Review

Towards a Reference Framework of Practices to Align Aviation with the Circular Economy ISO 59004:2024 Standard

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Abstract

Circular economy is considered essential towards sustainability in several sectors, including within the aviation sector. So far, the aviation sector focuses primarily on recycling, when discussing circular economy. This limits the effective application of circular strategies within the air transport system. A reference framework of practices, aligning circular economy with aviation, will contribute to implement circular strategies in the aviation sector.

This work aims to provide the first foundational step towards a framework connecting circular economy strategies and aviation. Specifically, the present work builds on the newly released ISO standard 59004:2024 to link its resource management actions to the current understanding of circular economy and circularity in the aviation sector. To this end, the work proposes a definition of circular economy that suits the specific aviation context. Then, an interpretation of the circular economy strategies (known as resource management actions or R-approaches) is proposed for adapting them to aviation practices. The results of the present work will provide the foundation towards developing a practically applicable assessment methodology, suitable to measure the circularity performance of aviation.

Keywords: Definition · ISO Standard · Resource Management Action · R-approach · Aviation · Aircraft

1. INTRODUCTION

The aviation sector's shift towards sustainability is pivotal, and it is prompting a quest for diverse solutions; both technological advancements and non-technical (socio-economical) approaches are investigated to achieve sustainable aviation objectives. Among the non-technical approaches, the concept of circular economy is gaining prominence and seen as a means towards sustainability in several sectors (Ellen Macarthur Foundation; European Commission, 2019).

The concept of Circular Economy (CE) has been around for over 50 years (Wautelet, 2018); CE gained prominence in the second decade of the current century and achieved a broader popularity with its inclusion in the European Green Deal (European Commission, 2019) (Figure 1). While the European Green Deal acknowledges the significant role of the CE, the Green Deal itself and its supporting documents notably lack a formal definition of this concept (Völker et al., 2020). Definitions are missing also in the directives which act as implementation of CE in European legislation, both in the 2015 “Closing the Loop” plan (European Commission, 2015), and in the “New Circular Economy Action plan” from 2020 (European Commission, 2020b). All those documents refer to “Growth within: a circular economy vision for a competitive Europe”, a report by the Ellen MacArthur Foundation, the McKinsey Centre for Business and Environment and the Stiftungsfonds für Umweltökonomie und Nachhaltigkeit, from June 2015. Within “Towards a circular economy: A zero waste programme for Europe” (European Commission, 2014), CE is defined as “a development strategy that entails economic growth without increasing consumption of resources, deeply transform production chains and consumption habits and redesign industrial systems at the system level. It relies on innovation being it technological, social, and organizational.” The European

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Parliament refers to CE as "[…] a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible" (European Parliament, 2023).

Figure 1. The European Green Deal (European Commission, 2019)

It appears that the European legislation and directives refer to what has been considered insofar the main reference regarding CE: the Ellen Macarthur Foundation (EMF) (Ellen Macarthur Foundation). The definition given by EMF describes CE as: "A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature" (Ellen Macarthur Foundation, 2021).

Despite the EMF's reputation, the concept of CE was elaborated before the establishment of EMF; CE connects to and builds upon industrial ecology, biomimicry, cradle-to-cradle, ecodesign and other concepts (Moreau et al., 2017). This heterogenous background results in a variety of definitions of CE spread across research literature and general publications, with emphasis on different aspects. For example, another common definition is that CE is "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al., 2017). In a first article in 2017 (Kirchherr et al., 2017) 114 definitions of CE are presented; a consolidated definition of CE is also given as: "an economic system that replaces the "end of life" concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level […], meso level […] and macro level […], with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by business models and responsible consumers." This article was followed in 2023 (Kirchherr et al., 2023) by the analysis of additional 221 definitions of CE, which produced a new consolidated definition highlighting core principles, aims and stakeholders of CE, as: "a regenerative economic system which necessitates a paradigm shift to replace the "end of life" concept with reducing, alternatively reusing, recycling and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities."

This context clearly highlights the need for standardization, which culminated in May 2024 with the release of the ISO (International Organization for Standardization) standards for CE (ISO, 2024a; ISO, 2024b). In those, circular economy is defined as *"an economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development"*. This definition is adopted by the authors in this work.

Another word frequently used in connection with CE is circularity. Literature (Hassan & Faggian, 2023) shows how the two expressions of "circular economy" and "circularity" have been used as synonymous, especially in technology and engineering contexts, focusing on technological solutions which could enable CE or sustainability. For example, in the UNEP definition (UNEP), circularity refers only to the technical cycle of the butterfly diagram (Ellen Macarthur Foundation). Thus, circularity appears to be used as a shorter, and to some supposedly clearer, way to express the concept of CE. Following the dictionary meaning for the word (for example, by the Cambridge dictionary) and CE research sources (e.g. (Asgari & Asgari, 2023; Hassan & Faggian, 2023)), the authors consider circularity as the characteristic or property of a product or service, to be assessed, by measurements or other means, to determine the degree by which any part of a system fits a circular economy system. This link between circularity and measurement is reflected in several tools and metrics already developed to quantify how much a system (or parts thereof) is close to a CE, one example being the Circularity Gap Report (Circle Economy Foundation). A comprehensive list of circularity indicators and metrics is available on the European Circular Economy Stakeholder Platform (European Union) and on other platforms (e.g. (Circle Economy Foundation)). This view aligns with the ISO definition (ISO 2024a) of circularity, presented as *"degree of alignment with the principles for a CE"*. This definition is used in this work.

Other examples of initiatives working towards standardisation of various aspects of CE are the European project CircularPSP, which aims to develop a common European circular economy taxonomy (*CircularPCP*), and the categorization system for the circular economy developed by the European Commission, which covers the R-approaches (European Commission, 2020a) [EU]. The expression R-approaches (or RE-approaches) identifies the strategies supporting CE; the most simplistic and known formulation is the so-called "3 Rs" ("reduce, reuse, recycle"), but many others also exist (Kirchherr et al., 2023; *SUSTAINair;* Tsironis et al., 2024). The ISO standard (ISO, 2024b) does not present the expression R-approaches, but it collects the same strategies as "resource management actions" (ISO, 2024b) (Table 1, p. 28), and those are presented in Table 1. Such classification is adopted by the authors further in the current work.

In the aviation sector, the expressions "circular economy" or "circularity" have started to appear more frequently in aviation-related publications (as examples (ACARE, 2022; European Commission, 2023)). Despite this, there are hardly established definitions used within the sector. This generates confusion regarding the concept itself, allows for misinterpretations; this context prevents the effective application of CE principles and strategies within the air transport system (ATS). This current work seeks to contribute on remedying this issue.

Aim of the present work is to establish a foundation for integrating circular economy strategies into the aviation sector through a structured reference framework of practices applicable within the sector. It builds upon the newly released ISO 59004:2024 standard, aligning its resource management actions to specific applications in aviation. To this end, the study proposes a sector-specific definition of the circular economy, tailored to address the industry's unique constraints, regulatory requirements, and sustainability challenges. Furthermore, it reinterprets circular economy strategies—commonly known as resource management actions or R-approaches—to enhance their applicability to aviation, encompassing areas such as aircraft design, maintenance, and end-of-life management. To achieve the objective, the paper is structured as follows: after describing the research methodology (Section 2), a review of how the aviation sector currently interprets CE, its concepts and strategies is presented (Section 3). A critical analysis of the different understanding of CE concepts between the aviation sector and the policy and sustainability perspectives is performed; this analysis has the intent of identifying knowledge gaps, their origin and associated challenges (Section 4). Building upon this analysis and on the newly released ISO standards for CE, in Section 5 the authors propose a definition of CE specified to the ATS context, and then tailored to aviation. Subsequently, the strategies for a CE (also known as resource management actions or R-approaches) are put in relation with the ATS and the aviation, by providing connections between those strategies and their application within the aviation industry (secondary objective).

Table 1. Definitions of the Resource Management Actions From ISO 59004:2024

Action	Description
Refuse	Make solutions redundant by abandoning its function or by offering the same function with a radically different solution.
Rethink	Reconsider design and manufacturing decisions. Make service use more intensive (e.g. through sharing or by putting multi-functional products on the market).
Circular sourcing	Select recovered or renewable, sustainably sourced or produced resources. Use resources that can be easily recycled or returned to the biosphere. Reconsider formulations.
Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
Repair	Restore a defective or damaged product so that it can be used in its original function.
Re-use	Re-use a discarded product which is still in working condition and fulfils its original function.
Refurbish	Restore to a useful condition during expected service life with similar quality and performance characteristics.
Remanufacture	Return an item, through an industrial process, to a like-new condition from both a quality and performance perspective.
Repurpose	Adapt a product or its parts for use in a different function than it was originally intended without making major modifications to its physical or chemical structure.
Cascade	Shift recovered materials from one loop to another to optimize feedstock flows through additional cycles, often with decreasing quality and quantity. When adopting for bio-based material, cascading implies repeated use of renewable resources at decreasing quality, with final treatments such as composting, energy recovery or biodegradation, and safe return of the material to the environment.
Recycle	Recover and process material to obtain the same (high grade) or lower (low grade) quality through activities such as recovery, collection, transport, sorting, cleaning and re-processing.
Recover energy	Generate useful energy from recovered resources.
Re-mine	Mining or extraction from landfills and waste plants can be possible in some cases if mining or extraction activities are sustainably managed.

