle was 2.5 billion USD, just in the US, with a fleet of over 4100 aircraft. Other studies forecast a global market size for AAM ranging between 74 and 641 billion USD by 2035 [3].

It has been proved that the biggest contribution to the CO_2 emissions of an aerial system comes from the use phase. This is particularly true for general aviation, where more than 99% of the emissions produced during the entire life cycle of an aircraft comes from the use phase [4,5], due to the fact that these are machines with a very high level of complexity, and hence of cost, which demands for a very long service life in order to grant economic feasibility. On the other hand, Electric Vertical Take-off and Landing systems (EVTOLs) have a shorter lifetime, which in some cases can range from 500 to 4000 hours of flight. In this case, the contribution to the lifecycle emissions coming from the operative phase and the End-of-Life (EoL) can range between 20% to 75% [6].

It is then important to consider the whole life cycle when evaluating the environmental impact of a system, also considering the production and end-of-life phases in the efforts to reach climate neutrality.

In this sense, Fiber Reinforced Polymers (FRPs) are critical, since they are widely used in the aerospace sector, but the vast majority of the employed materials is not easily recyclable and the most spread end of life strategy is landfilling followed by incineration [7]. These solutions are less than desirable for two main reasons. The first one is environmental, since both of these options relies on the disposal of the material. The second one is political, since regulations are becoming more stringent. For example, landfill of composite material waste has been banned in Germany since 2009 [8].

The EU (2008/98/EC) directive defines five stages of the EoL management, shown in Figure 1. Disposal is the worst option, which includes landfills and incineration without energy recovery, followed by recovery (e.g. incineration with energy recovery). Of course, the optimal solution is to avoid damages, extending the lifetime of a product, but, when damage occurs, the best alternative is to reuse it as much as possible. Efforts are being made to develop new FRPs that

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can be reprocessed or reshaped when damaged, which could have a positive impact both from an environmental and economic perspective for manufacturers and operators. The results could be relevant not only in the aeronautical industry but could also affect the wind-energy market and space exploration, where reuse and ease of repair could give a significant contribution, especially in terms of EoL and operations.

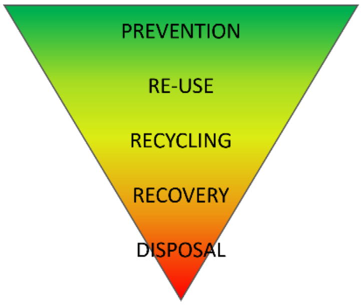

Figure 1: Hierarchy of disposal management defined by the European Commission.

2. Aerospace composite materials

High performance FRPs have been widely adopted for aerospace structural applications thanks to their high mechanical performances with reduced density, allowing lower fuel consumption with respect to metals. Even though aluminium alloys can be completely recycled, it's not enough to balance the emissions associated to the increased weight of the aircraft. In fact, since the impact of the production phase for traditional aircrafts is minimal, adopting a fully CFRP structure can save up to 20% of total CO_2 equivalent emissions compared to a traditional aluminium structure [9]. Composite materials can be classified by the reinforcing fibers and the polymeric matrix. In the following paragraphs will be briefly presented the state of the art of high-performance aerospace composite materials, which are based on carbon fiber reinforcements. An overview of different matrices will be carried out, with a focus on end-of-life perspectives.

