STRUCTURAL INTEGRITY AS ENABLER TOWARDS SUSTAINABILITY IN AVIATION

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Abstract: Aviation is undergoing an epochal transition to ensure air mobility will continue to provide its value to society, without impacting the climate. This transition will have an impact on future aircraft, but also on the current fleet. Structural integrity knowledge and practices will play a larger role in this transition than many are aware of. This paper wants primarily to put aeronautical structural integrity in relation to the field of sustainability, in the aviation sector and beyond. This paper shows how structural integrity is a fundamental enabler of sustainability in aviation and makes a case for speeding up the uptake of structural integrity knowledge which is not yet fully implemented, to enable more sustainable aircraft structures and operations. Next, a link is presented between structural integrity practices and sustainable product design, also in sectors beyond aviation. Last, additional benefits resulting from structural integrity embracing its own sustainable character are described.

Keywords: Circular Economy, Design, Structural Integrity, Sustainability

SETTING THE SCENE: SUSTAINABILITY IN AVIATION

Aviation is undergoing an epochal transition to ensure that air mobility will continue to provide its value to society, while at the same time stop impacting the climate in any way [1]. The current narrative about a "sustainable aviation" focuses on the operational emissions of flights, thus directing technological developments primarily towards propulsive solutions (sustainable aviation fuels [SAF] and other energy sources, such as electricity or hydrogen). Initiatives within the European civil aviation ecosystem, such as the Clean Aviation Joint Undertaking and the Alliance for Zero Emission Aviation, are targeting zeroing operational, in-flight, CO_2 and/or greenhouse gases (GHG) emissions. The activities covering operational emissions appear to address the majority of the aviation-related emissions [2]. Nonetheless, propulsive solutions are not all that it is necessary for the transition to a sustainable aviation [3]. "Sustainability" is a much broader concept than in-flight GHG emissions. New materials, new design concepts, new manufacturing technologies, new operations need to be considered, and beyond those, also new forms of mobility as advanced air mobility, new business models, and more; all those are (at various levels) necessary for a transition to a true sustainable aviation. Interestingly, a more complete meaning of sustainability appears in the military agenda. While still targeting primarily reduction of operational emissions, sustainability aspects such as life cycle management and self-sufficiency are clearly of interest for air force operations. Such broader approach is exemplarily represented by the IF-CEED initiative of the European Defence Agency.
Implementing novel solutions towards a sustainable aviation is foreseen to change the sector in its entirety; the entity of such change(s) is difficult to predict as it will depend on the specific solution(s)

considered. There is no doubt that the future aircraft will be heavily impacted by the sustainable solutions implemented, while it will need to fulfil the same safety standards and certification practices as the current airframes [4]. This includes fatigue, damage tolerance and structural integrity aspects.

In the context of this transition to a sustainable aviation, it seems like structural integrity will simply retain its current role, as part of the design and certification processes. On the other hand, when looking at the very concept of “sustainability”, it appears that structural integrity has more to offer than it currently does. In this paper, the connection between sustainability and structural integrity will be made clear. This connection will focus on the aviation sector, but it will also go beyond it. The transition to a sustainable aviation is only possible by a collaborative and multidisciplinary approach. Thus, this paper will also show how aviation can exchange with other sectors, in which there is a higher awareness of sustainability and theoretical knowledge of sustainable product design, but less “practical” knowledge of how to manufacture and operate sustainable products and assets. Last, how structural integrity could benefit by embracing its own sustainable character, and thus delivering societal impact, will be described.

