SUSTAINABLE CABIN DESIGN

New Approaches in Sustainable Aircraft Interior Design

FLY ZERO AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight.

This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements, and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions, and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology, and skills for years to come.

To discover more and download the FlyZero reports, visit **ati.org.uk**

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EXECUTIVE SUMMARY

Accounting for 10% of its empty weight and replaced 4 to 5 times [1] during the life of the airframe, the cabin is responsible for a significant proportion of an airliner's environmental impact.

FlyZero was established in early 2021 to enhance the capabilities of UK aerospace in the pursuit of zero-carbon emission aviation. Its ambition encompasses any opportunity to realise more sustainable flight, and for the cabin this has meant a focus on the contribution to operational emissions and the non-operational impact of manufacture, maintenance and end-of-life.

Presently, operational emissions comprise around 90% to 95% [2] of the carbon footprint of a kerosene fuelled airliner considering operation, manufacture and maintenance. However, in a future where hydrogen aircraft emit no carbon dioxide, the proportional significance of non-operational factors becomes far greater. This paper proposes technologies, design approaches and business models that could reduce the operational and non-operational footprints.

FlyZero's focus on future fuels means that many of its proposals will not be realised before the target date of 2030 and the launch of a new platform. An advantage of the measures described in this paper is that most can be pursued immediately and begin to deliver carbon dioxide reductions in the very near term.

FlyZero estimates that the cabin sector is responsible for between 5% and 10% of the turnover of the UK aerospace industry. The Aerospace Technology Institute (ATI) estimates there are over 250 suppliers in the UK involved in aircraft interiors with a combined turnover exceeding £2.0 bn and supporting more than 6,000 jobs [3]. The UK is home to manufacturers of almost every component of the cabin, innovative aviation materials suppliers, a world class specialist design industry and a high concentration of aircraft recycling companies.

The findings presented in this report summarise the results of a sustained partnership with Cranfield University. This drew from desktop analysis and interviews with a diverse set of cabin design, manufacture and management stakeholders and is available in four dedicated reports:

- FlyZero Sustainable Cabin: Performance Criteria & Goals, FZ_SoW_0018_A
- FlyZero Sustainable Cabin: State of the Current Market, FZ_SoW_0018_B
- FlyZero Sustainable Cabin: Technology Response, FZ_SoW_0018_C
- FlyZero Sustainable Cabin: Technology Roadmap, FZ_SoW_0018_D

Challenges

Incremental weight reduction is increasingly challenging as the designs of most cabin products are relatively mature and optimised. Certification developments tend to increase pressure to add weight and disincentivise cabin original equipment manufacturers (OEM) from taking risks in introducing new technologies. Price sensitivity in a commodified market also limits the applicability of new technologies which might deliver significant weight savings such as additive manufacturing.

The cabin is one of the most difficult parts of an aircraft to apply circular economy principles to, and as such accounts for a high proportion of the material from aircraft recycling that is sent to landfill or incinerated.

Many of the opportunities for increasing circularity require intra-sector and cross-sector partnerships that are currently underdeveloped to enable material and product flows at viable scales.

Stringent certification requirements incentivise OEMs to rely on proven designs, technologies and materials. This tends to suppress the introduction of novel, potentially greener technologies and encourage reliance on established designs and materials, many of which have negative sustainability characteristics.

As sustainability has not been a priority for the industry historically, there is a low level of understanding of the cabin's impact on the environment except as a consequence of its weight.

Recommendations

To address these challenges and realise the vision of UK leadership in the development of greener cabins, it is recommended that a range of measures are pursued covering the development of cabin sector practices, new product development targeting identified sustainability issues and the pursuit of certain new technologies.

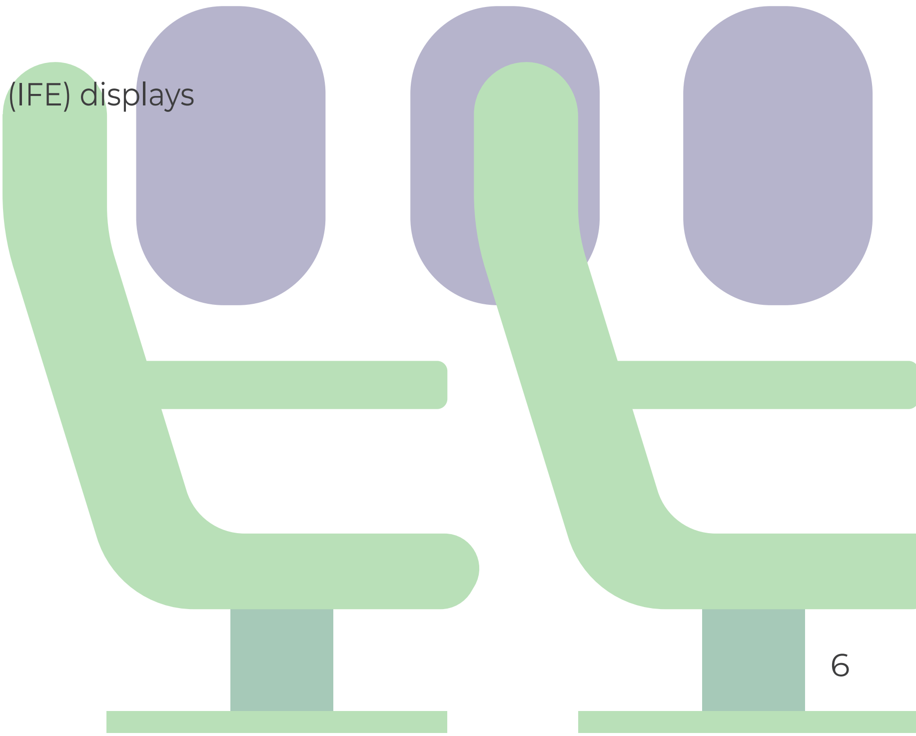
FlyZero has developed a set of recommendations to industry (see **Circular Design Recommendations Annex**). The following subset of these measures are prioritised as offering high potential impact with lower barriers to implementation.

1. Assess the development timeframe of promising cabin technologies and sequence their introduction in stages.
2. Involve the whole value chain (airlines, airframe OEMs, cabin OEMs and their suppliers) in co-developing sustainable cabin interiors.
3. Enable the re-use of production waste across industries.

4. Make materials identifiable and share data to enable re-use.
5. Define full-life strategies to minimise product impact.
6. Minimise total lifetime maintenance and disposal impact.
7. Cabin OEMs to consolidate their waste outflow into a suitable material source for other industries.
8. Enable recycled material from cabins to be used in other industries.
9. Enable easy rebranding of cabin furniture.
10. Use recycled materials from other industries in cabin products.

To take advantage of the fact that airlines and airframe OEMs are beginning to look for sustainability performance improvements from their suppliers, it is recommended that UK cabin product OEMs develop strategies to demonstrably improve their products accordingly. Investing in LCA capabilities to guide material and design choices is advised. FlyZero's investigation using such tools indicates that the following cabin components embody harmful materials (see **Table 5**) and should be prioritised for change:

- Carbon fibre reinforced plastic (CFRP) seat back structures
- Virgin aluminium seat structure / components
- Woollen seat covers
- Melamine and polyurethane (PU) seat cushions
- Inconel and steel fasteners
- Aramid core composite panels
- Polyethylene terephthalate (PET) and polypropylene (PP) air ducts
- Copper wiring
- Conventional in-flight-entertainment (IFE) displays



Finally, new technologies should be pursued that will reduce the cabin's carbon footprint via lightweighting, enhancement of circularity, and the selection of materials and processes that minimise embedded energy from extraction, processing, transportation, transformation into the finished product and related waste. This paper provides a set of 18 recommended technologies (see Table 8 to Table 11). Priorities among these being the technologies that provide benefits in both the weight and impact categories as follows:

- **Bio-inspired design:** Topology optimisation and generative design approaches applied to create lightweight structures.
- **Aerogels:** Lightweight replacement for fibre filling in insulation blankets and composite panel core.
- **Solid state batteries:** Lighter and safer than today's lithium-ion equivalents.
- **Multi-colour laser:** Enabling technology for replacing copper wire with lighter weight fibre-optics.
- **Rectennas:** Printable, smart material markings to enable easier recycling.

Direction for further work

To direct developments in product lifecycle circularity in cabins to achieve the greatest impact, it is recommended that further work in this area includes:

- Establishment of a baseline understanding of the carbon footprints associated with existing product management practices, circular and otherwise.
- Quantification of the opportunities for carbon footprint reduction presented by the creation and development of circular product pathways (see Figure 7).
- The cabins sector should align with the automotive sector where possible to facilitate knowledge transfer relating to sustainability initiatives' costs and benefits as well as best practice.

01. INTRODUCTION

01.1 BACKGROUND

Aviation's contribution to climate change is considerable and increasing. Other sectors can implement carbon dioxide reductions more rapidly as there are often fewer barriers to change. For the sector to address its carbon emissions contribution, it needs to do so not just in the operation of aircraft, where most of the impact arises, but also in terms of the non-operational factors (resource consumption and waste generated in the creation, maintenance and disposal of aircraft and their interior furnishings).

Pressure on airlines to address their environmental impact has been building for years but is now intensifying. 2021 saw the long-anticipated launch of International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), requiring airlines to purchase carbon credits to offset the impact of international flights. The same year also saw Google Flights providing emissions metrics alongside other flight information, presenting passengers with the carbon dioxide emissions they will be responsible for when they purchase a ticket. Since 2018, the flight shaming movement has signalled the social pressure placed on airlines by a shift in values, especially among younger generations.

Whilst in-flight emissions have historically received the most attention, there are other areas where aviation has the potential to reduce its carbon footprint. Compared to emissions generated during operations, the impact of non-operational factors is generally viewed as relatively minor. However, in absolute terms the impact is significant with tens of thousands of tonnes of material consumed and reduced to waste each year. The scale of both of these impact types is directly related to the mass of the cabin.

The design phase of the product lifecycle is critical because it is when the factors that determine its impact on the environment are largely set in place. FlyZero's investigations have examined how cabins are designed today and identified a range of ways in which designs, and design approaches can be developed to deliver greener products.

With this paper, FlyZero intends to raise awareness of the cabin's potential to lessen aviation's environmental impact and to stimulate debate on the topic of sustainable cabins. It aims to provide an accessible starting point for anyone seeking to understand how they can design greener cabin products in the future.

01.2 APPLICABILITY

Many of the technologies signposted by FlyZero are scheduled to support an entry-in-service of zero carbon emitting aircraft in 2030. As the cabin design is largely independent of other aircraft systems, most of the recommendations made by this paper can be pursued immediately and begin to deliver reductions in aviation's carbon footprint in the near term. Also, the findings and recommendations of this paper are applicable to any new or existing aircraft type, irrespective of fuel choice.

01.3 FOCUS

This paper concerns itself with the physical products that are installed into an airframe to define the passengers' on-board experience, typified by: seats, lavatories, galleys and storage closets, sidewalls, ceilings, overhead bins, etc. It seeks to provide pathways to greener products that are relevant to designers, manufacturers, maintenance and end-of-life (EOL) organisations.

FlyZero's intent is to drive dialogue around how the design, manufacture, use and eventual disposal of cabin furniture can be made less impactful to the environment. It does not concern itself with the design of the airframe, in-flight energy consumption of systems or the operational sundries such as in-flight magazines.

Whilst acknowledging the real-world necessity that sustainable design is pursued as part of a comprehensive business model, this paper is solely concerned with advancement of the sustainability performance of cabin designs. Its recommendations are intended to sit alongside more established requirements as part of a holistic design strategy.

01.4 THE UK CABINS SECTOR

It is estimated the cabin sector is responsible for between 5% and 10% of the turnover of the UK aerospace industry **[5]**.The UK supplies at least 7% of the world's aircraft interiors, including over 30% of all seats. UK companies design and supply almost every component of a cabin. The UK also offers interior design capabilities unmatched elsewhere in the world as home to around one third of the worldwide total of specialist design agencies who have been responsible for many of the most ground breaking and influential designs of past decades. The Aerospace Technology Institute (ATI) estimates there are over 250 suppliers in the UK involved in aircraft interiors with a combined turnover exceeding £2.0 bn, supporting more than 6,000 jobs. UK small and medium-sized enterprises (SME) generally source locally, retaining much of the associated value-added work in the UK **[3]**. The recommendations and opportunities discussed in this report encompass the entire value chain, from materials suppliers to EOL specialists.

02. CABINS AND THE ENVIRONMENT

02.1 CONTEMPORARY MARKET DRIVERS

Heightened awareness of climate change and ambitious targets for improvement have driven flyers, policymakers, airlines and OEMs to push for sustainability at every opportunity, and designers across the industry are increasingly redefining their priorities to recognise this shift in values. **Figure 1** below provides some examples of current thinking.

- 76% of Gen Z (born after 1996) say that climate change is one of their biggest societal concerns, 37% make it their number one concern **[6]**.

  Pew Research Centre 2021.