2. RESEARCH METHODOLOGY

2.1 Literature Review

In order to gather a comprehensive view of the interpretations of CE in the ATS, a literature review was carried out from September 2023 until October 2024, through Science Direct and Springer databases, and Google Scholar. The keywords considered in the search are: “Circular economy aviation”, “Circular economy air transport system”, “Circular economy aerospace”, “Circularity aviation”, “Circularity air transport system”, “Circularity aerospace”. No geographical restriction is considered, provided that the publications are in English language.

To provide a visual understanding of the outcomes of this literature, a separate literature search using Web of Science is performed with the same keywords. The search resulted in more than 600 references. Those references are then filtered by removing the following Web of Science categories: acoustics and optics, agriculture (and related fields), astronomy, automation, computer and IT technologies (and related fields), bio-sciences and technologies, medicine (and related fields), civil/electrical/electronic engineering. Entries in the remaining categories are filtered manually by looking at the titles; this would ensure that relevant publications beyond the “Engineering, Aerospace” category would be included. Last, engineering and aviation publications related to the circularity of holes are removed from the selection. The final count came at 121 references; their distribution over the various research areas defined by Web of Science is given in Figure 2.

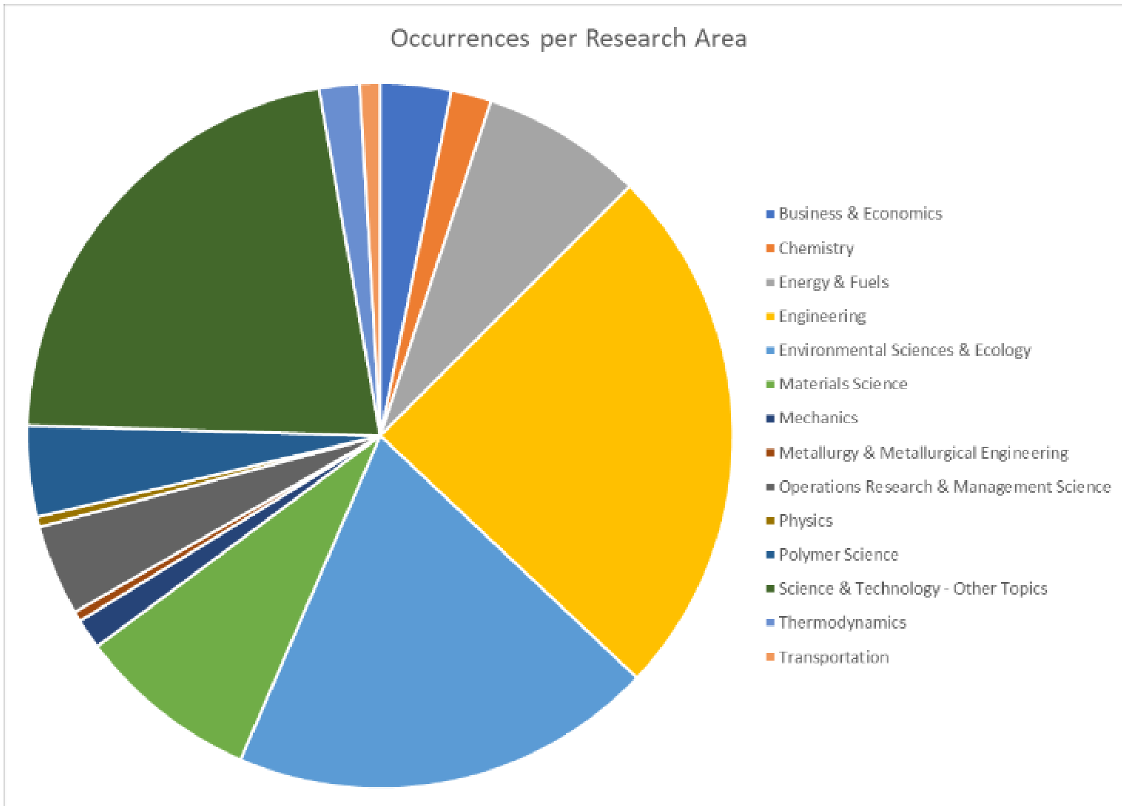

Figure 2. Distribution of the Literature Across Web of Science Research Areas

The figure shows a strong link to engineering, with social and economic research areas missing from the aviation literature. The same set of references is presented also in Figure 3, which shows all the connections among the keywords of the 121 references, evaluated with the software VOSviewer (van Eck & Waltman, 2010). The figure shows once again the strong focus on technological aspects of the literature available; the four strongest connections are towards the terms: sustainability, design, energy, recycling (in a larger font size in the figure). The presence of the word "energy" originates from several references relating CE with new energy sources for aviation; those references are not considered further in the scope of the current work.

Given the limited results of this structured literature search, in addition to the peer-reviewed literature, white papers, websites' content, marketing and commercial communications, publicly available case studies and other grey literature have been included in the scope. Last, additional sources from relevant stakeholders and entities of the air transport sector and of the aviation sector have been identified based on the extensive knowledge of those sectors by the authors. It is important to remark how the large majority of the sources, both from the literature review and from the additional references is originated in Europe, with few contributions from other parts of the world (at least in English language).

From this extensive source of references, this work focuses on aviation and on aircraft in particular; references regarding other pillars of the ATS (e.g. airlines or airports) are not detailed in this work, besides few examples for contextualization. A systematic content analysis was performed to ensure a thorough and objective evaluation of the references collected. The systematic screening process was supported by the collective expertise of the authors. Their extensive experience in the domains of aviation and circular economy played a critical role in guiding the selection and the evaluation of the references, and allowed for a more nuanced interpretation, ensuring that the most relevant and contextually significant information was considered.

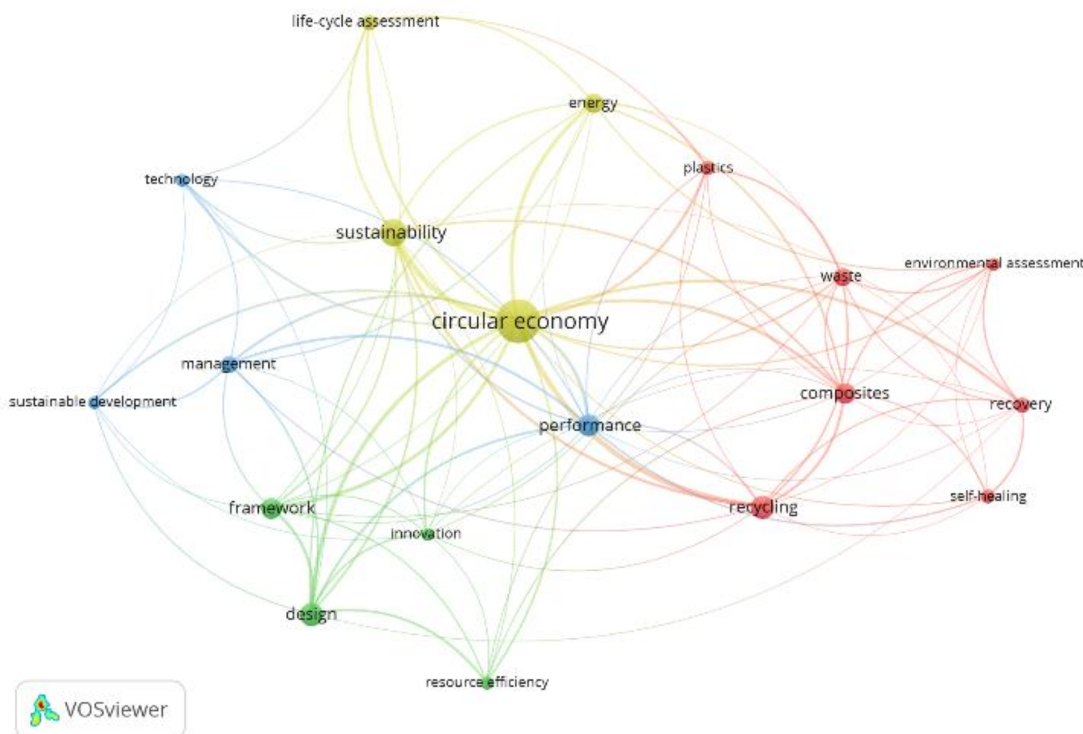

Figure 3. Visualisation of the Most Relevant Keywords for the Literature Sources Considered, in VOSviewer

2.2 Derive and Characterise the Definitions

Based on the analysis described in section 1.1, the ISO definitions of CE and of the resource management actions are contextualized for the air transport system and for aviation; particular focus is directed to aspects related to aircraft and airframe components.

2.3 Identification of Research Gaps

Following the analysis performed and the definitions proposed, gaps between the current understanding of CE in aviation and the definitions were identified. Those gaps identify the next research steps, and they range from expanding the implementation of CE strategies to social and economic aspects, to the assessment of the circularity of the ATS and its sub-systems. Detailed elaborations of those topics are beyond the scope of this work and will be presented in future publications from this group.

2.4 Harmonizing Circular Economy Definitions and Strategies for Aviation

Following the gap analysis, the final section of the paper proposes a harmonized interpretation of CE definitions and strategies specifically for aviation, using a two-step approach. First, key CE concepts are adapted to the context of the ATS, ensuring they align with aviation-specific challenges such as resource use, waste management, and lifecycle considerations. This involves reviewing and refining existing CE definitions to better suit the industry's requirements. Second, established CE strategies are translated into the aviation sector by mapping and organizing current ATS and aviation initiatives within a CE framework.