CONNECTING SUSTAINABILITY IN AVIATION AND STRUCTURAL INTEGRITY

Within the transition to a sustainable aviation, structural integrity appears, at first, to retain its classic role; as in the past 70 years, since fatigue became a “hot topic” for aeronautical structures, structural integrity will still be part of aircraft design and certification processes. In reality, such classic, but limited, role of structural integrity has already been slowly, but steadily, challenged. This “wind of change” has different justifications: from questioning long established assumptions on the basis of new knowledge, to challenging how models developed for the aircraft of 1950s (primarily made up of metal parts manufactured in conventional ways) are now being applied to “new” materials (like composite materials), or components based on new designs (like topology optimised components), or even manufactured by new technologies (like additive manufacturing). But also, from considerations based on the cost (in terms of time and resources) of F&DT analysis and testing, inspections and maintenance procedures, to the advancements of digital tools and of new NDI or MRO technologies [5-14]. The established approaches introduce often too much conservatism in terms of weight, limitations on the fatigue lives or unnecessary maintenance. Implementing more and up-to-date structural integrity knowledge may allow for designing and operating aircraft and structural components which are not only more lightweight and durable, but which also can be replaced and maintained more easily and which retain more value at end of life.

Besides this push to implement more from the volume of knowledge accumulated in decades of F&DT and structural integrity research in real-life design and MRO activities, the precise moment in the design process at which structural integrity considerations start to be accounted for should also be revised. In the current design process, fatigue assessments start when many design decisions (including material selection) have already taken place, limiting the options for addressing eventual issues, for example identified during full scale fatigue testing. In [15] the authors propose to move structural integrity to the front of the design process, highlighting how the current practice of evaluating F&DT and structural integrity criteria towards the end of design process is actually reducing the efficiency of the overall design, and may pose economic, but also safety, risks. An example of this latter is related to additive manufacturing (AM) [11,12]. AM enables designs based on topology optimisation to be manufactured (Figure 1); such designs are currently based primarily on static loads. As knowledge of the behaviour of AM components from a structural integrity perspective and viable NDI technologies are still being investigated, the resulting designs are at risk of unforeseen structural integrity issues. Consequences could be less optimised parts, safe-life certification of AM components or an excessively strict inspection schedule; none of those is desirable from an economic perspective. Including fatigue loads in the topology optimisation can reduce the risks, and contribute to industrialising AM.

Beyond this seemingly “academic” discussion, the implementation of sustainable solutions in aircraft and in airframes will require current structural integrity to be applied to a variety of novel cases. For

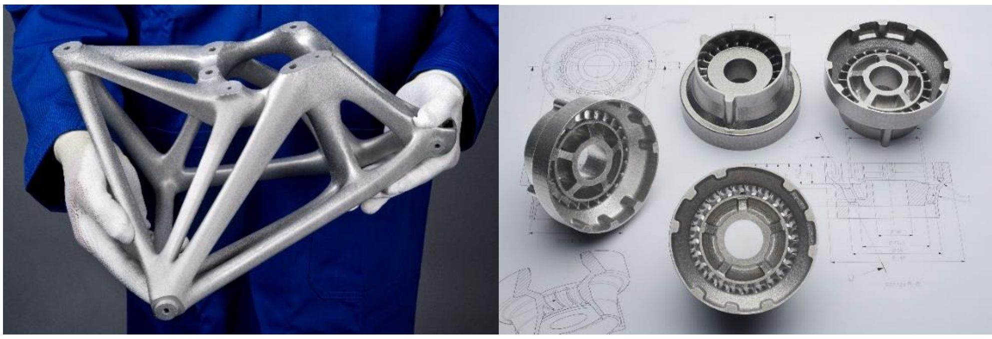
Figure 1: Examples of additive manufactured components [NLR copyright].

