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RESEARCH ARTICLE

Assessing Circularity Performance of Aircraft Component Design Based on ISO 59004:2024

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Abstract

Since the European Green Deal, circular economy and its strategies have gained interest across various industrial sectors, as a means for embedding sustainability in products and systems - including in the aviation sector. For the implementation of circular strategies to be successful, monitoring their effectiveness and progress is necessary. Though several methodologies, metrics and indicators to assess circularity have been developed, their application is fragmented and unstandardised across all sectors, thus including aviation. This work proposes a methodology to evaluate the circularity performance applied specifically to aircraft or components thereof; the general methodology could be applied to other products. As part of the methodology, a framework is developed which can account for the multi-level character of circular economy; within this framework, aviation-related indicators are put in relation with the resource management actions from ISO59004:2024. Such a framework can fulfil both the need to assess how much circular economy principles are embedded in aviation and the necessity to provide engineers with guidelines to implement circular economy principles in aviation, and in aircraft design specifically.

Keywords Circular Economy · Circularity · Circularity Performance · Assessment Methodology · Aviation · Aircraft Design

1. Introduction

The aviation sector is investigating numerous, technological and non-technological solutions to enable the transition to a sustainable aviation (ACARE, 2022; Clean Aviation Joint Undertaking and Single European Sky ATM Research Joint Undertaking, 2025). Among the non-technical solutions, the concept of circular economy (CE) is gaining prominence as a means towards sustainability, with its strategies being implemented in several initiatives (European Commission, 2023). Circular economy strategies are recognised in the sector as enablers to a more resilient and competitive aviation; beyond reducing the environmental impact of aviation, circular strategies can mitigate risks in the supply chain, ensuring materials and components needed for the current fleet and for the future production (ICAO, 2025).

As Wautelet shows (Wautelet, 2018), the concept of CE has been around for over 50 years; CE has then achieved popularity during the second decade of the current century with its inclusion in the European Green Deal (European Commission, 2019). Despite this political visibility, the concept of CE has remained broad and, until recently, has lacked a precise definition; the Green Deal and its implementing directives do not provide a definition of this concept (Völker et al., 2020). Insofar, one of the main sources of information regarding CE has been the Ellen Macarthur Foundation (Ellen Macarthur Foundation); its definition describes CE as: “A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. This is based on three principles, driven by design: eliminate waste and pollution,

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circulate products and materials (at their highest value), and regenerate nature". On the other hand, many definitions and interpretations of CE are present in research literature and general publications; two publications (first in 2017 and then in 2023) present, respectively, 114 and 221 definitions of CE (Kirchherr et al., 2017; Kirchherr et al., 2023). This context clearly highlights the need for standardization, which culminated in May 2024 with the release of the ISO standards for CE (International Organization for Standardization [ISO], 2024a, 2024b). In those, CE 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*".

The ISO standards also harmonise CE strategies, which can be considered as the practical actions to implement CE in various contexts and levels (from global - national, to micro - product). CE strategies had been insofar known as R-approaches; a variety of R-approaches, with different definitions, is present in the literature (European Commission, 2020; Kirchherr et al., 2023; Tsironis et al., 2024). The introduction of the ISO standard redefines the CE strategies as "Resource Management Actions" (ISO, 2024b) (RMAs) and presents detailed definitions for each action. All ISO definitions are adopted by the authors further in the current work.

In the aviation sector, the expressions "circular economy" or "circular aviation" have started to appear more frequently in sector-related publications (either strategic or research); despite this, there are no definitions that are consistently used within the sector. Most frequent is the reference to the Ellen Macarthur Foundation, followed by a link to the European Green Deal, or no further clarification about the concept provided. No commonly agreed definition or reference of CE is available from the major organisations of the sector; also, there are no consistent interpretations of the CE strategies, which are almost exclusively linked to recycling or waste management (Paletti et al., 2025). This generates confusion regarding the concept itself, allows for misinterpretations (potentially resulting in greenwashing) and prevents the application of CE strategies effectively. To resolve the issue of a CE definition for the aviation sector, the authors have proposed definitions for CE in the air transport system and for CE in aviation (Paletti et al., 2025):

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.

And:

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.

In order to suggest an alignment between the air transport system context, and the RMAs defined by ISO, the authors have also proposed interpretations of the RMAs for the air transport system and aviation (Paletti et al., 2025). This current work builds on that previous work for setting the basis for a future framework to quantify the circularity performance of aviation, with focus on aircraft and components thereof.

Circularity is another term associated with CE, which also has been subject to various interpretations. Especially within engineering fields (Hassan & Faggian, 2023), circularity is presented as synonymous of CE, as a shorter (and seemingly clearer) way to express the concept. The correct interpretation of circularity, as a property to be measured and assessed, is present in the more theoretical CE literature (Holly et al., 2024; Linder et al., 2017). In aviation-related sources, the concept of circularity reflects a similar unclarity. Circularity is commonly used as a synonymous of CE; when it is considered as the property to be evaluated, its determination does not reflect the systemic character of CE, being limited to one aspect linked to CE or to a qualitative statement (European Commission, 2023; Paletti et al., 2025). Such situation is being rectified by the ISO definition of circularity (ISO, 2024b), as "*degree of alignment with the principles for a CE*". This ISO definition is adopted from the authors and used in this work.

The combination of unclarity regarding CE, its strategies and circularity, and (until the release of the ISO standards in 2024) of the lack of harmonisation for the definitions explains the flourishing of proposals of indicators and methods for measuring or assessing CE; those range from global-national level approaches, industry-level meso-approaches, to product-level micro-approaches. Such classification mirrors the systemic character of CE, but without yet converging to a standardised systemic assessment method (nor to a common understanding of macro, meso and micro levels). The lack of a standardised process for circularity assessment prevents the evaluation of the impact of implementing CE strategies, in any industry, including aviation.

1.1. Aim and outline of the paper

Based on the previous considerations, the objective of this research is to develop a theoretically grounded and practically applicable methodology to assess the circularity performance of aviation, with a focus on aircraft and aircraft components. In doing so, this work addresses the following research objectives:

- Measure circularity, as defined in the ISO 59004:2024, for aviation assets;
- Translate systemic CE principles and RMAs into indicators that are meaningful for aircraft and aircraft component, specifically for their design.

Despite the increasing interest in CE within the aviation sector (Rodrigues Dias et al., 2022), no harmonised methodology currently exists to assess circularity performance in a way that reflects the systemic character of CE, aligns with the ISO 59004:2024, and is applicable at aircraft and component design. Existing approaches are either qualitative, limited to end-of-life aspects, or rely on environmental impact metrics such as LCA, which do not capture circularity. To address this gap, this work makes the following original contributions:

- It proposes a novel, ISO-aligned, framework to assess circularity performance in aviation, explicitly linking the ISO 59004:2024 RMAs to aircraft and component design characteristics;
- It develops an indicator-based methodology that combines top-down (RMA-driven) and bottom-up (design-level indicators) approaches, enabling a circularity assessment for the entire life cycle;
- It introduces a single-score circularity performance metric (CIRC), while preserving transparency at the level of individual strategies and indicators;
- It demonstrates the applicability of the framework through a worked example at aircraft component level, highlighting how design choices influence circularity performance.

To the authors' best knowledge, this is the first study to provide a comprehensive, design-oriented circularity assessment framework specifically tailored to aviation and grounded in the ISO CE standards.

To lay the foundations for such a framework, the current work is structured as follows: first, an overview of circularity indicators and assessments is provided, both from general CE literature (Section 2) and specifically from aviation sources (Section 2.1); an overview of existing assessment frameworks is given in Section 2.2. Based on previous work on the definition of circular aviation and on the interpretations of the RMAs by the authors (Paletti et al., 2025), a framework, based on indicators, to assess the circularity performance in aviation is proposed (Section 3). Such framework builds on various considerations from non-aviation knowledge of indicators and methodologies to assess circularity. The practical application of this framework is exemplified through a worked example involving an aircraft component (Section 4). This worked example aims to showcase the feasibility and effectiveness of the framework to support the assessment of circularity performance in aviation; the worked example also wants to provide insights on the potential of the framework to incorporate CE principles within the design process of aircraft and components thereof. Conclusions and future work are given in Section 5.

2. State of art of assessing the circular economy

The necessity for measuring CE became apparent as soon as CE was instated as a pillar of the European Green Deal (European Commission, 2018). This originated numerous European initiatives, at institutional level or by consultancies or academia, whose outcome has been a flourishing of indicators and metrics (Circle Economy Foundation; EEA; *European Circular Economy Stakeholder Platform;* European Union). Next to online resources, a broad literature regarding metrics and indicators for CE is available. Some metrics and indicators have a broad scope, with focus at global or national level or at specific sectors (Circle Economy Foundation; Holly et al., 2024; Potting et al., 2017); some focus on supply chains (Calzolari et al., 2022; Di Maio et al., 2017; Vinante et al., 2021); others target product -micro- level (Kristensen & Mosgaard, 2020). In the large majority of the cases, especially in initiatives related to the European Green Deal, the focus is on measuring resources in the technical cycle only (Moraga et al., 2019; Völker et al., 2020): material flows, mass-based recycling and other end of life streams (for example, the Material Circularity Index (Ellen Macarthur Foundation) and (Corona et al., 2019)). Longevity of resources and products (Figge et al., 2018) or economic value and its retention (Di Maio et al., 2017; Linder et al., 2017) have been seldom considered.

Other proposed circularity indicators focus on the environmental impact of CE strategies, connecting with life cycle assessment (LCA) (Brändström & Saidani, 2022; Haupt & Hellweg, 2019; Haupt & Zschokke, 2017; Picatoste et al., 2022; Rigamonti & Mancini, 2021).