- Reducing aircraft emissions is the number one priority for the industry in the eyes of the public (70% agreement), relative to other goals such as reducing flight times or expanding airport capacity **[7]**.

  NATS Aviation Index 2020.

- 36% would pay more for flight tickets to reduce the environmental impact of flying **[8]**.

  CAA UK Consumer Survey 2020.

- 70% of airlines plan to cut carbon dioxide emissions by 50% by 2050 **[9]**.

  Airbus research 2020.

“In 2020, we set the difficult but very necessary goal of achieving net zero carbon emissions by 2050. Our net zero pledge aligns with the requirements laid out in the Intergovernmental Panel on Climate Change goal of limiting global warming to no more than 1.5°C above preindustrial levels. This long term goal provides the focus we need in aligning our strategy as we plan for the recovery after COVID-19, from network resumption, fleet planning and carbon offsetting, to further investment in sustainable aviation fuel and the development of new technology.”

*Augustus Tang, Chief Executive Officer, Cathay Pacific **[10]** 2020.*

Figure 1 – Evidence of changing attitudes

02.2
THE SIGNIFICANCE OF THE CABIN

- The cabin accounts for around 10% of the total aircraft empty weight.

  *Airbus A320: c. 4,000 kg cabin weight **[11]** vs. 40,023 kg operational empty weight **[12]**.*

- Cabins are typically replaced around four to five times during the life of the aircraft **[1]**.

Figure 2 – Cabin key facts

The cabin's weight is fundamental to every aspect of its environmental impact. Every gram of cabin weight adds to an aircraft's greenhouse gas emissions. Weight and frequency of replacement define the scale of the resource consumption and waste issues associated with the manufacture and disposal of cabin products. Growing concern around these latter types of impact is motivating the cabin supply chain to be more sustainable in its operations and products. Increasingly, airframe OEMs are requiring cabin OEMs to provide sustainability data. Also, cabin OEMs and their suppliers are devoting more effort to developing sustainability strategies, and airlines are using evidence of sustainable operations and products as part of their sales and marketing strategies.

The cabin also has a unique value as a marketing asset. It is the only part of the aircraft that is directly engaged with for long periods by the passengers whose ticket revenues fund the industry. As public expectations for corporate environmental responsibility rise, the incentive for airlines to demonstrate their sustainability credentials through the passenger experience design will increase.

02.3 CABIN COMPOSITION

This paper defines passenger cabin interiors as any cabin component directly interfacing with passengers and cabin crew or having a direct effect on passenger experience through comfort, services, or perception. These products are presented in **Table 1** and **Figure 3**.

Item	*Key to Figure 3*
Seats	*1*
Linings	*2*
Stowage bins	*3*
Passenger service unit (PSU)	*4*
Services (lavatories and galleys)	*5*
Insulation blankets	*6*
Carpets	*7*
Floor panels	*8*

Table 1 – Cabin interiors top level breakdown

Figure 3 – Typical twin aisle passenger cabin

02.4 OPERATIONAL IMPACT

Emissions from aircraft operations currently contribute 2.4% of the global total [13] at around 885 million tonnes per year. If growth continues as predicted, this is projected to rise by between 200% and 360% by 2050, even when the maximum use of lower carbon alternative fuels is factored in [14].

Cabin weight, as a component of the aircraft operational empty weight (OEW), is an important driver for fuel consumption and thereby emissions reduction. Flight gravitational energy required to lift an aircraft is equal to mgh (m = aircraft mass, g = gravitational constant, h = height gained) and kinetic energy to propel it forwards is equal to $1/2\ mV^2$ (m = aircraft mass, V = aircraft velocity). In both cases, this energy is provided from chemical energy in the fuel. Mass is a fundamental factor in both equations, therefore, any reduction in the mass of the aircraft directly reduces fuel burnt for a given mission, and therefore emissions.

For shorter range missions, mass reduction is a more powerful lever for fuel consumption reduction than reducing cruise drag because the cruise segment is proportionally shorter. Notably, the hydrogen fuelled aircraft that are the focus for FlyZero tend to be more suitable for such shorter missions. For longer range missions, improvements in lift-to-drag ratio have a more powerful influence on fuel consumption given the proportionally longer cruise segment. However, empty weight improvements are still important because they can reduce the lift induced drag of the aircraft. For these reasons, lightweighting will remain a key consideration for cabin design and this paper's recommendations acknowledge its priority.

FlyZero has set a target of a 16% weight reduction for the cabin by 2030 based on assessing potential improvements for each item. This assumes no compromise to safety or comfort. For an aircraft such as an A320neo today, this delivers an annual reduction in emitted carbon dioxide per aircraft in excess of 175 tonnes, equating to 0.85% of its overall output [15]. For comparison, removing the cabin altogether would deliver in excess of 1,000 tonne carbon dioxide reduction equating to a 5.16% drop in overall output [15]. This 16% weight reduction is viewed as an ambitious but achievable aspiration for industry. Note that the initiatives proposed in this paper are not developed from this target, and individually or in combination may deliver a greater or lesser weight reduction if pursued. Further work is required to define suitable technologies for the industry to meet the Fly Zero targets and to establish a more developed understanding of the carbon footprints associated with cabins.

Item	*2020 weight, kg*	*2030 weight target, kg*	*2020-2030 weight reduction*
Seats	*1,601*	*1,290*	*20%*
Linings	*363*	*340*	*5%*
Stowage bins	*188*	*220*	*-20%*
Passenger service unit (PSU)	*172*	*130*	*20%*
Services (lavatories and galleys)	*563*	*450*	*20%*
Insulation blankets	*418*	*310*	*25%*
Carpets	*240*	*210*	*10%*
Floor panels	*376*	*330*	*10%*
Total	*3,919*	*3,320*	*16%*

Table 2 – A320 in low cost carrier (LCC) configuration, weights analysis

02.5 NON-OPERATIONAL IMPACT

Greenhouse gas emissions attributable to the manufacture and maintenance of the cabin account for only around 0.5% of the overall lifetime impact for a single aisle airliner and around 1% for a large twin aisle [2]. In absolute terms however, the impact of these non-operational factors can be viewed as significant.

Resource consumption

In 2018, 1,764 new aircraft were added to the global fleet [16] and while COVID-19 has caused a dip in numbers (down to 821 in 2020), most predictions indicate this will be temporary and precede a return to steady growth. Narrowbody aircraft like Airbus' A320 make up over half of this fleet and each will carry around four tonnes of cabin equipment. FlyZero's analysis indicates that for cabin products specifically, the mass of material consumed during manufacture is around two and a half times the mass of the final items (buy-to-fly ratio, not including consumables).

Waste management

Over the past ten years, an average of 750 commercial aircraft per annum have been retired [17], and following COVID-19 this is expected to increase to between 1,000 and 1,500 for the foreseeable future [18]. Current best practices are able to recycle around 85% to 90% of an airliner by weight [19], with much of the unrecycled material that is burnt or sent to landfill originating from the cabins [20].

Figure 4 illustrates FlyZero's forecast for the scale of the resource consumption and waste management issues, today and in ten years' time [21].

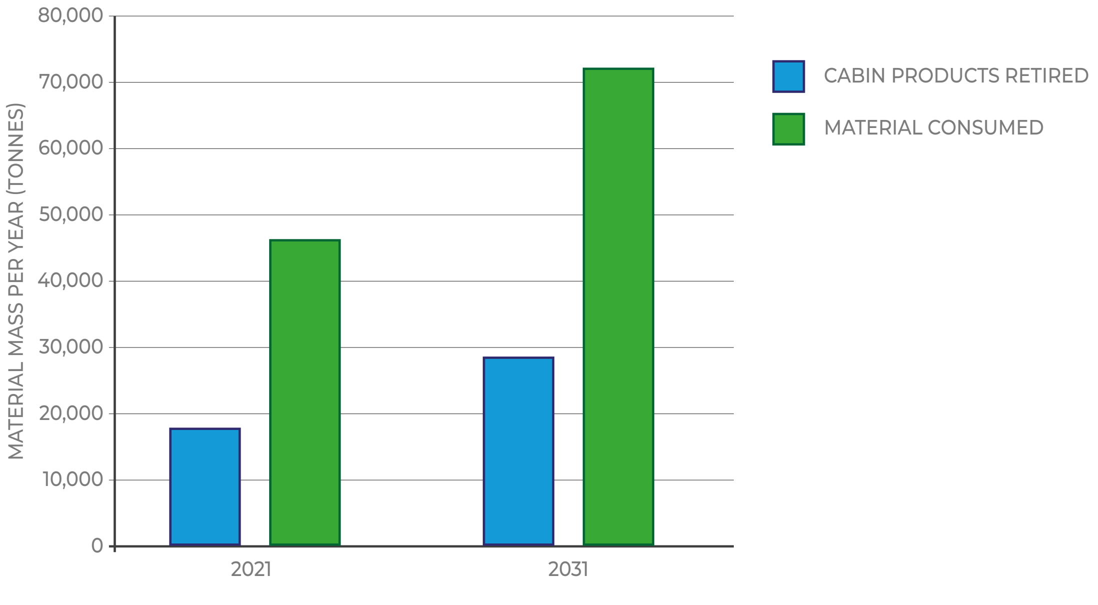


Figure 4 – Cabin material use forecast 2021 to 2031

FlyZero's analysis indicates that for a modern airliner, approximately 47% of all cabin products (by weight) are not currently being recycled. Each element of the cabin has its own technical and commercial challenges that contribute to this overall figure. The resultant breakdown by cabin component is shown in **Figure 5**.

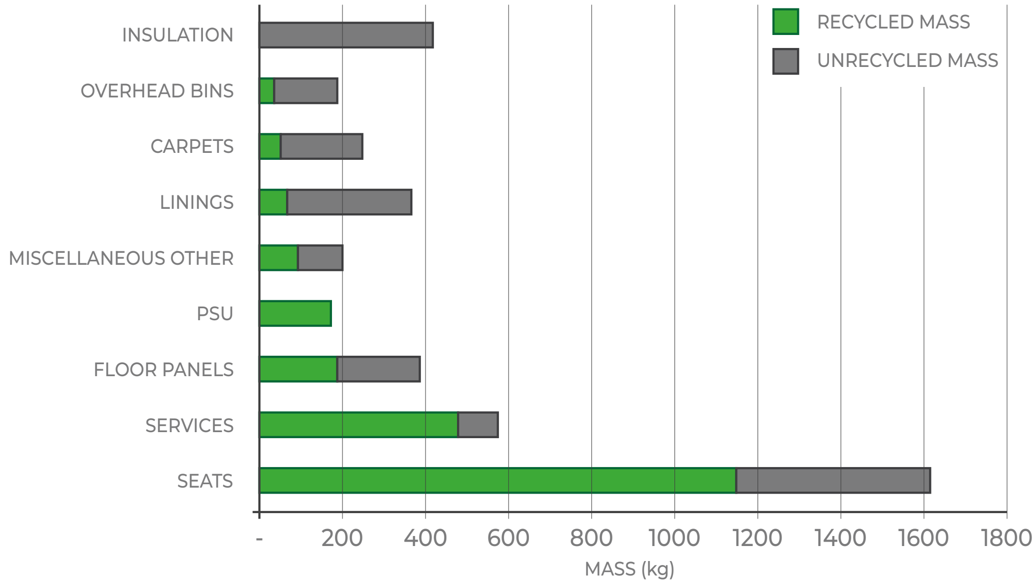


Figure 5 – Recycled vs. unrecycled mass breakdown

02.6 OTHER SUSTAINABILITY INITIATIVES

REACH

REACH stands for registration, evaluation, authorisation and restriction of chemicals and it is impacting the entire aviation sector, including cabins. It entered into force on 1st June 2007 and is a regulation of the European Union (EU), adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. To comply with the regulation, companies must identify and manage the risks linked to the substances they manufacture and market in the EU.

The move towards the replacement of harmful chemicals with safer alternatives is driven by two key factors:

- Restrictions and regulations, as well as the support for substitution of safer substances by the European Chemicals Agency (ECHA). Nearly one in five companies cite restriction as the main reason for replacing harmful chemicals.
- Demands from customers for sustainability.

It is critical that research into new materials ensures that they are not in breach of any foreseeable REACH compliancy.

UK aerospace manufacturing process development

The ATI is in discussions with The UK's High Value Manufacturing Catapult (HVMC) and the Centre for Research into Energy Demand Solutions (CREDS). The objective is to develop understanding around how the aerospace sector can, in collaboration with other sectors, fulfil its commitments in achieving net-zero greenhouse gas emissions by 2050 through efficient and sustainable processes and robust carbon accounting.

02.7 WHY DESIGN MATTERS

Design is key to improving both operational and non-operational sustainability. It is estimated that across all sectors, over 80% of a product's environmental impacts are determined during its design phase [22]. Design goals such as reducing the impact of material extraction, enabling re-use, facilitating disassembly, ensuring materials are identifiable and facilitating in-life upgrades have only been given limited attention in the past. This means that today there exists a situation in which a few simple measures could have a profound positive effect on the life cycle impact of cabins.

