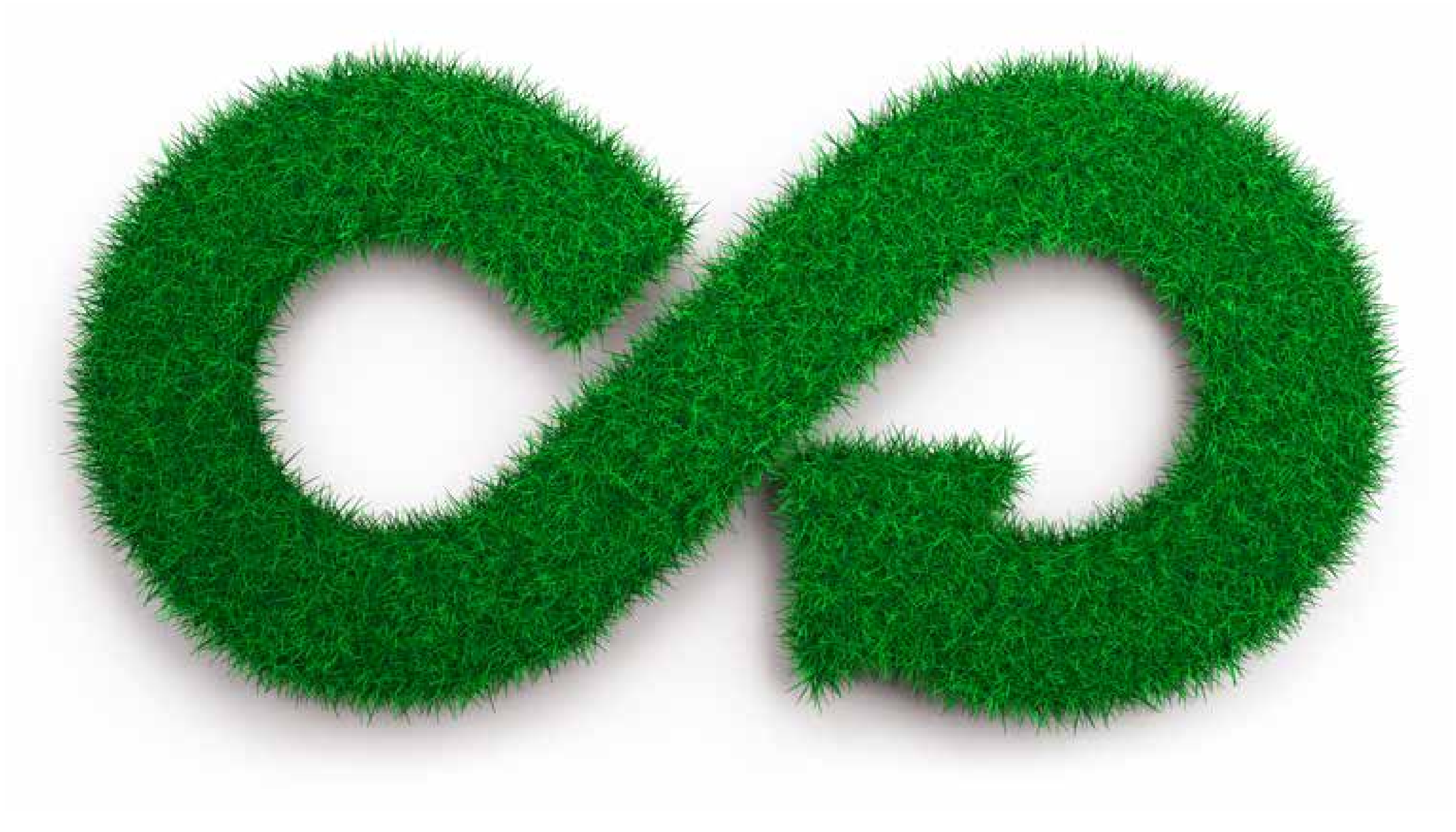
ATKINS
Member of the SNC-Lavalin Group

A Circular Economy for Civil Aerospace

By James Domone, Philippa Bliss and Matt Copus



Foreword

As the need for action to tackle the predicted climate breakdown emergency increases, combined with the economic effects of the Covid-19 pandemic, a fundamental re-evaluation is required into how we design, manufacture, recycle and reuse aerospace vehicles to support Net Zero ambitions.

The need to live within planetary boundaries will push us towards a Net Zero circular economy where the extraction of raw materials from the Earth is minimised, the use of fossil fuel energy sources is eliminated, and people are still able to travel globally at the highest safety and comfort levels.

This paper explores how the circular economy approach to manufacture, reuse and recycling, can be adopted within the aerospace market in pursuit of sustainability goals. A hierarchy of circular economy strategies are discussed and directly related to application within commercial aerospace.

Additive manufacturing, advanced recycling processes and digital twin are identified as key enabling technologies for application of the circular economy within aerospace. The approach of the circular economy strongly supports the implementation of an adjusted aircraft ownership model, focussed on leasing and the concept of “aircraft-as-a-service” which is introduced and described.

Contents

The Role of Materials and Production in Addressing the Climate Breakdown Challenge

The human contribution of greenhouse gases to the environment is a product of our 'take-make-waste' linear and extractive economy, Figure 1. For years, mankind has relied on natural resources, fossil fuels and raw materials, to feed economic growth. The linear model of production of goods sold to customers on demand is enabled by the availability of 'cheap' natural resources and the relative ease of landfill waste disposal. More growth has led to ever increasing rates of natural resource consumption.

Figure 1: A Linear Economy

In 2018 the Intergovernmental Panel on Climate Change issued a special report showing an average global temperature increase of 1°C to date, with a high confidence that this will reach 1.5°C by the middle of this century.

The report also forecast the climate breakdown effects that will likely result from this heating, which included: increased mean temperatures, increased extreme weather events, sea level rise, ocean acidification, biodiversity loss and increased risk to human food security. But, while the climate will change as a result of the emissions already released, collectively, we can prevent things getting worse.

Emissions must start declining from 2020

As is made clear by the IPCC, CO_2 emissions must start declining from 2020 to achieve Net Zero CO_2 by 2050 and minimise the negative effects of climate breakdown. Any strategy not targeting Net Zero relies on other industries generating negative CO_2 emissions (removal of atmospheric CO_2) and the use of market based measures such as offsetting to account for this. While this approach could be considered, it should form a secondary plan. If many other sectors took the same approach it would be extremely difficult, if not impossible to meet global Net Zero targets.

Putting on the pressure to act NOW!

Political incentives and targeted legislation forcing the hand of the industry to act

Post-pandemic government support only available to organisations with clear routes to Net Zero by 2050

Increased public 'flygskam' or flight shame, reducing potential revenues, particularly in high-income countries

Increased commercial acceptance that business can successfully be conducted remotely

Traditional aviation fuel price uncertainty as oil reserves are reduced as peak oil is approached

Increasing costs and restrictions on the extraction and purchase of raw materials.

Aircraft production is estimated to contribute 1% of commercial aviation's total greenhouse gas emissions (Airbus, 2020). Figure 2 illustrates this contribution and the major sources of these emissions.

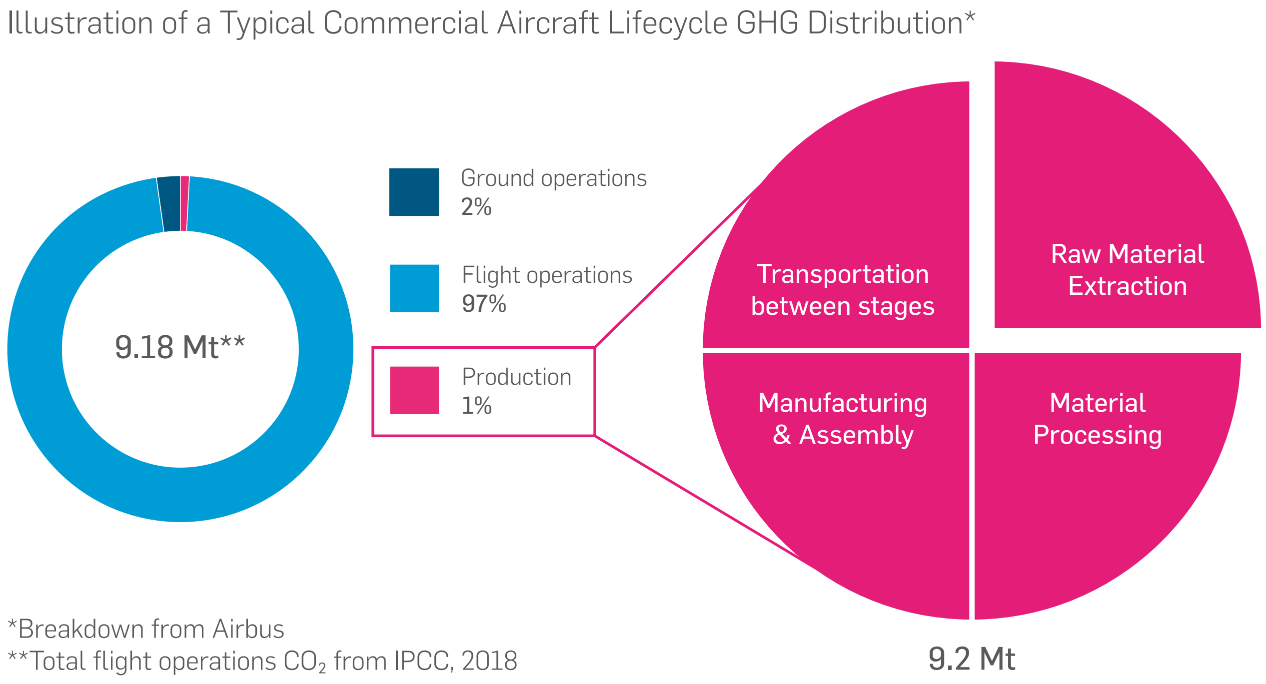


Figure 2: Illustration of a typical commercial aircraft lifecycle greenhouse gas distribution

Current Industry Approach to Materials Usage

At its outset, the commercial aerospace industry naturally established a linear economy where economic value is placed on products (aircraft, spare parts) with economic growth closely linked to the use of natural resources. Generally, the aircraft owner operates the aircraft for its service life, maintaining its function by purchasing replacements for faulty parts. At the end of its life, the product was often scrapped as waste.

This approach was based on the premise of cheap materials and high labour cost and the value in reuse or recycling was low. However, there are only a finite amount of raw materials available and their cost is rising. For a long time, the end-of-life stage of the aircraft was largely neglected, and aircraft were often simply stored in airports or deserts across the world including a well-known site in Arizona, Figure 3. More recently end-of-life aircraft are handed over to recycling companies who use the materials for applications in other sectors.