LCA is an ISO standardised method (ISO, 2006) to assess the environmental impact of products/services/systems; in this sense, LCA is often used as an indirect, sector-independent metric for the CE; however, its primary purpose is to assess environmental impacts. The connection between LCA and CE has been investigated primarily with regard to the ability of LCA to assess the environmental impact of end of life strategies (Haupt & Hellweg, 2019; Paletti et al., 2025); although LCA is able to capture such impact, there is no unified approach to model them, for example regarding appropriate allocation methods (Eltohamy et al., 2024). Beyond this specific aspect, LCA does not provide a complete picture of CE (see "Product circularity performance provides additional information than a LCA by focusing on possible ways and mechanisms to close the loops" (Saidani et al., 2017a)). The inputs of LCA are material and energy flows and its outcomes (i.e. impact categories in EF3.1 and ReCiPe) assess impacts on climate, environment, human health and biodiversity. As LCA does not account for economic or social impacts, which are part of the concept of CE ,it is plausible that a combination of LCA, LCCA and S-LCA can assess CE. Examples in this direction are the indicator $CI_{LCA-\,LCC-\,CA}$ (Arias et al., 2024) and the C-LCSA (Luthin et al., 2024); both approaches add a circularity indicator as an additional and separate element to LCA, LCC and S-LCA. Two limitations of this line of research need to be mentioned; first, the current formulation of LCC is based on linear economic models and does not include circular economy business models or indicators. In addition, this line of research appears to separate environmental impact from circularity. As also stated elsewhere (Haupt & Hellweg, 2019), circularity is not equivalent to environmental sustainability, but neither are the two concepts completely disconnected. The CE ISO 59004:2024 standard clarifies that LCA is only one of the methods, which can be used to provide information for a circularity performance measurement; this clarifies that LCA alone is not a measure of CE. This position is shared by the authors and contribute to development of the framework presented in this current work.

The inability of capturing the systemic character of CE is an outcome of many overviews of CE indicators and metrics. Saidani provides one of the most comprehensive review of CE indicators up to 2019 (Saidani et al., 2019). Parchomenko collects 63 metrics (Parchomenko et al., 2019), while De Pascale identifies 61 (Pascale et al., 2021). Other overviews are (Corona et al., 2019; Sassanelli et al., 2019; Völker et al., 2020). All those point out clearly how existing indicators or assessment methods do not cover all CE principles or its systemic character. Moraga shows visually that even the indicators proposed by the European Commission do not cover the entire scope of CE (Moraga et al., 2019). A visual summary of the multi-scale character of CE indicators provided by the European Commission shows also the unbalance existing across indicators and metrics (European Commission). In many attempts of developing indicators and metrics, the different systemic levels of CE appear intertwined. A connected issue is the lack of critical discussions regarding how the proposed indicators and metrics actually represent or measure CE and its principles; one exception is presented by Cayzer (Cayzer et al., 2017). For example, the unrealistic variety of indicators and metrics has generated many attempts of classification, according to various criteria (Saidani et al., 2019): level, origin, strategy or principle, applicability, etc. Such overviews and taxonomies are developed primarily to provide guidance for selecting appropriate indicators depending on the use-case considered; they do not sufficiently provide critical investigation concerning whether the indicators are indeed effective in assessing circularity. Also, they do not provide useful insight to designers willing to incorporate circular strategies in their designs (Boorsma et al., 2022). To overcome those issues, few studies attempt to create an overarching methodology, covering all CE strategies or principles towards a more systemic approach (e.g. (Boorsma et al., 2022; Elia et al., 2017)). The current work connects to this research line and aims to strengthen the systemic approach towards the correct characterisation of CE.

2.1. State of art of assessing the circular economy in aviation

To situate the present work and highlight the research gap, this section reviews existing approaches for assessing circular economy performance in aviation, identifying their strengths and limitations in the context of aircraft and aircraft components design.

Despite the interest of the aviation sector for CE, only a limited number of studies measuring or assessing CE or circularity exist in the literature to the authors best knowledge. Aligning with the most common narrative of CE in aviation, measuring circularity has focused on end-of-life aspects only: airport waste (*TULIPS)* or aircraft material and recycling rates (Bachmann et al., 2021; Coskun et al., 2023; EASA; *RECRATE)*. In other cases, measuring circularity is directly associated with LCA (*SUSTAINair)*. While the application of LCA on aircraft and other aviation systems is becoming more widespread, it must be highlighted that LCA focuses on environmental impacts rather than circularity performance, as mentioned in section 2.1. Consequently, LCA does not fully address the operationalisation of circular economy principles in aviation, highlighting the need for a dedicated circularity assessment framework as proposed in this work. Connecting to the previous considerations regarding LCA and end of life, discussions about circularity in aviation tend to focus on how to integrate end of life aspects in LCA (European Commission; Reichert et al.).

Examples of attempted quantification of circularity in aviation are extremely limited. In the majority of the examples, circularity is qualitatively assessed; the adoption of even one (CE) strategy (e.g., recycled materials or additive manufacturing) is regarded as a direct or indirect contribution to enhancing circularity (Clean Aviation Joint Undertaking; Clean Aviation Joint Undertaking; Clean Aviation Joint Undertaking, 2023).

Connecting to this state of art, previous work from some of the authors (Filippatos A. et al., 2024; Markatos & Pantelakis, 2022) evaluates circularity (referred as CIRC) with one quantification indicator, as a starting point, specific for the use case considered: for example, the percentage of components which can be reused or recycled, or the loss of specific stiffness of the material. Differently than all other existing work in aviation, this research line emphasizes current limitations of utilising only one indicator to measure circularity; the approach selected in those previous works was considered a beginning to include a quantification of circularity in a broader sustainability assessment, which this work builds on.

To summarise, despite the variety of indicators and metrics already available to quantify circularity (setting aside their limitations), to the best knowledge of the authors, none of them has been consistently applied to any aviation asset or aircraft component. A methodology for assessing the circularity performance of the air transport system, aviation and its subsystems appears necessary.

2.2. Characteristics of existing frameworks for the assessment of circular economy

Establishing definitions is the essential foundation in order to define and develop any measurement framework; it must be clear what properties or qualities of a specific phenomenon or concept need to be measured, before deciding on the how (i.e. indicators and metrics) (Moraga et al., 2019). The definition for circular aviation presented by the authors (Paletti et al., 2025) allows to identify what of the system in focus “aviation” or “aircraft” needs to be assessed. It also allows to place the system in focus in a systemic hierarchy. This system hierarchy is necessary as it establishes how the circularity performance depends on the relationships with the adjacent levels, the global system and other adjacent systems which are linked with the system in focus. In an ideal framework, all indicators at all levels are measured and then merged, towards a final overall circularity performance. Saidani mentions: “Using a lifecycle thinking approach (i.e. pre-life, life and end-of-life stages are considered), data collection and construction are performed regarding not only product features but also markets, business models, existing collaborations, or regulations related to the product” (Saidani et al., 2017a). Moraga also introduces the idea of measuring indicators at various levels, as at each level the systemic character (and thus the life cycle thinking) varies (Moraga et al., 2019). At the lowest levels there is limited possibility for lifecycle thinking; thus, the perception of no systemic approach reflected in the implementation of single indicators (which do not account for systemic thinking or have it simplified and codified in workable actions) in the examples mentioned in Section 2.1, which focus on aircraft component detailed design level.

The multi-level character of CE may appear to individual experts (engaged in one area of expertise within one level) as an excessive mix of indicators, including indicators which are not applicable for the level considered. Still, also within one level, multiple indicators can be identified, which cover various aspects of the system in focus, risking similar confusion as for the inclusion of indicators from multiple levels. Holly (Holly et al., 2024) presents an approach for the evaluation of circularity based on questions, grouped for areas of competence, targeting a large number of indicators. This approach allows the user to provide answers (quantitative or qualitative) only to questions within one’s field of competence or expertise. It is a separate task to merge the answers towards an overall score. This captures the systemic character of CE, while engaging experts only within specific areas of competence, thus capturing the most appropriate information at the source. Though the work of Holly focuses to measure circularity within one company, the approach can be extrapolated towards sector or towards product development (as performed in a team environment). Holly's approach can be seen as a combination of top-down and bottom-up. The top-down character is reflected by deconstructing the system in focus across levels and, within each level, different relevant aspects. In the context of a CE assessment framework, those aspects could connect to CE strategies as previous works propose (Moraga et al., 2019; Niero & Kalbar, 2019; Pauliuk, 2018). Pauliuk proposes to develop a derivation of CE indicators from the British Standard BS 8001:2017 (a predecessor of ISO standard), by linking the standard to existing tools for material flows and environmental and social impacts. Similarly, Moraga proposes to measure the impact of each CE strategy separately. The bottom-up character is represented by identifying indicators which are as close as possible to the decision-maker(s). Similar approaches are proposed also by (Pollard et al., 2022; Saidani et al., 2017a). Those are used as inspiration for the framework presented in this work, as a combination of top-down and bottom-up proves able to capture the complexity of CE (Saidani et al., 2017b).

One last consideration regarding the determination of the circularity performance in a top-down and bottom-up approach needs to be highlighted. Based on the literature review presented earlier in this section, there is a general preference towards single-score indicators for circularity performance. First of all, single-score indicators are considered the easiest solution in terms of communicating results. Saidani (Saidani et al., 2017a) identifies requirements for circularity measurement; among others, such circularity indicator framework needs to be holistic (encompassing life cycle and systems thinking, and multi-levels), modular (to be linked to existing methods and tools) and provide a single indicator to be as informative as possible. Also Cayzer (Cayzer et al., 2017) proposes a single-score indicator, resulting from the aggregation of various indicators and covering all life cycle phases, as preferable for communication and clarity purposes. A self-declared limitation of this approach is of hiding the complexity (and details) of CE, thus potentially misleading results, as those could be context-based or dependent on other assumptions.

3. A proposal for assessing circularity performance in aviation

The context outlined in Sections 2.1 and 2.2 explicates the need for a methodology aimed at determining the circularity performance in aviation. As this study adopts the ISO definitions, such determination involves a measuring phase and an assessment phase for a system in focus, within predetermined boundaries. In this section, a general methodology for aviation is presented and refined for an aircraft component as system in focus, which is used a worked example in Section 4. This section explains the rationale for setting up the methodology as a framework and for the specific choices made during the development. Finally, it presents the concept of the framework itself. The general methodology can be adapted to other sectors and products.

The terminology used in this work follows Moraga (Moraga et al., 2019) and the ISO standard (ISO, 2024b); such a terminology is reported and elaborated in the remaining of this paragraph, to ensure unambiguity. The circularity performance can be evaluated by combining measurement processes and assessments. Both measurements and assessments can be performed by one or more methodologies (e.g. LCA). Methodologies are composed of methods (e.g. LCA impact categories); in turn, methods include models, tools, and indicators which are relevant, in this case, for circularity. A model is a mathematical description of calculating an indicator; a model can be presented through a tool. An indicator is a variable or parameter that provide quantitative and/or qualitative information about circularity; an indicator may also be the result of the combined information of quantitative and qualitative data (Saidani et al., 2019). In this work, this definition of indicator is used.