example, the transition to alternative fuels has already highlighted missing knowledge of how material properties may be affected by SAF or hydrogen, and by environmental conditions which have been less relevant or completely disregarded until now, for example cryogenic. Assessment of the durability of tanks and other structural elements in contact with those new fuels will require structural integrity research. In addition to this, introducing new components, such as tanks, fuel cells and batteries, will also impact the surrounding structures with specific load cases (e.g. vibrations) and conditions connected to heat generation and dissipation, (e.g. risk of condensation). Those may expose structural components to unforeseen conditions, especially in retrofit cases, which are particularly popular at this stage of the industrialisation of electric aircraft.
Hybrid-, electric-engines will have specific needs in terms of maintenance. Though electric engine may require less maintenance than internal combustion engines, all systems associated with an electric engine will introduce new challenges for the entire MRO chain [16]. All those aspects emphasise the stringent need for the development and implementation of new knowledge and technologies, as lacking suitable MRO solutions may jeopardize certification and industrialisation of novel aircraft. A quicker implementation of, already developed and/or existing, novel inspection methodologies will deliver the original advantages (e.g. cost reduction, automation of MRO activities), while gathering in-service data of the new conditions, in order to guarantee the safety of the current fleet and to determine the future maintenance needs (by feeding the acquired information back to the design stage).

Looking again at environmental conditions, those will become even more relevant when sustainable materials (such as bio based materials) are considered. The lack of information and of repeatability of material properties has prevented so far, the introduction of bio materials, fibres and epoxies; new technologies allow now for the needed quality, making bio based materials interesting for high-tech, high-spec applications, including in aerospace. A similar trend has been visible for the implementation of thermoplastic composites, also considered a sustainable material option. Differently than thermoplastic composites, in order to fully exploit bio materials, the knowledge of their behaviour and the technologies to manufacture them are not sufficient. Bio materials will get to their full potential only in combination with appropriate design approaches, which may not be in line with current aerospace design practices. For example, in the case of bio based material, nature does not develop materials and then uses them; materials and structures are co-created, in what is defined as bio design [17], which intrinsically include structural integrity. Bio design is not yet correctly implemented in aircraft structural design. Next to material behaviour, novel structural components or novel design of existing components will engage structural integrity as well. An example concerns tanks for hydrogen storage. Though hydrogen (in its liquid or gaseous forms) have been used in propulsion systems for decades, the solutions used in other sectors (like space and energy production) are not directly transferable to the specificities of aviation. Those new concepts may benefit more from a holistic structural integrity design approach in order to guarantee crashworthiness, avoid risks of fire or explosion, and avoid fatigue (as in composite tanks with metal liners and inserts), rather than from various attempts of detail redesign or from further material development.

Last, structural integrity could be what is needed by the new forms of mobility, such urban air mobility (UAM), to be accepted by the market and society in terms of safety. The extreme push for UAM vehicles to be lightweight and zero emission has spurred many innovative designs and air vehicles concepts. The unnegotiable (regulatory and social) demand for safety require vehicles for UAM to fulfil the safety standard of traditional aviation [18]. The variety of innovative solutions cramped in those vehicles, from extreme lightweight design, electric propulsion, to autonomous flying, poses many challenges. A closer interaction with structural integrity from earlier in the design phase, or even possibly from completely reversing the design paradigm by using structural integrity as the first design requirement, may be an enabler to introduce safely this new form of mobility.

CONNECTING STRUCTURAL INTEGRITY TO DESIGN FOR SUSTAINABILITY

So far, this paper has highlighted how the transition to sustainable solutions for the aviation sector will require structural integrity. But aviation is not the only sector transitioning to more sustainable practices. Sustainability has become a field of research in its own right, with topics ranging from evaluation of the impact of human activities on the climate and on the planet, to technological solutions to mitigate such impact, from business models, to design approaches to develop systems and products which are inherently sustainable. As a way to achieve sustainability targets (e.g. the UN Sustainable Development Goals), the concept of "circular economy" (CE), or circularity, is frequently mentioned, especially following the publication of the EU Green Deal in 2020.