2.1 Thermoset matrices

Carbon Fiber Reinforced Polymers (CFRP) with thermoset resins are the most widespread solution for structural aerospace applications. Some examples of commercially available thermoset resins are: epoxy, phenolic, polyimide and cyanate ester. As anticipated, they grant competitive strength and stiffness to weight ratios, much higher than their metallic counterparts. Epoxy resins are the most widespread thermosetting polymer used to bind the reinforcements [10]. They have been preferred in the past years for the production of composite materials because the polymerization process happens thanks to a crosslinking agent and requires lower temperature with respect to thermoplastic composites production. The resulting molecular structure provides chemical stability and good mechanical properties thanks to the crosslinks of covalent bonds. Another advantage is the high impregnability presented by epoxy resins, which reduces the presence of defects in the final product [11]. Even though the chemical stability of covalent bonds is highly desirable during the use phase, it can result problematic once a major damage occurs. Thermosetting polymers can be repaired only applying a patch on the damage location, which can be bolted or glued to the main structure, depending on the structure characteristics. In the case of bolted patches, which can be performed only in the case of thick composite panels, the holes drilled in the structure usually create stress concentration points. This kind of repair can bear a higher ultimate tensile load, but it struggles in case of compression[12]. When the damage occurs in a thin panel, a sandwich structure or an aerodynamic surface, a bonded scarf repair is preferred. This option requires a complicated process and it introduces a discontinuity in the structure: part of the load will be carried only by the adhesive material, limiting ultimate and long-terms performances [13]. Another problem arises when the component must be discarded, since it can’t be easily recycled. The main waste management strategies used at the moment are landfilling or incineration. Some alternatives are being studied to recover at least the fibers, which consist in solvolisys and pyrolisis. Yet, it's not clear if their adoption can be justified, since both processes are quite impacting on the environment and the cost could be higher than the benefit obtained from the recycled fibers [14].

2.2 Thermoplatic matrices

Thermoplastic polymers can be an alternative matrix in composite materials. The main difference from thermosets resides in the chemical structure of the molecular chains, which can be linear or branched in the case of thermoplastics. Weak bonds between the chains grant the integrity of the material. Unlike covalent bonds, they grant the reversibility of the process. By heating the material, the weak bonds are broken, allowing the molecular chains' relative motion and making the polymer act as a fluid. When the temperature drops below the melting point, the material becomes solid again and,

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below the glass transition temperature, it becomes rigid. Thermoplastic polymers can be semi-crystalline or amorphous, depending on the presence of ordered structures. The level of crystallinity depends on the rate of cooling of the material, and in general the higher it is, the better the mechanical and thermal properties of the material are [15].

The major advantage of thermoplastic polymers is their reprocessability. In case of damage, they can be repaired with different techniques by heating the material above its melting temperature. This allows to weld the damaged area, guaranteeing a continuous repair, which can bear up to 95% of the non-damaged load scenario [16].

When the damaged area is wide and does not allow in-situ repairs, CFRP with thermoplastic matrices can still be reshaped or reprocessed, avoiding the complete disposal [17]. If the material cannot be repaired nor reprocessed, it's still possible to recycle it. Some studies are being carried out on additive manufacturing using as a feedstock material recycled CFRP with high performance thermoplastic resins such as PEEK [18].

In addition to the ketone family (PEEK, PEK, PAEK, PEKK), other examples of thermoplastic resins are polyamide (PA), polyetherimide (PEI), polyethersulfone (PES), and polyphenylene sulfide (PPS). The major downside of PEEK is the cost, both in terms of raw material production and in terms of processing due to the high melting temperature [11].

2.3 Novel composite matrices

As emerged from the previous paragraphs, thermoset and thermoplastic matrices have both their benefits and downsides. In recent years new polymers which merge some characteristics of both classes of materials have been developed. The idea is to make thermoset polymers repairable or recyclable by introducing reversible bonds in their chemical structure. One possible solution consists in introducing non-covalent bonds (e.g. ionic interactions or hydrogen bonding), but it leads to poor mechanical properties of the final material. A better alternative consists in the introduction of reversible covalent bonds in thermoset polymers, creating covalent adaptable networks (CANs), which offer good mechanical performances combined with some behaviours typical of thermoplastic materials. In fact, some parameters can be used to trigger the dynamic bonds causing a drop in viscosity and allowing the material to flow.

It is possible to split CANs in two main categories: dissociative CANs and associative CANs. In the first group the bonds break at high temperatures to reform when the network cools down, hence the crosslink density in not guaranteed. On the other hand, in associative CANs the bonds' cleavage and formation happen simultaneously, maintaining the number of links constant. A promising example of associative CANs is given by vitrimers, which can be obtained by exploiting reversible aromatic disulfide exchange in epoxy networks [19]. These materials present mechanical characteristics which are very similar to thermoset resins, but they assume a plastic or even fluid behaviour at high temperature, making them repairable, reprocessable and recyclable. In [20], the main static mechanical characteristics of vitrimer-based composite materials were studied, showing that they could be suitable for aerospace components. Since this class of polymers is relatively new, their resistance to hydrolysis and creep has not been sufficiently investigated yet.