The methodology proposed in this work connects to previous work by some of the authors towards the development of a Sustainability Index (Filippatos A. et al., 2024; Markatos & Pantelakis, 2022). In that research, a multi-criteria decision making model is proposed to assess the sustainability of an engineering product (aerospace or other), in terms of performance, costs, environmental impact, social impact, and circularity. The current work focuses on the determination of the circularity metric, identified as CIRC in the Sustainability Index and in this current work.

As CIRC can be identified with the circularity performance described by ISO, the aim of this work is to propose a methodology for the determination and quantification of CIRC; besides contributing to the Sustainability Index, the methodology can also be used as stand-alone assessment of the circularity performance. The methodology envisioned consists of a framework potentially able to capture the complexity and the systemic character of CE.

First of all, the CIRC framework should identify the system in focus and its boundaries; for this work, the system in focus is an aircraft and exclusively design aspects the aircraft (and components thereof) are included. Other aspects (e.g. business models or regulations) do influence the system in focus, but they are beyond the decision-making possible during the aircraft design process. While the current work focuses only at the aircraft-level, in future work the multi-level character of CE will be considered, including other aspects such as social and economic ones.

For the top-down contribution, the proposed framework aligns with the ISO RMAs, to support standardisation of CE and to build on previous work by the authors (Paletti et al., 2025), and with previous work (Moraga et al., 2019; Niero & Kalbar, 2019; Pauliuk, 2018). Each RMA can be expressed and described for the system in focus, by selecting relevant characteristics of the system considered, and by matching those characteristics to indicators (bottom-up contribution). Indicators can be quantitative or qualitative and serve as the bottom-up contribution. Whenever possible, indicators must be quantified in terms of units and ranges, and appropriate methods for quantification established (for example, LCA); when the former is not feasible or applicable, qualitative evaluations are established. By appropriately combining those single measurements and evaluations, an overall circularity performance can be then determined for the system in focus.

Regarding the top-down contribution, this work requires linking the RMAs to specific characteristics of aviation. An initial, high level, and non-exhaustive list of characteristics related to aviation has been provided in (Paletti et al., 2025); a list of characteristics related to aircraft and aircraft components is reported in Table 1. Based on the top-down contribution, a variety of indicators identified by the authors as applicable to aircraft and component design, can be attributed to each RMA, in the form of a checklist. The full checklist comprises 152 indicators (presented in Appendix A); examples of indicators are presented in Table 2 (and used in the use case in the remaining of this work). It must be highlighted that the same indicator can be applicable to multiple RMAs; for example, PUR1 "Documentation for end of life" – linked to Repurpose- is assigned also to Recycle, Recover Energy, and Re-Mine in the full checklist.

The list is indicative, as the framework provides the possibility for further expansion of the indicators, to achieve a more holistic circularity assessment. Also, the number of indicators for each RMA is unbalanced, with some RMAs having significantly more indicators than others. This unbalance is a consequence of some strategies not being well-developed in an aviation context and of limited sources available or known to the authors to identify possible indicators; however, this could also be a realistic representation of how the number of indicators varies across RMAs. A final comprehensive list of indicators lies beyond the scope of this work.

The full checklist can be used both as assessment and as foundation towards the future creation of guidelines for the design phase.

It is important to highlight how the proposed approach intertwines qualitative and quantitative aspects:

- Qualitative, as the characteristics of each RMA, the related indicators, the scoring range and the weighting factors are selected based on knowledge and expertise from the literature, relevant experts and the authors. Also, the characteristics and indicators are strictly linked to the system in focus, requiring its accurate definition.
- Quantitative, as the indicators must be selected either as values which can be measured or evaluated in a consistent manner. Also, the circularity performance is expressed numerically by a single score.

Such a mixed approach reflects the character of CE and of the RMAs, but also of the preliminary framework. It is expected that, with increasing understanding of CE and data availability (and its quality), more indicators could be expressed in a quantitative form. Nonetheless, the qualitative part of the framework is not foreseen to ever disappear.

Table 1. Resource management actions from ISO (ISO, 2024b) with commentaries and examples for aircraft and aircraft components.

Action [ISO]	Commentary	Current examples for aircraft and components
Refuse	This action focuses on decisions and choices taken when the product is being conceived or at early design stages.	Transition to electronic documentation and tools. Remove hazardous or non-recyclable materials.
Rethink	This action emphasises decisions made regarding the design and manufacturing processes.	Adopt a different design strategy. Change structural integrity philosophy.
Circular sourcing	This action is specifically about materials' choices.	Use bio-based materials. Use recycled materials.
Reduce	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.	Reduce weight of components. Reduce number of components. Reduce number of different materials. Reduce energy use for manufacturing.
Repair	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.	Plan regular inspections of aircraft components, engines and avionics systems. Optimise accessibility for repair.
Re-use	This action focuses on the product at the end of its (design) service life.	Components from retired aircraft to the spare parts market. In additive manufacturing, re-use powder in different batches.
Refurbish	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 a different engine on an existing aircraft. Install new cabin interiors.
Remanufacture	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.
Repurpose	This action shifts products across different parts of ATS or aviation or even outside of the sector.	Use aircraft cockpits as training simulators for pilot training. Create keychains from fuselage panels.
Cascade	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 materials recovered from aircraft for products in automotive. Mix used 3D printing metal powder with virgin powder.
Recycle	This action focuses on materials only and it involves industrial processes at material level.	Recycle material from decommissioned aircraft. Incorporate recycled materials into aircraft components.
Recover energy	This action requires the collaboration of ATS or aviation with energy sector.	Incinerate cabin interiors after retirement.
Re-mine	This action covers activities such as urban mining; in the case of aviation, this should refer to airplane boneyards.	Gather materials from decommissioned aircraft parked in boneyards.

Table 2. Examples of indicators for the determination of the circularity performance (CIRC) for aircraft and aircraft components.

Action [ISO]	ID	Indicator	Unit	Effect of indicator on circularity	Range
Refuse	NO5	Percentage of components that have a Digital twin	%	Increase	From 0 to 100%
Rethink	RT1	Number of newly manufactured components	[-]	Decrease	Integer value
Rethink	RT16	Percentage of components that have a Digital Product Passport	%	Increase	From 0 to 100%
Circular Sourcing	CS1	Percentage of virgin materials	%	Decrease	From 0 to 100%
Circular Sourcing	CS3	Percentage of recyclable materials	%	Increase	From 0 to 100%
Reduce	RD1	Number of different materials	[-]	Decrease	Integer value
Reduce	RD3	Number of (sub)components	[-]	Neutral	Integer value
Repair	RP4	Percentage of components which can be repaired (actual)	%	Increase	From 0 to 100%
Re-use	RE1	Design life of the product	Years	Increase	Integer value
Re-use	RE28	Possibility of life extension	[-]	Increase	Yes/No
Refurbish	RF5	Percentage of components which can be refurbished (theoretical)	%	Increase	From 0 to 100%
Refurbish	RF6	Percentage of components which can be refurbished (actual)	%	Increase	From 0 to 100%
Remanufacture	RM6	Percentage of components which can be remanufactured (theoretical)	%	Increase	From 0 to 100%
Remanufacture	RM38	Percentage of components that can be separated from the product	%	Increase	From 0 to 100%
Repurpose	PUR1	Documentation for end of life	[-]	Increase	Yes/No
Cascade	CA1	Percentage of materials recovered through recycling processes	%	Increase	From 0 to 100%
Cascade	CA10	Percentage of material at down grade recycling (properties lower original material)	%	Increase	From 0 to 100%
Recycle	RC3	Percentage of the product going to recycling	%	Increase	From 0 to 100%
Recycle	RC7	Percentage of critical materials recovered through recycling processes	%	Increase	From 0 to 100%
Recover energy	EN8	Percentage to incineration	%	Decrease	From 0 to 100%
Re-mine	MI8	Percentage to landfill	%	Decrease	From 0 to 100%

This mixed approach also results in a challenge towards a single-score. Other engineering methods and models produce quantitative results based (also) on combinations of quantitative data and qualitative assumptions and decisions; this is achieved by selecting an appropriate aggregation method. For the current work, once the initial quantification is completed, each indicator is scored by the authors in the range from 1 (less circular) to 5 (most circular) - also following (Saidani et al., 2017b). Other approaches are possible and have been used in previous works, for example Min-Max and Weighted Sum (Malefaki, S., Markatos, D., Filippatos, A., Pantelakis, S., 2025) and value-based model (Donelli et al., 2023). Those more advanced approaches are beyond the scope of this current work.

The attributed scores for all indicators within each RMA ($RMA_{i,j}$) are averaged over the number of indicators n identified for each RMA (Equation 1):

$$\boldsymbol{RMA_i = \frac{\sum_{j=1}^{n} RMA_{i,j}}{n}} \qquad (1)$$

resulting in a score RMA_i between 1 and 5 for each RMA.

As last step, the scores for all RMAs need to be combined. This can be achieved as a weighted sum approach, in line with the Sustainability Index (Filippatos A. et al., 2024; Markatos & Pantelakis, 2022). The weighting factors to be assigned to each RMA can be selected based on various considerations. It is relevant to highlight how not all RMAs are applicable to every part of a system; some RMAs might not be relevant or possible for certain (sub-)systems. However, this does not mean that a system where fewer RMAs apply is inherently less circular than one where all RMAs can be applied. Circularity depends on how the relevant RMAs are implemented within a system, not on the total number of RMAs applied. Conversely, the introduction of weighting factors for the RMAs aims to prevent the definition of a system as circular solely based on the adoption of strategies from a few (or even just one) RMAs. The complete formulation of the weighting factors lies beyond the scope of the current work and is the subject of on-going research by the authors.

The circularity performance CIRC can be assessed by Equation 2, as the total of the weighted contributions of each RMA:

$$\boldsymbol{CIRC = \sum_{i=1}^{13} w_i \cdot RMA_i} \qquad (2)$$

Where, RMA_i is the circularity score for each RMA [i=1…13], from Equation 1
w_i is the weighting factor assigned to each RMA.

It should be noted that achieving a circularity performance of 5 must be considered as an ideal state; such performance would imply maintaining the same technical performance without any energy or material losses for an indeterminate amount of time – which is beyond the laws of physics.