3. DEFINITIONS OF CIRCULAR ECONOMY WITHIN THE AVIATION SECTOR

In the aviation sector, the concept of CE is used in various contexts across the entire ATS, without properly or consistently referring to one single, commonly agreed, definition or reference.

ICAO (International Civil Aviation Organization) refers to CE in the 2019 environmental report (ICAO, 2019) and on its website (ICAO). In the 2019 report: “the concept of a “circular economy” was devised with the aim of minimizing waste and pollution and making the most of resources by keeping products and materials in use as much as possible, and by recovering and regenerating products and materials at the end of each service life". The ICAO webpage refers to CE as "an alternative way" which "seeks to extract the maximum value from resources in use and keeps materials in circulation for as long as possible. It aims to minimize the environmental and social impacts, as well as to reduce economical costs and create jobs. Circular economy prioritizes regenerative resources as material inputs and making the most out of existing resources and materials." Both the 2019 report and the website refer to EMF sources for further information and definitions. No further mention of CE is included in the 2022 environmental report (ICAO, 2022).

From a European research perspective, the vision document by ACARE, "Fly the Green Deal" (FTGD) (ACARE, 2022), mentions the goal of achieving the goal of climate-neutral aviation by 2050, by "integrating the circular economy concept to be an equitable contributor" (ACARE, 2022) (p. 15); it also mentions that in 2050 "the air transport system is fully circular" (ACARE, 2022) (p. 24) and, regarding air vehicles, that "circularity design principles" are applied (ACARE, 2022) (p. 31). A document that is also frequently mentioned within the sector in relation to the transition to a sustainable aviation is Destination 2050 (A4E et al., 2021). Though some of the identified "sustainability measures" belonging to the pillars of "Aircraft and engine technology" and "Smart economic measures" could directly link to CE, there is no mention of CE approaches or strategies in the document. In the white paper of EREA's Future Sky Theme Circular Aviation theme (EREA Future Sky, 2020), referring to the EMF's definition, a description is given as "CE (or circularity) is one approach to engage with sustainability. A CE is an alternative to a traditional linear economy (which can be summarized with "make, use, dispose") in which resources are kept in use for as long as possible, extracting the maximum value from them whilst in use, then re-covering and regenerating resources from products at the end of each service life. CE is "a new way to design, make, and use products within planetary boundaries". Shifting the system involves everyone and everything: businesses, governments, and individuals; our cities, our products, and our jobs".

Other mentions of CE are spread across various aerospace and aviation organisations. EASA (European Aviation Safety Agency) refers to CE in relation to the European CE Action Plan and explains it as "The 4R's of the circular economy concept (Redesign, Repair, Reuse, Recycle) consider the complete lifecycle of a product from production to disposal with the objective of an efficient use of resources and a reduction in waste" (EASA); this does not link to the definition given in the CE action plan itself. The leading aviation public-private joint undertaking Clean Aviation (Clean Aviation Joint Undertaking), and its predecessor Clean Sky 2 (Clean Sky Joint Undertaking, 2015), do not include explicit references to CE prior to the update strategic research and innovation agenda (SRIA) published in September 2024 (Clean Aviation Joint Undertaking, 2024). As Clean Sky 2 programme started in 2014, the lack of reference to CE in its SRIA is understandable. Nonetheless, some projects from Clean Sky 2 and even from its predecessor, Clean Sky, refer to CE, but without providing a definition and mainly relating CE to weight reduction and recycling (Clean Aviation Joint Undertaking; Clean Aviation Joint Undertaking; Clean Aviation Joint Undertaking; Coskun et al., 2023; Reichert et al.). CE is not mentioned in the publicly available information on the Clean Sky 2 Technology Evaluator activities (though those are still in progress at the time of writing), and not in the Technology Evaluator First Global Assessment, published in 2020 (Clean Sky Joint Undertaking, 2021b). CE is barely mentioned within Eco-Design Transverse Activity, but without further definition (Clean Sky Joint Undertaking, 2021a). From Clean Aviation, CE is mentioned in the updated SRIA, in relation to societal impact only, but not defined (Clean Aviation Joint Undertaking, 2024).

Mentions of CE have grown in the last years in several research projects related to aviation or to the ATS; a short summary of the European funded projects which are considered representative of CE activities in aviation is available at (European Commission, 2023). Despite this increase in projects, the link to definitions of CE is weak; for most projects, the connection is to the European Green Deal or to the EMF. An exception is project RECREATE (*RECRATE*), which proposes the following definition: "The Circular Economy (CE) is a visionary economic model that focuses on closed cycles where, ideally, there is an endless regeneration of resources. CE should be shaped through supportive regulations and policies. This transformative concept emphasizes the integration of renewable energy and sustainable practices. CE prioritizes circularity, minimizing waste and maximizing value creation, promoting a harmonious interaction between society, economy and environment, and reflecting a collaborative spirit of innovation and responsible resource management" (Vogiantzi & Tserpes, 2023). A summary of the definitions within the aviation sector is given in Table 2.

Table 2. Summary of Definitions of Circular Economy in Aviation-Related Publications

Reference	Does it contain a mention of CE?	Does it contain a definition of CE?	Is the definition specific for ATS?
ICAO (ICAO; ICAO, 2019; ICAO, 2022)	Yes	Yes	No
Fly the Green Deal (ACARE, 2022)	Yes	No	N/A
Destination 2050 (A4E et al., 2021)	No	N/A	N/A
EASA (EASA)	Yes	Yes	No
Clean Sky/Clean Aviation (Clean Aviation Joint Undertaking; Clean Aviation Joint Undertaking, 2024; Clean Sky Joint Undertaking, 2015, 2021b)	Partial	No	N/A
Future Sky Circular Aviation (EREA Future Sky, 2020)	Yes	Yes	No

The use of the term "circularity" within aviation-related documents and literature, aligns with the observation of the general CE sources; circularity is seen as a synonymous of CE, and the two are used interchangeably (e.g. (EREA Future Sky, 2020; European Commission, 2023; KPMG, 2024). In the 2025 update of Destination 2050 (A4E et al., 2021), circularity is mentioned and associated with reuse and recycling, with no further explanation given. In one research line (D. N. Markatos & Pantelakis, 2022; Dionysios N. Markatos & Pantelakis, 2022), circularity is correctly presented as an indicator of the performance of a product (i.e. airframe component). Yet, the quantities used to assess it are limited, for simplicity, to single indicators (e.g. stiffness), not mirroring the systemic nature of CE. In (Coskun et al., 2023), circularity is not defined, and its assessment limited to the material circularity index; as the material circularity index reflects only the quantity of recycled material, no considerations on the component's design or other aspects are included. Except for this latter, no connection with the tools for measuring the CE presented earlier is visible in existing aviation publications.

Aviation practices and examples which can be identified with CE strategies are retrieved from ATS and aviation literature; the mapping is presented in Table 3. This table also includes the ISO definitions for the resource management actions (presented also in Table 1), compared to the definitions of the R-approaches from the EU classification (European Commission, 2020a). The practices and examples listed are attributed to the different resource management actions based on the experience of the authors. Only in few cases, the reference to the strategy is present in the reference; in even fewer cases, the reference to circular strategies is made. This means several practices of the aviation sector connect to circular strategies (or resource management actions); this does not signify that there is a conscious and aware choice to connect to circular strategies. Given the current decision-making priorities within the industry (focusing on reducing carbon emissions, lightweight design, fuel efficiency, safety and cost-reduction), the connection of aviation practices is to be seen as a "lucky coincidence". This means that the full potential of applying specific circular strategies is not maximised.

From this summary, it appears that CE strategies in ATS and aviation, cover only one or few specific strategies of CE. Those strategies are primarily linked to recycling seldom with design and manufacturing (in relation to weight-saving or optimization for less resource usage) or with the application of recycled and biomaterials (as shown also in Figure 3). More rarely, maintenance, repair and overhaul practices are mentioned in connection with CE; when they are, the focus is on disassembly and dismantling practices (AFRA; *SUSTAINair*). Notable in this last group is the project PAMELA (European Commission). Within the context of airlines and airports operations (for example, (Salesa et al., 2023; *TULIPS*)), CE is almost exclusively linked to waste management (in particular, catering waste).