3. Life Cycle Assessment

3.1 Methodology

Life Cycle Assessment (LCA) is a reliable tool used to evaluate the impact of products from a holistic point of view. This methodology allows to consider the totality of processes associated to the production of goods, spacing from the extraction of raw materials and their treatment up to different EoL scenarios, such as disposal, recycling and re-use. LCA relies on a huge amount of data gathered by industry and research institutes and collected in different databases, such as Ecoinvent V3, which is considered as one of the most comprehensive.

Due to the intrinsic complexity entailed in this kind of analysis, it is mandatory to clearly identify its goal and scope. This is fundamental to define the perimeter of the study, as well as to justify the assumptions and the limitations of the model. Then, the first step consists in collecting all the meaningful input/output materials and processes, creating what is called a Life Cycle Inventory (LCI). Once all the data is gathered, they can be processed to evaluate the environmental relevance of all the inputs and the outputs. This step is referred to as Life Cycle Impact Assessment (LCIA). Several impact categories have been defined, which can be divided into midpoint indicators and endpoint indicators. The former refers to specific criteria, such as global warming potential, water or land use, freshwater or sea eutrophication and so on. The latter refer to an aggregation of midpoint indicators which represent more general concepts, such as damage to human health or to ecosystems.

Finally, the results must be interpreted in order to assess which are the critical issues in the production process.

For this study, the LCA model was developed using SimaPro 9.6.0.1.

3.2 Model description

The objective of this analysis is to establish a case study relevant to the comparison of different polymeric matrices for composite materials in the production of aerospace structures. In particular, the Global Warming Potential (GWP) of three alternatives will be evaluated: traditional thermoset resins, high performance thermoplastic polymers, and novel polymers

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with dynamic covalent bonds, such as vitrimers. Considering the potential growth of the AAM market, an interesting and insightful application is the life cycle of the structure of an EVTOL. A cradle-to-gate analysis has been performed, with the addition of the EoL scenario. Even if the use phase of the aircraft could be more relevant in terms of carbon footprint, it has been chosen not to include it. In fact, it is reasonable to assume that the performance of the system would not be affected by the choice of the polymeric matrix, since the most relevant mechanical characteristics of composite materials are driven by the fiber selection. In this study the same fibers will be taken in account for the three models. This means that the same fiber-to-matrix ratio will be considered, as well as the ratio between carbon and glass fibers, hence the difference will reside only in the polymer.

As anticipated, the first step consists in the generation of a LCI, which implies the collection all the necessary input. In this case, all the materials and processes involved in the production of a EVTOL must be included and, to accomplish this task, two main sources have been used. From [21] it was possible to retrieve some information on the materials used and their quantity, as well as the total mass of the aircraft. The side-by-side aircraft configuration was considered since it had the highest fraction of composite materials. In addition, the production of the battery pack and the motor has been neglected, being irrelevant to the scope of this analysis. The total mass of the considered aircraft is 1456.5 kg, while the mass fractions relative to each of the material are reported in Table 1**Errore. L'origine riferimento non è stata trovata.**.

For what concerns the manufacturing processes, the information on aeronautical manufacturing technologies and their energy demand has been retrieved from [14, 22]. The energy demand of those processes associated to the production of components and structures in composite materials has been scaled proportionally to the input mass of the process, while the processing time associated to subtractive technologies of metallic components and structures has been scaled accordingly to the mass of the scraps. All the processes and their energy demand are listed in Table A1.

Table 1 Mass fractions by material.