In addition to the limitations of the framework mentioned throughout this section, it is important to highlight that this proposal and related indicators rely on aviation literature and the extensive knowledge of the authors as no guideline currently exists. This may result in incompleteness during the assessment and inaccuracies of eventual comparisons, if the adopted assumptions are not properly described and reported. All those considerations indicate that the proposed framework requires extensive future research; on the other hand, it offers a foundational framework to assess circularity in the aviation sector, which can be adapted to other sectors and products as well.

4. Application to an aircraft component

The application of the proposed framework for assessing circularity in aviation is presented through a worked example related to an aircraft component. In Section 4.1 the worked example is presented, together with the assumptions, the data collection for both the quantitative and qualitative indicators, and the assessment results. Section 4.2 presents a discussion of the circularity performance assessment for the worked example considered.

The proposed framework is methodological in nature and aims to support the assessment of circularity performance in aviation. To demonstrate its applicability and feasibility at design level, the framework is applied to an illustrative worked example involving an aircraft structural component. This example is not intended as a statistical or empirical case study, but rather as a demonstrative application used to show how the framework can be operationalised and how different design options can be compared.

4.1. Worked example: circularity measurement of a hat-stiffened panel

The investigated system in focus is a hat-stiffened panel, a common aircraft component, which has been investigated in previous work by some of the authors (Filippatos et al., 2025; Filippatos A. et al., 2024). The geometry of the hat-stiffened panel is made of two components: the skin and the stringer (Figure 1). Five generic material combinations are considered for the circularity performance and they are shown in Table 3.

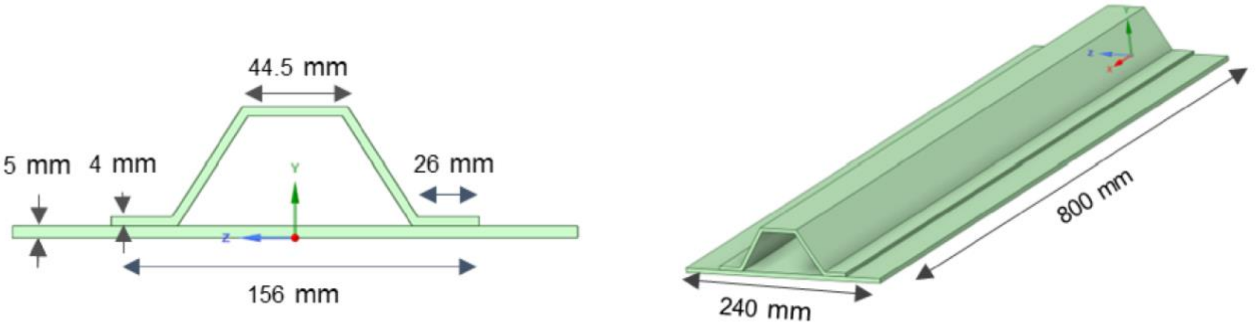

Figure 1. Worked example: hat-stiffened panel with its dimensions (Filippatos A. et al., 2024).

Table 3. Material options considered for the worked example (Filippatos A. et al., 2024).

Option	Skin Material	Stiffener Material	Estimated mass [kg]	Mass percentage - Skin [%]	Mass percentage - Stiffener [%]
1	Aluminium 2024-T3	Aluminium 2024-T3	4.52	58.8	41.2
2	Thermoplastic carbon fibre composite	Aluminium 2024-T3	3.36	44.7	55.3
3	Aluminium 2024-T3	Thermoplastic carbon fibre composite	3.71	71.6	28.4
4	Thermoplastic carbon fibre composite	Thermoplastic carbon fibre composite	2.55	58.8	41.2
5	17-4PH Stainless Steel	Thermoplastic carbon fibre composite	8.60	87.8	12.2

To evaluate the circularity performance of each option for this structural component, information regarding the indicators for the five options are necessary; information from publicly available engineering sources (e.g. websites) and from peer-reviewed sources, combined with the best-known information by the authors, are used; qualitative indications have also been considered in this case, when no quantification is possible. In this worked example, the following assumptions are made:

1. One skin panel and one stiffener are considered.
2. The design of each component for each material option is the same, with identical dimensions.
3. The design life of all options is the same.
4. As current state of the art in aircraft structures, no recycled material is used for any of the material options and all components are newly fabricated.
5. As manufacturing and joining options, standard industrialised processes for all materials and structural elements are selected.
6. For options 1, 2 and 3, aluminium fasteners are used. For option 5, steel fasteners are used. No fasteners are considered for option 4; thermoplastic welding techniques are assumed to be used in this option.
7. For options 1, 2, 3 and 5, the same number of fasteners is used.
8. Assumptions based on the current state of the art regarding maintenance, repair, overhaul and end of life operations are included.
9. Aluminium is considered 100% recyclable, steel 90%, while the thermoplastic carbon fibre composite is currently not recycled at industrial scale (so assumed as 0%).
10. Percentages are calculated based on the mass of the individual components. The difference in mass is also reflected in the scoring.
11. Overall, the composite is not considered a critical material (full list available at: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en); specific additives used in the composite could be classified as critical. As the exact composition of the composite

is not known, it is assumed that a minor percentage of critical material is present in the composite. Due to the assumption of a lack of recyclability of composite materials for the aviation industry, also the included critical materials are considered non-recycled.

For some indicators, it is not possible currently to provide values for all options; in this worked example, such indicators are removed for all options to avoid an unbalanced comparison.

For some indicators, despite the possibility to evaluate them numerically, such evaluation lies beyond the scope of the current work, due to difficulties to perform experiments or inaccessibility to relevant datasets; for those indicators, a qualitative evaluation is given, based on the knowledge of the authors.

An example of the evaluated indicators, based on Table 2, is given in Table 4. The full evaluation is given in Appendix A.

After gathering relevant information for all indicators (as per example presented in Table 4), that information is transformed in a score for each indicator, in the range of 1 (less circular) to 5 (most circular); examples of the scores for the five options are shown in Table 5.

This allows to determine a score for each RMA, by averaging the corresponding scores for different indicators for a selected RMA. The circularity performance CIRC is then determined by combining the scores for each RMA, as given in Equation 2.

Table 4. Examples of the indicators (from Table 2), evaluated for the five options given in Table 3.

ID	Indicator	Unit	Option_1	Option_2	Option_3	Option_4	Option_5	Assumption / Comment
NO5	Percentage of components that have a digital twin	%	0%	0%	0%	0%	0%	Assumption 5
RT1	Number of newly manufactured components	[-]	2+fasteners	2+fasteners	2+fasteners	2	2+fasteners	Assumptions 1, 4, 6, 7
RT16	Percentage of components that have a Digital Product Passport	%	0%	0%	0%	0%	0%	Assumptions 5 and 8
CS1	Percentage of virgin materials	%	100%	100%	100%	100%	100%	Assumption 4
CS3	Percentage of recyclable materials	%	100%	55,3%	71,6%	0%	87,8%	Assumptions 4 and 10
RD1	Number of different materials	[-]	1	2	2	1	2	Table 3
RD3	Number of (sub)components	[-]	2+fasteners	2+fasteners	2+fasteners	2	2+fasteners	Table 3, assumptions 1, 6, 7
RP4	Percentage of components which can be repaired (actual)	%	>87,8%	44,7%	71,6%	44,7%	87,8%	Assumptions 8 and 10
RE1	Design life of the product	Flight Hour/ Cycle	Same for all options	Same for all options	Same for all options	Same for all options	Same for all options	Assumption 3
RE28	Possibility of design life extension	[-]	Yes	Yes	Yes	Limited	Yes	Assumption 8
RF5	Percentage of components which can be refurbished (theoretical)	%	100%	55,3%	71,6%	0%	87,8%	Assumptions 8 and 10

Table 4 (cont.). Examples of the indicators (from Table 2), evaluated for the five options given in Table 3.

ID	Indicator	Unit	Option_1	Option_2	Option_3	Option_4	Option_5	Assumption / Comment
RF6	Percentage of components which can be refurbished (actual)	%	>87,8%	55,3%	71,6%	0%	87,8%	Assumptions 8 and 10
RM6	Percentage of components which can be remanufactured (theoretical)	%	100%	55,3%	71,6%	0%	87,8%	Assumptions 8 and 10
RM38	Percentage of components that can be separated from the product	%	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	Assumptions 5 and 6
PUR1	Documentation for end of life	[-]	No	No	No	No	No	Assumption 8
CA1	Percentage of materials recovered through recycling processes	%	90%	90%	90%	Lowest	90%	Assumption 8
CA10	Percentage of material at down grade recycling (properties lower original material)	%	100%	Composite 0%, Aluminium 100%	Aluminium 100%, Composite 0%	Lowest	Steel 100%, Composite 0%	Assumption 8
RC3	Percentage of the product going to recycling	%	100%	55,3%	71,6%	<55,3%	87,8%	Assumption 8
RC7	Percentage of critical materials recovered through recycling processes	%	90%	90%	90%	0%	Steel 90%, no Composite	Assumptions 8, 9 and 11
EN8	Percentage to incineration	%	0%	Composite 0%, Aluminium 100%	Aluminium 0%, Composite 100%	100%	Steel 0%, Composite 100%	Assumption 8
MI8	Percentage to landfill	%	0%	Composite 0%, Aluminium 100%	Aluminium 0%, Composite 100%	100%	Steel 0%, Composite 100%	Assumption 8

Table 5. Examples of the circularity score for the five options for selected indicators for all RMAs [1=least circular…5=most circular] for the same example presented in Table 4.