Legislation is Putting on Pressure to Act

The 21st century has brought more attention to environmental sustainability and increased legislative and social pressure on aerospace companies to reduce the environmental impact of aircraft. Improvements have occurred at all aircraft lifecycle stages, but to date the focus has very much been on waste management, both during manufacture and at end of life, as shown by the volume of policy responses shown in Figure 4.

Whilst it is true that the aerospace industry has made huge improvements to waste management over the last few decades, there is more to be done to reach Net Zero.


© U.S. Navy

Figure 3: Commercial and military 'boneyards', Pinal Airpark in Arizona (Twidell, 2016)

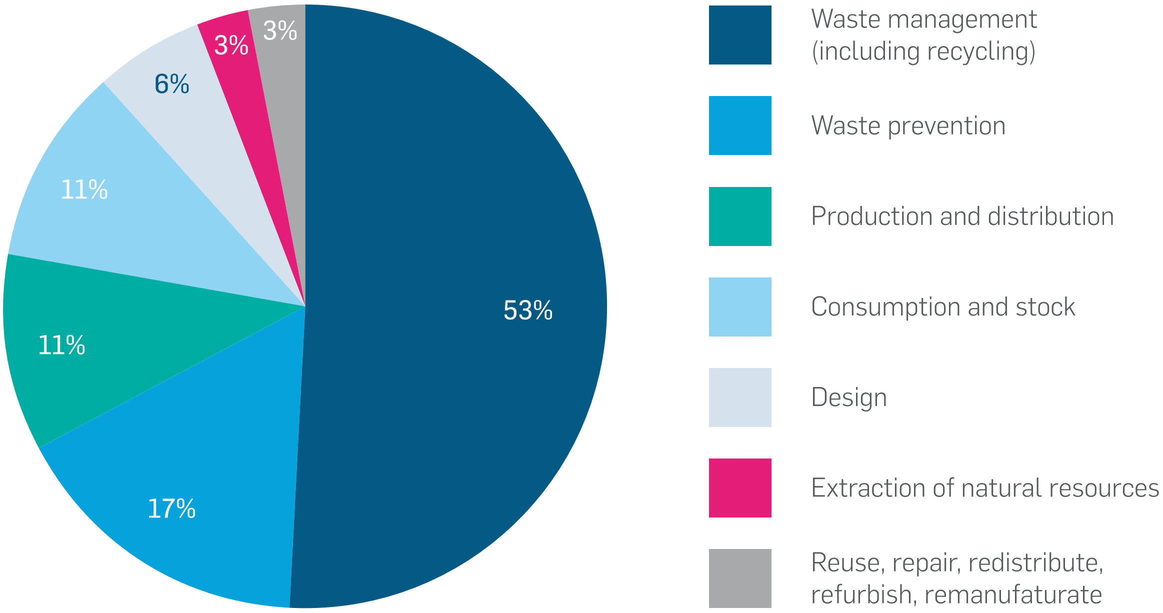


Figure 4: Distribution of responses on policy approaches to closing material loops in the economy/circular economy (European Environment Agency, 2017)

The Energy Cost of Aerospace Metal Extraction is High

One of the areas where attention is low is the initial extraction of raw materials. Aerospace uses a high proportion of metal components which vary in their extraction energy requirements. Some of the more commonly used elements, such as titanium, nickel and aluminium, have high energy cost associated with extraction, as shown in Figure 5 (Norgate, Jahanshahi, & Rankin, 2006).

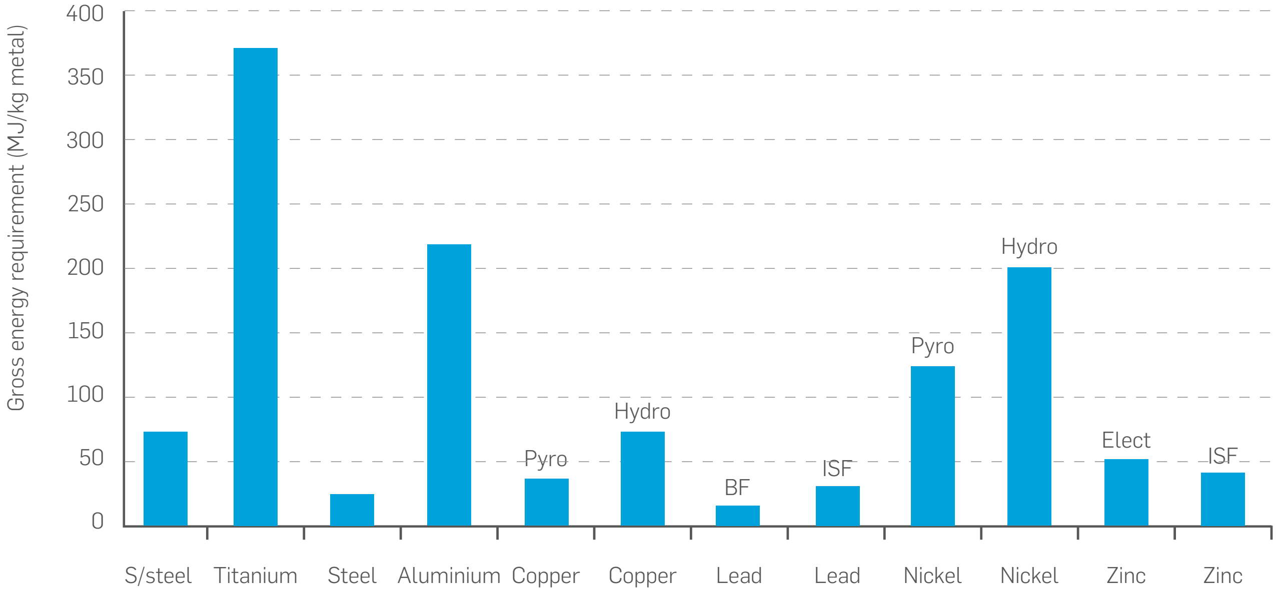


Figure 5: Gross energy requirement (MJ/kg) for mining and extraction of common metals (Norgate, Jahanshahi, & Rankin, 2006)

Introducing the Circular Economy to the Aerospace Industry

The linear economy model for production of aircraft is inherently wasteful and energy intensive. This model creates a dependency on natural resources and subjects it to fluctuations in material availability and rising material costs. Taking inspiration from natural cycles, the concept of the circular economy was introduced to provide better usage of the finite volume of materials available to us.

Concepts and strategies articulated by the circular economy are aimed at reducing waste and energy consumption, and therefore emissions. While aerospace is by no means unique in this, it faces some significant challenges to move away from a linear approach and towards a circular approach, not least due to the level of quality required to meet safety standards.

Transitioning from a linear to a circular economy is proposed as an effective way to tackle emissions connected to the production and maintenance of aircraft. By recirculating products rather than discarding them after use, the circular economy retains product and material values better than today's linear economy. Through minimising demand for materials and energy, and by minimising the generation of waste, the circular economy also contributes to a reduction, or even elimination of greenhouse gas emissions related to production. Figure 6 illustrates the concept of the circular economy and some of its strategies.

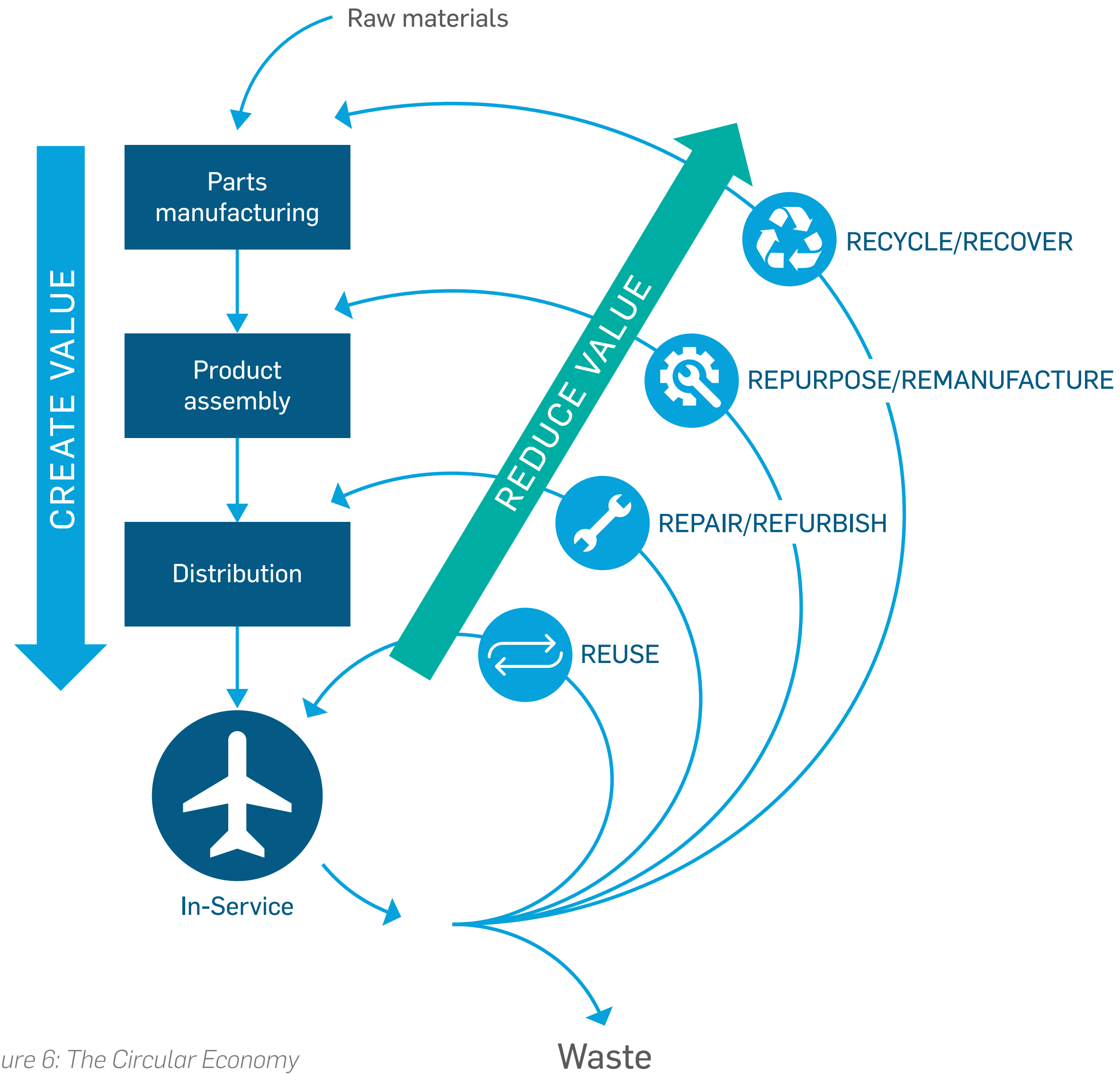


Figure 6: The Circular Economy

Aiming to Keep the Value of Materials High

The central theme of the circular economy model is to keep the value of materials and products as high as possible for as long as possible, reducing demand on natural resources. Value is created initially through material extraction with a big increase observed through the initial manufacturing chain as raw material is formed into a functional item. It then depreciates naturally through its operational life due to the effects of wear, fatigue, corrosion, increasing frequency of inspection and obsolescence. Value can be increased again through repair or remanufacturing to extend the operational life through some form of material or energy input. To avoid this additional input, it is desirable to keep using a product in its initial life as long as possible.