	Aluminium	**Steel**	**Titanium**	**Carbon fiber**	**Glass fiber**	**Polymeric Matrix**
Mass fraction	0.173	0.093	0.066	0.294	0.119	0.256

Three models have been developed, in which different matrices are adopted for the components and structure made of composite materials: thermoset resin, high-performance thermoplastic polymer, thermoset polymer with dynamic covalent bonds. All the processes associated to metallic materials are the same for each case. This choice was done to enhance the comparison of the environmental impact related to the three matrices, main focus of this study. They differ especially in the EOL scenario. Composite materials based on traditional thermoset resins, can be recycled by mechanical grinding, reducing the material to a coarse powder. This recycling strategy gives a downgraded result, which can be used as a filler to produce new composite materials, yet it is far from ideal. To simulate these solutions, a recycling scenario has been implemented in SimaPro, where the output of exhausted CFRP was virgin glass fiber [23]. Other recycling strategies were investigated, yet it is still in doubt if the recovered fibers can be adopted in aerospace grade solutions. A better alternative is given by the possibility to repair by welding or reprocess the damaged material. It is possible to do so when using a thermoplastic polymer or a vitrimer as a matrix [15, 19, 24]. This can be modelled in the EOL strategy by reusing a percentage of the material. The processes modelled for composite materials are represented Figure 2 and colour coded accordingly to the processing strategy of each matrix.

The full LCIs for the thermoplastic and thermoset scenarios are reported in tables A2 and A3 respectively.

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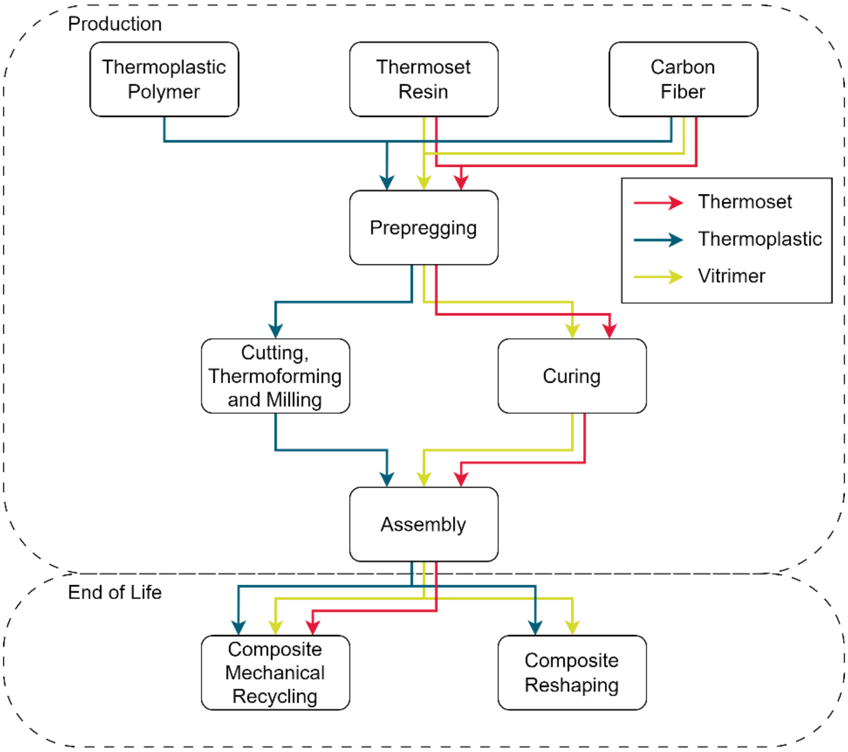

Figure 2: Diagram of all the processing steps associated to CFRP

3.3 LCA results

The LCIA has been carried out using the Recipe 2016 method, which collects 18 midpoint indicators that are representative at a global scale. In particular, the global warming potential has been considered as the most relevant parameter, which is expressed in terms of equivalent tonnes of carbon dioxide.