ID	Indicator	Option_1	Option_2	Option_3	Option_4	Option_5
NO5	Percentage of components that have a digital twin	1	1	1	1	1
RT1	Number of newly manufactured components	3	3	3	5	3
RT16	Percentage of components that have a Digital Product Passport	1	1	1	1	1
CS1	Percentage of virgin materials	1	1	1	1	1
CS3	Percentage of recyclable materials	5	3	4	1	4
RD1	Number of different materials	5	4	4	5	4
RD3	Number of (sub)components	3	3	3	5	3
RP4	Percentage of components which can be repaired (actual)	5	2	4	2	4
RE1	Design life of the product	5	5	5	5	5
RE28	Possibility of design life extension	5	5	5	2	5
RF5	Percentage of components which can be refurbished (theoretical)	5	2	4	1	4
RF6	Percentage of components which can be refurbished (actual)	5	2	4	1	4
RM6	Percentage of components which can be remanufactured (theoretical)	5	2	4	1	4
RM38	Percentage of components that can be separated from the product	5	5	5	1	5
PUR1	Documentation for end of life	1	1	1	1	1
CA1	Percentage of materials recovered through recycling processes	5	5	5	1	5
CA10	Percentage of material at down grade recycling (properties lower original material)	5	4	4	1	4
RC3	Percentage of the product going to recycling	5	3	4	1	4
RC7	Percentage of critical materials recovered through recycling processes	5	5	5	1	4
EN8	Percentage to incineration	5	2	3	1	3
MI8	Percentage to landfill	5	2	3	1	3

To evaluate CIRC by Equation 2, appropriate weighting factors need to be determined. In this case it is assumed that each RMA has the same potential impact and contribution to improve the circularity performance. This is open for debate; some researchers indicate that CE strategies (or RMAs) focusing to keep products in use are to be favoured as the most potentially impactful (Figge et al., 2018; Franklin-Johnson et al., 2016); others see circular strategies acting at design stage as more impactful, as early decisions made allow to exploit the full strength of CE (Boorsma et al., 2022); last, some highlight the need to incorporate context considerations when establishing the relevance of a specific strategy (van Kuijk & Wever, 2023). Further work on refining the approach for the determination of the weighting factors is already ongoing by the authors; for the current work and worked example a weighting factor of 0.08, approximatively corresponding to $1/_{13}$, given that the ISO standard defines thirteen RMAs.

The circularity performances for each RMAs and for all options are given in Table 6, together with the final circularity performance CIRC for each option (in the last row). The circularity performances given in Table 6 are calculated with the full list of indicators.

Table 6. Determination of the circularity performance CIRC.

Action [ISO]	Option 1	With weighting factor	Option 2	With weighting factor	Option 3	With weighting factor	Option 4	With weighting factor	Option 5	With weighting factor
Refuse	2,80	0,22	2,80	0,22	2,80	0,22	3,20	0,26	2,80	0,22
Rethink	2,97	0,24	2,68	0,21	2,82	0,23	2,24	0,18	2,79	0,22
Circular Sourcing	2,33	0,19	2,20	0,18	2,13	0,17	1,27	0,10	2,13	0,17
Reduce	1,52	0,12	1,70	0,14	1,78	0,14	1,93	0,15	1,37	0,11
Repair	3,00	0,24	2,62	0,21	2,76	0,22	1,68	0,13	2,79	0,22
Re-use	3,50	0,28	3,19	0,26	3,44	0,28	2,06	0,17	3,44	0,28
Refurbish	2,48	0,20	2,30	0,18	2,41	0,19	1,37	0,11	2,44	0,20
Remanufacture	2,37	0,19	2,37	0,19	2,37	0,19	1,41	0,11	2,41	0,19
Repurpose	1,00	0,08	1,00	0,08	1,00	0,08	1,00	0,08	1,00	0,08
Cascade	4,20	0,34	3,80	0,30	3,80	0,30	1,00	0,08	3,60	0,29
Recycle	2,67	0,21	2,33	0,19	2,50	0,20	0,67	0,05	2,33	0,19
Recover Energy	2,00	0,16	1,00	0,08	1,33	0,11	0,67	0,05	1,33	0,11
Re-mine	2,00	0,16	1,00	0,08	1,33	0,11	0,67	0,05	1,33	0,11
CIRC		2.63		2.32		2.44		1.53		2.38

4.2. Discussion

In this section, a discussion of the circularity assessment methodology based on the worked example carried out in Section 4.1 and on the results presented in Table 6 is given.

First, based on the worked example, the circularity performance assessment of the considered options is discussed. The considered design options can be ranked in terms of circularity performance. Option 1 (aluminium skin and stringer) has the highest circularity performance, while option 4 (composite skin and stringer) has the lowest circularity performance. Direct comparison of those results with currently applied methodologies (such as LCA or MCI) is not possible, as the proposed methodology is a novel contribution which aims to provide a more comprehensive circularity performance assessment than currently performed approaches. Indeed, the proposed methodology also enables linking the circularity performances of each design option to specific RMAs. For example, when prioritizing repairability and (potential closed-loop) recycling, the options including metallic materials exhibit a higher circularity performance than the composite option. When prioritizing lightweight design, the composite option has the highest circularity performance. By comparing the overall circularity performance and the results per RMA, it can be shown how the current state of the art of aviation circularity assessments presents only a partial view. For example, composite materials are often presented as the sustainable material choice and they are more and more often chosen over metallic materials. Composites contribute to efficient material use by achieving excellent mechanical properties with a lower weight (beneficial for in-flight consumptions and emissions); also, through their manufacturing processes, they tend to generate less manufacturing waste than traditional metal manufacturing. On the other hand, composite materials score less positively towards end-of-life RMAs. Current state of the art presents composites as a possible recyclable material; however recycling processes especially for the aerospace market, are not yet industrialized and, when possible, the materials properties of recycled composites are inferior to the original ones. The proposed methodology for determining the circularity performance allows to bring a broader perspective with regard to some established assumptions in the aviation sector.

It is important to note that currently the circularity performance is intended as a comparative, relative, assessment, with values ranging from 1 (fully linear) to 5 (idealized fully circular). While higher CIRC values indicate a higher degree of circularity, there is currently no universally accepted threshold for determining a "sufficiently circular" product. If required, such threshold can be established autonomously by designers or companies, based on strategic priorities, design requirements, or policy considerations. It is the opinion of the authors that the matter of a universal "minimum circularity" threshold should be discussed within relevant standardisation groups.

It needs to be highlighted that this assessment only covers the circularity performance at the level of aircraft components; it does not cover circular aspects at other levels (e.g. aircraft emissions) or other sustainability-related aspects, such as the economic or the social dimensions. The economic and social dimensions of CE should be incorporated in the circularity performance; this is part of future work. A complete sustainability assessment is not part of this current work.

It is also essential to mention that the current results of Table 6 depend on the weighting factors chosen. Further research on the impact of different weighting factors or weighting strategies is planned by the authors. The circularity performance is also affected by data availability. Those two issues mean that the results presented here shall be taken only as indicative, and meaningful only in terms of comparison of the options considered in this use case (as all options affected in a similar way). In general, results of a circularity performance assessment are not to be considered in absolute terms, but only in relative terms within a specified use case (in parallel to LCA and LCC results).

Within its assumptions and limitations, the authors consider the proposed framework as an approach and a future tool that can support decisions during the design stage. By analysing the circularity performance per RMA, designers can investigate the indicators affected by specific design choices and evaluate alternatives and trade-offs. By providing a list of detailed indicators, designers less familiar to CE can still implement strategies towards a higher circularity performance, lowering the barrier of implementation. The current work presents indicators specific for aircraft and aircraft components; by adjusting the indicators to the specificities of different industries, the methodology can be applied to other products.

5. Conclusions and future work

CE has emerged as a fundamental means towards sustainability. Despite the increasing popularity of CE strategies, assessments of circularity performance do not account neither for the systemic character of CE, nor for all circular strategies (also known as RMAs). This results in circularity assessments providing partial or contradictory views, with a risk of less sustainable (design) decisions. This situation applies also to the aviation sector, where circularity performance assessments are either qualitative or linked to LCA. Such a gap prevents the aviation industry from fully leveraging CE strategies. In response to this challenge, the current work proposed an approach for evaluating the circularity performance of aviation, developed to be adaptable to various (sub)systems in aviation, focusing specifically on aircraft and components thereof.

The proposed methodology for assessing circularity in aviation provides a framework for evaluating the alignment of the air transport (sub)systems, in this case aircraft and aircraft components, with CE strategies, identified by the RMAs of the ISO standard. This framework builds on a mixed top-down bottom-up approach, linking the RMAs with specific characteristics of aviation and of aircraft and component design. Following this, indicators are established to assess each RMA. As output of this approach, a weighted sum is derived, representing the circularity performance (CIRC). A practical application of this methodology is demonstrated through a worked example involving the assessment of different options of the design of an aircraft component. Beyond assessing the circularity performance for the selected worked example, the feasibility and effectiveness of the proposed framework to act as guidelines for designers seeking to incorporate CE strategies into the design is shown. Last, while the current work focuses on the aviation sector (and on aircraft and aircraft components), the methodology can be adapted to the specificities of different industries; by identifying relevant indicators, the methodology can be applied to every product.

The findings underscore the importance of considering the entire life cycle of products (aircraft, components or materials) when evaluating circularity performance. Moreover, although in this work the emphasis is on measuring circularity at the aircraft and component level, it is important to include different levels of the air transport system to capture correctly the complexity of CE. Though a global circularity performance lies beyond the capabilities of the authors, the systemic character of CE for the air transport system will be included by capturing indicators across all levels, and by modelling their influences; eventual interactions from other sectors shall also be incorporated when relevant. In this way, indicators at different levels may orient decisions at the level of the selected system in focus. It is understood by the authors that attempting to identify all components of a system (and their respective contributions, mutual relationships, and indicators) may prove unrealistic. This will pose a challenge when attempting to determine the circularity of a system by aggregating the contributions of its components.

Last, this study emphasizes the need for standardized metrics for the assessment of circularity performance; future research shall focus on defining metrics and quantifying indicators more comprehensively. Overall, the successful integration of CE within any sector, thus including aviation, requires collaboration among stakeholders, investment in research and development, and commitment to continuous improvement. By prioritizing sustainability and circular economy, the aviation industry can achieve its objectives of reducing environmental impact, increasing competitiveness, and driving long-term value creation. This initial assessment represents a critical first step, but further effort from researchers is essential to advance our understanding of sustainability and circular economy within the aviation industry. Agreement and awareness concerning definitions and assessment methodologies are imperative. While speaking in general terms can increase visibility, stakeholders across the industry require specific metrics to effectively assess progress towards sustainability goals. Thus, researchers must prioritize the development of robust measurement frameworks to quantify accurately sustainability and circular economy within aviation.

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Declarations

Competing Interests The authors declare no competing interests.

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Appendix A

The table below presents the full set of indicators used in this study.