The lack of a universal definition for both "sustainability" and "circular economy" [19,24] has contributed to develop distorted narratives about their meanings, especially in the engineering domain. Within the aviation sector, "sustainable" has become synonymous of "zero emissions", while "circularity" is associated with "recycling". A less superficial look at CE presents the so-called R-approaches, defined in [20] and represented in Figure 2; several of the R-approaches find a direct match in structural integrity. Another visual representation of CE is the "product value hill", presented in Figure 3 [21]. Its highest point, "Retain value", represents one of the principles of CE, "Circulate products and materials (at their highest value)" [24]; this also matches the outcome of structural integrity activities: maintaining assets in service as long as possible. An in-depth literature review of sustainability and of CE reveals more overlaps between structural integrity practices (in particular aviation ones) and strategies to design products to be sustainable and circular [22,23].

The following subsections link "design for sustainability", "design for circular economy" and related design approaches, to structural integrity practices.

Design for sustainability and design for circular economy/circularity

Mirroring the vagueness of the definition of "sustainability", "design for sustainability" is a broad ensemble of practices and approaches, considerations and judgement calls, which a designer can make at various moments of the design process to design a sustainable product [22]; among those, maintenance and repair, refurbishment and remanufacturing are mentioned, establishing a direct link between structural integrity and sustainability. Circularity is indicated as one aspect to consider in design for sustainability, making "design for CE/circularity" (or circular design) a subset of design for sustainability. Given the clearer principles and goals of CE [24], circular design is more suited to be codified and transferred into actual processes, than design for sustainability. Though simplistically circular design is seen as a solution to reduce resource usage (and indirectly emissions) and waste, actually the goals of design for CE are beyond "design for emission control", as this latter is limited to energy consumption and in-use phase life cycle assessments [25]. Circular design focuses on the full life cycle of products, in a cradle-to-cradle approach. Primarily, six circular design strategies have been defined [23], contributing to the primary goals of CE of long product lifespan and product integrity. Those CE design strategies are explained in relation to structural integrity, in the following subsections.

Design for attachment and trust (A&T)

This design strategy may appear elusive with respect to structural integrity, as it focuses primarily on the relationship between product and customer. Different product-costumer pairs exist in aviation (e.g. OEM-airline, airline-passenger) and links with structural integrity seem indirect. Nonetheless, links do exist, as aircraft are not single-use products; economic aspects create "attachment", as an intrinsic motivation to preserve expensive products. Structural integrity is the instrument by which the aircraft

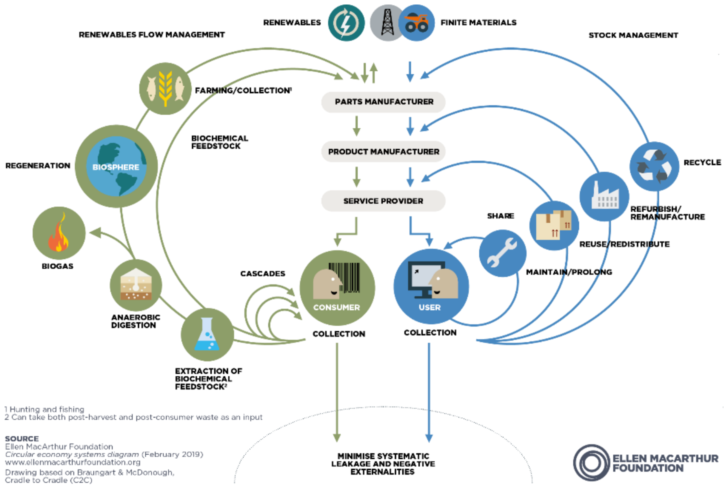

Figure 2: Circular Economy representation by the Butterfly Diagram [24].