A product's value is finally entirely degraded when it is sent to landfill as waste. The guiding principle of the circular economy is to use materials in a continuous cycle, mirroring natural processes, and minimising, or eliminating, the need for additional input or waste. Doing this maximises the value of a product, and the material itself, for as long as possible, and avoids value ever dropping to zero. This contrast in the value is illustrated by Figure 7.

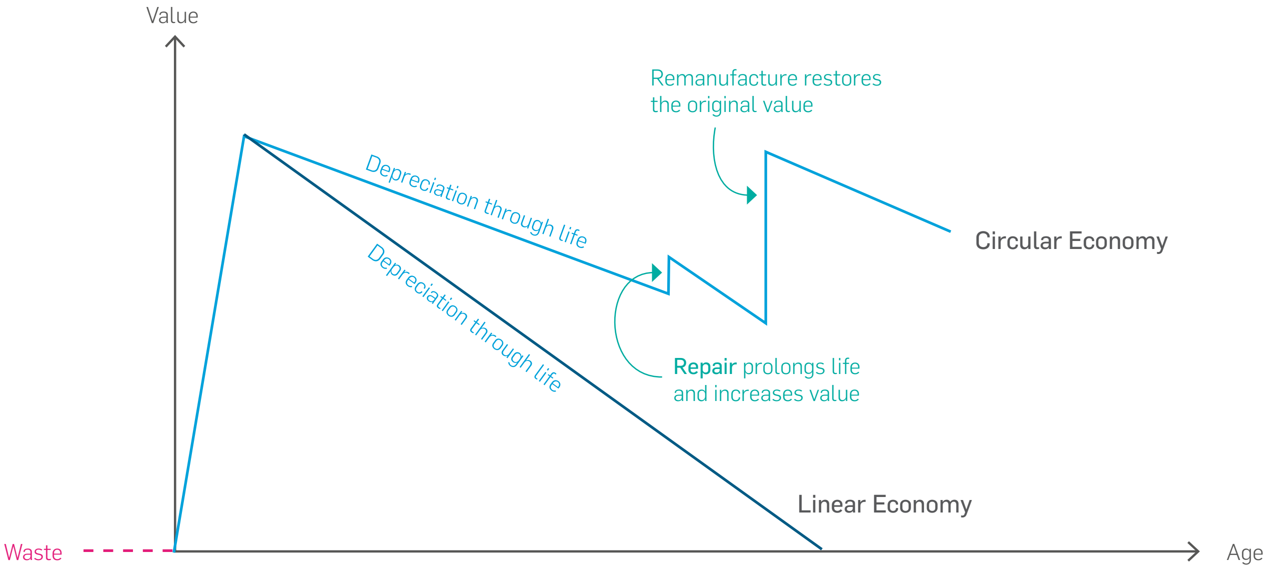
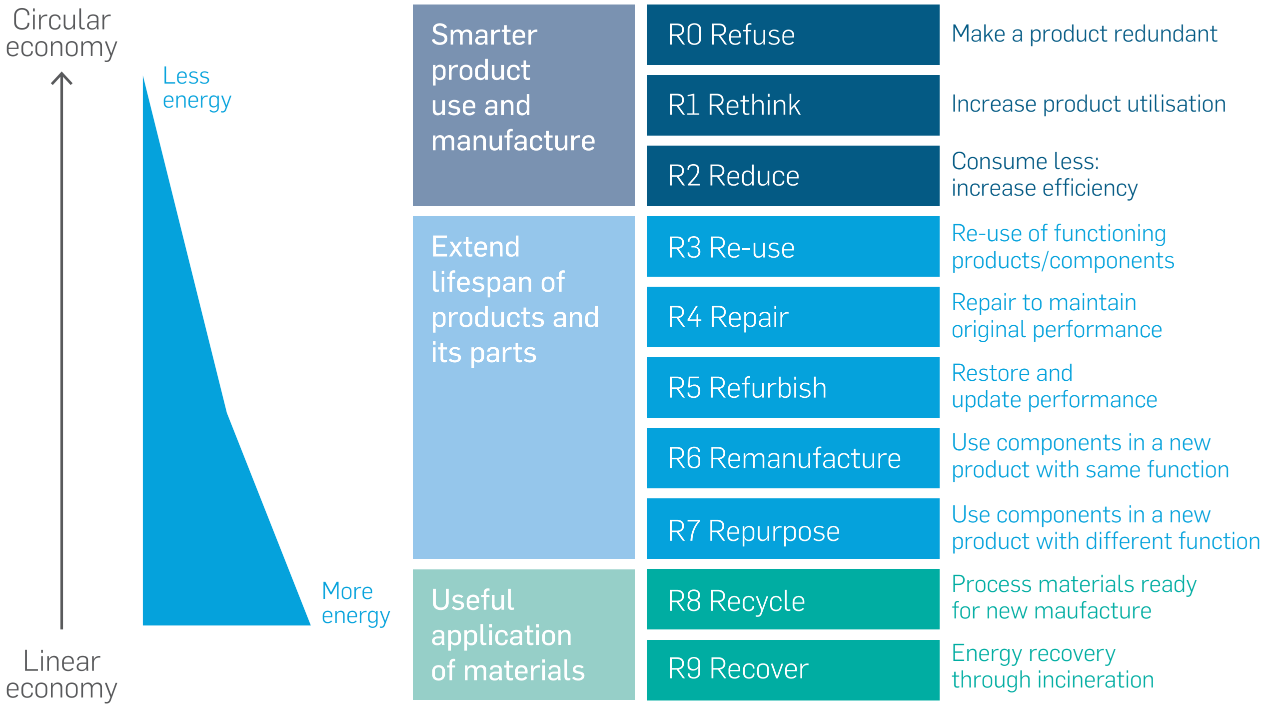


Figure 7: value of a product throughout its life in the linear and circular economies



Smarter product use and manufacture	R0 Refuse	Make a product redundant
	R1 Rethink	Increase product utilisation
	R2 Reduce	Consume less: increase efficiency
Extend lifespan of products and its parts	R3 Re-use	Re-use of functioning products/components
	R4 Repair	Repair to maintain original performance
	R5 Refurbish	Restore and update performance
	R6 Remanufacture	Use components in a new product with same function
	R7 Repurpose	Use components in a new product with different function
Useful application of materials	R8 Recycle	Process materials ready for new maufacture
	R9 Recover	Energy recovery through incineration

Figure 8: Strategies in a circular economy indicating the relative total energy requirements for each stage

Which Value Strategies are Desired in the Circular Economy?

Strategies to maintain value throughout a product lifecycle range from consuming fewer natural resources during manufacture to the recovery of energy through incineration at end of life. Figure 8 lists the high-level approaches in hierarchy from a linear approach up to an ideal circular strategy.

The most favourable strategies to achieve the benefits of a circular economy are those that implement smarter product use and manufacture through part or process design: refuse, rethink, reduce. Extending a product' s lifespan may be necessary at times and requires input: reuse to repurpose. Strategies that recycle and recover the materials which constitute the product at the end of its life are important to capture the remaining value but should be implemented as a last resort.

The strategies are organised in ascending order of energy and raw material usage, which are key considerations within the circular economy. By minimising overall inputs required, we naturally serve to reduce emissions and increase sustainability. The different strategies available for a given aircraft, assembly or component, when identifying circular processes should be reviewed in the same order shown to arrive at the least input outcome.

Smarter Product Use and Manufacture

Smarter product use and manufacture includes the strategies of ‘refuse, rethink, reduce’. These strategies are all related to the highest-level objectives and requirements for any given product, or system. By reviewing the need to fly, the number of aircraft operating and basic design philosophies around the use of the materials we can ensure that demands placed on downstream elements of the circular economy are appropriate.

Refuse: Could we just fly less?

As starkly highlighted by the Covid-19 pandemic, one approach to reduce the impact of aviation on the environment is to refuse to travel altogether. Information and communications technology is at a level where much business travel can arguably be reduced, including journey’s previously completed by air. Combined with increasing awareness of the climate emergency and flygskam (flight shame), and the potential increase of high-speed rail over land, the appetite of the general public amongst high income countries to fly has the potential to plateau or even reduce.

But, finding an alternative means of travelling long distances, either over land or especially sea, is difficult at the speeds which aircraft can achieve. The desire of countries with increasing wealth will inevitably support the continuation of the historical trend of increased demand for travel by air. This continued demand is even more likely, over the longer-term, if flight operations move towards Net Zero CO_2 through the use of alternative fuels or energy storage means such as sustainable aviation fuel, hydrogen or batteries.

Rethink: Aircraft utilisation and design for the circular economy

Rethinking in the context of aviation includes ensuring that each aircraft is utilised as fully as possible, reducing the overall need for additional aircraft. It also covers designing aircraft and their systems and parts for the circular economy.

Enabling the increasingly intense use of aircraft is already a strong consideration for design and certainly for operations performed by airlines. The aims are to reduce turnaround times at airports, ensuring available capacity is maximised and the time aircraft spend on the ground (e.g. overnight or for maintenance) is minimised. The opportunities for further improvement exist, but gains may be limited.

An important aspect of designing in a circular economy is consideration of system and component value in subsequent stages of an aircraft lifecycle, not just the initial value for the 'first life'. Therefore, designing for the circular economy is essential to maximise the Net Zero opportunity. Aircraft should be designed in such a way that they can be easily dismantled and then components reused, repaired, refurbished or recycled at the end of their useful life. This will support increased availability for reuse, repair or refurbishment and increased quality of recycled material. It will also help to minimise the costs associated with each option and support the reduction of waste due to material that cannot be recycled.

Rethinking design in support of the circular economy

Standardised designs: components or assemblies can be removed from one aircraft and be placed, unchanged, into a new one.

Modular and reconfigurable interiors: increasing the life span of the underlying aircraft platform.

Material choice: fewer dissimilar materials that can be readily recycled, eliminate non-recyclable materials, careful selection of coatings.

Design for disassembly: reversible joints and interfaces of dissimilar materials.

These considerations are likely to lead to a tension between design for circular economy, and design for increased performance and efficiency. For example, the use of thermoset reinforced plastic composites can reduce aircraft mass and consequently fuel burn, making them an attractive way to reduce energy use. However, composite materials are inherently difficult to recycle, due to challenges around separation. Switching to a thermoplastic composite may require increased mass but the components can be cycled within the circular economy more readily.