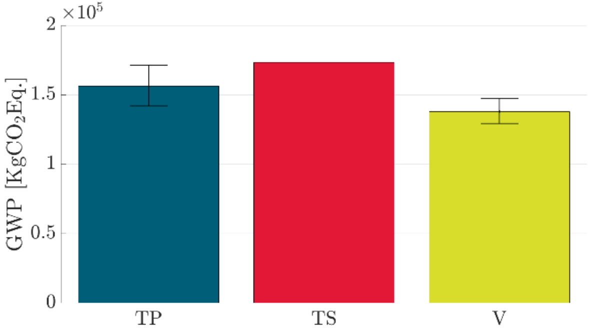

Figure 3: GWP for all the matrices with different reuse percentages.

In Figure 3, the environmental impact of the EVTOL production and EOL scenario are presented for each one of the considered polymeric matrices: thermoplastic polymers (TP), thermoset resins (TS) and vitrimers (V). The GWP was computed for three different scenarios, in which the percentage of reused material was set to 50%, 70% and 90% respectively. This is highlighted in the interval represented in the graph, where the upper limit, hence the highest level of emissions, is associated with the least amount of reshaped composite materials. Of course, the thermoset case impact is always the same, since traditional epoxy resins can't be reshaped.
Both cases which allow for material reuse present a lower environmental impact with respect to the case which uses traditional thermoset resin. Focusing on the case in which 70%, considered as the baseline scenario in this study, of the material can be reshaped, the avoided emissions are presented in Tab.

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Table 2 Avoided emissions.

Reuse percentage	TP	Vitrimer
50%	1.2%	15.0%
70%	9.8%	20.4%
90%	18.1%	25.4%

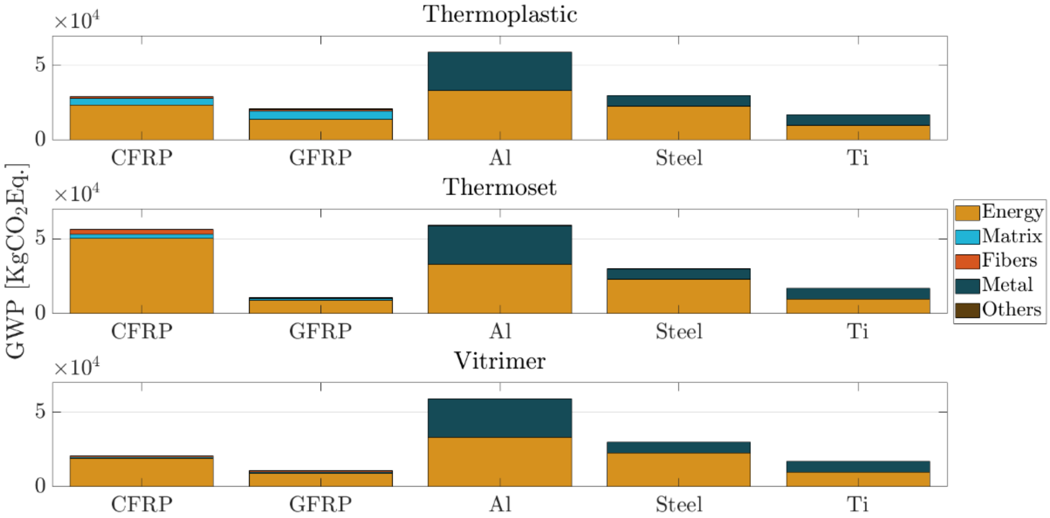

Figure 4: Baseline scenario GWP split by materials and emission sources.

The Global Warming Potential associated with the baseline scenario, was unwrapped both by material classification, split in different bars, both in terms of emissions origins, which are colour coded, as it can be seen in Figure 4.

The first thing that can be noticed is the fact that the major contributor to the GWP in all three cases is the aluminium, hence a larger adoption of composite materials could reduce the overall impact associated with production and EOL, but it also could contribute to the reduction of the emissions produced during the operative life, since the aircraft would be lighter.

Looking at the emissions coming from the production and processing of the CFRP, it emerges that in the case of thermoset resins, the impact is similar to the one given by aluminium, but, looking at the scenarios where composite materials can be reshaped and reused, the impact associated to CFRP drops significantly, highlighting how this strategy could help in the decarbonisation process of the aerospace industry.