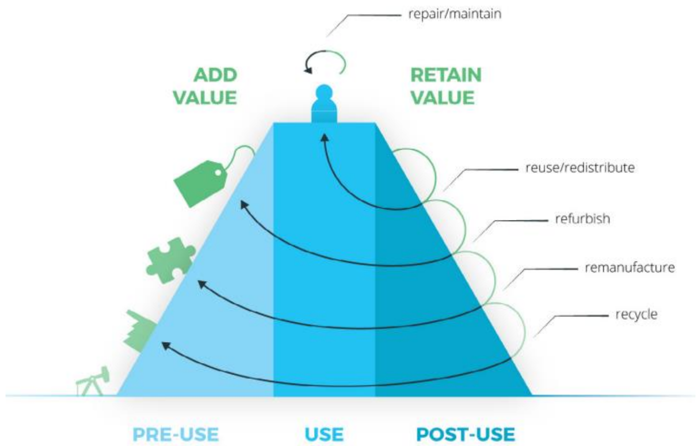

Figure 3: Product value hill for Circular Economy [21].

(product) is taken care of (primarily for safety reasons, but also economic ones). Another link between design for A&T and structural integrity connects to the practice of airlines of operating fleet of aircraft from a single OEM and/or of same aircraft type, in order to optimise operations practices and costs, including MRO. A last link between design for A&T and structural integrity regards the “trust” of passengers towards flying, towards specific airlines and towards a specific OEM or aircraft type; such “trust” is a reflection of the high safety levels, achieved also through structural integrity practices.

Design for durability

Design for durability resonates as an aircraft design approach and relates directly to structural integrity practices, though it can conflict with another important aircraft design driver: lightweight design. Both design for durability and design for lightweight are circular design approaches, with design for lightweight addressing the advantages of using less material without compromising the function of the component. On the other hand, the goal of circular design is primarily durability; in a CE context, the trade-off will favour durability over lightweight, in direct opposition with aircraft design practices.
Design strategies which belong to design for durability, and which are gathering interest in connection with the implementation of bio based materials and topology optimised components, are biomimicry and bio (inspired) design. Nature’s goal is to survive, to resist natural forces; thus, bio materials in combination with bio design are intrinsically durable and linked to structural integrity. This combination is not yet exploited for engineering components, as currently bio design connects mainly to the “inspiration” for a shape, rather than to take advantage of an inherently structural integrity-driven design approach; also, currently bio design is not per se applied to bio materials (and vice versa). Bio design is seen as synonymous of, and thus confused with, ecodesign. From a theoretical perspective, ecodesign

aims at reducing environmental impact, which is not the goal of biomimicry or bio design. Thus, ecodesign applies bio design or biomimicry when suitable. Ecodesign became known within the aviation sector for its focus on chemical content (e.g. REACH directive), but there is more to it; another pillar of ecodesign is life time extension, which clearly links to structural integrity, but which somehow has gone unnoticed so far.

Design for standardization and compatibility (S&C)

Design for S&C relates to the requirement for products to function in systems; connections to other products are required, for example in an assembly, for installation or for inspection purposes. Such requirements result in components with similar and/or matching design features. Structural integrity practices have generated design rules fitting design for S&C; for example, minimum pitch between holes or minimum fillet radius. Also, design for S&C links to modular design, which is the strategy to design products made up of components which can installed in other (identical, similar or even different) products. Modular design is widespread in aircraft structures for standardised components, for example fasteners, and for specific structural components, especially within one aircraft family. Nevertheless, more modular design for aircraft components will benefit MRO and end of life activities, enhancing the availability of spare parts and facilitating remanufacturing. As in other sectors, full S&C or modularity is difficult to achieve; first of all, the high performance requirement for each aircraft type means that each and every component is optimised for the specific type, and might not be interchangeable even within the same aircraft family. Next to this, the competitiveness within the aviation sector has been a major obstacle to S&C, not only among OEMs, but also among airlines. It is not uncommon that specific aircraft are tailored to airlines' needs and wishes, reducing opportunities for S&C. Regulations enforcing S&C have been applied in other sectors, while the aviation sector has been insofar exempted.