Similarly, the inclusion of alloying elements in metals can significantly improve performance. For example, aluminium lithium alloys are lower density than traditional aluminium alloys, but, the presence of lithium creates an explosion hazard during the re-melting phase of recycling (Suomalainen, Celikel, & Venuat, 2014).

Reduce: Eliminate waste and use recycled material as input

Reducing material waste is arguably the most widely applied strategy in aerospace manufacturing at present, albeit predominantly for financial reasons rather than sustainability. Changing component geometry, material or manufacturing process has potential to reduce raw material demand, waste and emissions. Typically extracting the raw material and the initial processing stages of manufacture are the most energy intensive, so reducing the material demand will have the biggest effect on overall energy needs.

Two main strategies exist for reducing the raw material required in the manufacture of new aerospace components: lowering manufacturing buy-to-fly ratio (weight of raw material required compared to the weight of the final part) and topological design optimisation to increase the structural efficiency of components.

Metal aerospace components are often manufactured by following a subtractive process which tend to produce parts with high buy-to-fly ratios and are dependent on scrap recycling to avoid waste. Implementation of recently developed additive manufacturing technologies can significantly reduce the volume of scrap from the manufacture of metal components.

Additive Manufacturing can dramatically reduce waste and energy usage

Material deposited only where required: near-net shape products

Reduced material input

Reduced energy usage during manufacturing process.

Topological design optimisation can reduce the raw material with one example of its application shown in Figure 9. This part achieved a 30% weight reduction compared to the existing part (Firmo & Cheng, 2017).

Figure 9: Optimised titanium bracket with a 30% weight reduction demonstrated (Firmo & Cheng, 2017)

Extending Life Span

The circular economy approach aims to extend aircraft and component life for as long as possible to reduce the demand for new products and material. Strategies for product life extension are reuse, repair, refurbish, remanufacture and repurpose.

While these strategies are in-use across the aerospace sector, they are only used in limited areas and based almost entirely on linear economic considerations. As the focus on sustainability and Net Zero increases, the economic incentive to move to a circular model is unlikely to keep pace with the need to reduce emissions without significant government policy support. This could include aspects such as taxation or quotas on the extraction and use of raw materials and grants for necessary technology development.

Reuse: the number one circular strategy

Reuse is using a component again for the same purpose it was originally completing. Reuse occurs when parts are removed from an aircraft to be used for the same function on another aircraft.

Clever reuse of parts can prolong the function of an aircraft, extending its service life and reducing demand for new aircraft and components, with associated reductions in energy and raw material requirements.

The aerospace industry currently successfully reuses some components from in service or retired aircraft in the case where the cost of new parts is high, such as landing gear. Yet in many cases replacement parts are relatively inexpensive and easily sourced, meaning new components are fitted by default when part replacement is required. To increase the reuse of parts, more value must be attributed to the second-hand component. Some ways to do this are listed:

- Keeping a complete record of the flight data and loads for each component.
- Increase the relative cost of new parts during maintenance and repair.
- Increase the availability of second-hand parts (improve access).

There is a danger where raw materials are inexpensive and highly abundant or readily available that reuse of components is not attractive and there is no incentive to reuse. Recent trends show growing instability in material supply which is impacting cost and may make the reuse approach more attractive.

Repair and Refurbish: new processes are able to repair more parts than ever before

Repair and refurbish are strategies used to restore the original function of a damaged component. This temporarily prolongs component life and extends the functional use of the aircraft. Repair of aerospace components is already routine for larger, more expensive items, but less prevalent for small, lower value, items.

Recent developments in additive technologies are opening more repair opportunities for previously unrepairable components and reducing the need for spare parts. Figure 10 shows the energy requirement for creation of a new part following a traditional manufacturing processes compared with a wire based direct energy deposition process that could be used for repair. The initial extraction of material and billet production is by far the most energy costly process. Reducing the raw material requirement of the overall system is key to reducing energy usage and repairing a part rather than manufacturing a new part will inevitably use significantly less material and energy.

In 2016, BeAM reported that by using a directed energy deposition additive process for Pratt & Whitney turbine engine parts the part lifetime was extended from 10,000 to 50,000 flight hours (BeAM Machines, 2016). Rolls-Royce is working on the automated repair of gas turbine compressor blisks (bladed discs) shown in Figure 11. These are high-value components that are usually costly and difficult to repair (Nathan, 2019).

Refurbishing parts could reset fatigue lives

For structural components, a refurbish process could be used to ‘reset’ fatigue lives. By removing a surface layer of material, and then using additive technology to recreate it, fatigue initiation sites are removed, and the component is ready to be reassembled into an aircraft.

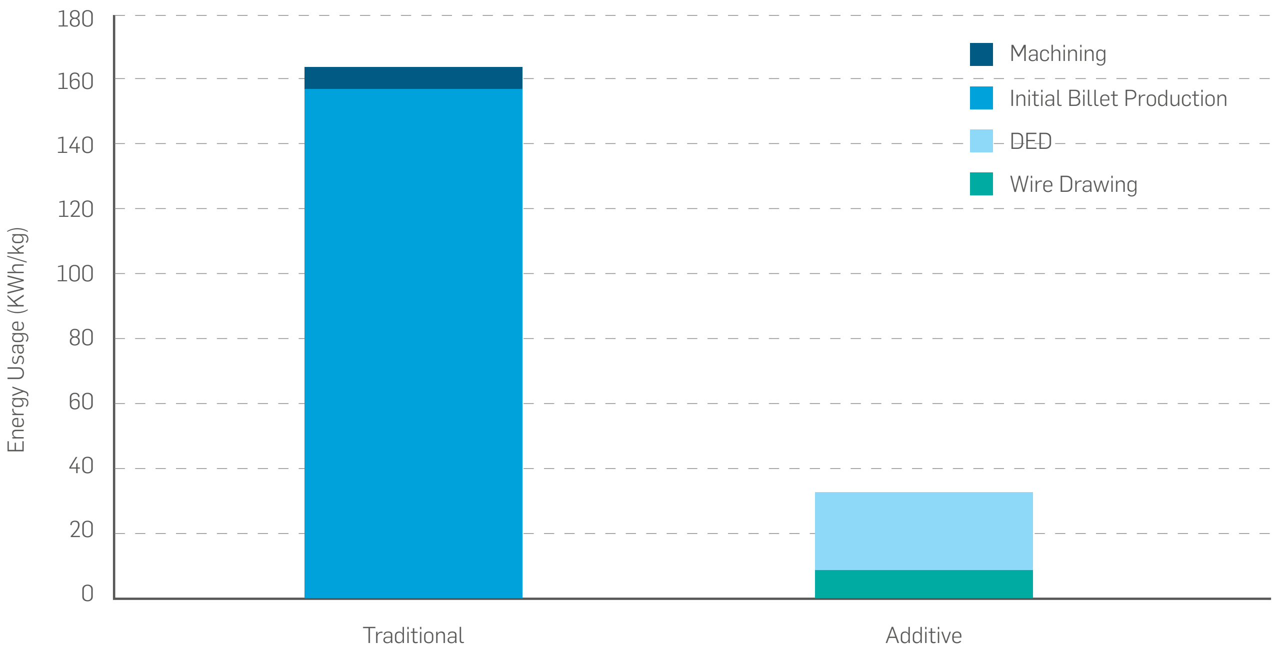


Figure 10: Comparison of Energy Requirements of Different Manufacturing Processes

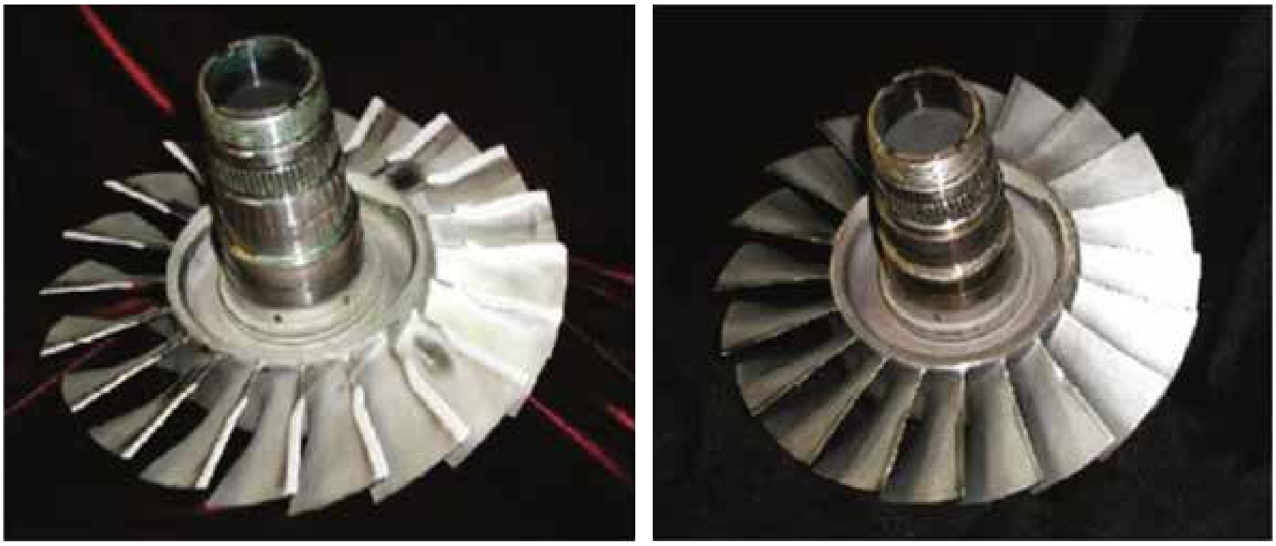


Figure 11: Left: Blisk after additive leading-edge repair Right: Blisk after finishing (Guo & Leu, 2013)

As the technology matures, market competitiveness will likely drive the cost down, in doing so the business case for less expensive components will improve.

Remanufacture and Repurpose

Remanufacture sees existing components or assemblies reworked and reassembled into new parts distinct from the originals but performing the same function. Repurposing is the same operation, only the parts or assemblies are reworked to perform a new function. Remanufacturing and repurposing are different to repairing and refurbishing in that the output is a like-new component or assembly. These strategies are already used on occasion: passenger aircraft are often repurposed to become freight aircraft and jet engines are often repurposed to provide static power for the oil and gas sector.

The aim of remanufacturing and repurposing is to increase the value of the parts and material by creating something new and better, using components already in operation but without the need for complete recycling.

In this respect, remanufacturing and repurposing can result in a net reduction in material use for a whole aircraft fleet over a long period. An item, such as an engine, can undergo development to increase efficiency through changes in geometry or configuration, which could be achieved through remanufacture and repurpose of the components used in the previous iteration.

The same can apply to the whole aircraft, supporting a continuous innovation approach to development. Remanufacture could allow aircraft cabin interiors to be upgraded to install the latest media technology, or aircraft having whole wings upgraded.