03. OPPORTUNITIES PRESENTED BY THE CIRCULAR ECONOMY

03.1 CIRCULARITY IN CABINS

The circular economy is...

"...restorative or regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times."

Ellen MacArthur Foundation ***[23]***.

Figure 6 – Circular economy definition

Introduction

The circular economy (CE) is a widely recognised model of production and consumption enabling reductions in resource use via repeated material application. Re-use, refurbishment and recycling of products and components is key to its effectiveness. Guidelines on recycling approaches [24] and [25] advise that waste-to-energy (incineration) and material reprocessing are not the most sustainable solutions. The more effective approach is to consider the opportunities for realising the lowest impact solutions first (refusing or re-using products), then gradually moving towards the higher impact options if more effective solutions are impractical or inappropriate.

From literature reviews and consultation with industry experts, FlyZero has developed a bespoke CE model for the cabin sector as seen in **Figure 7**. This describes the extent of circularity in the cabins industry today, problematic aspects and areas for improvement. The model shows that while some circular practices are established, there is significant scope for development.

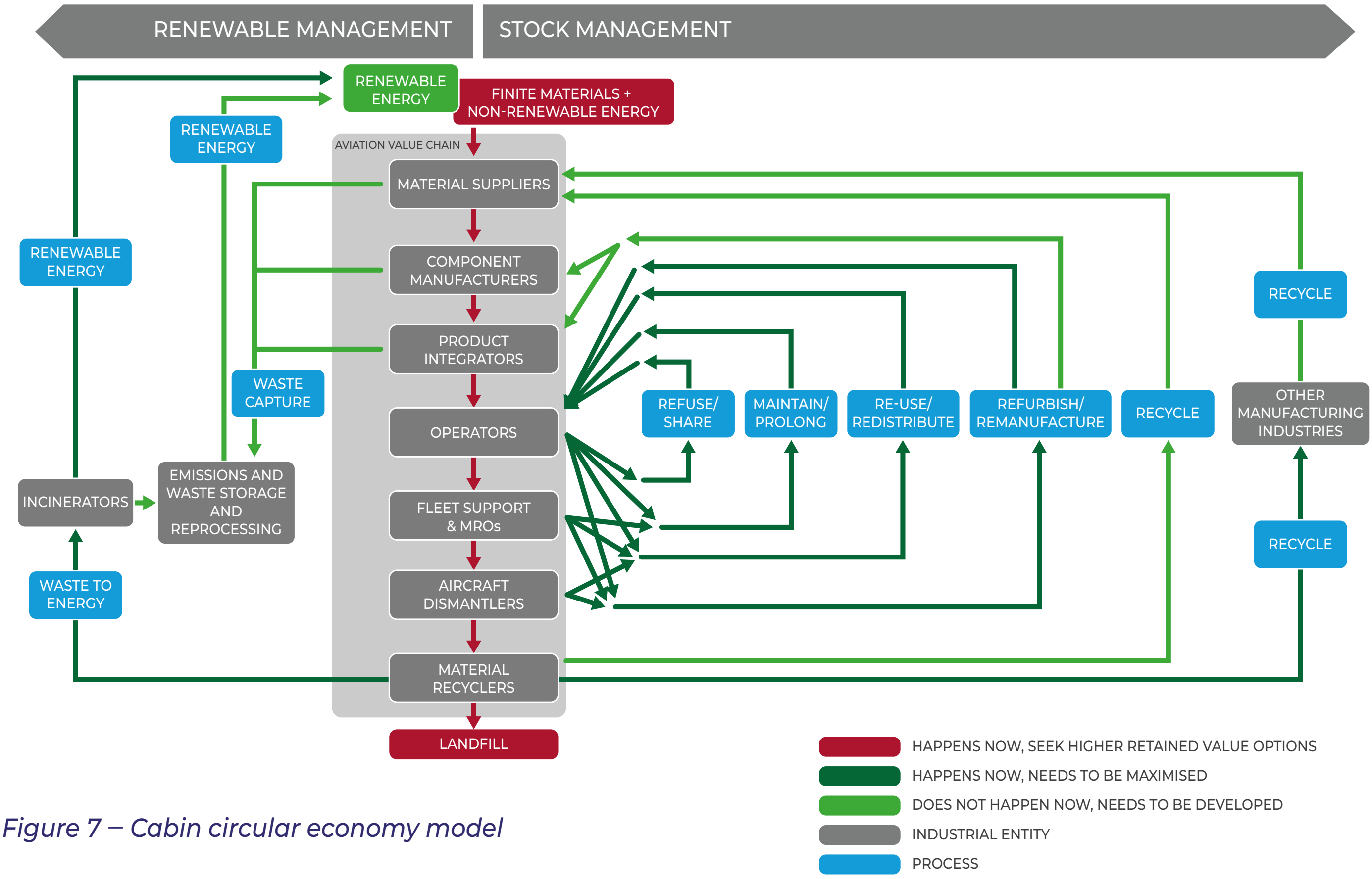


Figure 7 – Cabin circular economy model

Circularity in cabins at present

Only part of the infrastructure represented in **Figure 7** exists to date. Some materials are recycled into other industries but not retained within the cabins industry, and some components are refitted onto other aircraft. Energy recovery has only been done once as an experiment by Finnair. The in-sector material recycling loop does not exist, and other industries are not recycling into aircraft interiors. Other industries such as automotive who would like to use recycled materials from the cabins industry have not been successful in securing sufficient volume inflow (although generally, there is sufficient volume of material generated cumulatively across the competing cabin OEMs). Emissions capture is not practiced. Progress in reducing the amount of product used by challenging preconceptions regarding passenger needs is very slow.

As **Figure 7** shows, cabin products are frequently repaired, upgraded, sold to other operators and broken down for recycling at EOL. There remains significant potential however to maximise these practices and reduce the need to manufacture replacements by designing to promote:

- Re-sale to other operators for the product's original purpose.
- Retention of products (or their component parts) for use as spares.
- Upgrades to components.
- Like-for-like replacement of worn components.
- Repurposing of products, e.g. galley carts sold as novelty domestic furnishings.
- Products that can be cost effectively broken down to components which can be recycled, and their raw materials reintroduced into industry.

It should be noted however that the design of cabin products introduces a set of unique barriers to these preferred lifecycle routes. The heavily branded (operator-specific) designs, complexity, reliance on hard to recycle materials and passenger expectations for newer products means that interiors are one of the most challenging items to re-sell, re-use or recycle. Conducting a life cycle analysis in the initial phases of new cabin design and considering how to best mitigate probable EOL scenarios would enable improved sustainability and place less of a burden on airlines, leasing companies and aircraft dismantlers. Approaches which could be considered to support this mitigation are outlined in the **Circular Design Recommendations Annex**.

03.2 CHALLENGES AND OPPORTUNITIES FOR IMPROVED CIRCULARITY

To understand the challenges and opportunities to the implementation of CE practices in aircraft cabins, FlyZero conducted extensive literature reviews and interviews with experts from across the cabins industry (see **Table 3**), from aircraft OEMs and airlines to materials suppliers and EOL specialists. The objective of the process was to discover new information without constraint, therefore the data gathered is qualitative.

No.	Organisation type	Interviewee job function
1	Airline 1	Senior manager, passenger experience
2	Airline 2	Senior manager, passenger experience
3	Airline 3	Senior manager, passenger experience
4	Aircraft manufacturer	Vice president cabin
5	Cabin OEM	Chief technology officer
6	Cabin design agency	Managing director
7	Dismantler 1	Managing director
8	Dismantler 2	Chief executive officer
9	Dismantler 3	Managing director
10	R&D institution 1	Professor
11	R&D institution 2	Interviewee 1: senior lecturer in aircraft systems
12	R&D institution 2	Interviewee 2: professor of sustainable manufacturing and impact assessment
13	R&D institution 3	Reader in sustainable systems
14	Component supplier	Research and development manager

Table 3 – Expert interviewees

From this research, FlyZero was able to identify a number of key challenges to sustainability enhancement whose potential resolution was agreed to hold significant value, and these are described in the following paragraphs.

Material marking

A significant barrier to effective realisation of CE for cabin interiors is the lack of appropriate material marking or data sharing between OEMs, airlines and recyclers. Available data typically provides mechanical properties only. Residual values are not a consideration of cabin product customers when items are first purchased so there has been no incentive for OEMs to enable this type of data logging and sharing. There has also been no regulatory requirement to do so.

Unidentifiable plastics are particularly challenging, each type requiring a specific recycling method. These are often complicated by the presence of fire retardants requiring higher energy to process and resulting in greater toxicity. A current priority of the cabin product recycling industry is to find cost effective means of recycling such fire retardant plastics for profitable re-sale.

A potential solution to the issue with data transparency across cabin product life cycle is to embrace data sharing. The automotive industry serves as a role model to follow, with material data both clearly marked on products and uploaded into databases available for industry wide review. The homogeneity of the computer aided design (CAD) tools used in the aerospace sector provides an opportunity for such practices to quickly become established.

Branding

Representing nearly half of cabin's weight, seats, bulkhead panels, galleys and other products pose a particular challenge to re-use because they are often heavily customised by the airlines to express their brands. As well as overt representations of the airline logos, unique shapes, the use of colour, signature patterns incorporated into fabrics and decorative laminates, digital interfaces and other characteristics are all often indelibly integrated into the products, presenting the following problems:

- Spares can be harder to procure, reducing potential for longer in-service lives.
- Opportunities to lease aircraft with heavily branded cabins to other operators are less attractive.
- Seats and other furniture cannot be sold to other operators, reducing the possibility of extending in-service life with secondary operators.

A trend in recent years has been for a greater homogenisation of the designs for cabin furniture in all classes and the promotion of a catalogue approach by airframe and cabin OEMs. The flexible platform products that characterise these approaches look to minimise the manufacturing impact of customisation, often through modular design, whilst maximising experiential differentiation for the customer. These benefits apply to their customisation for the first operator but will also apply to any re-customisation if the product is re-sold. For the manufacturer also, a platform approach tends to increase repeatability, allowing for investment in more sustainable manufacturing processes and materials.

Business models

CE models are already visible in the cabins industry but are typically limited to serving the interests of individual cabin OEMs. Platform approaches and modular designs are commonplace, and some suppliers will buy back their used equipment.

These same circular approaches need to be scaled up to an industry-wide level and extended to prioritise sustainability in a way that is compatible with overarching commercial goals. As the costs to companies with poor carbon footprints rise and demand for more sustainable flight increases, new models favouring recycling will begin to have a greater impact on the cabin. There is an opportunity to secure the UK's position by incentivising green cabin design in ways that align the business models of supply chains, operators, and the EOL industry.

Development of such wider models should begin by considering probable EOL scenarios and how they can be managed to maintain cabin products in the higher value phases of their lifecycles for as long as possible.

Certification and recycling

Aircraft cabin structures need to be designed to withstand up to 16 G crash loads, minimise risk to occupants in the event of fires and provide a highly refined experience to passengers, leading to high quality expectations for cabin materials. Unfortunately, recycled materials tend to exhibit inconsistent structural and visual performance compared to equivalent virgin material. This is due to impurities, inclusions, and microstructure inhomogeneities that result from the recycling processes **[26]**.

The approach of the certification authorities and airlines has therefore been to consider recycled materials unfit for in-flight use in areas that are visible to passengers or critical in terms of crashworthiness or fire, smoke and toxicity compliance. This has, severely restricted the opportunities for cabin products to be made of such materials.

To address this issue, the industry must develop appropriate technologies and certification approaches for integrating recycled materials that ensure consistency in their observed performance.

A related issue is that cabin OEMs produce thousands of tonnes of manufacturing waste annually (see **Figure 4**) that cannot currently be put back into the production process. There is therefore a significant value stream potentially if this waste can be reintroduced as raw material into cabins or other sectors.

Scarce metals

Metals represent the largest revenue stream presently realised by aircraft dismantling businesses due to the stable demand in the market. However, limiting the use of scarce resources is a part of the United Nations' (UN) Sustainable Development Goals (SDG) [27].

The Economic Co-operation and Development (OECD) organisation lists the critical raw materials whose extraction, consumption, and recycling must be carefully managed in the coming decades [28]. Virgin aluminium, iron, and copper have the most significant impacts in all categories and thus, their use should be limited in cabin interiors and assessed for replacement with sustainable alternatives. For example, virgin aluminium structural components could be replaced by recycled aluminium or bio-composites. Similarly, copper wiring could be replaced by new conducting materials or removed in favour of localised power generation.

Collaboration with other transport industries

Land and sea-based transport benefits from less stringent fire, smoke and toxicity requirements compared to aerospace cabins. This results in very high rates of upstream and downstream material recycling achieved in these industries, with growing application of biomaterials.