Another aspect which should be considered is the fact that in terms of emissions' origin, energy production is the major contributor.

Finally, it can be appreciated that the impact associated with the production of the matrix is higher in the case of thermoplastic materials, which is reasonable comparing the data available on the production of PEEK and epoxy resins. Yet, this is totally compensated in terms of energy-related emissions thanks to the avoided production of virgin material.

In addition to the GWP, the Cumulative Energy Demand (CED) was also computed. This indicator is evaluated with a dedicated single issue method in SimaPro, and it sums all the energy needed for each step of the modelled life cycle. It takes in account energy coming from different sources, like fossil fuels, nuclear, wind, solar, etc. and it's expressed in MJ.

Like the GWP, also the CED was computed for the different matrices and for different percentages of reused material (50%, 70% and 90%). Also in this case the model in which thermoset resin was used is the one which requires the most energy, as it can be appreciated in Figure 5.

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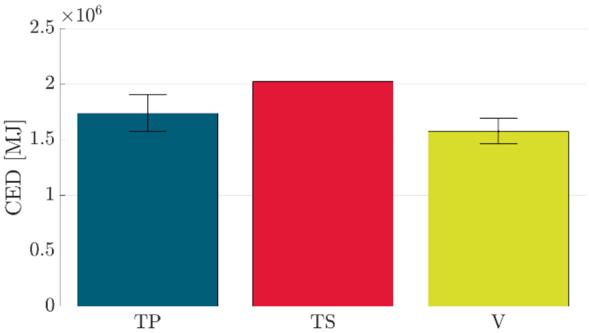

Figure 5: CED for all the matrices with different reuse percentages.

The CED was unwrapped as well in terms of material classification, as shown in Figure 6. Also in this case the majority of energy demand comes from the metallic materials, especially aluminium. Yet, there is one exception in the case of thermoset resin, where the most energy-intensive category is CFRP. Again, looking at the scenarios where the composite material is reused, it's possible to appreciate the savings that could be obtained by adopting this strategy.

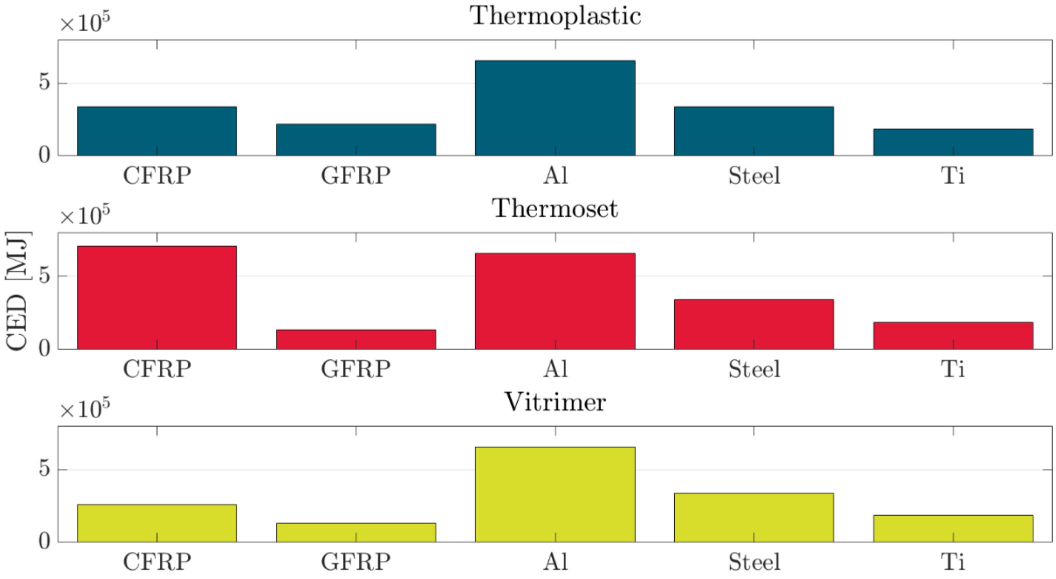

Figure 6: Baseline scenario CED split by materials.