Additive manufacturing also opens the possibility of repurposing parts for use where different loading or geometric constraints may exist. This could be particularly useful for aircraft where there is often a trend towards increasing the load capacity and range over time or upgrading engines. Thinking further into the future, additive manufacture could enable the remanufacture of whole airframes to enable alternative energy sources, like batteries or hydrogen, to be utilised.

Useful Application of Materials: Recycle and Recover

Where lower energy circular strategies are no longer viable, recycle and recover strategies can be employed. These processes require the most energy to return value from the material. Recycling should only be implemented once the lifespan of a product or component has been extended as far as possible and recovery only where no other options exist, even in other sectors.

Recovery is used as a method to extract the last remaining value from aircraft through melting down or incineration of the constituent materials in order to extract energy. This energy can feed any number of applications, including the facilities and plants in operation to support the other elements of the circular economy.

Recycling: What Does the Aerospace Industry do Already?

Reclaiming value from end of life aircraft has received greater attention in the last decade due to the increasing number of aircraft reaching retirement age. Over the next 20 years, 10,000 aircraft are estimated to reach retirement (Junior & Jefferson, 2015).

Circular economy strategies and smart retirement of aircraft can increase the volume of parts and materials recirculated within the industry, reducing the demand for raw material.

ICAO present the current approach to aircraft decommissioning management, shown in Figure 12, which does include some circular strategies.

Figure 13 shows that recovered metal waste often enters a shredder, is sorted and melted down to create new material used in other sectors. Material that cannot be recycled is either recovered for energy generation or sent to landfill.

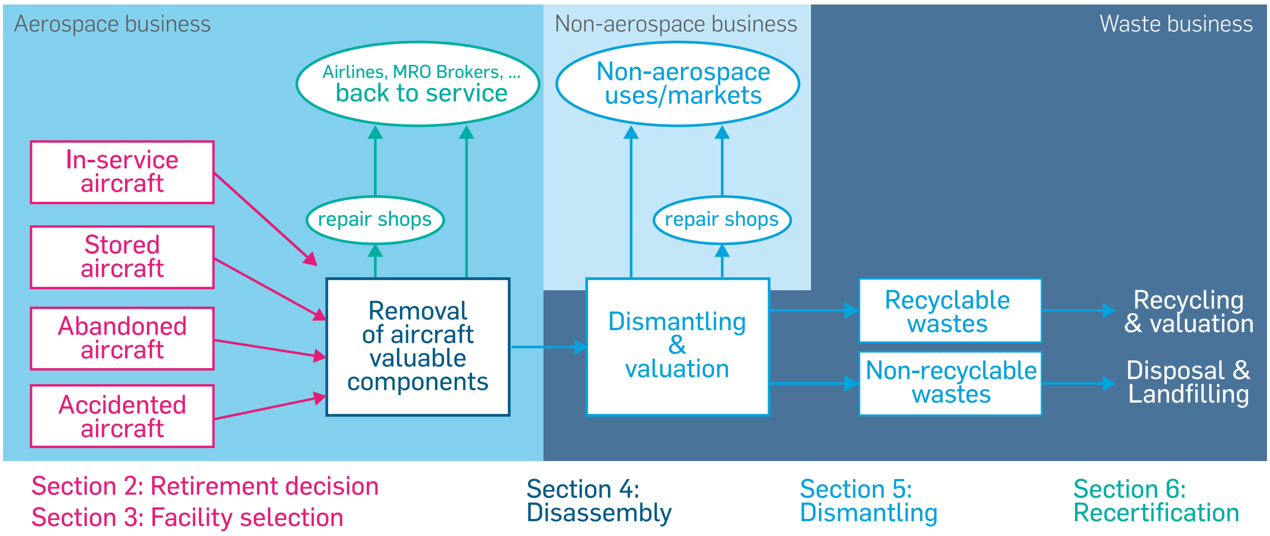


Figure 12: Aircraft decommissioning process (ICAO, 2019)

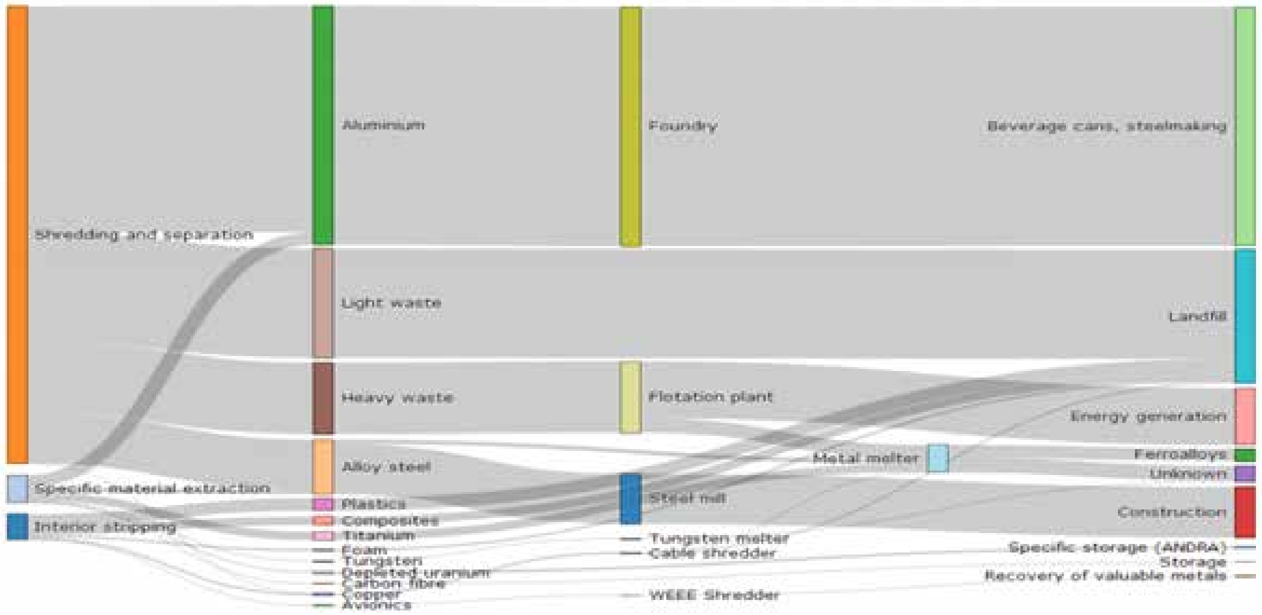


Figure 13: Material recycling and recovering at aircraft retirement (ICAO, 2014)

Despite some circular strategies already being followed, the proportion of the aircraft that is reused and remanufactured is small and remanufacturing typically only occurs at aircraft retirement. Furthermore, an aircraft may be retired for economic reasons even before its functional life has run out.

Another issue with the current recycling scenario is that most aerospace materials recycled and recovered are fed into other industries, waste companies and landfill, as shown in Figure 14. If aerospace companies could enable direct recycling within the industry, the value of the material would be dramatically increased and requirement for new raw material would fall.

This same scenario is suggested in a GKN circular economy study performed in 2015, where they considered internally processing scrap metal into material feedstock rather than selling to external waste companies (Andersson & Stavileci, 2015).

Current aircraft are not designed with disassembly in mind

Current aircraft were not designed with ease of recycling in mind, which leads to many challenges to recycle aircraft materials. For example, aircraft were not designed to be easily disassembled into constituent materials. Components and assemblies may also be made from numerous different materials. This makes recycling time consuming and costly.

Metal scrap is typically shredded and separated using techniques such as density separation (air stream), Eddy current separation and magnetic separation. As the separating processes are not entirely effective, recovered metals are often of reduced quality compared to the virgin metal. This is especially so in the recovery of precious and rare earth metals from avionics and electrical equipment. Manual dismantling can increase the quality of recovered material (Suomalainen, Celikel, & Venuat, 2014) but increases the duration and cost.

Hazardous materials need to be carefully managed

Another issue faced by aircraft recyclers is the presence of hazardous materials. For example, "old military aircraft can contain asbestos, fire extinguishers contain Halon 1301 and smoke detectors and emergency exit signs found in commercial aircraft enclose radioactive elements. Hexavalent chromium can also be found in the aircraft paint primer" (Suomalainen, Celikel, & Venuat, 2014).

These non-compliant materials must be separated and disposed of safely or used for energy recovery if possible.

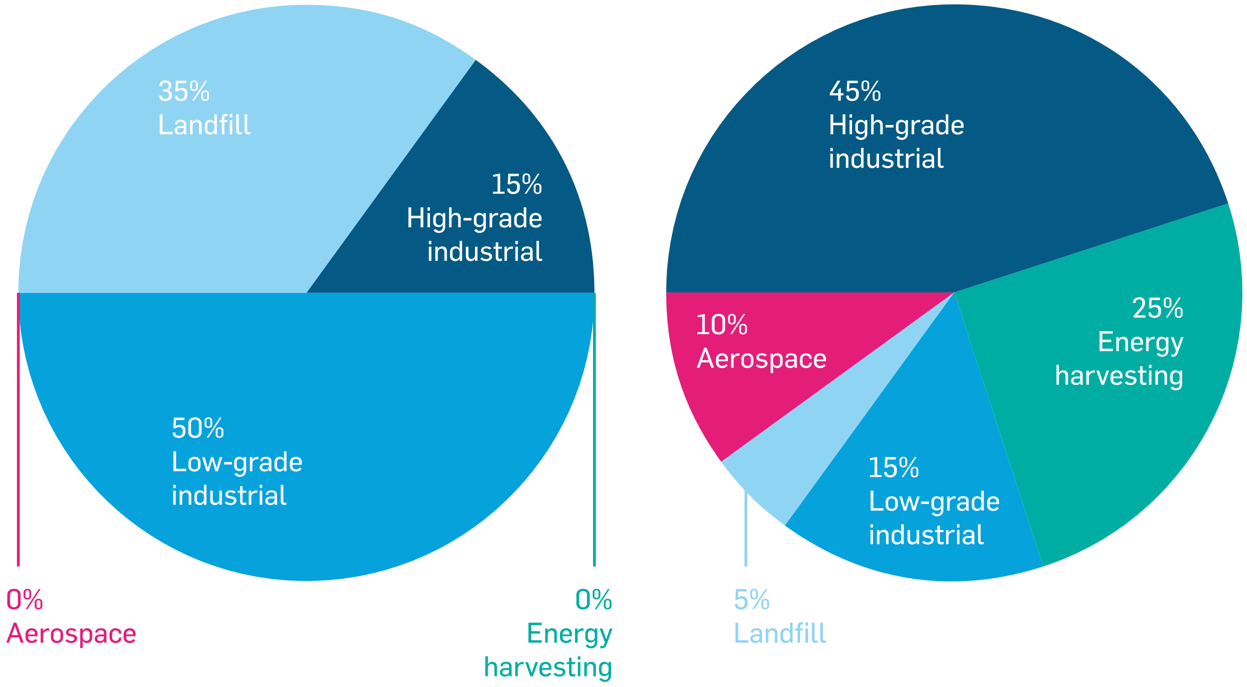


Figure 14: Utilisation fields of recycled aircraft materials (Carberry, 2008)