While these industries are not a suitable source for recycled materials that could be used in the cabin due to different quality standards, they offer an attractive opportunity as destinations for material recycled from cabin products. The sources of recycled material used in car interiors are diverse, including fishing nets recovered from the ocean, fabric offcuts from the clothing industry, recycled industrial plastic and bottles. A similar level of flexibility applies to material output flows, with potential destinations including drainpipes, toys and plant pots. The automotive industry is actively looking for recycled plastic sources, although the volume of output from any single aircraft cabin OEM is presently insufficient, cooperation across the cabins supply chain could address this limitation.

03.3
ROUTES TO ENHANCED CIRCULARITY

Considering these key challenges, this paper offers a comprehensive set of recommendations for organisations seeking to develop cabin products that leverage the CE model to enhance sustainability. These are described fully in the **Circular Design Recommendations Annex** and summarised below. The recommendations are graded in terms of relative complexity and positive sustainability impact.

As the recommendations tend to require a multifaceted approach, each is described through two aspects, administrative and technical:

- The administrative aspect involves procedural action resulting from discussing and formalising new ways of working among involved stakeholders. For example, changing regulations or deriving a new standard which must first be realised by negotiation, and then by signing written agreements.
- The technical aspect reflects the physical implementation of an improvement opportunity using technology. For example, regulatory changes may adjust some values that apply to a product, such as limitations or allowances of permitted materials.

Each recommendation is grouped into one of the following six development themes:

Theme	*Recommendation summary*
Legislation, requirements and standards	*Establishment of regulatory frameworks that encourage best practice and limit impactful behaviours.*
Cabin design	*Consider and prioritise design features and materials that deliver sustainability benefits.*
Business models	*Developments that enable circularity to operate more effectively thereby reducing new material requirements over time.*
Materials and technologies	*The development of new product design features that directly and immediately confer sustainability benefits.*
Collaboration	*Developments enabled by a collaborative approach between airframe and cabin OEMs and their supply chains, airlines and design companies as well as organisations from adjacent industries.*
Production	*Development of processes and standards that will drive more safe, efficient and responsible product manufacture.*

Table 4 – Recommendation themes

04. MATERIAL SUSTAINABILITY IMPACT

04.1 MATERIAL SELECTION CONSIDERATIONS

Material selection is a key consideration in the pursuit of more sustainable cabin products, particularly as it is so intrinsically linked to design. Choice of material is a factor driving a product's weight (operational performance) and its ability to embody principles of circular design (non-operational performance). Considered in isolation, materials also have inherent sustainability characteristics such as toxicity, energy required for extraction and processing, and resistance to bio-degradation. This section considers the cabin in terms of its embodiment of materials, seeking to identify those which present sustainability challenges and therefore which commonly found product components should be prioritised for change. The section concludes with a prioritised list of cabin products that can be addressed immediately by industry.

Design conservatism

Due to cabin products' stringent and costly certification procedures and high perceived quality standards, the industry has a strong aversion to risk. Most new cabin product development draws on successful designs for parts or assemblies that embody proven materials applications. Developing more sustainable products is therefore facilitated if designers understand the issues inherent in existing products.

Industrialisation constraints

New materials continue be invented, simulated, optimised and matured to improve performance and/or reduce cost, tuning for particular applications. This can also include development of design solutions that create functionally graded materials or the joining of dissimilar materials. It is however important to recognise there are some key constraints that limit the potentially infinite creativity of the material and design solutions that can realised. Only a small selection of new alloys or composites will be qualified for future programmes due to the cost, time and resource commitment necessary, so the UK must work with end users to determine where to focus development efforts and what is likely to be qualified due to its technical and commercial exploitation opportunities. Also, each material qualified will typically need a means of segregating waste (from off-cuts, swarf from machining, etc.) and a recycling route back into aerospace or another sector. Where graded materials or joining of dissimilar materials are considered in future products, repair and EOL splitting into constituent elements may be challenging or impractical. This may limit use, even where performance provides substantial quantified benefits.

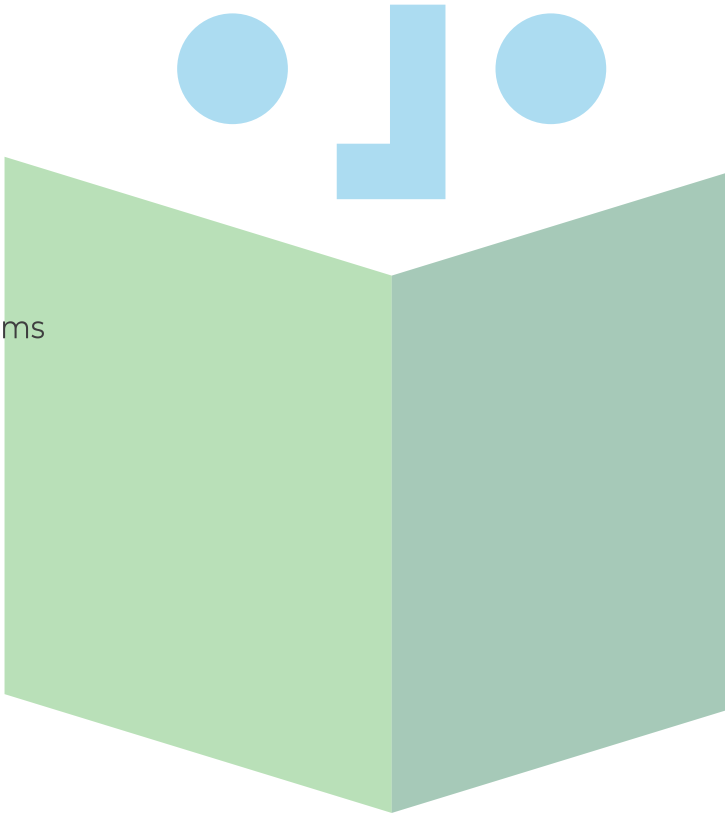
04.2 EVIDENCE-BASED IMPACT ASSEESMENT

Cabin component breakdown

Through compilation and analysis of available data as well as consultations with aircraft dismantling companies, FlyZero created a breakdown of a typical complete cabin interior by weight and material. The analysis considered all products typically found in a single aisle airliner cabin, including:

- Crew seating
- Passenger seating, economy class*
- Lavatories
- Galleys
- Emergency equipment
- Data, power and in-flight entertainment (IFE) systems
- Ceilings and overhead bins
- Sidewall panels*
- Cabin flooring assembly (floor panel and carpet)*
- Decorative items and finishes

** Life cycle assessment (LCA) performed on these items.*



Assessment methodology

This breakdown enabled a qualitative sustainability assessment to be made for all items, as well as a dedicated top-level LCA using industry standard tools (SimaPro 9 and Ecoinvent 3 database) for items where sufficiently detailed data was available. Both analysis approaches looked primarily at the qualities of the materials used in each product and as such is complementary to the more general review of design considerations that formed the basis of **Section 3**.

The assessment considers the following criteria:

- **Impact** – assessment of performance in three key metrics: economic, social and environmental impact
- **Prevalence** – how much of each material is found in the cabin
- **Density** – weight efficiency

04.3 PROBLEMATIC MATERIALS

Table 5 presents the top 20 most problematic materials ranked in terms of impact (lowest ranking = highest impact). Operational impacts and non-operational impacts are considered. More sustainable alternatives to these materials should be sought.

Rank	Material	Component	Issues
1	*Inconel*	*Fasteners*	*High energy demand, density, raw materials, toxicity*
2	*High-strength steel*	*Fasteners and brackets, emergency location transmitters*	*High density*
3	*Liquid crystal display (LCD)*	*IFE displays; cabin management system (CMS) crew interfaces*	*High weight / m², complexity makes disassembly challenging, precious metal content, electrical and electronic equipment (EEE), short lifespan relative to other items*
4	*Copper*	*EEE, wiring and connectors*	*High density, difficult to separate from the complex assemblies used on-board*
5	*Carbon fibre reinforced plastics (CFRP)*	*Seat back structure, air ducts*	*High energy demand, difficult recyclability, toxic dust*
6	*Stainless steel*	*Fasteners and bracketry, seat belts, lavatories, galleys (various items e.g., high-pressure water piping), cabin fire bottles*	*High density*
7	*Polyethylene terephthalate (PET)*	*Seat belts, insulation blankets, cabin transparencies and furnishings, air ducts, emergency equipment*	*Toxic manufacturing and EOL (unless recycled), energy demand, carbon intense (oil), releases microplastics*
8	*Perfluoroalkoxy alkanes (PFA)*	*Waste system (lavatory), galleys*	*Toxic and persistent production and disposal waste, EOL energy*
9	*Polyvinylidene fluoride (PVDF)*	*Passenger seating components, cabin linings and window frames, cabin monuments, cabin trolleys*	*Carbon intense (oil), harmful and toxic production and EOL inputs and emissions; global warming potential (GWP) impacts*
10	*Nylon / Polyamide (PA)*	*Seat belts, cabin floor carpets, seat track covers, cabin dividers and decorations, emergency equipment*	*Carbon intense (oil), manufacturing and EOL energy demand and emissions, indefinitely persistent*
11	*Acrylonitrile butadiene styrene (ABS)*	*Passenger seating components (IFE screen frames, tray tables, misc.)*	*Carbon intense (oil), poor performance (high smoke, ultraviolet (UV) degradation, poor bearing), non-biodegradable, toxic fume, harmful process inputs*
12	*Acetal / polyoxymethylene (POM)*	*Fasteners and brackets, toilet seat, galley components (e.g., tabletop), lighting sub-components, oxygen*	*Carbon intense (oil), non-biodegradable, toxic, cost*

13	*Polyvinyl fluoride (PVF)*	*Cabin linings, overhead stowage, lavatory structure*	*Carbon intense (oil), non-biodegradable*
14	*Virgin aluminium*	*Passenger seating primary structure, various components in the lavatory, galleys, EEE, air filtering*	*Medium density with high cabin presence; manufacturing impact (GHG) global raw material depletion and energy demand*
15	*Polyether sulfone (PESU)*	*Passenger seating components (cushions, tray table), cabin linings, cabin dividers, cabin decorations, lavatory and galley structures*	*Carbon intense (oil), non-biodegradable*
16	*Aramid core composite panels*	*Cabin furnishings*	*Identified as issue by the OEMs and aircraft dismantlers (difficult to treat waste and dispose of)*
17	*Polyvinyl chloride (PVC)*	*Accumulation of low presence in: passenger seating, cabin linings, air ducts, emergency equipment*	*Toxic manufacturing and EOL (unless recycled), carbon intense (oil), excess waste*
18	*Polypropylene (PP)*	*Air ducts, passenger seating components (screen frame, etc.)*	*Toxic production inputs, non-biodegradable*
19	*Polybrominated diphenyl ethers (PBDE)*	*Fire retardant chemicals*	*Toxic in production and use*
20	*Genuine leather*	*Seats – covers*	*Ethical concerns with some parts of the public; overall impact due to growing livestock over its entire life is spread out among its output uses: in-life (food), after-life (leather, bones, etc.)*

Table 5 – Qualitative prioritisation of the FlyZero cabin sustainability issues

04.4 PROBLEMATIC PRODUCT TYPES

The application of these materials indicates where designers looking for sustainability improvements should focus their attention. The following list identifies the top ten problematic products to be addressed. They will inform the focus for the sustainable cabins development roadmap presented in the next section of this paper.

Cabin item	*Problematic component*	*Development goal*
Seats	*CFRP back structure*	*Replacement of the material or more sustainable life cycle*
	Aluminium primary structure	*Reduction of virgin aluminium presence in cabin*
	Seat covers	*Wool sustainability enhancement or replacement*
	Seat cushions	*Replacement for melamine and PU Foams*
Fasteners and brackets	*Inconel and steels*	*Lighter weight alternatives such as bonding*
Cabin furnishings	*Aramid core composite panels*	*Sustainable recycling options or more sustainable material alternatives*
Air ducts	*PET*	*More sustainable material alternatives*
	PP	*More sustainable material alternatives*
Electrical and electronic equipment	*Copper wiring*	*Lighter weight alternatives or make redundant (e.g. wireless technologies)*
	IFE displays	*Lighter weight alternatives or make redundant (e.g. enable bring your own device models)*

Table 6 – Problematic cabin product types

Table 6 serves as a starting point for materials suppliers, cabin product OEMs and their supply chains in a strategy to create more sustainable products. It also enables airlines and airframe OEMs to assess their fleets and product catalogues respectively and to exert targeted pressure on the market to improve sustainability. **Table 5** is complementary to **Table 6** and allows those same parties to take a broader view.

Due to the LCA based approach, these lists present a materials focused assessment of existing sustainability issues and must be used as part of a holistic appraisal of other factors. Key among these, the weight and emissions impact of any material change must be balanced against the removal of harmful materials. Resolution of these issues will require a far broader focus to maintain a viable business model. For example, going from heavy steel fasteners to a bonded construction for lighter seating would require consideration of engineering and aesthetic design, certification, platform approaches and modularity, assembly, maintenance and EOL. Cost modelling and analysis must be developed alongside these proposed changes to enable the development of comprehensive, coherent and viable business models.