Table 3. Definitions of Resource Management Actions From ISO 59004:2024 [ISO], Compared With Definitions of R-Approaches From (European Commission 2020a) [EU] and Citations From Aviation Sources

Action [ISO]	**Description [ISO]**	**R-approach [EU]**	**Definition [EU]**	**Citations from aviation sources**
Refuse	Make solutions redundant by abandoning its function or by offering the same function with a radically different solution.	Refuse	Make product redundant by abandoning its function or by offering the same function by a radically different (e.g. digital) product or service.	• UAM as alternatives to airplanes (Roland Berger) • Plans to remove plastics (Salesa et al., 2023) (Table 1) • (Hybrid-) electric aircraft and alternative fuels (EREA Future Sky, 2020) (p. 6) • Implementation of digital records (EREA Future Sky, 2020) (p. 6) • Use of drones to provide agricultural aviation services, telemetry and georeferencing. (Rodrigues Dias et al., 2022) (p. 8) • The replacement of paper maintenance with digital, use of iPad for the elaboration of digital flight plan, digitization of aircraft documents were also virtualization initiatives mentioned by the companies. (Rodrigues Dias et al., 2022) (p. 8) • Use of technologies to optimize production processes by intensifying digitization (drawings and project reports, production and testing routes, aircraft documentation, maintenance manuals, etc.). (Rodrigues Dias et al., 2022) (p. 8) • Refuse: Could we just fly less? (Domone et al., 2021) (p. 10) • Circular lighting at Schiphol Airport (Philips) • Fuel cells as replacement for traditional APUs (Paula Andrade et al., 2022)

Rethink	Reconsider design and manufacturing decisions. Make service use more intensive (e.g. through sharing or by putting multi-functional products on the market).	Rethink	Make product use more intensive (e.g. through product-as-a-service, reuse and sharing models or by putting multi-functional products on the market).	• Multifunctional structures with quasi-solid state Li-ion battery cells and sensors for next generation climate neutral aircraft (Matisse) • Multi-sided Platform (MSP) (Hisan H., Yusof K. H., Arshad, A., 2024) • Internet of things [for] participation [...] in the use of airports (Castillo Malagón et al., 2024) (p. 43) • AI can improve and accelerate the development of new products, components, and materials suitable for a circular economy through iterative machine learning (ML)-assisted design processes that enable rapid prototyping and testing (Castillo Malagón et al., 2024) (p. 43) • Airport [...] has [...] designed the new terminal [...] as a covered space in which structures and buildings can be reorganized over time to respond to commercial, safety, and security changes. By using a standardized kit of parts for building construction that can be disassembled and reused multiple times in different configurations, the terminal can avoid the traditional demolitions associated with refurbishments (Castillo Malagón et al., 2024) (p. 44) • Circular economy business models (Andersson & Stavileci, 2015) • Use and manufacturing of biocomposites (Bachmann et al., 2021) • Circular Manufacturing (EREA Future Sky, 2020) (p. 5) • Extending durability (for example via modularity solutions), ease to repair approaches, disassemble, reuse of components (EREA Future Sky, 2020) (p. 5) • Standardised designs: components or assemblies can be removed from one aircraft and be placed, unchanged, into a new one. (Domone et al., 2021) (p. 11) • Modular and reconfigurable interiors: increasing the life span of the underlying aircraft platform (Domone et al., 2021) (p. 11) • Material choice: fewer dissimilar materials that can be readily recycled, eliminate non-recyclable materials, careful selection of coatings. (Domone et al., 2021) (p. 11) • Design for disassembly: reversible joints and interfaces of dissimilar materials. (Domone et al., 2021) (p. 11)

Circular sourcing	Select recovered or renewable, sustainably sourced or produced resources. Use resources that can be easily recycled or returned to the biosphere. Reconsider formulations.	N/A	N/A	• [Airport] using low-carbon pavements and [...] challenging the traditional methods and materials used in their runways and taxiways. (Castillo Malagón et al., 2024) (p. 45) • Adoption and recycling of thermoplastic composite (Coskun et al., 2023) • New eco-friendly materials, Food eco-friendly packaging (Salesa et al., 2023) (Table 1) • Use and manufacturing of biocomposites (Bachmann et al., 2021) • Choice of materials, Resourcing of (recycled) materials (EREA Future Sky, 2020) (p. 5) • Environmentally friendly chemicals for the surface treatment of parts (Rodrigues Dias et al., 2022) (p. 8) • Honeycomb composites, which were light and use other materials, including carbon, and coconut fiber (Rodrigues Dias et al., 2022) (p. 8)
Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	• Fuel Efficiency, Electric Aircraft and Ground Vehicle, Waste Management, Energy Saving), Water Management, Decision Making Model, Legislation and Taxation, Multi-sided Platform, Multi-sided Platform, Maintenance, Repair and Overhaul (Hisan H., Yusof K. H., Arshad, A., 2024) • Additive-manufactured [...] parts [...] can improve functionality and reduce weight. Lighter parts help reduce aircraft weight and, consequently, fuel consumption. (Andersson & Stavileci, 2015; Castillo Malagón et al., 2024) • Electronic airway bills, Providing tablets to reduce paper, Using electronic boarding passes, Plans to remove plastics (Salesa et al., 2023) (Figure 6) • Adoption of technologies through the use of computational tools and robots for the simulation of aerodynamic and structural tests, which has reduced material waste and waste generation (Rodrigues Dias et al., 2022) (p. 8) • The use of these technologies can provide a reduction in general costs for design, manufacture and operations, as well as a reduction in environmental impact when adopting practices such as reducing the number of components in an assembly through the use of new technologies. (Rodrigues Dias et al., 2022) (p. 8) • Use of industry 4.0 technologies as a way of optimizing material resources and reducing waste (Rodrigues Dias et al., 2022) (p. 8) • Use of 3D printer as a way to change technologies towards faster product development and using less materials and generating less waste as practices (Rodrigues Dias et al., 2022) (p. 8) • Eliminate waste and use recycled material as input (Domone et al., 2021) (p. 12) • Additive Manufacturing can dramatically reduce waste and energy usage (Domone et al., 2021) (p. 12)

Repair	Restore a defective or damaged product so that it can be used in its original function.	Repair	Repair and maintenance of defective product so it can be used with its original function.	• Maintenance, Repair and Overhaul (Hisan H., Yusof K. H., Arshad, A., 2024) • New products design—repairability (Salesa et al., 2023) (Table 1) • Maintenance, repair and overhaul is an area of significant expertise in aviation (EREA Future Sky, 2020) (p. 3) • Extending durability (for example via modularity solutions), ease to repair approaches, disassemble, reuse of components (EREA Future Sky, 2020) (p. 5) • Design for maintenance and repair is undeniably part of structural integrity, with design for maintenance being an important driver in the design of aircraft components (Paletti, 2023) (p. 6)
Re-use	Re-use a discarded product which is still in working condition and fulfils its original function.	Reuse	Re-use of a product which is still in good condition and fulfils its original function (and is not waste) for the same purpose for which it was conceived.	• Waste Management, Multi-sided Platform, Maintenance, Repair and Overhaul (Hisan H., Yusof K. H., Arshad, A., 2024) • Digital twins [...] can also be placed on operating aircraft to gather information to improve critical parts and components. (Castillo Malagón et al., 2024) (p. 43) • Airport implemented actions to redeploy facilities and equipment and to dismantle them during modernization work. (Castillo Malagón et al., 2024) (p. 44) • Extending durability (for example via modularity solutions), ease to repair approaches, disassemble, reuse of components (EREA Future Sky, 2020) (p. 5) • Functional parts being recovered from retired or decommissioned aircraft and other parts being repurposed or recycled responsibly (KPMG, 2024) (p. 2) • Practices of reuse and recycling of aeronautical products” and “reuse of the aircraft fuselage in the manufacture of motorboats (Rodrigues Dias et al., 2022) (p. 7) • Reuse occurs when parts are removed from an aircraft to be used for the same function on another aircraft. (Domone et al., 2021) (p. 12)
Refurbish	Restore to a useful condition during expected service life with similar quality and performance characteristics.	Refurbish	Restore an old product and bring it up to date (to specified quality level).	• AI can help build and improve the reverse logistics infrastructure needed to "close the loop" with products and materials by improving product sorting and disassembly, component remanufacturing, and material recycling processes. (Castillo Malagón et al., 2024) (p. 43) • Once deemed serviceable and after undergoing recommission processes and the required testing and certification, these parts are sold as used serviceable material (USM). (KPMG, 2024) (p. 3) • Refurbishing parts could reset fatigue lives (Domone et al., 2021) (p. 13)

Remanufacture	Return an item, through an industrial process, to a like-new condition from both a quality and performance perspective.	Remanufacture	Use parts of a discarded product in a new product with the same function (and as-new-condition).	• AI can help build and improve the reverse logistics infrastructure needed to "close the loop" with products and materials by improving product sorting and disassembly, component remanufacturing, and material recycling processes. (Castillo Malagón et al., 2024) (p. 43) • Engines remanufacture (Andersson & Stavileci, 2015) • Once deemed serviceable and after undergoing recommission processes and the required testing and certification, these parts are sold as used serviceable material (USM). (KPMG, 2024) (p. 3) • Remanufacture sees existing components or assemblies reworked and reassembled into new parts distinct from the originals but performing the same function. (Domone et al., 2021) (p. 14) • Remanufacturing and repurposing are different to repairing and refurbishing in that the output is a like-new component or assembly. (Domone et al., 2021) (p. 14) • Remanufacture could allow aircraft cabin interiors to be upgraded to install the latest media technology, or aircraft having whole wings upgraded. (Domone et al., 2021) (p. 14) • Additive manufacture could enable the remanufacture of whole airframes to enable alternative energy sources, like batteries or hydrogen, to be utilised. (Domone et al., 2021) (p. 14)
Repurpose	Adapt a product or its parts for use in a different function than it was originally intended without making major modifications to its physical or chemical structure.	Repurpose	Use a redundant product or its parts in a new product with different function.	• Furniture (*Aeroplane Furniture)* • Hotels (Simple Flying) • Waste Management, Multi-sided Platform, Multi-sided Platform (Hisan H., Yusof K. H., Arshad, A., 2024) • Uniforms to manufacture amenities, Uniforms reused to create furniture blankets (Salesa et al., 2023) (Table 1) • Functional parts being recovered from retired or decommissioned aircraft and other parts being repurposed or recycled responsibly (KPMG, 2024) (p. 2) • Scrapped aircraft are also used for teaching and training practices.(Rodrigues Dias et al., 2022) (p. 7) • Parts or assemblies are reworked to perform a new function (Domone et al., 2021) (p. 14) • Remanufacturing and repurposing are different to repairing and refurbishing in that the output is a like-new component or assembly. (Domone et al., 2021) (p. 14)
Cascade	Shift recovered materials from one loop to another to optimize feedstock flows through additional cycles, often with decreasing quality and quantity.	N/A	N/A	• The use of these residues for the production of tools in order to save virgin material in the manufacture of these structures”(Rodrigues Dias et al., 2022) (p. 8) • Recovered metal waste often enters a shredder, is sorted and melted down to create new material used in other sectors (Domone et al., 2021) (p. 15)