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of virgin materials	CS1	100%	100%	100%	100%	100%	%	Decrease	Assumption 4
Percentage of recycled materials	CS2	0%	0%	0%	0%	0%	%	Increase	Assumption 4
Percentage of recyclable materials	CS3	100%	55,3%	71,6%	0%	87,8%	%	Increase	Assumptions 4 and 10
Percentage of critical materials	CS6	100%	At least 55,3%	At least 71,6%	Lowest	At least 68,5%	%	Neutral	Assumptions 10 and 11
Percentage of critical raw materials which are recyclable	CS8	100%	100%	100%	0%	100%	%	Increase	Assumption 11
Percentage of critical raw materials which are not recyclable	CS9	0%	0%	0%	100%	0%	%	Decrease	Assumption 11
Percentage of renewable materials	CS13	0%	0%	0%	0%	0%	%	Increase	Table 3
Number of newly manufactured components	RT1	2+fasteners	2+fasteners	2+fasteners	2	2+fasteners	[-]	Decrease	Assumptions 1, 4, 6, 7
Number of refurbished components	RT2	0	0	0	0	0	[-]	Increase	Assumption 4
Number of remanufactured components	RT3	0	0	0	0	0	[-]	Increase	Assumption 4
Percentage of product that follow ecodesign principles	RT4	0%	0%	0%	0%	0%	%	Increase	Engineering judgement
Number of different materials	RD1	1	2	2	1	2	[-]	Decrease	Table 3
Total mass	RD2	4,52	3,36	3,71	2,55	8,60	Kg	Decrease	Table 3
Number of (sub)components	RD3	2+fasteners	2+fasteners	2+fasteners	2	2+fasteners	[-]	Neutral	Table 3, assumptions 1, 6, 7
Design life of the product	RE1	Same for all options	Same for all options	Same for all options	Same for all options	Same for all options	Flight Hour	Increase	Assumption 3
Minimum design life of any component of the product	RE4	Lowest	Only higher than option 1	Lower than option 4, higher than options 1 and 2	Highest	Lower than option 4, higher than options 1 and 2	Flight Hour	Neutral	Engineering judgement

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Expected service life	RE5	Lowest	Only higher than option 1	Lower than option 4, higher than options 1 and 2	Highest	Lower than option 4, higher than options 1 and 2	Flight Hour	Increase	Engineering judgement
Total energy for material production (from extraction to manufacturing)	RD4	47,98	36,52	39,96	28,49	47,99	kW	Decrease	Ecoinvent database
Percentage of modularity across product	RE11	Highest	High, lower than option 1	High, lower than option 1, further reduction for the CFRP stringers	Lowest	High, lower than option 1, further reduction for the CFRP stringers	%	Increase	Engineering judgement
Possibility of overhaul	RF1	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumption 8
Possibility of overhaul	RM1	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumption 8
Percentage of components that follows biomimicry principles	RT5	0%	0%	0%	0%	0%	%	Increase	Engineering judgement
Percentage of components (in one product) with any type of sustainability certificate (EPD, B-corp...)	RT7	0%	0%	0%	0%	0%	%	Increase	
Percentage of components (in one product) with any type of sustainability certificate (EPD, B-corp...)	CS15	0%	0%	0%	0%	0%	%	Increase	
Percentage of materials with any type of sustainability certificate (EPD, B-corp...)	RT9	0%	0%	0%	0%	0%	%	Increase	
Percentage of materials with any type of sustainability certificate (EPD, B-corp...)	CS16	0%	0%	0%	0%	0%	%	Increase	
Presence of Bill of energy	RD8	No	No	No	No	No	[-]	Increase	
Presence of Bill of materials	RD11	Yes	Yes	Yes	Yes	Yes	[-]	Increase	

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Presence of Bill of materials	RT11	Yes	Yes	Yes	Yes	Yes	[-]	Increase	
Presence of Bill of waste	RD14	No	No	No	No	No	[-]	Increase	
Percentage of production waste	RD16	96%	93%	95%	15.5%	89%	%	Decrease	Buy to fly ratio of 25:1 https://link.springer.com/article/10.1007/s11367-014-0824-0; 15.5% Figure 3 https://www.addcomposites.com/post/composites-manufacturing-tracking-and-reducing-waste; https://www.sciencedirect.com/science/article/pii/S2666789421000611#bib44 (normal buy to fly ratio 10:1)
Percentage of reused production waste	RD17	0%	0%	0%	0%	Steel 26%, CFRP 0%	%	Increase	https://www.dovetailinc.org/upload/tmp/1579886221.pdf (home+new scrap)
Percentage of reused production waste	CS18	0%	0%	0%	0%	Steel 26%, CFRP 0%	%	Increase	https://www.dovetailinc.org/upload/tmp/1579886221.pdf (home+new scrap)
Percentage of recycled production waste	RD18	90%	Aluminum 90%, CFRP 0%	Aluminum 90%, CFRP 0%	0%	Steel 26%, CFRP 0%	%	Increase	https://www.aluminum.org/Recycling; 'https://www.dovetailinc.org/upload/tmp/1579886221.pdf (home+new scrap)
Percentage of recycled production waste	CS19	90%	Aluminum 90%, CFRP 0%	Aluminum 90%, CFRP 0%	0%	Steel 26%, CFRP 0%	%	Increase	https://www.aluminum.org/Recycling; 'https://www.dovetailinc.org/upload/tmp/1579886221.pdf (home+new scrap)

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Number of manufacturing processes	RD19	Lowest	Higher than options 1, 3, 5, lower than option 4	Higher than option 1, same as option 5, lower than option 2 and option 4	Highest	Higher than option 1, same as option 3, lower than option 2 and option 4	[-]	Neutral	Engineering judgement
Number of manufacturing processes	RT13	Lowest	Higher than options 1, 3, 5, lower than option 4	Higher than option 1, same as option 5, lower than option 2 and option 4	Highest	Higher than option 1, same as option 3, lower than option 2 and option 4	[-]	Neutral	Engineering judgement
Percentage of manufacturing energy from renewable sources	RD22	0%	0%	0%	0%	0%	%	Increase	
Percentage of components with defects or deviation from design after manufacturing	RT15	Lowest	Higher than option 1, slightly lower than options 5 and 3, lower than option 4	Higher than option 1, comparable to option 5, lower than option 4	Highest	Higher than option 1, comparable to option 3, lower than option 4	%	Decrease	Engineering judgement and assumption 5
Inspection threshold	RP1	Lowest	Intermediate	Higher than option1	Highest	Lower than options 2 and 4	Flight Hour	Neutral	Assumption 8
Inspection threshold	RF3	Lowest	Intermediate	Higher than option1	Highest	Lower than options 2 and 4	Flight Hour	Neutral	Assumption 8
Inspection threshold	RM3	Lowest	Intermediate	Higher than option1	Highest	Lower than options 2 and 4	Flight Hour	Neutral	Assumption 8
Possibility of life extension	RE14	Yes	Yes	Yes	Maybe	Yes	[-]	Increase	Assumption 8
Percentage of components that have a Digital Product Passport	RT16	0%	0%	0%	0%	0%	%	Increase	Assumptions 5 and 8
Documentation for remanufacture	RM5	No	No	No	No	No	[-]	Increase	Assumption 8
Documentation for end of life	PUR1	No	No	No	No	No	[-]	Increase	Assumption 8
Documentation for end of life	RC1	No	No	No	No	No	[-]	Increase	Assumption 8
Documentation for end of life	EN1	No	No	No	No	No	[-]	Increase	Assumption 8
Documentation for end of life	MI1	No	No	No	No	No	[-]	Increase	Assumption 8

Indicator	**ID**	**Option_1**	**Option_2**	**Option_3**	**Option_4**	**Option_5**	**Unit**	**Effect of high value on circularity**	**Comment / assumption**
Percentage of components which can be repaired (theoretical)	RP3	100%	50,00%	71,6%	100%	87,76%	%	Increase	Assumptions 8 and 10
Percentage of components which can be repaired (actual)	RP4	Highest	44,70%	71,6%	44,7%	87,76%	%	Increase	Assumptions 8 and 10
Percentage of components which can be refurbished (theoretical)	RF5	100%	55,30%	71,6%	0%	87,76%	%	Increase	Assumptions 8 and 10
Percentage of components which can be refurbished (actual)	RF6	Highest	55,30%	71,6%	0%	87,76%	%	Increase	Assumptions 8 and 10
Percentage of components which can be remanufactured (theoretical)	RM6	100%	55,30%	71,6%	0%	87,76%	%	Increase	Assumptions 8 and 10
Percentage of components which can be remanufactured (actual)	RM7	0%	0%	0%	0%	0%	%	Increase	Assumptions 8 and 10
CO2-footprint (use)	RD27	2,70E+06	2,01E+06	2,21E+06	1,52E+06	5,13E+06	CO_2 eq	Decrease	
Accessibility to human operator for repair	RP9	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumption 8
Accessibility to robotic tool for repair	RP10	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumption 8
Time taken to disassemble product for repair	RP11	Possible to disassemble	Possible to disassemble	Possible to disassemble	Not possible to disassemble	Possible to disassemble	Hour	Decrease	Assumptions 5 and 6
Degree of repairability of product	RP12	Highest	Intermediate	Intermediate	Lowest	Intermediate	[-]	Increase	Assumption 8
Presence of maintenance plan (how many checks, duration, schedule...)	RP16	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of maintenance plan (how many checks, duration, schedule...)	RM11	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of maintenance plan (how many checks, duration, schedule...)	RF10	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of product following a single load path approach	RT18	0%	0,00%	0%	50%	0,00%	%	Neutral	Engineering judgement
Percentage of product following a multiple load path approach	RT19	100%	100,00%	100%	50%	100,00%	%	Increase	Engineering judgement
Percentage of product following a safe life approach	RT20	0%	0%	0%	0%	0%	%	Decrease	Engineering judgement
Percentage of product following a fail-safe approach	RT21	100%	100%	100%	100%	100%	%	Increase	Engineering judgement
Percentage of product following any structural integrity certification approach	RT22	100%	100%	100%	100%	100%	%	Increase	Assumption 8
Cost of repair	RP17	Lowest	Lower only to option 4	Higher than option 1, similar as option 5, lower than options 2 and 4	Highest	Higher than option 1, similar as option 3, lower than options 2 and 4	Euro	Decrease	Engineering judgement
Presence of inspection schedule	RP18	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of inspection schedule	RM12	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of inspection schedule	RF11	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Percentage of the product which can be disassembled (disassembly or demountability)	RP19	100%	100%	100%	0%	100%	%	Increase	Table 3
Percentage of the product which can be disassembled (disassembly or demountability)	RM14	100%	100%	100%	0%	100%	%	Increase	Table 3