05. TECHNOLOGIES FOR SUSTAINABILITY

05.1 CABIN SUSTAINABILITY ROADMAP

Developments in technology will be key to delivering greener cabins. The following sustainable cabins roadmap encompasses technologies that respond to the challenges and opportunities identified in preceding sections of this paper across structures, materials, comfort, on-board electronics and promotion of circular product lifecycles.

These diverse areas each offer high potential opportunities to reduce operational and non-operational impact. The technologies presented are grouped into four swim lanes that would reward immediate funding, research and development to maturity.

Technology scouting and downselection

To focus the technology selection, the specific challenges highlighted by FlyZero's research were employed as drivers alongside a set of general cabins suitability criteria. The resulting 67 sustainability enhancing technologies (see - *FlyZero Sustainable Cabin: Technology Response, FZ_SoW_0018_C* for full details) were graded and down selected to a set of 18 high potential and low implementation complexity items according to a set of suitability and implementation criteria. These were grouped into swim lanes and scheduled to create the roadmap.

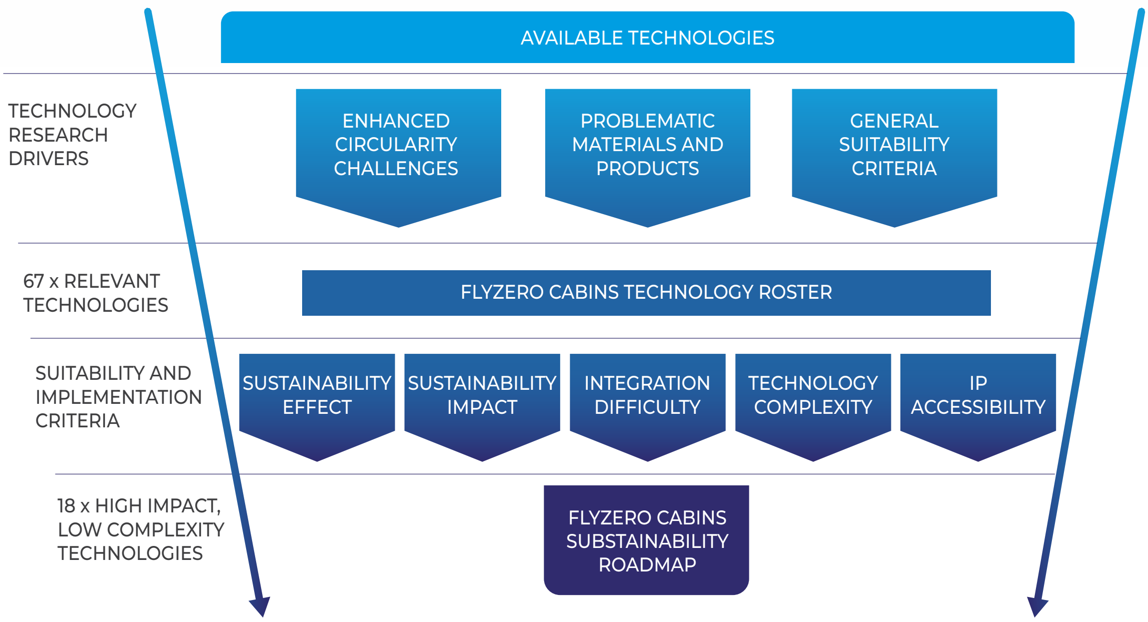


Figure 8 – Technology selection process

Sustainable Cabins Roadmap

The following roadmap lays out the technologies with the highest impact over the period between the present and 2035. They are presented in timeline format and grouped into appropriate development themes.

The technology readiness levels (TRL) and technology criteria presented in this report are the authors' view (FlyZero supported by Cranfield University), independent from the ATI.

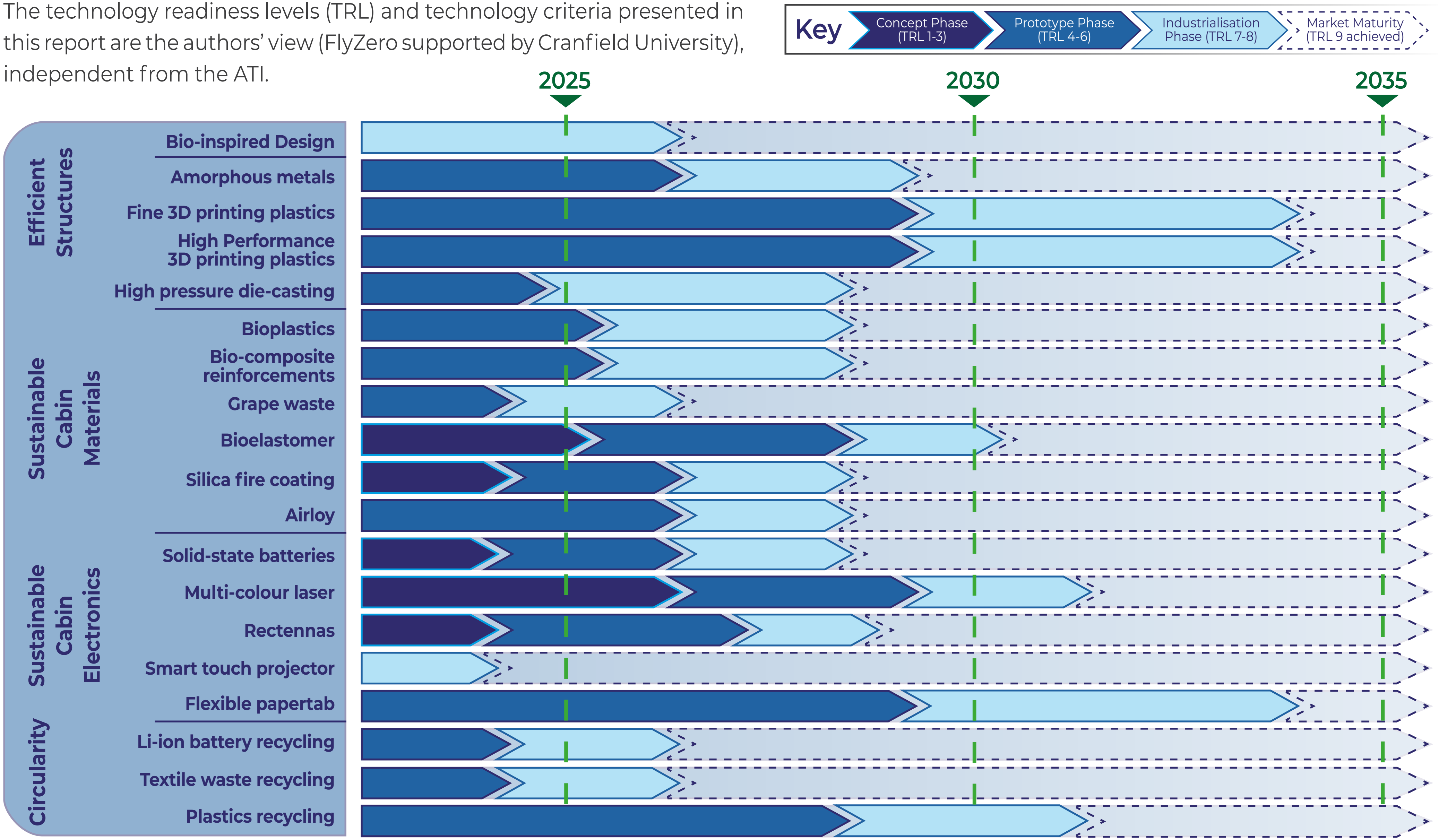


Figure 9 – Sustainable cabins roadmap

05.2 TECHNOLOGY INDICATORS

A technology indicator assessment for cost, weight and impact has been performed based on literature reviews, academia and industry engagement, and expert judgement to show the potential estimated benefits of technologies.

Technology indicators show likely characteristics to be achieved at aircraft level by 2030 to 2035, but these may change as technology is further developed and matures. Technology indicators may change depending on the application of the technology on aircraft or advances in key enablers. To achieve the potential benefits for a given technology full resourcing and sufficient funding needs to be available today.

The definition of each technology indicator is presented below.

Cost

- Non recurring costs (NRC) for the manufacture of the novel cabin components compared to established equivalent.
- Cost indicators reflect today's cost to enable technology deployment, but costs should reduce with maturity and the introduction of more advances in materials and manufacturing technologies.

Weight

- The difference relative to current equivalent cabin product weights.
- The weight indicator reflects that while some technologies may be heavy or lighter individually, their integration on to an aircraft may result in an overall weight increase or reduction by addition to, or replacement of other technologies.

Impact

- Cabin level impact on passenger demand (accelerates market penetration) and sustainability impact compared to current technologies.
- Includes non-operational impacts such as recyclability, reduced toxicity and scarce material usage.
- Does not include operational impact improvements. These are covered by the weight indicator.

Benefit

- The overall impact of the three indicators with weight reductions where relevant.

The following pages show the expected benefit of the most promising technologies identified. A colour scale gives a qualitative assessment of each technology against the technology indicators.

Combining the percentage benefit with the colour scale provides an overview of the potential for each technology.

All the technologies merit further development but priority should be given to those scoring highly for impact and weight.

Key

--	Negative trend - high
-	Negative trend - medium
0	No change / marginal change
+	Positive trend - medium benefit
++	Positive trend - high benefit
n/a	Not applicable

Table 7 – Technology indicator scoring key

Efficient structures

The efficient structures group is centred around the bio-inspired design approach (combining topology optimisation and generative design approaches) to creating efficient, high-performance structures, and its enabling technologies. Bio-inspired design exists at a developed level featuring a variety of methods to identify and analyse the requisite structural or functional behaviour. However, the implementation of bio-inspired design relies on the ability to manufacture the designed components, which in many cases involves fine detail and intricate 3D shapes. The four material solutions described below: amorphous metals, fine 3D printing metals, high-performance 3D printing plastics and high pressure die casting aim to provide such capability.

Identified product relevance (see Table 6): seat backs and primary structure.

Technology	Description	Cost	Weight	Impact	Benefit
Bio-inspired design (central technology)	An approach to designing and building the materials, components and systems by drawing inspiration (processes, functionality) from nature. May serve structural and functional goals and relies on precise 3D forming technologies.	-	++	++	**10% to 20% seat structure weight reduction and nearly zero-waste production.**
Amorphous metals (enabling technology)	Also known as bulk metallic glasses, a group of metallic materials that retain their metallic properties but are as mouldable as plastics. Can be blown into complex shapes without losing properties in a low-pressure, low-temperature process.	-	++	++	
Fine 3D printing metals (enabling technology)	A new, efficient method to produce fine metallic powder of ideal spherical shapes for high-quality 3D printing. Benefits over traditional techniques that use significant energy, produce waste and deliver larger particles of irregular shapes.	-	++	++	
High performance 3D printing plastics (enabling technology)	A new method for printing precise 3D shapes out of polymer structures while retaining or exceeding the mechanical properties of the original polymer material and reaching that of composites by applying custom molecular orientation.	0	++	++	
High pressure die casting (HPDC) (enabling technology)	Possible to use entirely secondary, end of life aluminium in an inherently circular process. Parts can be topologically optimised in a high rate, low lead time and low RC process which is used widely in automotive.	0	+	++	

Table 8 – Efficient structures technology indicators

Sustainable cabin materials

This group addresses sustainable cabin materials, including both structural elements (ceiling and sidewall panels) and the large variety of non-structural furnishings used in cabin interiors. Bio-derived plastics and composite reinforcements can replace fossil derived incumbents. Improvements can be made to tactile comfort and well-being of cabin occupants in an environmentally friendly manner using grape waste leather in seat covers and a bio-elastomer material to apply on armrests and other touchpoints. Aerogel acting as a structural thermal and noise insulator outperforms any other existing material in the combination of these properties, replacing sidewall insulation blankets and increasing usable cabin space.

Identified product relevance (see Table 6): seat backs, seat covers, air ducts, aramid core composite panels.