Design for ease of maintenance and repair (M&R)

Together with design for durability, design for M&R is undeniably part of structural integrity, with design for maintenance being an important driver in the design of aircraft components. Other design philosophies which connect to design for M&R are design for modularity, which was detailed previously, and design for remanufacturing. Remanufacturing is defined as "a standardised industrial process that takes place within industrial or factory settings, in which products are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products" [30]. The definition itself resonates with the concept of airworthiness. From a theoretical design perspective, in order to be remanufactured, products need to have one or more specific properties; those properties are summarised in the RemPro-matrix (Figure 4). The terminology used in the table is easily recognizable as MRO processes.

Remanufacturing Step / Product Property	Inspection	Cleaning	Disassembly	Storage	Reprocess	Reassembly	Testing
Ease of Identification	×		×	×			×
Ease of Verification	×						
Ease of Access	×	×	×		×		×
Ease of Handling			×	×	×	×	
Ease of Separation			×		×		
Ease of Securing						×	
Ease of Alignment						×	
Ease of Stacking				×			
Wear Resistance		×	×		×	×	

Figure 4: The RemPro-matrix relating products' properties to remanufacturing processes [26].

Despite the clear overlap, awareness for remanufacturing in aviation has been limited until recently. The increased interest follows a geo-political perspective, as remanufacturing components will retain aerospace, high-spec, materials in the sector, contributing to a more resilient supply chain, which in turn gives economic and environmental advantages. Current and foreseen structural integrity practices and tools, such as structural health monitoring, predictive maintenance, digital product passport, will also enable more remanufacturing in the aviation sector.

Design for upgrading and adaptability (U&A)

While the goal of design for M&R is to keep the original product in use in its original design function, design for U&A focuses on future uses of the product; uses which lie beyond the original product design function and life, and which cannot be entirely foreseen during the initial design. This design approach requires strategies from design for maintenance, design for modularity, design for remanufacturing, and design for S&C. Design for U&A overlaps with what in aviation is defined as refurbishment, for example upgrade of avionics, interiors, but also the retrofit of sharklets [27]. Another example of design for U&A is the concept of aircraft family (e.g. A320 family or the TU Delft Flying V family [28]). Structural integrity is an enabler for design for U&A as structural elements will be required to withstand loads which are different than those considered for the original design (e.g. lifetime extension programs).

Design for disassembly and reassembly (D&R)

Design for D&R can be associated easily with structural integrity and linked to all previously mentioned design strategies as enabler of repairs, remanufacturing, refurbishment, and so on. Its application requires trade-offs in terms of costs, weight, and other circular objectives, such as durability. Design for D&R relies on the selection and use of joints and fasteners; traditional metal airframe structures are connected by those discrete elements, and can be disassembled and reassembled multiple times. This has made the behaviour of joints a major research topic in structural integrity. The transition to composite structures, integrated structures, and adhesive or welding bonding, has been challenging structural integrity models and MRO practices. Though beneficial in terms of weight saving (and consequently fuel consumption) and, possibly, of structural integrity, it is arguable whether such transition to integrated structures will provide benefits when further environmental and sustainability considerations will be included in decision-making and trade-off assessments.

A MUTUAL EXCHANGE BETWEEN SUSTAINABILITY AND STRUCTURAL INTEGRITY

Now that design for sustainability and for circularity have been presented in a structural integrity context, opportunities for the two disciplines to mutually exchange practices and lessons learnt will appear more evident and will be detailed in this section.

From generalisation to practice, and from qualitative to quantitative

From a literature overview of the current research in sustainability, the development of general (and theoretical) design frameworks and approaches [29,30] appears to cover a large part of the research performed. What appears to be missing is the implementation: how to transform such knowledge in practice. As example, in [30] a theoretical design management approach is used to identify how remanufacturing could be successfully introduced as a requirement in the early design phase of products; this approach would help to remove the barriers towards remanufacturing currently identified by (non-aviation) companies. On the other hand, the barriers indicated in [30] have been long successfully dealt with in aviation, also via structural integrity practices; for example: risks associated to designing products for the long term, and cost and price of repairs or replacements. Though some aviation-specific solutions are not transferrable to other sectors (aircraft spare parts will always be cheaper than buying a new aircraft), aviation’s extensive experiences with design for M&R can lower some of the costs in other sectors, making repairs more attractive.