Recycle	Recover and process material to obtain the same (high grade) or lower (low grade) quality through activities such as recovery, collection, transport, sorting, cleaning and re-processing.	Recycle	Recover materials from waste to be reprocessed into new products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.	• Aircraft recycling and aircraft end of life, combining 1. decommissioning, 2. careful disassembly and 3. dismantling. (Reichert et al.) • Waste Management, Decision Making Model, Multi-sided Platform), Maintenance, Repair and Overhaul (Hisan H., Yusof K. H., Arshad, A., 2024) • AI can help build and improve the reverse logistics infrastructure needed to "close the loop" with products and materials by improving product sorting and disassembly, component remanufacturing, and material recycling processes. (Castillo Malagón et al., 2024) (p. 43) • (Coskun et al., 2023) • (Andersson & Stavileci, 2015) • Recycling plastic, Recycling paper, Recycling tracking system, Recycling cans, In-cabin material recycling, Recycling hazardous waste (Salesa et al., 2023) (Table 1) • Recycling activities for aircraft operations (EREA Future Sky, 2020) (p. 5) • Functional parts being recovered from retired or decommissioned aircraft and other parts being repurposed or recycled responsibly (KPMG, 2024) (p. 2) • Recycling and reusing aircraft components (KPMG, 2024) (p. 3) • Practices of reuse and recycling of aeronautical products (Rodrigues Dias et al., 2022) (p. 7) • Recovered metal waste often enters a shredder, is sorted and melted down to create new material used in other sectors (Domone et al., 2021) (p. 15) • Principles of circular economy need to be mainstreamed, regarding recycling of the lithium-ion batteries (Afonso et al., 2023) (p. 14) • Recycling aircraft aluminium (*RecAl)*
Recover energy	Generate useful energy from recovered resources.	N/A	(Comment: explicitly excluded by the categorisation, as mentioned in (European Commission 2020a)).	• Waste Management (Hisan H., Yusof K. H., Arshad, A., 2024) • [Airport] invests in waste-to-energy, converting food scraps from flights and other types of organic waste into biomass fuel to provide heating for the [...] terminal. (Castillo Malagón et al., 2024) (p. 45) • Burning waste to recover energy, Burning hazardous waste to recover energy (Salesa et al., 2023) (Table 1)
Re-mine	Mining or extraction from landfills and waste plants can be possible in some cases if mining or extraction activities are sustainably managed.	N/A	N/A	• Urban mining activities, already introduced in cities and communities, can be phased in airports and aircraft boneyards (EREA Future Sky, 2020) (p. 5)

4. DECIPHERING CIRCULAR ECONOMY IN CIRCULAR AVIATION

From the overview given earlier of general CE definitions, it appears evident that the concept of CE is vague and open to various (mis)interpretations. Summarizing the intervention of EMF's Circular Design Programme Lead Joe Iles during DLD Circular 2023: "Circular economy principles are still vague to designers, but that is deliberate because designers need to understand the systemic implications of what they create and what is appropriate for their product (with the example of do not repair a sandwich), which means to have as deep as possible understanding of circular economy principles and then grapple with the system around the product or organization or industry. Such a combination will inform the specific design strategies to implement" (DLD Circular 2023). This helps to understand why the number of definitions of CE is humongous, and why, according to some authors (Kirchherr et al., 2017), a consensus definition for CE may never be achieved. This last statement may appear now superseded by the recent release of the ISO standard on circular economy (ISO, 2024a, 2024b). On the other hand, the release of an ISO standard is not a guarantee of no further theoretical development of the concept, nor of quick and widespread adoption of terminology and knowledge. In addition to this, a transition phase needs to be accounted for the new terminology to be implemented, both in the general sustainability field and in the aviation sector.

The inherent vagueness of CE is reflected in the aviation sector as shown by the overview in Section 3; it has somehow allowed and enhanced the narrative in aviation initiatives to equate CE with recycling and waste management activities (Figure 3). Lack of knowledge and expertise made appear CE as an additional requirement to be included in the design and operations of the aviation products (aircraft and airframe components). Lacking the regulatory enforcement present in other sectors, CE strategies got side-lined within a sector already highly regulated with low profit margins. In fact, despite the number of directives at European level which support a transition to CE, transportation, and aviation in particular, has almost always being exempt from adopting such regulations. This overall context prevented investment in increasing knowledge, expertise and awareness of the topic. In the past couple of years, given the recent challenges regarding supply chain resilience and critical raw material supply and related upcoming European legislations, CE has become more visible to the aviation sector. Last, given that sustainability strategies in ATS and aviation address strongly the environmental impact only, and in particular in-flight and operational emissions, CE as a means to achieve full sustainability (in line with the UN concept of sustainable development (World Commission on Environment and Development, 1987) and the 17 UN sustainable development goals (United Nations)) has not played a prominent role insofar.

On the other hand, the vagueness of CE definition is counterbalanced by implementation strategies and approaches which are specific, focused and tangible (refer to Table 1); as such, CE has the potential to be more easily understood within an engineering domain, compared to other sectors. In this view, the incorrect identification of CE with waste management and recycling, though not specific for the aviation sector, appears particularly problematic given that the aviation sector is already embedded with CE strategies and practices (Castillo Malagón et al., 2024; Domone et al., 2021; EREA Future Sky, 2020; Hisan H., Yusof K. H., Arshad, A., 2024; Paletti, 2023; Rodrigues Dias et al., 2022).

The lack of common definitions across the sector shown in Section 3 can be seen also as a consequence of the lack of definitions by the most relevant and influential organisations in aviation and aeronautics (e.g. ICAO or, in Europe, ACARE). For example, despite being prominent in the sector's vision FTGD (ACARE, 2022), CE is not defined or described in more detail, giving the impression that the meaning of CE is clear and unambiguous within the aviation community. As shown, this is far from the reality and, given that the predecessor of FTGD, FlightPath2050 (European Commission, 2012), has been the leading reference document for the sector for more than a decade, the lack of position of FTGD on CE definitions can be seen as a signal regarding the unclarity of the concept, and as a risk, as it does not help to clarify the concept for the sector. Nevertheless, it would be limiting to explain the disconnect of the aviation sector from sustainability (thus including CE) only by the lack of definitions or knowledge. As a number of NGOs are critical towards the actual efforts the sector is making for a real and effective transition to sustainability (Kumar & Rutherford), research has pointed out that there are characteristics of the aviation sector which enable the establishment of "a gendered system of thinking, being and doing which forecloses radical action and change required for a climate-safe and just energy future" (Hopkins et al., 2023).

It is evident that the sector is approaching the transition to a sustainable future primarily from a technological (or technical) perspective, as visible from the typology of high level initiatives (for example, Clean Aviation) and projects (e.g. (Afonso et al., 2023; Domone et al., 2021; European Commission, 2023)); the emphasis of those projects and initiatives is on (part of) environmental sustainability, with a strong attention to maintain or increase competitiveness of aviation players in the current economic model (thus with current business models). As shown by the UN Sustainable Development Goals (United Nations) and, specifically for CE, by the ISO standard (ISO, 2024b) (Figure 3, p. 15), all interactions between the environmental, social and economic systems need to be considered for a transition to sustainability; this is clearly not represented in the aviation initiatives presented in Section 3. Also, based on a life cycle perspective, CE must include all phases of both the biological cycle and the technical cycle (ISO, 2024b) (3.2.5). Currently, the focus is primarily on the in-flight (use) phase (as established as the most critical in terms of CO2 and non-CO2 emissions (Roosien et al., 2024)) and considerations regarding biological cycle seem limited to discussions regarding SAF and its sourcing feedstock (Rodrigues Dias et al., 2022). Thus, the scope of the aviation is on the technical cycle and even on a particularly narrow part of it; as mentioned earlier (Hopkins et al., 2023), this forecloses the implementation of approaches and strategies of CE which are really radical and disruptive: new business models and consumer behaviours, and early design actions (such as Refuse and Rethink, Table 1).

This is also visible by the current trend in current aviation strategic documents to fit existing aviation practices in a CE narrative (Castillo Malagón et al., 2024; Domone et al., 2021; EREA Future Sky, 2020; Hisan H., Yusof K. H., Arshad, A., 2024; ICAO; KPMG, 2024). The question answered by this type of publications can be framed as “How does aviation contributes to the concept of CE?”, rather than establishing CE as an objective (in line with the European Green Deal objectives) and then answering a more disruptive question of “How should aviation innovate to fit within a CE system?”. There has been no attempt known to the authors of answering the latter question. Answering such question would require first to tailor the concepts of CE to aviation, the air transport system or parts thereof. An example of this would be defining a concept of “circular aviation”. The expression “circular aviation” is first presented in the white paper of EREA’s Future Sky Theme Circular Aviation theme (EREA Future Sky, 2020) as the objective of a transition that the sector needs to experience, but it is not defined or detailed. Another reference to “circular aviation” is present in SUSTAINair project (*SUSTAINair*); also, in this project, the expression is framed as a goal to achieve and with the project’s results as contribution to such goal. As the project is branded in relation to the EREA Future Sky’s initiative mentioned above, the similarity in meaning is to be expected.