Technology	Description	Cost	Weight	Impact	Benefit
Bio-plastics	A new group of plastic materials that are based on naturally occurring or grown compounds rather than processed fossil resource. Serves to replace fossil-based, non-biodegradable plastics (PP, PU, PET, etc.) offering similar properties.	-	0	++	**Resolve health and toxicity impacts across the life cycle.**
Bio-composite reinforcements	Plant-based replacements to synthetic composite reinforcements e.g., carbon or glass fibre. A large variety of candidate fibres or discrete reinforcement materials exist e.g., bamboo, agave, soy, bark and many more.	-	0	++	
Grape waste	A synthetic bio-leather made of grape marc, the solid part of the grapes that comes as waste from wine industry.	++	0	++	
Bio-elastomer	A synthetic dry elastomeric biomaterial characterised by well-organised nano-microstructures to offer natural tissue like touch, 3D-print formability, and considerable mechanical properties in a fast, energy efficient synthesis process.	-	0	++	
Silica fire coating	A fire retarding treatment based on proven natural materials (silica) to replace toxic PBDEs.	+	0	++	
Aerogel	A potential replacement for the existing fibre filled blankets used to insulate cabins from the aircraft fuselage exterior and a wide range of other foam elements used in sandwich construction. High strength aerogels (e.g., Airloy®) offer similar properties to aerogels in terms of low density, high insulation performance (noise and thermal) and strength (holds 20,000 times own weight); but are also flexible and without the brittleness issues that occur in aerogels.	-	++	++	**Around 5% cabin weight reduction. High recyclability. Good insulator for passenger comfort.**

Table 9 – Sustainable cabin materials technology indicators

Sustainable cabin electronics

Solid state batteries provide a more sustainable substitute for the heavy Li-ion batteries whose manufacture is harmful to the environment and have been the cause of multiple serious aircraft fires. Anticipating a big data future aligned to the worldwide trend for data-based applications, novel sensor and data carrying solutions will be key enablers for systems such as integrated product health monitoring. Increasing passenger satisfaction and reducing cabin weight will be enabled by novel technologies. Passenger in-flight entertainment (IFE) systems could see the screens replaced with flexible, paper thin touch displays, or more radically with a single smart projector per three or four seats, potentially saving over 300 kg in an A320. Whilst costs may be higher than established alternatives, especially for early adopters, it is likely that other industries will bear much of the development burden for these technologies with aviation chiefly funding their adaptation for aerospace.

Identified product relevance (see Table 6): copper wiring, IFE displays.

Technology	Description	Cost	Weight	Impact	Benefit
Solid-state batteries	Fire safe, fast charging, high energy density batteries that use aluminium-ion, sodium-ion, and other bases and do not use liquids as a cathode. Offer significant performance, weight, and safety improvements over the current Li-ion batteries. Adoption reduces the overall systems weight, a proportion of which serves the cabin requirements. Increasingly valuable for more modern aircraft that forego the use of bleed air for electric driven systems and are more reliant on batteries.	-	+	++	**Significant safety, health and toxicity, material use improvements.**
Multi-colour laser	A set of new light manipulation techniques and materials that increase the capacity of fibre optic connectivity multi-fold (aiming for 1 Tbit/s) by splitting laser signal into colours and carefully managing and capturing it at photon scale. Enables replacement of copper wire for data carriage.	-	+	++	**Lighter cabling, 2% reduction in cabin weight. Faster data speeds improves system functionality and passenger experience.**
Rectennas	A microscopic print that uses electronic ink to combine antenna and AC/DC converter functionality for near field communication (NFC) capability. Enables marking of parts with materials information to facilitate recycling.	+	0	++	**Circularity enabler.**
Smart touch projector	Replace IFE screens with a lightweight projector equipped with precise gesture recognition to allow touchscreen-like projection control.	+	+	+	**Replace traditional IFE components. Approximate potential 6% cabin weight saving.**
Flexible PaperTab	Replace IFE screens with a system of flexible, thin, light touch displays driven by a single processor, which look like paper to the viewer's eye.	+	+	+	

Table 10 – Sustainable cabin electronics technology indicators

Recycling

Several new technologies that would not be implemented within the cabin, yet improve its overall through-life sustainability by introducing material circularity as described in **Section 3**. These technologies enable recycled material flow into cabins and from cabins into other industries. Offered as a holistic set, this group motivates the OEMs and aircraft dismantlers to consider new solutions for recycling the materials and components that currently offer challenges. This includes textiles, plastics, and Li-ion batteries (or solid-state battery solutions from another group in this roadmap, if implemented).

Cabin interiors circularity

Technology	Description	Cost	Weight	Impact	Benefit
Li-ion battery recycling	A novel process for efficient (high volume, short time) recycling of Li-ion batteries by extracting high grade metals.	++	0	++	**Lower input material costs due to resolved EOL issues.**
Textile waste recycling	A set of methods, processes, and practices to apply the recycled fibres from the textile industry in composite materials.	+	0	+	
Plastics recycling	A set of methods, practices, and processes to recycle various plastic material with mild degradation of properties.	++	0	++	

Table 11 – Cabin interiors circularity technology indicators

06. RECOMMENDATIONS

To realise the vision of UK leadership in the development of greener cabins, it is recommended that a range of measures are pursued covering the development of cabin sector practices, new product development targeting identified sustainability issues and the pursuit of certain new technologies. These recommendations are directed to the whole UK aerospace community, including industry, trade bodies, research, academia, the ATI and UK Research and Innovation (UKRI).

Some circular product management practices are established in the industry today but there is significant potential for these to be maximised and further complementary practices to be introduced (see **Figure 7**). The commercial models and incentives, and relevant enabling technologies need to be considered to create the shift to a new business and operating model for sustainable cabin interiors.

To enable these improvements, FlyZero has developed a set of recommendations to industry (see **Circular Design Recommendations Annex**). The following subset of these measures are prioritised as offering high potential impact with lower barriers to implementation. They will be most impactful if applied globally but the UK should consider taking a leadership position where practical. In order of priority, starting with those that are assessed to have the highest impact potential and should be considered first, these are:

1. Assess the development timeframe of promising cabin technologies and sequence their introduction in stages.

- Promote a step-by-step approach to improving sustainability performance to promote predictable cross-sector improvements.
- Identify, prioritise then assess the timeframe of the most promising cabin technologies and get buy in of OEM's, airliners, cabin interior manufacturers and relevant material producers and recyclers.
- Implement staged sustainability innovation cycles to manage industry wide efforts into smaller scale initiatives (like Euro 1-7 [4]).
- Relevant organisations: cabin OEMs, ADS Cabins group, European Commission.

2. Involve the whole value chain in co-developing sustainable cabin interiors.

- Develop the approaches and best practices for industry wide collaboration in the creation of value cascade.
- Identify technologies and co-develop products to improve the perception of sustainable value by passengers.
- Relevant organisations: airlines, airframe OEMs, cabin OEMs, cabins supply chain, The National Aerospace Technology Exploitation Programme (NATEP).

3. Enable the re-use of production waste across industries.

- Implement business models and practices for secondary production material (i.e., not a part of product) recirculation across industries. To include cross sector working groups to define the standards, technical and commercial models for success.
- Develop technical solutions to recirculate secondary production materials and waste into other industries.
- Relevant organisations: recipient industry trade associations, HVMC.

4. Make materials identifiable and share data to enable re-use.

- Introduce legislation for minimum necessary content and appropriate medium to govern marking for material data sharing.
- Identify appropriate technical means to communicate material data across cabin supply chain.
- Relevant organisations: product lifecycle management (PLM) software companies, airframe OEMs, cabin OEMs, cabin materials suppliers.

5. Define full-life strategies to minimise product impact.

- Define common ways of working to plan cabin product life and EOL scenarios (e.g., material destinations) in advance.
- Develop operational and EOL solutions (processes and technologies) to support specific destinations in advance.
- Relevant organisations: Aircraft Fleet Recycling Association (AFRA), International Air Transport Association (IATA).

6. Minimise total lifetime maintenance and disposal impact.

- Impose best practices to balance product longevity versus reliability to avoid long life, high maintenance products.
- Extend product longevity for low maintenance items; enable lower impact of early disposal for high maintenance items.
- Relevant organisations: airlines, airline alliances, cabin OEMs.

7. Cabin OEMs to consolidate their waste outflow into a suitable material source for other industries.

- Develop collaborative practices across industry to accumulate waste into sufficient outflow to feed into other industries.
- Identify suitable cabin materials and recycling practices for the other industries (e.g., automotive).
- Relevant organisations: cabin OEMs, cabins materials suppliers, ADS Cabins group.

8. Enable recycled material from cabins to be used in other industries.

- Derive feasible business models for using the recycled material from aircraft cabins in other industries (e.g. automotive).
- Identify or develop processes to adapt the materials recycled from cabin interiors for use in other industries.
- Relevant organisations: cabin OEMs, ADS Cabins group, recipient industry trade associations.

9. Enable easy rebranding of cabin furniture.

- Develop common standards and regulations for sustainable branding practices of cabin products, both hardware and software.
- Develop technologies and processes to increase branding flexibility in cabin products for quicker change and less impact.
- Relevant organisations: airlines, cabin OEMs.

10. Use recycled materials from other industries in cabin products.

- Derive feasible business models for using recycled material from other industries in aircraft cabins.
- Identify or develop processes to adapt materials recycled from other industries for use in cabins.
- Relevant organisations: cabin OEMs, European Union Aviation Safety Agency (EASA), Federal Aviation Administration (FAA).

To take advantage of the fact that airlines and airframe OEMs are beginning to look for sustainability performance improvements from their suppliers, it is recommended that UK cabin product OEMs develop strategies to demonstrably improve their products accordingly. Investing in LCA capabilities to guide material and design choices is advised. FlyZero's investigation using such tools indicates that the following cabin components embody harmful materials (see Table 5) and should be prioritised for change:

- **Carbon fibre reinforced plastic (CFRP) seat back structures -** more sustainable alternative materials used such as bio-composites or sustainability of CFRP to be improved.
- **Aluminium seat structure / components -** reduce the presence of virgin aluminium in the cabin.
- **Woollen seat covers -** more sustainable alternative materials to be used such as grape marc leather or sustainability of wool to be improved.
- **Melamine and polyurethane (PU) seat cushions -** more sustainable replacement materials to be found.
- **Inconel and steel fasteners -** lighter weight alternatives (such as more integral structures) to be found.
- **Aramid core composite panels -** alternative materials to be used or sustainable recycling options to be found.
- **Polyethylene terephthalate (PET) and polypropylene (PP) air ducts -** more sustainable alternative materials to be found.
- **Copper wiring -** lighter weight alternatives to be found.
- **In-flight entertainment (IFE) displays -** lighter weight alternatives to be found.

Finally, new technologies should be pursued that will reduce the cabin's carbon footprint via lightweighting and enhancement of circularity, and the selection of materials and processes that minimise embedded energy from extraction, processing, transportation, transformation into the finished product and related waste. This paper provides a set of 18 recommended technologies (see Table 8 to Table 11). Priorities among these being the technologies that provide benefits in both the weight and impact categories as follows:

- **Bio-inspired design -** (combining topology optimisation and generative approaches) and enabled by developments in amorphous metals, fine 3D printing metals, high-performance 3D printed plastics and high pressure die-casting. Offers a 10% to 20% weight reduction for structural components.
- **Aerogel** - A potential replacement for the fibre filled blankets used to insulate cabins and core materials in composite panels, offering an increase in passenger comfort and a whole cabin weight reduction of around 5% compared to existing options.

- **Solid state batteries** - Fire safe, fast charging, high energy density batteries that use aluminium-ion, sodium-ion, and other bases and do not use liquids as a cathode. Offer significant performance, weight, and safety improvements over the current Li-ion batteries. Adoption reduces the overall systems weight, a proportion of which serves the cabin requirements.
- **Multi-colour laser optics** - A set of new light manipulation techniques and materials that increase the capacity of fibre optic connectivity multi-fold (aiming for 1 Tbit/sec) by splitting laser signal into colours and carefully managing and capturing it at photon scale. Enables replacement of copper wire for data carriage.
- **Rectennas** - A microscopic print that uses electronic ink to combine antenna and AC/DC converter functionality for near field communication (NFC) capability. Enables marking of parts with materials information to facilitate recycling.

Direction for further work

To direct developments in product lifecycle circularity in cabins to achieve the greatest impact, it is recommended that further work in this area seeks to quantify the relative benefits in terms of carbon dioxide reduction of the different pathways described in **Figure 7**. Thus, further work is required to establish a baseline understanding of the carbon footprints associated with existing product management practices, circular and other.

The cabins sector should align with the automotive sector where possible to facilitate knowledge transfer relating to sustainability initiatives' costs and benefits as well best practice. Engagement on this topic should be pursued with the Advanced Propulsion Centre (APC), UKRI and relevant companies supplying materials and providing solutions and recycling services for the automotive sector.

07. CONCLUSIONS

The FlyZero project has identified that cabins can reduce aviation's environmental impact by becoming lighter, increasing circularity in the product lifecycle and reducing their use of harmful materials. Their design and use of materials determines all these aspects of their performance and consequently is the greatest opportunity the cabin community has to reduce their environmental impact. Recommendations for developing these designs and material choices have been made.

The global aviation community is committed to reducing its carbon footprint and consequently, sustainability performance is increasingly effective in providing a sales and marketing advantage. Weight reduction remains vital but cabin OEMs that can offer other forms of sustainability improvement with no cost or weight penalty, particularly those that confer a marketing value to the customer, stand to gain.

FlyZero's research indicates that development of such products requires design and materials innovation and collaboration within the cabins community and beyond. The UK, with its high concentration of design expertise and industrial capabilities across the whole product range, and the whole product lifecycle, is well positioned to respond. As this new priority gains prominence in the sector, investment now is necessary to enable the UK to adopt a leadership position.