While sustainability knowledge is currently at a very high level of abstraction and generalisation, decades of research in fatigue, damage tolerance and structural integrity have generated a fragmentation of the resulting knowledge, divided in small research activities, frequently dedicated to one specific aspect or variable (for example, one material or one loading condition), and lacking assessments of the interaction of multiple variables. The implementation of product design methodologies and overarching frameworks will enable to consolidate scientific knowledge from the amount of results generated during decades-long of research. Also, it will allow to identify research gaps, providing a better understanding of research needs, and also making a more effective use of research funding. Interestingly, new engineering research areas are already adopting product design methodologies; for example, in [16] a mind-map is built to identify needs in terms of MRO for future electric aircraft and their impact on operations and operators.

As much as sustainable product designers are unaware of practical solutions already available within the structural integrity domain, a lack of awareness and knowledge of design for sustainability practices in aeronautical engineers and designers has been slowly becoming apparent, especially in relation to bio inspired design and AM. In this context, beyond the vagueness of the concept of sustainability, there seems to be a dichotomy which associates engineering with quantity, and sustainability with quality. An example lies in the different meaning given to the word "design": for engineers, it refers to technical drawings with specifications for manufacturing and assembly, while for sustainable product designers, it relates to conceptual drawings focusing on appearance and vision. It appears that the qualitative side of engineering has been forgotten. In [31], the quantitative and the qualitative characters of structural integrity, and of the reliability of fatigue predictions, are mentioned as "it must be accepted that fatigue predictions are speculative […]" and that "[..] should be evaluated with appreciable judgement"; also, "uncertainties about the fatigue performance of a structure cannot be solved by accurate and rational arguments". Similar, but reversed, considerations are given from CE's perspective in [32]: "[…] not underestimate the value of the qualitative elements of circularity. Instead, these should be rationalized, explained and embraced as necessary component of circularity and should be presented in combination with the quantitative aspects as a part of sustainable design". Those considerations point out that for the exchange between theory and practice to be successful, both disciplines need to recognise both their qualitative and quantitative characters. It will then be possible to design more durable products, not only conceptually, but by substantiating the design choices.

Know your supply chain

Another aspect identified as critical for the implementation of sustainable or circular approaches in non-aviation sectors is limited knowledge of supply chains and of their complex dependencies [22,23,30]. In [26] it is indicated that "one reason why design for remanufacturing is not happening to a larger extent is that few companies have been able to establish information channels for retrieving feedback from remanufacturing operators to product designers". On the other hand, "within aerospace […] industries, remanufacturing is a natural and essential part of the business" [26]. The knowledge and management of aviation supply chain(s) are key for the aviation sector, and connect to structural integrity, life cycle management and MRO. Structural integrity is the enabler of the second-hand market for aircraft and aircraft components, jointly with existing regulations. Without knowledge of the status of aircraft components, those cannot be used in other aircraft. The activities of MRO, the dismantling aircraft and the sale of components, require regulated accreditation and licences, in compliance with EASA/FAA regulations and, when necessary, in strict collaboration with the OEM. Traceability of all actions and processes for each component removed from an aircraft must be ensured, as the airworthiness of such component (thus its value) depends on it.