In addition to seemingly preserving the status-quo of current aviation practices while fitting them in a new narrative, those overviews tend to collate various strategies and approaches from different pillars of the ATS, and from different levels of a system, mixing macro-scale aspects with micro-scale (e.g. number of passengers next to aircraft material recycling (Domone et al., 2021)), as to create an overall contribution from the aviation sector to CE. Such collation does not create a coherent picture, thus adding to the overall confusion regarding CE in aviation. Moreover, as the considered approaches and strategies are not considered in relation with each other or in relation with economic and business models, or social aspects, the holistic character of CE is lost, resulting in probably overestimating the contribution of each topic to CE (and, more risky, drifting towards greenwashing); for example, designing integrated structures reduces material usage and saves weight, resulting in less fuel usage, while on the other hand becoming more difficult to repair or to manage at end of life. The lack of a circularity measurement for aviation prevents making any assessment of current claims.

Given the unique characteristics of the ATS, in order for organizations in the aviation sector to effectively incorporate and exploit CE strategies, existing CE knowledge, including the ISO standards on CE (ISO, 2024a, 2024b), needs to be adapted and complemented with industry-specific definitions, frameworks, guidelines, and best practices, tailored to the specific complexities of aviation dynamics and sustainability challenges.

This current work wants to initiate this trajectory, focusing on tackling two aspects: first, providing definitions for the most relevant concepts of CE tailored to the ATS and aviation; second, mirroring and translating the CE strategies to aviation, in order to organise the existing ATS and aviation initiatives and strategies more coherently towards a higher impact.

5. A PROPOSED INTERPRETATION OF CIRCULAR ECONOMY FOR AVIATION

5.1 Proposed Approach

The aim of this section is to propose an interpretation of CE, based on the existing CE definitions in the literature, and focused on and aligned to the guidelines of ISO 59004:2024. To reach this interpretation aviation will be positioned in relation to CE and its systemic character.

To this end, Section 5 proposes a hierarchical model to define CE at different levels—global, aviation, and aircraft—forming a structured hypothesis. The methodology is then applied by analysing existing CE definitions, identifying their limitations within the aviation sector, and proposing new sector-specific definitions. Finally, the findings are linked to practical applications and future research directions, ensuring that the proposed framework can be implemented and further refined through practical applications.

5.2 Aviation as a Subsystem

CE embodies a systemic character (Hassan & Faggian, 2023; ISO, 2024b). This is reflected in various definitions of CE, which range from general to specific (e.g. circular industrial system, circular product), and in the current variety metrics and assessment tools; for example, the material circularity index covers only the detailed level of materials, while the Circularity Gap Report measures national economies or sectors (European Union).

Considering aviation as "system in focus" (ISO, 2024b), it is important to highlight not only its own systemic nature, but also its relation as a subsystem of the ATS. It is relevant here to remind that aviation covers the design, development, production, operation, and use of aircraft, especially heavier-than-air aircraft. As such aviation is part of the ATS, which is the overarching system allowing the transfer of people and goods in aircraft, and which primarily includes airports, air traffic control, and airlines.

To derive the definitions applicable for aviation, it is important first to consider the position of ATS within the global level, this latter being identified as the "planet Earth", or World, system (Figure 4). In this sense, the ISO definition (together with the EMF's definition (Ellen Macarthur Foundation, 2021)) must be regarded as a **global-level**, overarching, definition.

Something that needs to be emphasized is that, given that the very nature of CE is systemic and holistic, a system can be considered fully circular only when the system of interest coincides with the system "planet Earth". In this light, CE needs to be regarded as an ideal state, which can never be achieved when the system in focus is any smaller than the global system, the "planet Earth". This assumption accounts for the losses which are unavoidable in every physical system (Cullen, 2017; Valero & Valero, 2019); as it happens in physical systems, parts of a system can exhibit the ideal behaviour (in this case, being fully circular); but, when parts of a system are combined, the level of circularity of the system unavoidably decreases and the real system itself never achieves the full CE.

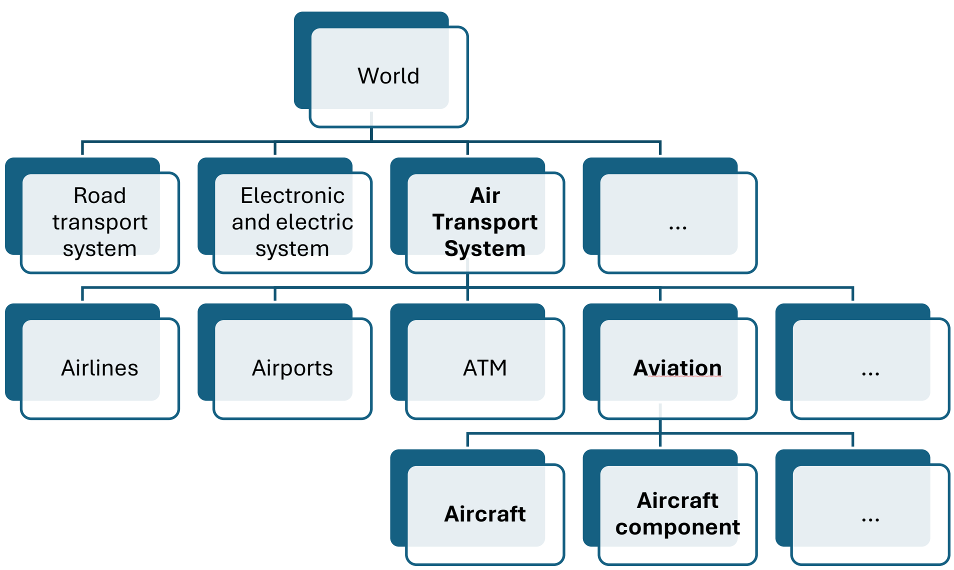

Figure 4. Positioning of the Air Transport System in a Hierarchical Framework, From the System World (Planet Earth) Towards the Subsystems Composing the Air Transport System

Having established the ISO definition (and also the much referred to EMF definition), as global-level helps to understand the remoteness of the meaning of CE when the system of focus is at lower levels of the hierarchy; indeed, specific industrial sectors can be identified as systems within the World system (Figure 4). The need for connection of the subsystems to the global-level explains the need felt by each sector (as a subsystem) to derive its own definition or, better, its own interpretation of CE (EREA Future Sky, 2020; Vogiantzi & Tserpes, 2023). Sector-specific definitions can then be seen as a **macro-level** definition. Concluding, it is worth of noticing that several of the definitions discussed above are case-specific and oversimplified thus giving raise to personal interpretation.

To resolve both the unclarity of the global-level definition and the subjectivity of existing proposals, the authors want to propose the following interpretation of the ISO CE definition applied to the air transport system:

A circular air transport system is an economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development of the air transport system.

As based on the ISO definition, this interpretation focuses on the economic aspect of CE, while also emphasising the systemic approach necessary to achieve a circular system. While the proposed interpretation satisfies the need to link CE and ATS, it still remains at a high level of granularity, and it does not contribute to fill the gap between CE as a concept, its strategies and practical application in the various areas of the ATS, particularly in aviation.

5.3 Definitions for Aviation

From the perspective of aviation, and more specifically of aircraft design or of aircraft component design, the definitions given in the previous sections at global- and macro-levels are abstract to be of practical use. The abstract character may explain how the association of CE with recycling is particularly popular in the domain of aircraft design, as it provides a pragmatic connection when dealing with aircraft and airframe structural design.

As the objective of this paper is to bridge the gap between a vague global-level definition of CE and the levels at which CE strategies and approaches can be implemented, definitions of CE applicable to aviation, and to aircraft and airframe component design, are necessary. The definition of circular air transport system given above should be transitioned to its meso-levels and to aviation in particular; from the definition for aviation, micro-level definitions can be adapted as necessary, for example for aircraft systems or for aircraft components.

As the proposed definition of circular air transport system focuses the economic aspect of CE, this appears of limited application towards the meso-levels and lower, especially when design activities are considered. To remedy, the authors want to propose a **meso-level** definition for “circular aviation” based on an interpretation of the EFM definition (Ellen Macarthur Foundation, 2021), rather than on the ISO definition. Ideally, the definition should be formulated as:

Circular Aviation is defined as a systems design framework within which life cycle engineering methods and tools are used to retain the value embedded in aviation products and services, specifically aircraft, without loss.

It must be highlighted that, reflecting previous considerations, this proposed definition identifies an ideal state, that is physically impossible, as losses are present in every (sub)system of focus which is not isolated (Valero & Valero, 2019). As aviation is not an isolated system, but it interacts with the ATS, aviation on its own can never be fully circular. Many decisions taken in other parts/levels of the air transport system may have an impact on aviation, and specifically on the aircraft design. For example, decisions made at airport and airline business model level result in several economic, social, performance and environmental considerations (ACARE, 2022); the majority of those are beyond the area of influence of the aircraft engineer/designer, who mainly looks at performance and circularity, followed by economic and environmental considerations, and last societal aspects. Providing definitions for each level (and potentially per domain) enables to retain all systemic aspects in an overarching assessment of sustainability at macro-level, while enabling designers to make the best possible choices within their area of influence based on adapted information.

Thus, the ideal definition given of circular aviation is reformulated towards a more physically realistic definition, as follows:

Circular Aviation is defined as a systems design framework within which life cycle engineering methods and tools are used to retain as much as possible the value embedded in aviation products and services, specifically aircraft, while minimising its loss.