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of the product which can be disassembled (disassembly or demountability)	RF13	100%	100%	100%	0%	100%	%	Increase	Table 3
Technical lifetime / functional lifetime	RT23	Same for all options	Same for all options	Same for all options	Same for all options	Same for all options	Flight Hour	Increase	Assumption 3
CO2-footprint (manufacturing)	RD28	5,85E+01	1,11E+02	9,54E+01	1,48E+02	1,29E+02	CO_2 eq	Decrease	
Percentage of components equipped with SHM systems	RP22	0%	0%	0%	0%	0%	%	Increase	Assumption 8
Percentage of components equipped with SHM systems	RM17	0%	0%	0%	0%	0%	%	Increase	Assumption 8
Percentage of components equipped with SHM systems	RF16	0%	0%	0%	0%	0%	%	Increase	Assumption 8
Percentage of life extension achieved through operation maintenance strategy	RP24	Highest	Lower than option 1, 3, 5, higher than option 4	Lower than option 1, similar to option 5, higher than options 2 and 4	Lowest	Lower than option 1, similar to option 3, higher than options 2 and 4	%	Increase	Assumption 8
Percentage of life extension achieved through operation maintenance strategy	RF18	Highest	Lower than option 1, 3, 5, higher than option 4	Lower than option 1, similar to option 5, higher than options 2 and 4	Lowest	Lower than option 1, similar to option 3, higher than options 2 and 4	%	Increase	Assumption 8
Time needed for repair	RP26	Lowest	Only lower than option 4	Higher than option 1, similar to option 5, lower than options 2 and 4	Highest	Higher than option 1, similar to option 3, lower than options 2 and 4	Hour	Decrease	Assumption 8
Time needed for manufacturing	RT26	Lowest	Only lower than option 4	Higher than option 1, similar to option 5, lower than options 2 and 4	Highest	Higher than option 1, similar to option 3, lower than options 2 and 4	Hour	Decrease	Assumption 5
Time taken to dismantle the product (total)	RP27	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Highest	Lower than option 4, similar to other options	Hour	Decrease	Assumption 8
Time taken to dismantle the product (total)	RM20	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Highest	Lower than option 4, similar to other options	Hour	Decrease	Assumption 8

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Time taken to dismantle the product (total)	RF23	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Lower than option 4, similar to other options	Highest	Lower than option 4, similar to other options	Hour	Decrease	Assumption 8
Percentage of non-reusable components or materials (glue, sealants...)	NO1	1%	1%	1%	0%	1%	%	Decrease	Engineering judgement
Percentage of the product which is repurposed	PUR3	0%	0%	0%	0%	0%	%	Increase	Assumption 8
Percentage of the product going to recycling	RC3	100%	55,30%	71,6%	Lowest	87,76%	%	Increase	Assumption 8
Percentage of materials recovered through recycling processes	RC6	90%	90%	90%	Lowest	90%	%	Increase	Assumption 8
Percentage of materials recovered through recycling processes	CA1	90%	90%	90%	Lowest	90%	%	Increase	Assumption 8
Percentage of critical materials recovered through recycling processes	RC7	90%	90%	90%	0%	Steel 90%, no CFRP	%	Increase	Assumptions 8, 9 and 11
Percentage of critical materials recovered through recycling processes	CA2	90%	90%	90%	0%	Steel 90%, no CFRP	%	Increase	Assumptions 8, 9 and 11
Percentage of renewable material actually produced	CA8	0%	0%	0%	0%	0%	%	Increase	
Percentage of resources that is organically sourced	CS20	0%	0%	0%	0%	0%	%	Increase	Table 3
Percentage of material at high grade recycling (properties higher or equal original material)	CA9	Possible	Aluminium possible, CFRP no	Aluminium possible, CFRP no	0%	Steel possible, CFRP no	%	Increase	Assumption 8

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of material at down grade recycling (properties lower original material)	CA10	100%	Aluminium 100%, CFRP 0%	Aluminium 100%, CFRP 0%	Lowest	Steel 100%, CFRP 0%	%	Increase	Assumption 8
Percentage to landfill	MI8	0%	Aluminium 0%, CFRP 100%	Aluminium 0%, CFRP 100%	100%	Steel 0%, CFRP 100%	%	Decrease	Assumption 8
Percentage to incineration	EN8	0%	Aluminium 0%, CFRP 100%	Aluminium 0%, CFRP 100%	100%	Steel 0%, CFRP 100%	%	Decrease	Assumption 8
Material with better ageing properties	RT34	Worse than option 5, similar to option 3, better than options 2 and 4	Only better than option 4	Worse than option 5, similar to option 1, better than options 2 and 4	Worst of all	Best	[-]	Increase	Engineering judgement
Material with better fatigue properties	RT35	Worst option	Worse than option 4	Only better than option 1	Best of all options	Intermediate	[-]	Increase	Engineering judgement
Material with better corrosion properties	RT36	Worse than option 5, similar to option 3, better than options 2 and 4	Only better than option 4	Worse than option 5, similar to option 1, better than options 2 and 4	Worst of all	Best	[-]	Increase	Engineering judgement
Material with better wear properties	RT37	Best option	Better than option 5	As good as option 1	Better than option 5	Worst option	[-]	Increase	Engineering judgement
Repair by user	RP35	No	No	No	No	No	[-]	Increase	Assumption 8
Repair by specialised staff	RP36	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of a repair manual	RP37	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Maintenance by user	RF39	No	No	No	No	No	[-]	Increase	Assumption 8
Maintenance by user	RM32	No	No	No	No	No	[-]	Increase	Assumption 8
Maintenance by specialised staff	RF40	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Maintenance by specialised staff	RM33	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of maintenance manual	RF41	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Presence of maintenance manual	RM34	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of monomaterial components (from one product) which can be retrieved (overall EoL)	RE24	100%	55,3%	71,6%	0%	87,8%	%	Increase	Assumption 9
Percentage of components that can be maintained (repaired, refurbished, remanufactured)	RE25	100%	100%	100%	100%	100%	%	Increase	Assumption 8
Percentage of the product that can be reused	RE26	100%	55,3%	71,6%	0%	87,8%	%	Increase	Assumption 8
Percentage of components that can be reused	RE27	Less than 100% (no fasteners)	55,3%	71,6%	0%	87,8%	%	Increase	Assumption 8
Possibility of design life extension	RE28	Yes	Yes	Yes	Limited	Yes	[-]	Increase	Assumption 8
Possibility to upgrade	RM35	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumptions 5 and 6
Degree of accessibility of a specific component	RP38	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	Not possible	Better than option 4, similar to all others	[-]	Increase	Engineering judgement
Degree of accessibility of a specific component	RE30	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	Not possible	Better than option 4, similar to all others	[-]	Increase	Engineering judgement
Degree of accessibility of a specific component	RF42	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	Not possible	Better than option 4, similar to all others	[-]	Increase	Engineering judgement
Degree of accessibility of a specific component	RM37	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	Not possible	Better than option 4, similar to all others	[-]	Increase	Engineering judgement
Percentage of components that can be separated from the product	RP39	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components that can be separated from the product	RE31	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components that can be separated from the product	RF43	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Percentage of components that can be separated from the product	RM38	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components which can be sorted	RP40	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components which can be sorted	RE32	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components which can be sorted	RF44	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Percentage of components which can be sorted	RM39	Better than option 4, similar to all others	Better than option 4, similar to all others	Better than option 4, similar to all others	0%	Better than option 4, similar to all others	%	Increase	Assumptions 5 and 6
Number of functionalities	RD37	1	1	1	1	1	[-]	Neutral	
Number of functionalities	RT38	1	1	1	1	1	[-]	Neutral	
Possibility of detection of damage or failure?	RP41	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Percentage of components that have a Digital twin	NO5	0%	0%	0%	0%	0%	%	Increase	Assumption 5
Can connections be disassembled?	RT39	Yes	Yes	Yes	No	Yes	[-]	Increase	Assumption 5
Standardized product shape(s) for modular assembly	RT40	Yes	Yes	Yes	Less than other options	Yes	[-]	Increase	Engineering judgement
Similar lifetime for all components of assembly	RT41	No	No	No	No	No	[-]	Neutral	Engineering judgement
Better material orientation (composites or alloying for crack growth)	RT43	Should be	Should be	Should be	Yes	Should be	[-]	Increase	Engineering judgement
Presence of coatings	RT44	Yes	Yes	Yes	Yes	Yes	[-]	Neutral	Assumption 5
Presence of coatings	CS21	Yes	Yes	Yes	Yes	Yes	[-]	Neutral	Assumption 5
Presence of surface treatments	RT45	Yes	Yes	Yes	No	Yes	[-]	Neutral	Assumption 5
Presence of documentation - information to user	RP42	Yes	No	No	No	No	[-]	Increase	Assumption 5

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5	Unit	Effect of high value on circularity	Comment / assumption
Presence of documentation - information to user	RM40	No	No	No	No	No	[-]	Increase	Assumption 5
Presence of documentation - information to user	RF45	No	No	No	No	No	[-]	Increase	Assumption 5
Presence of ID on component	NO7	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 5
Presence of ID on product	NO8	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 5
Presence of documentation - traceability of use	RE33	No	No	No	No	No	[-]	Increase	Assumption 8
Presence of documentation - traceability of repair/maintenance	RP43	Yes	Yes	Yes	Yes	Yes	[-]	Increase	Assumption 8
Percentage of the product that adheres to any design standardisation	RT46	Fasteners	Fasteners	Fasteners	0%	Fasteners	%	Increase	Engineering judgement
CO2-footprint (cradle to grave)	RD41	2,70E+06	2,01E+06	2,21E+06	1,53E+06	5,13E+06	CO_2 eq	Decrease	
Percentage of recyclable production waste	CS22	90%	Aluminum 90%, CFRP 0%	Aluminum 90%, CFRP 0%	0%	Steel 20%, CFRP 0%	%	Increase	Assumption 8

The table below presents the complete scoring used in this study.