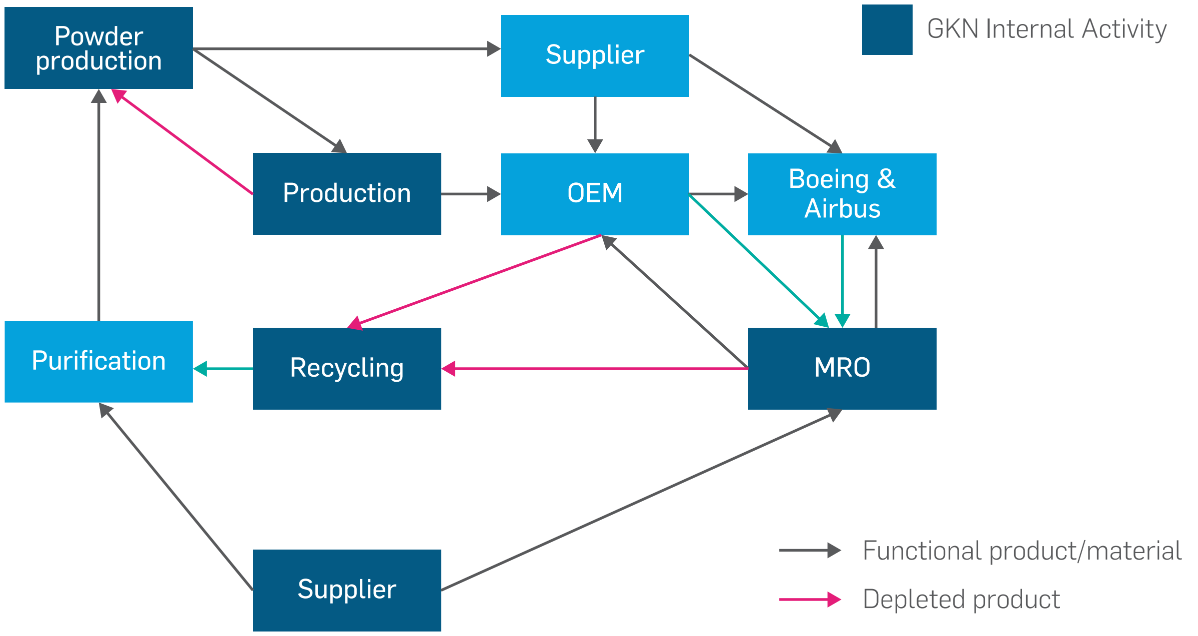


Figure 15: Material flow for the 'G model' in GKN study (Andersson & Stavileci, 2015)

Fibre reinforced plastic composites are especially challenging

Composite materials (fibre reinforced plastics), which form an increasingly large proportion of aircraft, also pose a significant challenge to recycling. Thermoset resin composites are typically recycled by removing resin through pyrolysis and fibre recovery. Recovered fibres are made into chopped fibre matting or used as short fibres for reinforcing plastic.

The chopped fibre matting, or short fibres, cannot be used to manufacture a material that is as strong and stiff as a continuous or long fibre reinforced plastic. Therefore, there is obviously a degradation in the value of the material in composite recycling by current techniques. Furthermore, the thermoset resin is not recycled, although energy recovery is possible.

Recycling: Opportunities for Improvements within Aerospace

The next generation of aircraft could be designed for a circular economy by designing with consideration of a recycling phase at the end of an extended life. Improved design for recycling is key to tackling the current challenges in recycling and will improve recycled material quality and cost effectiveness. However, techniques for recycling existing designs are also important given the volume of aircraft currently flying.

Improved composite recycling methods will be needed to regain value from the large number of composite airframe components currently in operation or due to be produced. However, the inherent corrosion and fatigue resistance of fibre reinforced plastic composite structures support life span extension strategies. Much development activity is focussed on the use of thermoplastic resin composite materials which, while not as strong as thermosets, could serve to increase the ability of composite material to fit within circular strategies. These materials have the potential to be repaired or refurbished under the application of heat in a process analogous to forging and welding for metal components.

Technology could also be used to both enable greater recycling volume and reduce the cost. The use of robots to dismantle aircraft will reduce labour costs and improve safety. Robots could be used to do tasks like removing rivets, reducing the mix of material sent for shredding and recycling.

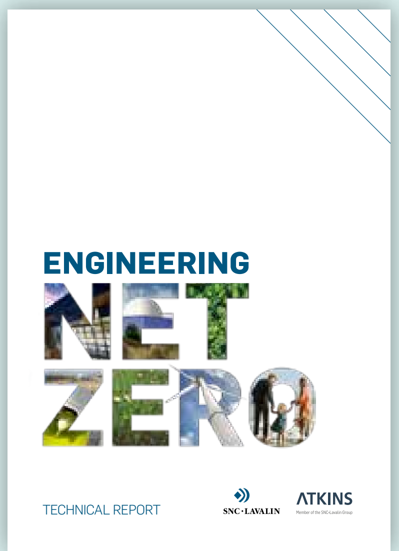
As is the case for other stages in the circular economy it is recognised that legislation and government incentives will also strongly influence the prevalence of aircraft recycling. Government grants and loans could enable the development of aircraft recycling facilities, providing the significant capital investment required to establish recycling facilities.

METALS	Directed Energy Deposition (DED)	Thermal energy fuses material as it is deposited
BOTH	Sheet Lamination	Sheets of material are bonded together to form an object
	Powder Bed Fusion (PBF)	Thermal energy fuses select regions of a powerbed
	Binder Jetting	Thermal energy fuses materials as it is deposited
PLASTICS	Vat Photo-polymerization	A vat of photopolymer is selectively cured by light activated cross linking of polymer chains
	Material Jetting	Droplets of build material are selectively deposited
	Material Extrusion	Material is deposited through a nozzle/orifice in layers

Figure 16: Seven additive manufacturing methods

To achieve Net Zero the whole system must be Net Zero

For all of the alternative fuel options to be considered Net Zero there is a challenge on the provision of the input energy required to create them, and recharge the batteries, to also be Net Zero – a challenge not unique to aerospace and one that must be addressed globally.



For aerospace, it is important to articulate the energy required and the form it is required in, to ensure consideration within wider energy strategies and systems. A high-level ‘system of systems’ approach that considers whole life energy costs is necessary to support this.

Atkins’ Engineering Net Zero provides the basis of such a study for the UK by considering the wider energy demands and how these can be met (Atkins, 2019).

The basis of such studies is also well-described by David MacKay in an easy to access book available for free online (MacKay, 2009).

www.atkinsglobal.com/EngineeringNetZero

Additive Manufacturing: A Key Enable for The Circular Economy

International standards recognise seven distinct additive manufacturing methods, listed in Figure 17. Powder bed fusion and directed energy deposition methods are most mature and have therefore been of most interest to the aerospace industry for metallic parts. There is also interest in the manufacture of plastic parts, particularly for interiors, typically using vat photopolymerization, powder bed fusion and material extrusion. Composite additive manufacturing is typically based on material extrusion with the inclusion of a filament or fibres during deposition.

Additive manufacturing can contribute to multiple stages of a circular economy in the aerospace industry. During the initial manufacturing stage additive manufacturing can reduce the amount of material and energy consumed.

Additive manufacturing places material only where needed and so material is used much more efficiently. Figure 18 shows a wing rib manufactured using a direct energy deposition process. The buy-to-fly ratio of the rib manufactured using the baseline method (machining from billet) is 45:1, this was reduced to 3:1 by using an additive manufacturing process (Lockett, 2019).

More structurally efficient designs can also support reduced material usage. Additive manufacturing makes it possible to produce designs that are not possible using conventional methods, for example, the topology optimised bracket discussed previously and shown in Figure 9.

Figure 17: Additive manufactured wing rib demonstration (Design@Open, 2019)

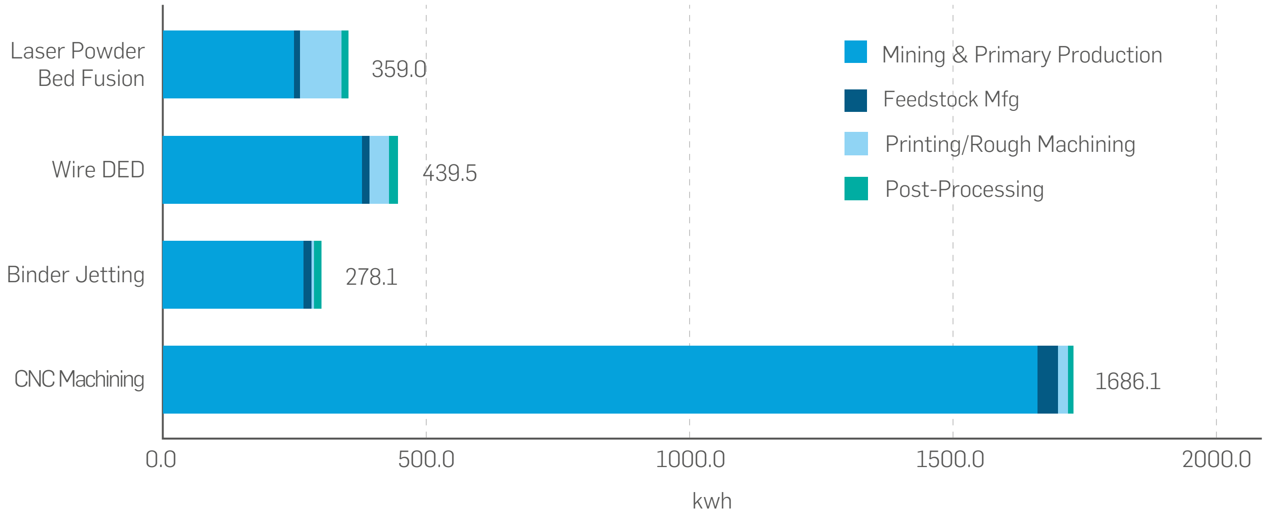


Figure 18: Energy required for a 1kg titanium part (Huckstepp, 2019)