CIRCULAR DESIGN RECOMMENDATIONS ANNEX

The following is a comprehensive set of recommendations drawn from literature review and the expert interviews conducted by FlyZero. They propose changes to contemporary industry practice which will deliver sustainability improvements.

Each recommendation has been assessed for its impact and complexity relative to others in the total set with a view to identifying the best starting points for progress.

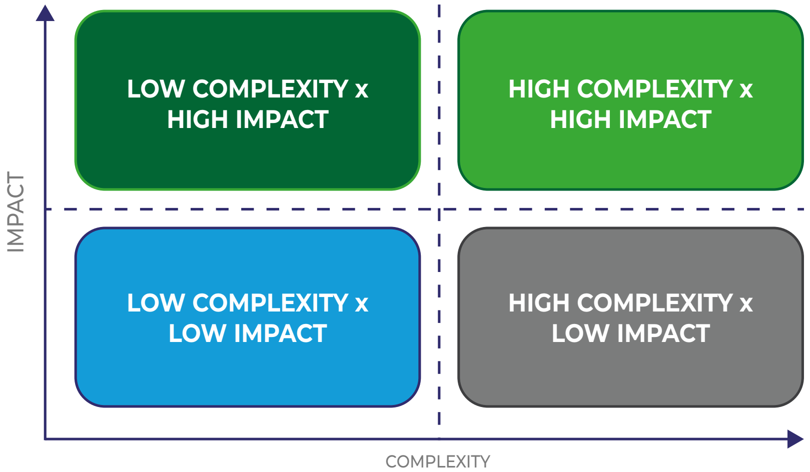


Figure 10 – Prioritisation matrix for design recommendations

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Legislation, requirements and standards	1	*Improve cabin materials recycling practice.*	*Develop and enforce best practices for reusing and recycling cabin interiors.*	*Facilitates material return loops: increased material selection freedom, reduced waste.*	*Identify / develop appropriate technology and processes to recycle current cabin materials more sustainably.*	*A recognised technical challenge especially for composites.*
	2	*Develop certification routes enabling greater on-board use of recycled materials.*	*Review the certification requirements (e.g., strength, Fire, smoke and toxicity performance) for using recycled materials in future cabins.*	*Facilitates material return loops: increased material selection freedom, reduced waste.*	*Develop appropriate and feasible solutions to recycle materials for aerospace applications; identify new compliant materials.*	*A recognised technical challenge especially for composites.*
	3	*Make cabin OEMs responsible for their products over more / all of their lives.*	*Develop and enforce regulations for extended manufacturer responsibility for the sustainability impacts of cabin products.*	*Pushing stakeholder liability may not be fair if technology is not ready.*	*Identify or develop cabin recycling solutions to minimise the cost of handling, recycling, or disposal processes.*	*A recognised technical challenge especially for composites.*
	4	*Limit use of critical raw materials.*	*Impose limitations and goals for the content of critical raw materials or other valuable resource present in cabins.*	*Limits the design freedom especially where the use of raw materials is unavoidable.*	*Develop sustainable replacements or reduce cabin presence of critical raw material and other valuable resource.*	*Sustainable replacements depend on the design philosophy and not primarily a technological challenge.*
	5	*Promote a standardised and simplified approach to use of materials in cabins to enable the EOL industry.*	*Introduce best practices and recommended standards for the volume and variety of materials used in cabin to avoid complexity.*	*High impact balanced out with detrimental effects on the design freedom.*	*Identify optimum technologies and materials that could be solely used to replace multiple cabin materials / components.*	*Requires careful search for potentially multi-functional materials.*
	6	*Limit water absorption to insulation.*	*Introduce the standards or limitations for water absorption performance by cabin materials.*	*Sufficient material selection freedom may be able to achieve this without regulatory push.*	*Develop replacements or solutions for cabin materials that exhibit excessive water intake (e.g., sidewall insulation blankets).*	*Some low-absorption materials currently available, although not eco-friendly.*

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Legislation, requirements and standards	*7*	*Minimise operational waste in cabins.*	*Define the regulations and standards for minimising the operational cabin waste, including system outputs.*	*More related to operations i.e., under airline control and less of the OEM control.*	*Develop the technical solutions (e.g., filters) to maximise the recirculation of cabin air, water and consumables.*	*Multiple novel options available.*
	8	*Develop fire retardants that do not impede recycling.*	*Revise certification requirements for sustainable fire protection.*	*Increased material selection freedom, positive human health impacts through life cycle.*	*Develop sustainable (e.g., bio-based) cabin fire retardants.*	*A recognised technical challenge to replace currently used PBDEs that are and toxic.*
	9	*Develop best practice to reduce the impact of maintenance.*	*Update the regulations for more sustainable cabin interior daily servicing and maintenance (e.g., less consumables, easy repairs).*	*More related to operations i.e., under airline and maintenance, repair and overhaul (MRO) company control, less of OEM control.*	*Develop technical solutions for more efficient and effective servicing and maintenance.*	*The preferred philosophy is to reduce maintenance need rather than optimise it.*
	10	*Design to promote good health and wellbeing.*	*Define the standard for cabin health and hygiene parameters.*	*Currently not a critical sustainability issue.*	*Implement efficient passenger health and hygiene solutions.*	*Multiple novel options available.*
	11	*Use clean energy for creation, maintenance, re-use and EOL for cabin products.*	*Promote the use of clean (renewable, recycled, localised, closed loop) energy and fuels across cabin interiors life cycle.*	*Relatively low energy demand vs. other industries or the rest of aerospace industry.*	*Identify the existing sources and / or new technologies for clean energy and fuels to use across cabin product life cycle.*	*Multiple novel options available but not currently applied in the cabin interiors industry.*
	12	*Make materials identifiable and share data to enable re-use.*	*Introduce legislation, minimum necessary content and medium to govern appropriate marking for material data sharing.*	*Facilitates material return loops: increased material selection freedom, reduced waste.*	*Identify efficient and effective technical means to communicate material data across cabin supply chain.*	*Multiple novel options available but not currently applied in the cabin interiors industry.*
	13	*Enable innovation projects that are disassociated from commercial constraints / timelines to allow experimentation.*	*Integrate innovation intellectual property (IP) protection practices to avoid adverse impact on competitive advantage.*	*Addresses internal stakeholder business drivers but not large scale sustainability issues.*	*Identify and develop new cabin technology to set independent industry standard outside of any specific products.*	*While this aids technology development, the organisational element of this goal is challenging.*

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Cabin design	14	*Increase efficiency of use of space within the cabin.*	*Revise cabin configuration standards and develop novel and efficient cabin space use concepts.*	*Allows re-thinking cabin design for better PAX demand, but does not guarantee sustainability.*	*Develop modular cabin interiors focused on cabin space efficiency and use versatility.*	*Cabins are highly optimised between PAX density and lowest weight; more efficient use of space may require complex tech.*
	15	*Consolidate cabin products where possible.*	*Review and revise cabin content effectiveness e.g., remove the need for some products or combine few products into one.*	*Motivates re-thinking cabin design for improved sustainability, particularly lower weight.*	*Identify or develop solutions to make cabin products lighter than current standard or deliver combined functionality.*	*Cabin products are highly weight optimised, breaking the plateau will require novel technology that is not currently applied.*
	16	*Strategically apply sustainable product design principles.*	*Define and enforce the principles for sustainable product design and innovation in a competitive market environment.*	*Improves the OEM practices but does not guarantee sustainability improvements.*	*Identify the technical solutions for high-value cabin interior items that currently use inefficient processes or materials.*	*Current cabin products use the best technology available with current regulations, improvement requires disruption.*
	17	*Promote platform and modular design approaches for production and through-life efficiencies.*	*Define the standard (rules, approaches) to delivering cabin products as a platform model through a subset of archetypes.*	*Streamlines product development and improves commonality but does not guarantee sustainability.*	*Integrate product features enabling the realisation of product platform model e.g., interchangeable components.*	*Platform approach simplifies the technical aspect of product development.*
	18	*Promote a step by step approach to improving sustainability performance to promote predictable cross-sector improvements.*	*Identify, prioritise then assess the timeframe of the most promising cabin technologies and get buy in of OEM's, airliners, cabin interior manufacturers and relevant material producers and recyclers. Implement staged sustainability innovation cycles to constrain industry wide efforts into smaller scale initiatives (like Euro 1-7 [4]).*	*Relaxes the burden for all cabin interior stakeholders, facilitates staged improvement.*	*Assess the development timeframe of promising cabin technologies and sequence their introduction in stages.*	*Facilitates a more organic development of complex technology.*

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Cabin design	19	Develop data enabled, more granular approaches to cabin product maintenance for more efficient through life management of cabin product.	Develop a framework for flexible maintenance planning based on the real use patterns of cabin products.	Allows for optimised cabin maintenance scheduling and may prevent premature product replacements.	Develop and integrate the technical means for gathering operational cabin product use data.	Multiple novel options available but not currently applied in the cabin interiors industry.
Business models	20	Innovate cost management for transition to sustainable cabins.	Develop business models and best practices to reduce, share, or externally finance sustainable cabin interior costs.	Enables sustainable innovation by resolving the key current challenge.	Identify sustainable materials and processes to incur lower overall through-life cycle costs.	Combining low cost and high sustainability is a recognised challenge.
	21	Enable cabin OEMs to support circularity in a commercially sustainable way.	Identify sustainable to prevent cannibalisation of cabin products by the reused or repaired cabin products.	Addresses internal OEM business drivers but not large scale sustainability issues.	Develop sustainable upgrades to existing cabin equipment that could be sold to its new owners via refurbishment.	A recognised technical challenge e.g., rebranding, reshaping composites.
	22	Reduce mass of on-board items wherever possible.	Identify appropriate BM and operational procedures to reduce cabin content.	More related to operations i.e., under airline control, less of OEM control.	Develop sustainable solutions for disposable or replaceable cabin items e.g., replacements for the in-flight magazines.	Multiple novel options available but not currently applied in the cabin interiors industry.
	23	Explore means of procuring sustainable materials.	Introduce the BM and practices for sustainable material sourcing.	Currently addressed by supplier quality assurance functions at the cabin and airframe OEMs.	Identify efficient and bio-based cabin material replacements.	A recognised technical challenge to achieve high sustainability and satisfy certification requirements.
	24	Minimize the impact of the industries that create, maintain and dispose of cabin products.	Put in place the BM and processes to extend sustainability beyond cabin interiors (production facilities, infrastructure).	Relatively low sustainability impact vs. other industries, rest of aerospace industry, or operations.	Identify, adapt, or develop technologies to improve the sustainability of cabin production facilities and infrastructure.	Multiple novel options available but not currently applied in the cabin interiors industry.

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Business models	25	Use recycled materials from other industries in cabin products.	Derive feasible BM for using the recycled material from other industries in aircraft cabins or its production.	Facilitates material return loops: increased material selection freedom, reduced waste.	Identify or develop the processes to adapt the materials recycled from other industries for use in cabin interiors.	More of a regulatory challenge than technical.
	26	Enable the re-use of production waste across industries.	Implement business models and practices for secondary production material (i.e. not a part of product) recirculation across industries. To include cross sector working groups to define the standards, technical and commercial models for success.	Facilitates material return loops for reduced waste.	Develop technical solutions to recirculate secondary production materials and waste into other industries.	More of a regulatory challenge than technical.
	27	Look to other industries for technologies that can be adopted / adapted.	Diversify existing cabin interior innovation BM to include unconventional technology sources.	The selection of technology is based on the need and does not necessarily prefer conventional technology.	Identify and adapt breakthrough or disruptive technologies that originate outside of the industry (e.g. SME, start-ups).	Depends on a specific technology; the type of business organisation does not affect nor depend on technological complexity.
	28	Develop the furniture as a service (FAAS) model to promote CE in cabin product deployment.	Develop feasible BM to implement FAAS model to airlines.	In high demand by some airlines but no interest from the others, depending on carrier type and BM.	Design, adapt, or adjust cabin products to fit with the FAAS model by enabling quick reconfiguration.	Product supply model does not affect technology complexity.
	29	Enable recycled material from cabins to be used in other industries.	Derive feasible BM for using the recycled material from aircraft cabins in other industries (e.g. automotive).	Facilitates material return loops: increased material selection freedom, reduced waste.	Identify or develop the processes to adapt the materials recycled from cabin interiors for use in other industries.	A mainly administrative / organisational issue than technical.
	30	Partner with other industries to promote the transfer of promising technologies into cabin design.	Develop BM and practices for collaboration with other industries to use their products as a testbed for new cabin.	Offers an option for testing new materials but is not essential for achieving higher sustainability.	Develop products that could be used both in other industries (e.g. F1) and in cabin interiors effectively and attractively.	Common materials are used across multiple industries with similar requirements and comparable purposes (e.g. lightweight structures).