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5
Percentage of virgin materials	CS1	1	1	1	1	1
Percentage of recycled materials	CS2	1	1	1	1	1
Percentage of recyclable materials	CS3	5	3	4	1	4
Percentage of critical materials	CS6	1	3	2	5	2
Percentage of critical raw materials which are recyclable	CS8	5	5	5	1	5
Percentage of critical raw materials which are not recyclable	CS9	5	5	5	1	5
Percentage of renewable materials	CS13	1	1	1	1	1
Number of newly manufactured components	RT1	3	3	3	5	3
Number of refurbished components	RT2	1	1	1	1	1
Number of remanufactured components	RT3	1	1	1	1	1
Percentage of product that follow ecodesign principles	RT4	1	1	1	1	1
Number of different materials	RD1	5	4	4	5	4
Total weight	RD2	2	4	4	5	1
Number of (sub)components	RD3	3	3	3	5	3
Design life of the product	RE1	5	5	5	5	5
Minimum design life of any component of the product	RE4	1	2	3	5	3
Expected service life	RE5	1	2	3	5	3
Total energy for material production (from extraction to manufacturing)	RD4	1	3	3	5	1
Percentage of modularity across product	RE11	5	4	3	1	3
Possibility of overhaul	RF1	5	5	5	1	5
Possibility of overhaul	RM1	5	5	5	1	5
Percentage of components that follows biomimicry principles	RT5	1	1	1	1	1
Percentage of components (in one product) with any type of sustainability certificate (EPD, B-corp...)	RT7	1	1	1	1	1
Percentage of components (in one product) with any type of sustainability certificate (EPD, B-corp...)	CS15	1	1	1	1	1
Percentage of materials with any type of sustainability certificate (EPD, B-corp...)	RT9	1	1	1	1	1
Percentage of materials with any type of sustainability certificate (EPD, B-corp...)	CS16	1	1	1	1	1
Presence of Bill of energy	RD8	1	1	1	1	1
Presence of Bill of materials	RD11	5	5	5	5	5
Presence of Bill of materials	RT11	5	5	5	5	5
Presence of Bill of waste	RD14	1	1	1	1	1
Percentage of production waste	RD16	1	2	2	5	2
Percentage of reused production waste	RD17	1	1	1	1	3
Percentage of reused production waste	CS18	1	1	1	1	3
Percentage of recycled production waste	RD18	5	4	4	1	3

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5
Percentage of recycled production waste	CS19	5	4	4	1	3
Number of manufacturing processes	RD19	5	2	3	1	3
Number of manufacturing processes	RT13	5	2	3	1	3
Percentage of manufacturing energy from renewable sources	RD22	1	1	1	1	1
Percentage of components with defects or deviation from design after manufacturing	RT15	5	4	3	1	3
Inspection threshold	RP1	1	4	2	5	3
Inspection threshold	RF3	1	4	2	5	3
Inspection threshold	RM3	1	4	2	5	3
Possibility of life extension	RE14	5	5	5	3	5
Percentage of components that have a Digital Product Passport	RT16	1	1	1	1	1
Documentation for remanufacture	RM5	1	1	1	1	1
Documentation for end of life	PUR1	1	1	1	1	1
Documentation for end of life	RC1	1	1	1	1	1
Documentation for end of life	EN1	1	1	1	1	1
Documentation for end of life	MI1	1	1	1	1	1
Percentage of components which can be repaired (theoretical)	RP3	5	2	4	5	4
Percentage of components which can be repaired (actual)	RP4	5	2	4	2	4
Percentage of components which can be refurbished (theoretical)	RF5	5	2	4	1	4
Percentage of components which can be refurbished (actual)	RF6	5	2	4	1	4
Percentage of components which can be remanufactured (theoretical)	RM6	5	2	4	1	4
Percentage of components which can be remanufactured (actual)	RM7	1	1	1	1	1
CO2-footprint (use)	RD27	3	4	4	5	1
Accessibility to human operator for repair	RP9	5	5	5	1	5
Accessibility to robotic tool for repair	RP10	5	5	5	1	5
Time taken to disassemble product for repair	RP11	5	5	5	1	5
Degree of repairability of product	RP12	5	3	3	1	3
Presence of maintenance plan (how many checks, duration, schedule...)	RP16	5	5	5	5	5
Presence of maintenance plan (how many checks, duration, schedule...)	RM11	5	5	5	5	5
Presence of maintenance plan (how many checks, duration, schedule...)	RF10	5	5	5	5	5
Percentage of product following a single load path approach	RT18	5	5	5	3	5
Percentage of product following a multiple load path approach	RT19	5	5	5	3	5
Percentage of product following a safe life approach	RT20	5	5	5	5	5
Percentage of product following a fail-safe approach	RT21	5	5	5	5	5
Percentage of product following any structural integrity certification approach	RT22	5	5	5	5	5

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5
Cost of repair	RP17	5	2	3	1	3
Presence of inspection schedule	RP18	5	5	5	5	5
Presence of inspection schedule	RM12	5	5	5	5	5
Presence of inspection schedule	RF11	5	5	5	5	5
Percentage of the product which can be disassembled (disassembly or demountability)	RP19	5	5	5	1	5
Percentage of the product which can be disassembled (disassembly or demountability)	RM14	5	5	5	1	5
Percentage of the product which can be disassembled (disassembly or demountability)	RF13	5	5	5	1	5
Technical lifetime / functional lifetime	RT23	5	5	5	5	5
CO2-footprint (manufacturing) [CO2eq]	RD28	1	4	5	3	4
Percentage of components equipped with SHM systems	RP22	1	1	1	1	1
Percentage of components equipped with SHM systems	RM17	1	1	1	1	1
Percentage of components equipped with SHM systems	RF16	1	1	1	1	1
Percentage of life extension achieved through operation maintenance strategy	RP24	5	3	4	1	4
Percentage of life extension achieved through operation maintenance strategy	RF18	5	3	4	1	4
Time needed for repair	RP26	5	2	3	1	3
Time needed for manufacturing	RT26	5	2	3	1	3
Time taken to dismantle the product (total)	RP27	5	5	5	1	5
Time taken to dismantle the product (total)	RM20	5	5	5	1	5
Time taken to dismantle the product (total)	RF23	5	5	5	1	5
Percentage of non-reusable components or materials (glue, sealants...)	NO1	3	3	3	5	3
Percentage of the product which is repurposed	PUR3	1	1	1	1	1
Percentage of the product going to recycling	RC3	5	3	4	1	4
Percentage of materials recovered through recycling processes	RC6	5	5	5	1	5
Percentage of materials recovered through recycling processes	CA1	5	5	5	1	5
Percentage of critical materials recovered through recycling processes	RC7	5	5	5	1	4
Percentage of critical materials recovered through recycling processes	CA2	5	5	5	1	4
Percentage of renewable material actually produced	CA8	1	1	1	1	1
Percentage of resources that is organically sourced	CS20	1	1	1	1	1
Percentage of material at high grade recycling (properties higher or equal original material)	CA9	5	4	4	1	4
Percentage of material at down grade recycling (properties lower original material)	CA10	5	4	4	1	4
Percentage to landfill	MI8	5	2	3	1	3
Percentage to incineration	EN8	5	2	3	1	3
Material with better ageing properties	RT34	4	2	4	1	5
Material with better fatigue properties	RT35	1	4	2	5	3

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5
Material with better corrosion properties	RT36	4	2	4	1	5
Material with better wear properties	RT37	5	3	5	3	1
Repair by user	RP35	1	1	1	1	1
Repair by specialised staff	RP36	5	5	5	5	5
Presence of a repair manual	RP37	5	5	5	5	5
Maintenance by user	RF39	1	1	1	1	1
Maintenance by user	RM32	1	1	1	1	1
Maintenance by specialised staff	RF40	5	5	5	5	5
Maintenance by specialised staff	RM33	5	5	5	5	5
Presence of maintenance manual	RF41	5	5	5	5	5
Presence of maintenance manual	RM34	5	5	5	5	5
Percentage of monomaterial components (from one product) which can be retrieved (overall EoL)	RE24	5	3	4	1	4
Percentage of components that can be maintained (repaired, refurbished, remanufactured)	RE25	5	5	5	5	5
Percentage of the product that can be reused	RE26	5	3	4	1	4
Percentage of components that can be reused	RE27	5	3	4	1	4
Possibility of design life extension	RE28	5	5	5	2	5
Possibility to upgrade	RM35	5	5	5	1	5
Degree of accessibility of a specific component	RP38	3	3	3	1	3
Degree of accessibility of a specific component	RE30	3	3	3	1	3
Degree of accessibility of a specific component	RF42	3	3	3	1	3
Degree of accessibility of a specific component	RM37	3	3	3	1	3
Percentage of components that can be separated from the product	RP39	5	5	5	1	5
Percentage of components that can be separated from the product	RE31	5	5	5	1	5
Percentage of components that can be separated from the product	RF43	5	5	5	1	5
Percentage of components that can be separated from the product	RM38	5	5	5	1	5
Percentage of components which can be sorted	RP40	5	5	5	1	5
Percentage of components which can be sorted	RE32	5	5	5	1	5
Percentage of components which can be sorted	RF44	5	5	5	1	5
Percentage of components which can be sorted	RM39	5	5	5	1	5
Number of functionalities	RD37	3	3	3	3	3
Number of functionalities	RT38	3	3	3	3	3
Possibility of detection of damage or failure?	RP41	5	5	5	5	5
Percentage of components that have a Digital twin	NO5	1	1	1	1	1
Can connections be disassembled?	RT39	5	5	5	1	5
Standardised product shape(s) for modular assembly	RT40	5	5	5	2	5
Similar lifetime for all components of assembly	RT41	1	1	1	1	1
Better material orientation (composites or alloying for crack growth)	RT43	4	4	4	5	4

Indicator	ID	Option_1	Option_2	Option_3	Option_4	Option_5
Presence of coatings	RT44	2	2	2	2	2
Presence of coatings	CS21	2	2	2	2	2
Presence of surface treatments	RT45	2	2	2	5	2
Presence of documentation - information to user	RP42	1	1	1	1	1
Presence of documentation - information to user	RM40	1	1	1	1	1
Presence of documentation - information to user	RF45	1	1	1	1	1
Presence of ID on component	NO7	5	5	5	5	5
Presence of ID on product	NO8	5	5	5	5	5
Presence of documentation - traceability of use	RE33	1	1	1	1	1
Presence of documentation - traceability of repair/maintenance	RP43	5	5	5	5	5
Percentage of the product that adheres to any design standardisation	RT46	5	5	5	1	5
CO_2-footprint (cradle to grave)	RD41	3	4	4	5	1
Percentage of recyclable production waste	CS22	5	4	3	1	2