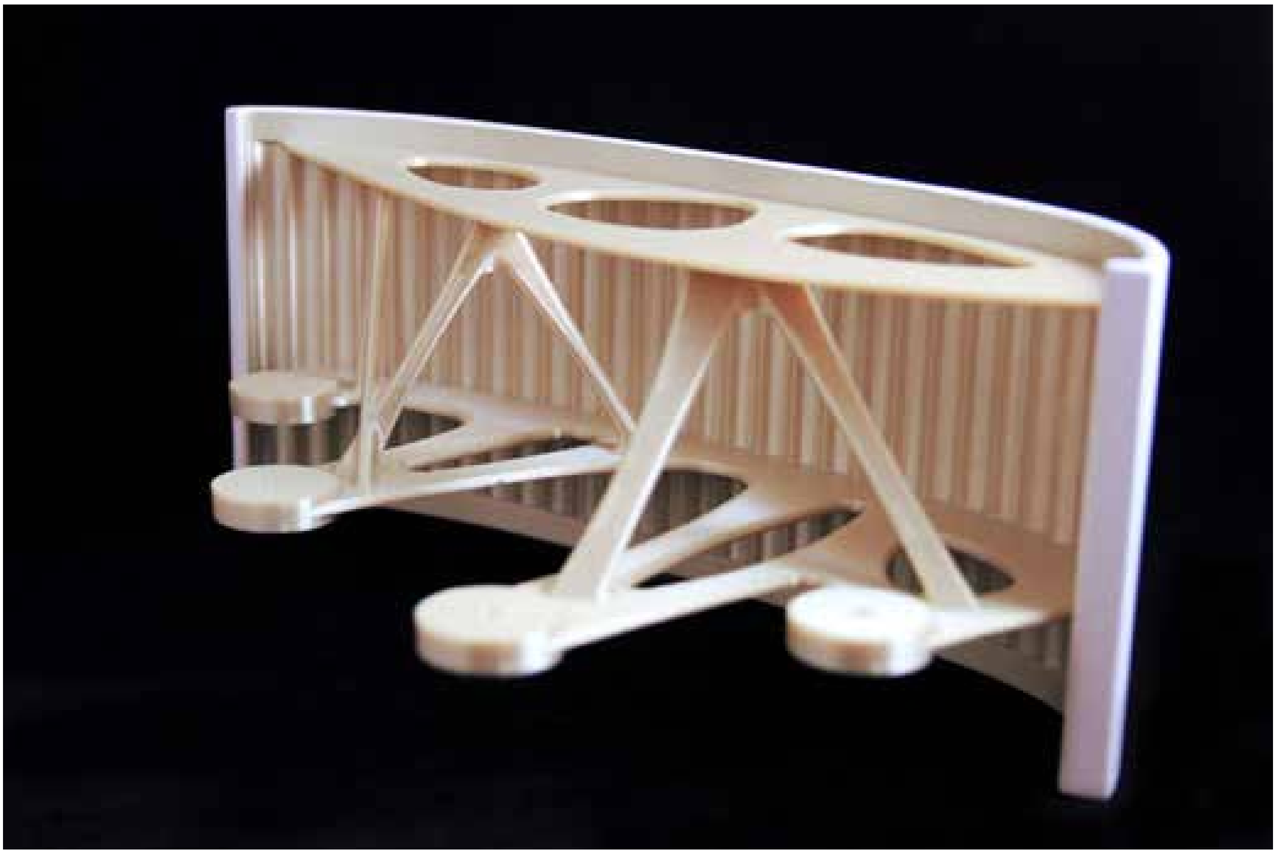
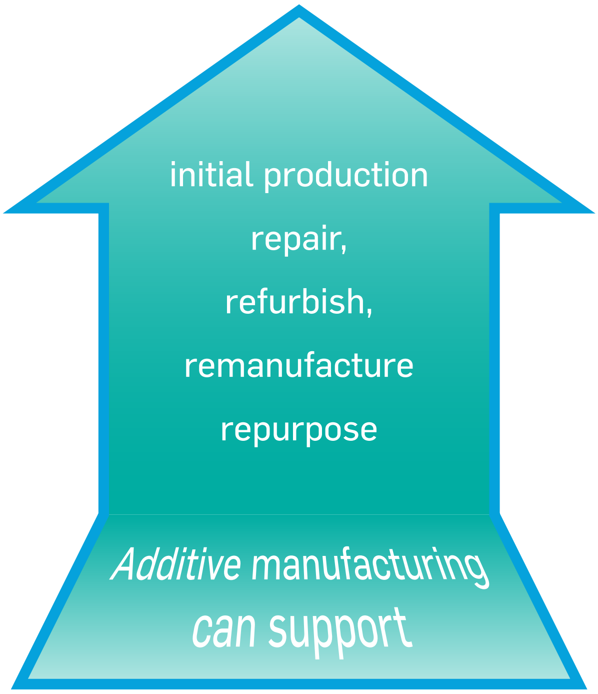


Figure 19: Airbus A320 spacer panel, (Airbus, 2018)

By using less raw material, the energy required for components produced by additive manufacturing is greatly reduced. Figure 18 shows the energy required to produce a 1 kg part, with a buy-to-fly ratio of 17 for the machined part, and a buy-to-fly ratio of 2 for the wire direct energy deposition part.

To extend the life or repurpose components, additive manufacturing can be used without the need for additional tooling. Airbus have previously used a plastic additive method to produce a spacer panel, to fill a gap left when an aircraft interior was modified, see Figure 19. Additive processes led to an optimised design with reduced material usage and no additional tooling is required.

Additive manufacturing can support many stages of the circular economy



Stocks of replacement components can also be reduced significantly by creating digital inventories where digital models of parts are stored and manufactured on demand at the location they are required. If combined with sufficient real-time health monitoring, production of the replacement item can be completed to be available for the aircraft when it lands, minimising down-time. Obsolete parts can be manufactured where original tooling is no longer available, making it financially viable to continue using an aircraft or assembly for longer.

Certification is a big challenge for additive manufacturing

One of the main challenges to increased adoption of additive manufacturing in aerospace is certification. Figure 20 shows a process flowchart for development of a certified aerospace part. Much of this process is no different to the process for certifying a part manufactured by conventional routes.

Where the process does differ is that for conventionally manufactured parts the initial material qualification stage has usually been done already, and design allowables can be found in recognised databases. This information is rarely available for material produced by additive manufacturing. Furthermore, because the final material properties of an additive component are so strongly linked to the geometry and process parameters used, additional qualification of the part and process is required.

Likewise, the site and machine producing the part must also be qualified, and during production stringent inspection and quality control measures are necessary to ensure the integrity of each part. For example, often every single part will be x-rayed to identify any flaws or inclusions.

Future developments will ease the burden of certifying aerospace parts; in-process monitoring holds promise to identify flaws as material is formed and the development of computational analysis methods will reduce the volume of testing required. Creating a digital twin of the part including data from in-process monitoring will mean flaws formed during production can be closely monitored in service, and it may be possible to maintain safety whilst easing current stringent quality control requirements.

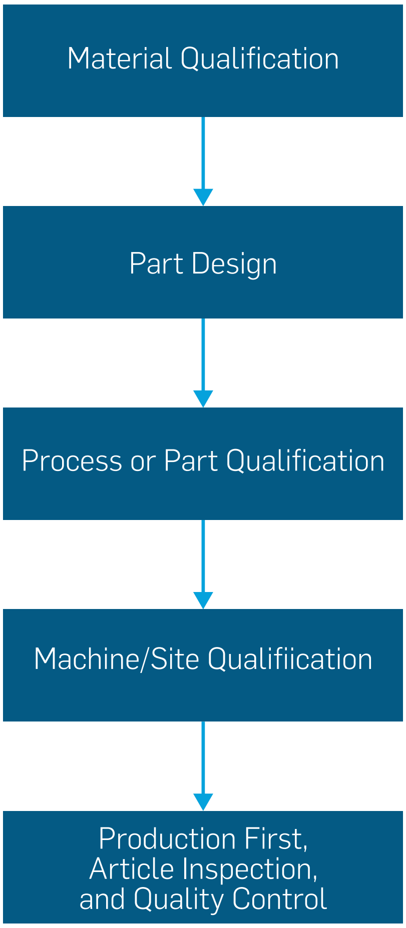


Figure 20: Process flowchart for development ofcertified aerospace parts

Using Digital Twin to Support the Circular Economy

Looking over the different strategies within the circular economy indicates that to fully realise the benefits, traceability of materials and their usage is imperative. Digital twins can be used as a means to provide this traceabilty and track components through life, providing details of material composition, component usage and other pertinent details.

The records of the materials kept with an aircraft or component, combined with their usage, can be used to define circular economy pathways. Reuse, repurpose and remanufacture options can be presented and the optimum pathways can be selected for minimal energy requirements.

The details of certain parts or materials, including material treatments and coatings will also aid improved recycling by quickly identifying the most appropriate processes to provide suitable quality material back into the production chain.

Identification of hazardous materials is also supported allowing appropriate safety measures to be followed during any refurbishment or recycling process.

Digital twins for circular economy purposes can be achieved through a progressive implementation approach aligned to other Industry 4.0 technologies. Initially, recording and storage of component material composition information requires capture of the material quality data that is already produced during manufacture. A second step would be to align this data reliably with components in-service, particularly where parts are not serialised. Addition of RFID tagging or laser etching of a barcode to components could be ways to achieve this. From this starting point, in-service usage data covering loading, performance, environmental exposure and repair details can be added, as the means to capture these data points are developed and installed on aircraft.

A New Business Model: Aircraft-As-A-Service

The processes and activities within the circular economy change the economic opportunities and motivations when compared to a linear model. The linear model tends to support the production of an aircraft which is then sold to an operator. The operator is then responsible for the maintenance of the aircraft, including the decisions on whether to buy spare parts or conduct repairs and finally what to do at the end of the aircraft life. Aircraft manufacturers offer continued services along the way but typically at additional cost. Operators, typically, do not have options for who to buy spare parts from; this leads to reduced incentive for manufacturers to extend component life as required by a circular economy.

With the circular economy, more emphasis is placed on longevity of components, reuse into other aircraft or remanufacturing for changed applications. For an individual operator, with a limited fleet and a lack of design details or ability to develop their aircraft, the options available within circular economy pathways are limited with minimal gains. The original manufacturer is responsible for the creation of the entire fleet of an aircraft type, its development, related variants and ongoing innovation.

They therefore could find the most optimal routes for extending life spans and recycling through circular economy strategies across the complete fleet they produce (or are to produce in the future).

Thus, aircraft and their components have more value to the manufacturers than operators. This increased value leans towards a subscription-based business model from the manufacturer to operators. The manufacturer, who has the highest ability to implement circular economy strategies, is then further incentivised to actually push, develop and optimise circular economy pathways to maintain the subscription income. This can be described as aircraft-as-a-service.

The leasing model provides the manufacturer 'cradle-to-grave' knowledge, insight and control of the product, allowing the manufacturer to easily introduce smart tracking equipment and interchange parts between products more efficiently.

Propulsion-as-a-Service already exists

This type of leasing model is already seen in offerings from propulsion manufacturers. Rolls-Royce's leasing option TotalCare, allows Rolls-Royce to access the flight data history and implement smart maintenance, life extension and reuse strategies (Fitzgerald, 2018). This offering is driven through advances in sensor and real-time communications technology, which enable Rolls-Royce to continually monitor its engine fleet.