Looking at the results of the LCA, it is clear that the amount of reused material is the most relevant factor in terms of possible savings, yet few studies have been carried out to assess how much of the material can be actually recovered. Also, this strategy has not been applied yet at industry level, hence reliable data could not be found and the level of reused material were just assumed for this study. Hence it was necessary to carry out a sensitivity analysis to investigate how much this parameter affects the results.

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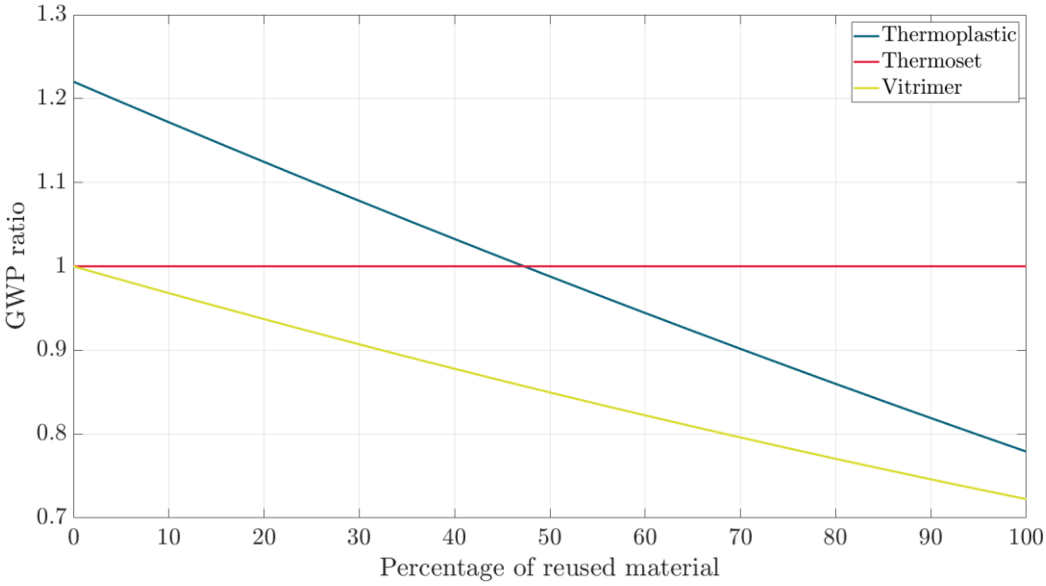

Figure 7: Sensitivity analysis.

In order to compare the results for the different scenarios, the GWP ratio is introduces. This parameter is just the ratio of the GWP associated to the models in which composite materials can be reshaped (hence TP and Vitrimer) and the one associated to the model in which epoxy resin is adopted, which represents the actual industrial standard. This value can be plotted for different values of recovery percentage, as done in Figure 7.

Of course, in this study vitrimers can only have an impact which is equal or lower with respect to thermoset resins, but this comes from the approximation according to which they are treated as a thermoset in the production phase and as a thermoplastic for what concerns the EOL. On the other hand, it is visible that for low amounts of reused composites, thermoplastic polymers present a high impact with respect to thermoset resins. Only when at least 48% of the material is reshaped it is more convenient to adopt this solution.

4. Conclusion

As emerged in this study, the road to decarbonisation in the aerospace industry should be pursued with an organic strategy, which takes into account also production and decommissioning. Even if these phases are less impacting than the operative life, they can still be relevant in AAM applications. In particular, the impact of composite materials has been highlighted, which is quite relevant due to the lack of green solutions to manage their end-of-life, often destined to landfills or mechanical recycling. The possible benefits coming from the reuse of composite materials produced with a thermoplastic or dynamic covalent bond matrix have been investigated, showing that even for a single reuse the emissions could be cut by 20%. This result can mainly be achieved thanks to the reduced necessity of energy intensive processes. The strongest limitation of this model, resides in the high level of approximation, which can be reduced in two ways. The first one would be to generate more LCA data relative to the production of advanced polymeric matrices, and in general to the production of composite materials. The other solution to enhance the accuracy of such a model, would be to develop a case study in collaboration with a manufacturer of EVTOLs. This would allow to have a better estimation of the real inputs in all the processes, while in this study all data came from what could be found in literature.