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Materials and technologies	31	Find sustainable alternatives for problematic materials.	Identify relevant material parameters to enable the choice towards more sustainable materials in any given cabin product.	Streamlines product development processes, but does not guarantee nor is essential for sustainability.	Identify or develop sustainable replacements for the less sustainable cabin materials currently used.	Current cabin designs use the most efficient, optimised materials available to date; identifying replacements requires disruption.
	32	Minimise total lifetime maintenance and disposal impact.	Impose best practices to balance product longevity vs. reliability to avoid long life, high maintenance products.	Allows for products requiring less maintenance and may prevent premature product replacements.	Extend product longevity for low maintenance items; enable lower impact of early disposal for high maintenance items.	Practices exist to prioritise either long life or low impact; early cabin interior replacements are related to non-technical issues.
	33	Enable greater use of recycled materials.	Revise or define material quality standards to extend the scope of permitted cabin materials.	Increased material selection freedom.	Identify or develop reliable recycling practices to ensure consistent performance of recycled materials.	A recognised technical challenge across high performance, safety critical industries.
	34	Minimise energy and materials consumption by cabin.	Define the best practices (including the quality standards) for reduced consumption of disposable materials or energy in cabin.	Minor sustainability impact, a large portion of which comes from small % reduction in operational weight.	Develop solutions for reduced need of consumables e.g. self-cleaning surfaces, lower water / power need for the galley.	Multiple novel options available but not currently applied in the cabin interiors industry.
Collaboration	35	Look to other industries for sustainability practices that can be adopted / adapted.	Implement cross industry learning and synergies for better sustainability.	Resolves current issue of insufficient transparency for improved sharing of experience and lessons learnt.	Identify and adapt effective sustainability solutions from other industries e.g., automotive; co-develop where required.	More of an organisational / business driven challenge than technical.
	36	Involve the whole value chain (airlines, airframe OEMs, cabin OEMs and their suppliers) in co-developing sustainable cabin interiors.	Develop the approaches and best practices for industry wide collaboration in the creation of value cascade.	Involving the entire value chain would ensure multi-faceted assurance for achieving sustainable design.	Identify technologies and co-develop products to improve the perception of sustainable value by passengers.	A matter of design to a larger extent than technology.

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Collaboration	37	Cabin OEMs to consolidate their waste outflow into a suitable material source for other industries.	Develop collaborative practices across industry to accumulate waste into sufficient outflow to feed into other industries.	Facilitates material return loops for reduced waste.	Identify suitable cabin materials and recycling practices for the other industries (e.g. automotive).	Multiple novel options available but not currently applied in the cabin interiors industry.
	38	Minimise use of energy for creation, maintenance, re-use and EOL for cabin products.	Develop and enforce best practices for engaging with the energy industry for advanced energy supply planning and optimisation.	Ensures optimised energy consumption profile over long term despite lower energy demand of the industry.	Implement technologies requiring lower energy consumption across cabin product life cycle (e.g. production equipment).	Current priority across industries; an investment issue for the interiors industry to implement novel high-tech equipment available.
	39	Raise awareness of cabin product sustainability potential with the public.	Increase public awareness of deeper aviation sustainability issues and possible solutions.	Facilitates the drive for sustainability on the PAX side, which has ultimate influence on cabin design.	Develop products to improve tangible perception of sustainable value by passengers.	A matter of design to a larger extent than technology.
	40	Define full life strategies to minimise product impact.	Define common ways of working to plan cabin product life and EOL scenarios (e.g. material destinations) in advance.	Ensures the prevention of detrimental EOL effects (landfill, emissions, inefficient recycling) in advance.	Develop operational and EOL solutions (processes and technologies) to support specific destinations in advance.	A matter of organisational setup and collaboration to a larger extent than technology.
Production	41	Develop ways to re-use production and EOL waste and emissions.	Develop effective practices for re-using secondary waste i.e., production and EOL process emissions.	Relatively low sustainability impact vs. other industries, rest of aerospace industry, or operations.	Develop the technologies and processes to capture waste and emissions for repeated re-use in production or EOL process.	Multiple novel options available but not currently applied in the cabin interiors industry.
	42	Minimise production process impact.	Review and revise production processes for better sustainability e.g., reduced intake of consumables and waste output.	Streamlines interior production processes, but relatively low overall sustainability impact.	Identify sustainable cabin production processes and substitutes for hazardous or restricted materials / consumables.	Existing production processes are already optimised to use the minimum possible extent of hazardous substances, further optimisation requires a design or technological evolution.

Theme	ID	Goal	Administrative aspect	Impact assessment	Technical aspect	Complexity assessment
Production	43	*Minimise production material waste.*	*Introduce waste management and handling standards (rules, metrics, limits) for cabin interiors production.*	*Streamlines interior production processes, but relatively low overall sustainability impact.*	*Develop appropriate processes and technical solutions for better waste handling or recirculation in production.*	*A process challenge rather than technical*
	44	*Minimise production emissions.*	*Define and enforce the standards, regulations, and BM for the complete capture and recycling of non-solid waste.*	*Streamlines interior production processes, but relatively low overall sustainability impact.*	*Implement the technologies to capture and reuse non-solid emissions (greenhouse gasses, volatile organic compounds, particulate matter, water, etc.) in production and EOL.*	*Novel solutions available but not highly adopted, recent pilot projects still tested in few locations globally.*
	45	*Enable easy rebranding of cabin furniture.*	*Develop common standards and regulations for sustainable branding practices of cabin products, both hardware and software.*	*Resolves some of the noticeable current sustainability issues, especially at interior EOL.*	*Develop technologies and processes to increase branding flexibility in cabin products for quicker change and less impact.*	*A procedural issue rather than technical.*

Table 12 – Design recommendations

TECHNOLOGY INDICATORS ASSESSMENT ANNEX

The table below (continued on the following two pages) outlines the rationale for the technology assessments presented in **Section 5.2**.

Technology	Cost	Weight	Performance	Benefit
Bio-inspired design	Cheaper than current equivalent due to less material, but with complex and potentially more time-consuming production.	Weight reduction due to significant improvement to components' structural efficiency is the key benefit of bio-inspired design.	Likely low impact on passenger demand, but will reduce the use of raw materials; significant impact on waste material during production (nearly zero-waste).	Weight saving of 40% per part reported by several existing 3D suppliers + further 10% improvement assumed due to advanced 3D printing materials; optimisation considers aluminium, PVC, CFRP, Nomex parts (assuming that some composites would be replaced with lighter-weight components made of recyclable plastic).
Amorphous metals	Materials costs comparable to high-end steel. Processing costs are comparable to plastics.			
Fine 3D printing metals	Advances in powder metallurgy are an effective cost control strategy. Parts are made into near-final shapes, minimising waste.			
High performance 3D printing plastics	Based on existing plastic 3D printer technology with limited amendments.			
High pressure die-casting	Comparable to established processes			

Technology	Cost	Weight	Performance	Benefit
Bioplastics **Composite biofillers**	Currently longer and more expensive to produce than traditional plastics; but the costs are balanced by reduced EOL burden.	Generally similar mechanical properties with variations depending on the specific materials compared.	Major EOL issues resolved (currently an issue to recycle composite materials).	Key benefits are: zero toxicity (natural materials; but depends on the production methods and involved chemicals for specific materials); zero human health impact.
Grape waste	Cost effects accumulate over the entire life cycle when comparing real leather vs. wine industry waste.	Similar mechanical properties.	Positive health and environmental toxicity impacts.	
Bioelastomer	Easy processability but the process is slower than current practices used for cabin interior components.	Consists of existing plastic materials, aimed for replacing plastic seating elements and seat covers at PAX body contact.	Antibacterial (health impact), non-toxic (nature impact), favourable tactile performance (increases PAX demand by offering unprecedented comfort levels).	
Silica fire coating	A widely available natural material.	Will result in added weight vs. PBDEs due to the nature of technology.	Positive health and environmental toxicity impacts.	
Aerogel (Airloy®)	Made of existing plastic materials; higher production cost is balanced by the reduced weight of material used.	Lightest material existing, offers the mechanical performance of conventional plastics.	Significantly reduced use of material (by weight), recyclability (plastic), very high thermal and acoustic insulation performance for increased PAX comfort.	Offers lowest possible weight of components with mechanical capability of plastics and resolved the mechanical issues (brittleness) of aerogels, proposed for wide-spread replacement of the foam components (seats, cabin insulation, sandwich panels throughout).
Li-Ion battery recycling	Batteries are generally expensive and contain critical raw materials; allowing its re-use spreads out the initial costs.	Material recycling does not affect cabin weight if sufficient quality is achieved, which is ensured with certification.	Li-ion batteries cause significant environmental impact due to harmful and critical raw materials; recycling helps implementing CE.	No weight impact, but a significant impact on the non-operational life cycle phases.
Textile waste recycling	Secondary source of filler and carpet material has a lower cost than primary source.		Recycling fillers reduces the need for new materials, but impacts of textile fillers are generally low.	
Plastics recycling	Using secondary plastic has a lower cost than producing new materials.		High-quality recycling enables better design freedom and a change in cabin design mindset.	

Technology	Cost	Weight	Performance	Benefit
Solid-state batteries	Need further development and will likely come at a higher cost than current battery technology at early adoption stages.	Some developments offer higher capacity than current Li-ion technology.	Significant reduction in the use of harmful or critical raw materials, much faster charging times produce less impact on the energy grid and offer more efficient generator-based recharging, much higher durability than current Li-ion technology offers longer life and less maintenance, removal of fire hazard associated with Li-ion technology improves safety.	Precise weight impacts are challenging to estimate due to a variety of options and low maturity with overall certainty; main benefits are not weight-related and address various important sustainability metrics (health, safety, raw material use).
Multi-colour laser	A more sophisticated (and thus, costly) technology than current wired cabin data transmission solutions.	Glass fibre optic is five times lighter than traditional data wires; 500 g wires / seat saves 72 kg.	Radical increase in data transfer speed enables novel passenger experience capabilities, affecting passenger satisfaction and thus, demand.	
Rectennas	Cheaper than other electronic solutions e.g., RFID; mechanical solutions (e.g., engraving) are not considered due to ineffectiveness as a data carrier for a centralised system.	Negligible weight (nano print).	Resolves long-standing issue with insufficient data transparency across cabin product lifecycle, with particular benefits for CE.	
Smart touch projector	Three times less projectors needed than screens.	One projector (0.95 kg) replaces three economy screens and two business class screens, assume full service carrier A320 with 138 economy seats (46 triples each with a 1.8 kg screen) and 12 business class seats (each with 3 kg IFE screen) = 235 kg.	Improved passenger experience - may positively affect the demand.	Average between the two potential options = 254 kg, which is 6% of total cabin weight.
Flexible PaperTab	Lower cost than LCD screens due to lower use of components.	Same aircraft basis, each IFE screen is reduced with a PaperTab assumed at 100 g (50 g + wiring) = 256 kg.	Less material used; no hazardous / toxic substances used.	

Table 13 – Technology indicator assessment

APPENDIX A - LIST OF ABBREVIATIONS

3D	Three Dimension
ABS	Acrylonitrile Butadiene Styrene
AC/DC	Alternating Current / Direct Current
AFRA	Aircraft Fleet Recycling Association
ATI	Aerospace Technology Institute
BM	Business Model
CAD	Computer Aided Design
CE	Circular Economy
CFRP	Carbon Fibre Reinforced Polymer
CMS	Cabin Management System
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus Disease 2019
CREDS	Centre For Research into Energy Demand Solutions
CTO	Chief Technology Officer
EASA	European Union Aviation Safety Agency
ECHA	European Chemicals Agency
EEE	Electrical And Electronic Equipment
EOL	End Of Life
F1	Formula One
FAA	Federal Aviation Administration
FLT	Fluorescent Light Tubes
FST	Fire, Smoke and Toxicity
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDD	Hard Disk Drive
HVMC	High Value Manufacturing Catapult
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFE	In-Flight Entertainment
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Assessment
LCD	Liquid Crystal Display
MRO	Maintenance, Repair and Overhaul
MTC	Manufacturing Technology Centre
NATEP	The National Aerospace Technology Exploitation Programme
NATS	National Air Traffic Services
NFC	Near-Field Communications
NRC	Nonrecurring Cost
OECD	Organisation for Economic Co-Operation and Development
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
PA	Polyamide
PAI	Polyamide-Imide
PAX	Passenger
PBDE	Polybrominated Diphenyl Ethers
PESU	Polyether Sulfone
PET	Polyethylene Terephthalate
PFA	Perfluoro alkoxy Alkanes
PLM	Product Lifecycle Management
POM	Polyoxymethylene
PP	Polypropylene
PSU	Passenger Service Unit
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
PVF	Polyvinyl Fluoride
PVF	Polyvinyl Fluoride
REACH	Registration, Evaluation, Authorisation and Restriction Of Chemicals
RFID	Radio Frequency Identification
SDG	Sustainable Development Goals
SME	Small and Medium Sized Enterprise
TRL	Technology Readiness Level
UK	United Kingdom
UKRI	UK Research and Innovation
UN	United Nations
UV	Ultraviolet

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