Smart, predictive, maintenance also becomes possible to minimise aircraft downtime through unexpected failures, supporting increased aircraft utilisation under the rethink circular pathway. By applying this approach, the performance of parts throughout their lifetime, the service offering from the manufacturer and the subscription cost become key considerations for aircraft choice by operators. It reduces the need for operators to source large amounts of funding, or capital, during initial purchase of aircraft and instead spreads the cost and aligns closer to revenue generation.

Leasing ultimately works towards decoupling economic growth from the consumption of finite resources, a central theme in the circular economy model and working towards a Net Zero industry

Conclusions

To achieve carbon Net Zero the aerospace industry cannot ignore material use and emissions due to production. Currently emissions released as a result of raw material extraction and aircraft production seem insignificant compared to in-service emissions from fuel burn. However, they must be addressed alongside the flight energy storage challenge if the sector is to achieve Net Zero.

Tackling this problem means a shift from a largely linear economic model to a circular economy. A circular economy looks to decouple the use of natural resources from economic growth, minimising the energy requirements, and thus the environmental impact. This paper highlights three key enablers for the circular economy in aerospace, show in Figure 21.

The transition to a circular economy begins with a review of existing processes and pathways with the circular philosophy in mind. Then new technology enablers can be considered to improve economics and make new pathways viable: additive manufacturing, advanced recycling processes and digital twin. Introducing different design philosophies and approaches which take into account these enablers will support aerospace in truly taking advantage of circular principles and achieving Net Zero. While the imperative to do this may be environmental, perhaps driven by legislation, the by-product of a successful transition is likely to be increased economic opportunities for manufacturers.

Circular economy strategies work to keep the value of an aircraft, and its components, high for as long as possible, reducing the need for product replacement and increased use of raw material. By reducing the need for raw material extraction additional sustainability goals are supported including good health for workers by moving from mines to controlled factor environments and reducing damaging by-products that could affect local ecology.

In a perfect circular economy, material input is not required and materials never leave the circle but instead rotate on an endless loop. The only input required is energy to keep the circle moving, which could come from renewable and sustainable sources and Net Zero can be achieved. To achieve this in practice is a significant challenge, but why can't that be the target?

Figure 21: Key enablers/strategies to move towards a circular economy in the aerospace industry

References and Further Reading

ACARE. (2011). Flightpath 2050. Retrieved from https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf

Airbus. (2018, April 9). Retrieved from Bridging the gap with 3D printing: https://www.airbus.com/newsroom/news/en/2018/04/bridging-the-gap-with-3d-printing.html

Airbus. (2018, April 9). Airbus. Retrieved from Bridging the gap with 3D printing: https://www.airbus.com/newsroom/news/en/2018/04/bridging-the-gap-with-3d-printing.html

Airbus. (2020). Annual Report 2019. Retrieved from https://www.airbus.com/investors/financial-results-and-annual-reports.html#annualreports

Andersson, D., & Stavileci, S. (2015). An assessment of how Circular Economy can be implemented in the Aerospace Industry. Karlskrona: Blenkinge Institute of Technology.

Ball, P., Howle, R. J., & Huatuco, L. H. (2019). Sustainable Design and Manufacturing. Proceedings of the 6th International Conference on Sustainable Design and Manufacturing (KES-SDM 19). Springer.

Barnes, J., Kingsbury, A., & Bono, E. (2016). Does Low Cost Titanium Powder Yield Low Cost Titanium Parts. PowderMet.

BeAM Machines. (2016, November 10). BeAM to introduce new industrial machines at international additive manufacturing trade show, formnext. Retrieved from BeAM: https://www.beam-machines.com/events/new-industrial-machines-formnext

Boeing. (2019). Commercial Market Outlook 2019 - 2038. Retrieved from Boeing Commercial Market Outlook: https://www.boeing.com/commercial/market/commercial-market-outlook/#/downloads

Bono, E. (n.d.). Controlling Metal Powder Costs in Additive Manufacturing. Retrieved from Carpenter Technology: https://www.carpentertechnology.com/en/alloy-techzone/technical-information/technical-articles/controlling-metal-powder-costs/

Brummelhuis, A. (2015, June 19). Light as a Service as enabler for Remanufacturing by Anton Brummelhuis from Philips Lighting. Retrieved from SlideShare: https://www.slideshare.net/circleeconomy/presentatie-4-philips-laas-and-remanufacturing-rematec

Campatelli, G. (2017). Retrofit System for Repairing through Additive Manufacturing. Retrieved from ManuNet: https://www.manunet.net/success-stories/284-retrofit-system-for-repairing-through-additive-manufacturing.html

Carberry, W. (2008). Airplane Recycling Efforts Benefit Boeing Operators, Aeromagazine Q4. Retrieved from Boeing: https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_08/article_02_4.html

Cooper, T., Smiley, J., Porter, C., & Precourt, C. (2018). Global Fleet & MRO Market Forecast Commentary. Marsh and McLennan Companies.

Department for Business Innovation & Skills. (2016). UK Aerospace Maintenance, Repair, Overhaul & Logistics Industry Analysis.

Design@Open (2019): http://www.open.ac.uk/blogs/design/additive-manufacturing-helping-to-reduce-waste-in-aircraft-production/

Directive 2008/98/EC. (2008, November 19). Official Journal of the European Union. European Parliament and of the Council.

Eckelman, M. J., Ciacci, L., Kavlak, G., Nuss, P., Reck, B. K., & Graedel, T. E. (2014). Life Cycle Carbon Benefits of Aerospace Alloy Recycling. Journal of Cleaner Production.

Ellen MacArthur Foundation. (2019). Completing the Picture: How the Circular Economy Tackles Climate Change.

European Environment Agency. (2017). Circular by design: Products in the circular economy.

Firmo, E., & Cheng, T. (2017, May 24). Immelt Updates Investors on GE's Digital Industrial Strategy. Retrieved from GE Reports: https://www.ge.com/reports/immelt-updates-investors-ges-digital-industrial-strategy/

Fitzgerald, L. (2018, April 24). The Engine Lease Market Today: More Dynamic Then Ever. Retrieved from Engine Lease Finance: https://elfc.com/the-engine-leasing-market-today/

Government, S. (2016). Making Things Last: A Circular Economy Strategy for Scotland.

Guardian. (2020). How Renewable Energy Could Power Britains Economic Recovery. Retrieved from https://www.theguardian.com/environment/2020/may/19/how-renewable-energy-could-power-britains-economic-recovery?CMP=Share_iOSApp_Other

Guo, N., & Leu, M. C. (2013, September). Additive manufacturing: Technology, applications and research needs. Frontiers of Mechanical Engineering, pp. 215-243.

Huckstepp, A. (2019, March 28). Digital Alloys' Guide to Metal Additive Manufacturing – Part 7, Energy Consumption in Metal Additive Manufacturing. Retrieved from Digital Alloys News & Blog: https://www.digitalalloys.com/blog/energy-consumption-metal-additive-manufacturing/

ICAO. (2014, September 9-10). What's new in aircraft materials recycling? AiMeRe Project. Montreal, Canada: envisa, ICAO.

ICAO. (2019). 2019 Environmental Report, Destination Green – The Next Chapter.

ICAO. (2019). 2019 Environmental Report: Destination Green The Next Chapter. International Civil Aviation Organisation.

ICCT. (2018). CO2 Emissions From Commercial Aviation 2018. Retrieved from ICCT.org: https://theicct.org/publications

International Civil Aviation Organisation. (2019). 2019 Environmental Report: Destination Green The Next Chapter. ICAO.

IPCC. (2018). Global Warming of 1.5C Special Report. Retrieved from IPCC.ch: https://www.ipcc.ch/sr15/

Jawaid, M., & Thariq, M. (2018). Sustainable Composites for Aerospace Applications. Woodhead Publishing.

Junior, S. R., & Jefferson, d. G. (2015). Proposed framework for End-Of-Life aircraft recycling. 12th Global Conference on Sustainable Manufacturing.

Kira. (2016, February 4). BeAM repairs more than 800 aerospace parts with industrial metal 3D printers. Retrieved from 3ders: http://www.3ders.org/articles/20160204-beam-repairs-more-than-800-aerospace-parts-with-industrial-metal-3d-printers.html

Kirby, M. (2019, August 27). Key ways aviation is trying to improve its environmental credentials. Retrieved from Runway Girl Network: https://runwaygirlnetwork.com/2019/08/27/key-ways-aviation-is-trying-to-improve-its-environmental-credentials/

Lockett, H. (2019, May 23). Additive Manufacturing – helping to reduce waste in aircraft production. Retrieved from Design@Open: http://www.open.ac.uk/blogs/design/additive-manufacturing-helping-to-reduce-waste-in-aircraft-production/

MacKay, D. (2009). Sustainability Without The Hot Air. Retrieved from https://www.withouthotair.com/

Metal AM. (2016, December 14). Sciaky to deliver industrial-scale metal Additive Manufacturing system to Airbus. Retrieved from Metal AM: https://www.metal-am.com/sciaky-deliver-industrial-scale-metal-additive-manufacturing-system-airbus/

Mieras, E. (2016, June 16). 5 Roads To A Circular Economy – Part IV: Sharing. Retrieved from Pre sustainability: https://www.pre-sustainability.com/news/5-roads-to-a-circular-economy-part-iv-sharing

Nathan, S. (2019, September 11). Repairs on high: engineering innovation in aircraft maintenance. Retrieved from The Engineer: https://www.theengineer.co.uk/repairs-on-high-engineering-innovation-in-aircraft-maintenance/

Norgate, T., Jahanshahi, S., & Rankin, W. (2006). Assessing the environmental impact of metal production processes. Journal of Cleaner Production, 838-848.

Raworth, K. (2017). Doughnut Economics.

Suomalainen, E., Celikel, A., & Venuat, P. (2014). Aircraft Metals Recycling: Process, Challenges and Opportunities.

Totin, A., Macdonald, E., & Conner, B. P. (2019). Additive Manufacturing for Aerospace Maintenance and Sustainment.

Twidell, A. (2016, May 18). Aviation Graveyards: Where Do Retired Aircraft Go? Retrieved from Privatefly: https://blog.privatefly.com/us/aviation-graveyards-where-do-retired-aircraft-go

Xu, Y., Zhu, J., Cao, Y., Yubo, Z., & Weihong, Z. (2018). A review on the design of laminated composite structures: constant and variable stiffness design and topology optimization. Advanced Composites and Hybrid Materials.

Member of the SNC-Lavalin Group

About the authors

James Domone
Senior Engineer

Philippa Bliss
Assistant Engineer

Matt Copus
Engineer

James, Philippa and Matt are all engineers in aerospace, design, security and technology for Atkins, a member of the SNC-Lavalin Group, that is working to transform aerospace engineering for faster design, reduced downtime, and lower costs.

Transforming aerospace engineering, for faster design, reduced downtime and lower costs.

atkinsglobal.com/aerospace