This second -physically sound- definition is retained in the remaining of this work.

From this definition, micro-level definitions for specific aviation assets can be derived, for example:

A circular aircraft is defined as an air vehicle which is designed, manufactured and operated throughout its entire life cycle according to circular economy principles within a circular aviation system.

Or:

A circular airframe component is a structural element which belongs to the circular aircraft.

The proposed definition aims to provide a clear framework to guide the industry towards a common language regarding CE within the ATS; this shall reduce the risk of misinterpretations and ensure a more systemic and comprehensive application of CE principles across all three dimensions (environmental, economic and social).

The hierarchy first presented in Figure 4 is now evolving in the breakdown shown in Figure 5, which mirrors ATS and its subsystems to the definitions proposed in this section.

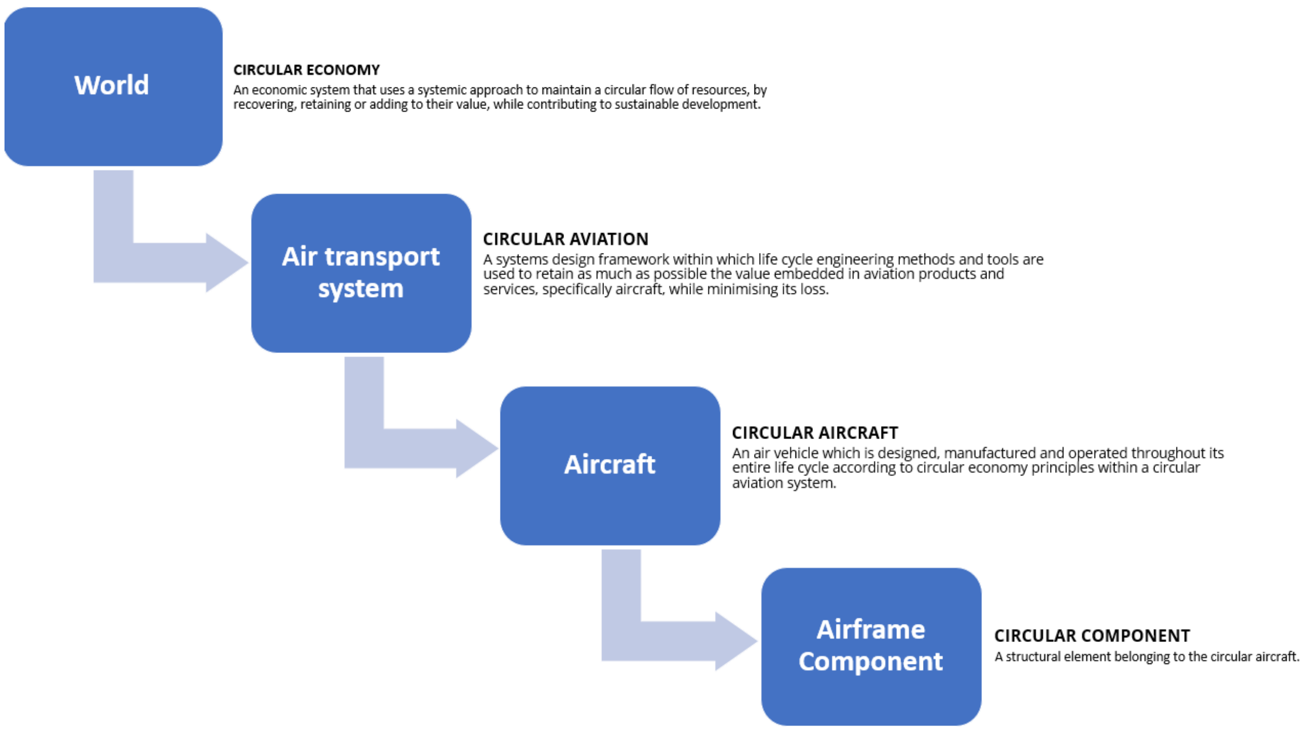

Figure 5. Breakdown of the Definitions of Circular Economy from Air Transport System to Airframe Component Level

5.4 Circular Economy Strategies for Aviation

To implement CE principles in the ATS (and parts thereof, including aviation), the definitions provided in the previous section are only the foundation. Two other elements are essential: implementation strategies and an assessment method (Saidani et al., 2017). For CE, the resource management actions presented in the ISO standard, and more commonly known R-approaches, provide the backbone for the implementation strategy of CE principles in every sector. This section presents an interpretation of CE strategies for aviation, and more generally for ATS. Such interpretation will then provide the foundation for an approach for the assessment of circularity performance in ATS and its subsystems, which is not presented as part of this work. In order to provide a link between CE and aviation, the use of correct terminology in both domains is essential, even when it results in aviation technical jargon.

As indicated previously, a large number of strategies (insofar known as R-approaches) has been identified as already applied or potentially applicable to support the implementation CE in various sectors. This is true also for ATS and aviation, as shown in Table 3. What also appears from Table 3 is that CE approaches presented in ATS or aviation literature, are not always defined correctly or coherently with CE terminology, not only according to the recent ISO standard, but also to previous R-approaches classifications, such as (European Commission, 2020a).

This confirms the importance to create a clear understanding of the ISO actions in relation to ATS and aviation practices and products. Such understanding is presented in Table 4 for ATS and aviation in general, and in Table 5 specifically for aircraft and aircraft components. The content of the tables is the novel contribution of the authors, developed from general aviation knowledge and the expertise of the authors. The tables include commentaries and examples by the authors and a summary of the tables is described in the following paragraphs.

Following the ISO classification, the first four actions (from Refuse to Reduce) are already in line and compatible with the terminology and understanding within the sector. Repair includes activities which ensure the product meets its design service life, such as inspections and tasks from the aircraft maintenance and repair manual. Re-use focuses on enabling multiple loops of usage of the product, within its service life and towards extensions of the service life. Refurbishment and Remanufacture are similar in the way that they both require additional (industrial) processes on the product, but while Refurbishment aims at improving the product for the expected design life (with no significant improvements in its performance), Remanufacture extends the service life and the performance of the product. In this sense, Refurbishment connects to maintenance activities focusing at maintaining the product, while Remanufacture aims at activities which result in the product to be "like-new", but also "same-as-when-new" or "better-than-when-new" (ISO, 2024b) (3.5.21 p. 12). With this meaning, upgrading the cabin interior of an existing aircraft is an example of Refurbishment, while an engine upgrade can be an example of Remanufacture. Repurpose signals the boundary between the system in focus (and its loops) and other systems and/or different loops; this translates in the boundary between ATS and, for example, the Electronic and Electric system or between aviation and automotive. In the case of an aircraft, it represents the limit of the airworthiness certification; no aircraft (nor parts thereof) is certified to fly beyond airworthiness. Cascade connects to materials, and replaces terminology as upgrading (or upcycling) and downgrading (or downcycling). This latter terminology tends to imply a judgment on the subsequent use of the material in comparison with the original product; what can be seen as a downgrading from the aviation perspective, may appear as an upgrading in a different sector. Cascade refers only to the retainment of the materials in any loop possible. Recycle also only refers to materials; products are not recycled (a common misinterpretation). Recover energy focuses on energy production from recovered resources and last Re-mine connects to practices as urban mining, which are not yet structurally organised in the ATS or aviation.

By comparing the two categorizations of ISO actions and European R-approaches (as presented in Table 3), two aspects are worthwhile highlighting. First, the ISO actions expand on previous attempts of standardization of CE strategies, for example (European Commission, 2020a), especially by including the Recover Energy, and by openly identifying strategies specific for materials (e.g. Re-mine and Circular sourcing).

A second aspect is the change in order of the ISO actions Repair and Re-use, compared to the Re-use and Repair of the EU classification (European Commission, 2020a). Given the (long) service life of ATS and aviation products, the European classification appeared unclear as to whether Repair was applicable to practices during the service life (before Re-use) or whether Repair was an enabler for the Re-use of the product. The ISO classification clears this, and it also helps to distinguish aviation activities grouped under the maintenance, repair and overhaul (MRO) umbrella, which, from a CE perspective, are spread across several actions. For example, airframe repairs may be performed directly on the aircraft, or at times components are removed from the aircraft to be repaired. In this case, to avoid extending the downtime of the aircraft, a second (new or used) component is installed as replacement. This is seen as repair from the aviation MRO perspective, but it could fit either as Repair (of the aircraft) or as Refurbishment (both of the aircraft and the component) or as Remanufacturing (depending on the actual work performed on the component).

The actions (strategies) now are specific, focused and tangible for applications in aviation. On the other hand, it appears clearly that they intertwine qualitative and quantitative aspects, and also require connections to other systems (sectors) to be effective. It is also evident that the strategies (or actions) are connected with each other, and this interconnection varies according to the product or system in focus considered. In this sense, statements equating CE to one of the actions (common in the aviation sector) are incorrect and misleading. It is true that not all actions (or R-approaches) are applicable to every product or part of a system. This inapplicability does not imply that such product or system is less circular than one in which all actions are applicable. On the other hand, adopting strategies from few (or even only one) actions without a holistic view limits the chances for a product to be circular.

For an effective implementation of CE in aviation (and ATS), it is not sufficient to connect with the strategies, but it is also necessary to measure this connection, to perform an assessment of the circularity performance of a product (in line with the ISO terminology). Having connected aspects, practices and characteristics of aviation (and ATS) to CE actions, will allow to list (quantitative and qualitative) indicators for each aspect, practice and characteristic. Those indicators can then be evaluated and measured individually and last combined in the circularity performance of the aviation product (e.g. aircraft). The development of such measurement and assessment process lies beyond the scope of the present work, and it is under development, based on the theoretical content presented in this work.