Also, it emerged how relevant the amount of reused material in the reduction of CO2 equivalent emissions. This implies that would be interesting evaluate how much composite material could be reshaped in a real scenario. Above this, it should be assessed how many times such materials can be reshaped while keeping the necessary mechanical performance and how novel materials would be impacted by the environmental conditions found during the operative life, such as fatigue, radiations, humidity and so on.

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Appendix

Table A1: Output mass, waste mass, energy density, power, processing time and energy associated to each production process.

Process	Output Mass [kg]	Waste [kg]	ρ [kWh/kg]	P [kW]	t [h]	E [kWh]
CFRP TS						
Prepregging	1083,79		11,10			12030,10
Lay up	867,03	216,76				
Curing	693,63	173,41		6936,27	8,00	55490,17
GFRP TS						
Prepregging	437,85		11,10			4860,16
Lay up	350,28	87,57				
Curing	280,23	70,06		2802,25	8,00	22418,03
CFRP TP						
Prepregging	1205,89		11,10			13385,36
Panel prod.	964,71	241,18	6,10			5884,74
Processing	693,63	271,08				84000,44
GFRP TP						
Prepregging	487,18		11,10			5407,69
Panel prod.	389,74	97,44	6,10			2377,43
Processing	280,23	109,52				33936,18
Aluminium						
Machining	251,59	4780,26		120,00	1673,09	200771,08
Steel						
Machining	135,21	2568,99		120,00	1156,04	138725,21
Titanium						
Machining	95,84	191,69				58733,75

Table A2: LCI thermoplastic EVTOL

Process	Database	Unit	Quantity
Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, S	Ecoinvent 3	kg	4780,27
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, S	Ecoinvent 3	kg	5031,86
Electricity, high voltage {Europe without Switzerland}| market group for electricity, high voltage | Cut-off, S	Ecoinvent 3	MJ	343772,6
Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, S	Ecoinvent 3	MJ	1955599
Glass fibre {RER}| glass fibre production | Cut-off, S	Ecoinvent 3	kg	302,58
Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	ELCD	kg	748,96

PEEK (Polyetheretherketone)	IDEMAT2025	kg	641,53
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	Ecoinvent 3	kg	2760,68
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	Ecoinvent 3	kg	2704,2
Titanium {GLO}| market for titanium | Cut-off, S	Ecoinvent 3	kg	287,53
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	Ecoinvent 3	tkm	2090,929
Waste plastic, mixture {RER}| market group for waste plastic, mixture | Cut-off, S	Ecoinvent 3	kg	719,22

Table A3: LCI thermoset EVTOL

Process	**Database**	**Unit**	**Quantity**
Aluminium (waste treatment) {GLO}| recycling of aluminium | Cut-off, S	Ecoinvent 3	kg	4780,27
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for aluminium, primary, ingot | Cut-off, S	Ecoinvent 3	kg	5031,86
Electricity, high voltage {Europe without Switzerland}| market group for electricity, high voltage | Cut-off, S	Ecoinvent 3	MJ	308962,1
Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, S	Ecoinvent 3	MJ	1774903
Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, S	Ecoinvent 3	kg	576,58
Glass fibre {RER}| glass fibre production | Cut-off, S	Ecoinvent 3	kg	271,94
Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	ELCD	kg	673,12
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	Ecoinvent 3	kg	2760,68
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	Ecoinvent 3	kg	2704,2
Titanium {GLO}| market for titanium | Cut-off, S	Ecoinvent 3	kg	287,53
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	Ecoinvent 3	tkm	2041,698
Waste asphalt {RoW}| market for waste asphalt | Cut-off, S	Ecoinvent 3	kg	390,17
Waste plastic, mixture {RER}| market group for waste plastic, mixture | Cut-off, S	Ecoinvent 3	kg	157,62