Table 4. Resource Management Actions from ISO 59004:2024 [ISO], with Commentaries and Examples for the Air Transport System and Aviation

Action [ISO]	**Description [ISO]**	**Commentary**	**Examples for ATS and aviation**
Refuse	Make solutions redundant by abandoning its function or by offering the same function with a radically different solution.	This action focuses on decisions and choices taken when the product is being conceived or at early design stages.	• Avoid building a new airport or runaway. • Reschedule flights with very low occupancy. • Transition to electronic documentation and communication. • Remove in-flight entertainment system.
Rethink	Reconsider design and manufacturing decisions. Make service use more intensive (e.g. through sharing or by putting multi-functional products on the market).	This action emphasises decisions made regarding the design and manufacturing processes.	• Adjust flight routes to optimize fuel efficiency and reduce emissions. • Adapt airport layouts to maximize natural lighting and reduce energy consumption.
Circular sourcing	Select recovered or renewable, sustainably sourced or produced resources. Use resources that can be easily recycled or returned to the biosphere. Reconsider formulations.	This action is specifically about materials' choices.	• Introducing eco-friendly catering options with locally sourced ingredients. • Use bio-based or recycled materials.
Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	This action focuses on the amount of resources used for the production, but also for the operation of products. As such it covers both design, in-flight and on-ground activities.	• Minimise water consumption in airport facilities by using collected rain water. • Implement waste reduction programs for in-flight and airport operations. • Implement fuel-efficient practices during taxiing and take-off. • Reduce fuel consumption with more efficient engines.
Repair	Restore a defective or damaged product so that it can be used in its original function.	This action regards maintenance on the product itself meant to ensure the product meets its design service life. The repair does not extend the product service life.	• Repair runway surfaces and airport infrastructure. • Repair ground support vehicles and equipment. • Regular inspections of aircraft components, engines and avionics systems.
Re-use	Re-use a discarded product which is still in working condition and fulfils its original function.	This action focuses on the product at the end of its (design) service life.	• Reuse in-flight service items, such as trays, cutlery, and blankets. • Implement reusable packaging solutions for cargo and baggage handling. • Components from retired aircraft to the spare parts market.
Refurbish	Restore to a useful condition during expected service life with similar quality and performance characteristics.	This action focuses on modifications made to maintain or improve a product during its service life, which have the potential to extend such service life.	• Install renewable energy generators at airports, such as solar panels. • Refurbish airport lounges and waiting areas with eco-friendly amenities. • Install a different engine on an existing aircraft.

Remanufacture	Return an item, through an industrial process, to a like-new condition from both a quality and performance perspective.	This action focuses on modifications which can give products a service life extension of (minimum) the same duration as the original design service life.	• Remanufacture aircraft engines. • Update air traffic control systems to improve efficiency and reduce delays.
Repurpose	Adapt a product or its parts for use in a different function than it was originally intended without making major modifications to its physical or chemical structure.	This action will shift products across different parts of ATS or aviation or even outside of the sector.	• Use retired aircraft as training simulators for pilot and crew training. • Repurpose airport cargo containers for storage applications. • Transform old airport signage into educational displays and exhibits.
Cascade	Shift recovered materials from one loop to another to optimize feedstock flows through additional cycles, often with decreasing quality and quantity.	This action focuses on materials only. It can be linked with recycle, but it could also cover manufacturing waste used in the manufacturing of a different product.	• Use composite materials recovered from aircraft for products in automotive. • Mix used 3D printing metal powder with virgin powder.
Recycle	Recover and process material to obtain the same (high grade) or lower (low grade) quality through activities such as recovery, collection, transport, sorting, cleaning and re-processing.	This action focuses on materials only and it involves industrial processes at material level.	• Recycle materials from decommissioned aircraft to manufacture new aircraft parts. • Implement recycling programs for in-flight waste such as plastics and paper. • Incorporate recycled materials into airport construction and renovation projects.
Recover energy	Generate useful energy from recovered resources.	This action requires the collaboration of ATS or aviation with energy sector.	• Local energy generation using airport waste. • Recycle used cooking oils from in-flight meals for biofuel production.
Re-mine	Mining or extraction from landfills and waste plants can be possible in some cases if mining or extraction activities are sustainably managed.	This action covers activities such as urban mining; in the case of aviation, this should refer to airplane boneyards, such as the Mojave Air and Space Port (MHV) in California (USA).	• Gather materials from decommissioned aircraft parked in boneyards. • Recover construction materials, such as concrete and steel.

6. CONCLUSIONS AND FUTURE WORK

As first foundational step towards a framework linking circular economy and aviation, this work has proposed definitions and interpretations of circular economy and related concepts for aviation, seen as a subsystem of the air transport system. The following definitions are presented:

- For the air transport system:

A circular air transport system is an economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development of the air transport system.

- For aviation:

Circular Aviation is defined as a systems design framework within which life cycle engineering methods and tools are used to retain as much as possible the value embedded in aviation products and services, specifically aircraft, while minimising its loss.

- For aircraft:

A circular aircraft is defined as an air vehicle which is designed, manufactured and operated throughout its entire life cycle according to circular economy principles within a circular aviation system.

- For airframe (aircraft) components:

A circular airframe component is a structural element which belongs to the circular aircraft.

Interpretations of the resource management actions (which reflect circular strategies and have been insofar known as R-approaches) in relation to aviation have also been presented; in particular, actions are put in relation to aircraft and aircraft components design aspects.

The structured interpretation of the resource management actions and the conceptual definitions proposed in this study represent an initial step toward developing a comprehensive reference framework for circular economy practices in the air transport system. While the current focus is on establishing the theoretical foundation, future research shall build upon this work to provide actionable and practical guidance. The main priority of future work is to develop an assessment methodology for the circularity performance of ATS. Following steps will include integrating case studies, stakeholder inputs, and other methodologies to create a robust framework that can guide the industry in identifying, adopting, and implementing circular strategies effectively.

The definitions and interpretations included in this work are to be considered proposals from the authors to connect aviation to circular economy more clearly and effectively. While various strategies already implemented in aviation align with certain circular strategies (e.g. minimizing weight or improving fuel efficiency), these strategies have been often driven by economic motives rather than a holistic circular approach. The implementation of isolated strategies does not necessarily translate to a genuinely systemic approach to circular economy (or sustainability); rather, it may risk being a superficial application of circular principles, potentially bordering on greenwashing. A systemic view of circular economy, addressing its three dimensions—environmental, economic, and social—is essential for its effective implementation in the air transport system.

Given that circular economy in aviation is an emerging field, the groundwork for future, transformative and innovative, research and practice has been laid in this study. Future research is expected to build upon this foundation to investigate possible areas for advancing the implementation of circular economy in aviation; possible directions could be, among others: the implementation of modular design principles to enable the reuse and repurposing of aircraft components, the development of self-healing materials to enhance durability, the establishment of closed-loop systems for materials recycling, the creation of business models to support circular supply chains across the industry, the exploration of sustainable manufacturing (e.g. additive manufacturing techniques) for aircraft part production, the uptake of renewable energy sources into aviation operations, and the design of more efficient end-of-life management strategies for aviation products.

The proposed definitions provide a framework to guide the industry, reducing the risk of misinterpretations and greenwashing, while ensuring a more consistent and comprehensive application of circular strategies. The authors are open for engaging in constructive discussions about the proposed definitions and interpretations. It is important to highlight that the newly-released ISO standard for circular economy is and will remain the primary source of terminology for circular economy concepts. The authors urge colleagues in the aviation sector to inform themselves concerning the most recent and standardised terminology. This terminology is expected to undergo a transition phase of coexistence with older definitions. Given the fragmentation around the concept of circular economy present in the aviation sector highlighted in this work, the authors expect that the transition phase will be significantly longer; they recommend that relevant high-level stakeholders (e.g. ICAO, ACARE, major OEMs) adopt the newly released definitions as soon as possible in all relevant activities and documentations.

The proposed definitions and interpretations are meant to be the foundation for several research directions, all contributing to the overarching goal of implementing of circular economy in the air transport system, as mentioned by the ACARE: "By 2050, achieve climate neutral1 aviation based on validated and globally accepted tools and models, in the full sustainability context (environmental, economic and societal) in line with United Nations (UN) Sustainable Development Goals (SDGs), integrating the circular economy concept to be an equitable contributor, with other transport modes, to fully climate neutral mobility" (ACARE, 2022). As first step, the development of an assessment method to measure the circularity performance of aviation products is the focus of upcoming work from this group of authors; such circularity performance assessment will be developed initially for airframe components and for aircraft.

Next, addressing the social and economic aspects missing from the current circular economy narrative within the aviation sector. Both the current work and the future work connect to broader collaborative efforts among academia, researchers, industry stakeholders, regulatory bodies, and standardization organizations to develop specialized tools and methodologies to promote circular economy and sustainability in the air transport industry effectively. In this sense, it is essential to recognize that an assessment of the circularity performance should and will involve connections across the various levels of aviation (aircraft, components) and of aviation with the other pillars of the air transport system; last, connections with other sectors (including different transportation modes) should and will be included when relevant.

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Ligeia Paletti: Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization.
Dionysios Markatos: Conceptualization, methodology, resources, writing—review and editing.
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DECLARATIONS

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