In other sectors, lack of such standardised and codified practices is preventing the effective implementation of end of life approaches for a large variety of products. This implementation is becoming urgent as, in Europe, products from almost all sectors are covered by directives regulating their end of life aspects, from enforcing reuse and recycle rates to requiring original manufacturers for extended warranty and right to repair. It is to be mentioned that various forms of repair, remanufacturing, and other end of life practices are historically already present in many sectors, for example the textile and fashion sectors. On the other hand, such practices are not are codified, harmonised, standardised and monitored. The level of standardisation within the aviation sector stems from safety requirements and economic considerations. As such safety requirements were less severe in other sectors, and the value of the products lower, the necessity for codifying, retaining or systematically implementing end of life practices was never apparent. There is clearly an opportunity for the aviation sector to share its knowledge to other sectors. In return, the aviation sector can benefit from an exchange with other sectors about digital tools for MRO and life cycle management. For example, in the MRO and end of life activities, the aviation sector still relies significantly on physical paperwork. The implementation of digital solutions is high on the R&D agenda, but not yet fully implemented. On the other hand, the

European Commission defined the concept of digital product passport [33], which is already implemented in, for example, the food industry. Digital product passports can provide a less demanding (and more sustainable) way to record information about the status of components. In addition to this, the security of the information will increase, thus allowing more components to be reintroduced in the aircraft second-hand market or in higher reuse options in other markets, avoiding plain downcycling and material recycling.

The thin line between sustainability and greenwashing

Design for lightweight is the design approach that most easily resonates with aeronautical engineers. Design for lightweight is associated with less material usage for the component(s) and less energy demand (less fuel, less emissions) during use. In the aviation sector this has been the full sustainability narrative until recently. Then end of life aspects gained prominence, and, within those, reuse and recyclability. Reuse is a term which is becoming popular in aviation, as associated to the easiest description of CE: reduce-reuse-recycle. In this description of CE, reuse targets applications both within the original sector and beyond, while, in later descriptions of CE (formalised in [20]), reuse is meant as finding applications for the product in other uses or sectors different than the original one. Combining those two aspects with the recyclability of aerospace materials, the aviation sector has developed a "sustainability in aviation" narrative for itself, narrative which gets questioned as "greenwashing" by parts of the general public and sustainability experts.

First, design for lightweight is not necessarily sustainable. Without doubt it is a possible design approach towards sustainability, but other aspects need to be taken into account, for example the environmental impact of the materials chosen. Secondly, though reuse and recycle are part of design for sustainability and for CE (Figure 2 and Figure 3), they should be seen as the last resort. Given the safety standards of aircraft parts, displacing them for reuse in other sectors means removing them from airworthiness conditions, thus losing the majority of the "aerospace" value embedded in them. Given the high value of aircraft components, such downcycling should be prevented as much as possible. In the opinion of the author, reuse and any other downcycling of aircraft components should not be encouraged in the aviation sector, and only addressed as last options for current products, until proper design strategies are implemented in future products and future policies and regulations will limit or forbid them.

The recyclability of aerospace materials deserves a dedicated note. It is frequently mentioned that aerospace materials can be recycled, up to 85% of an entire airframe [35]. Examples of applications of recycled aerospace materials get big titles and attention. In reality, when materials from aircraft primary structural elements gets recycled, the resulting components are for secondary (or more frequently even lower specifications) structural elements. As mentioned previously, the blocking factor of the implementation of those materials in aviation is identified with the lack of knowledge (and repeatability) of their material properties and behaviours. Plenty of research on recycled materials is available in other sectors; thus, a proper exchange between structural integrity and other disciplines, combined with a more thorough implementation of structural integrity knowledge and a more standardized approach on reporting material properties from material testing (another major task of structural integrity), can enhance synergies and foster the application of recycled materials in primary, high-spec airframe components.

THE SOCIETAL VALUE OF STRUCTURAL INTEGRITY

As presented in the previous section, structural integrity is not only beneficial for the sustainability of the aviation sector itself, but it has the potential for a broader impact in other sectors. Beyond the technological impact already detailed, there is another type of impact which structural integrity could have: a societal impact.

The aviation sector has long focused on technological advancements linked to economic impact; more recently, environmental aspects have started to be taken more and more into account, while still barely considering (if not, neglecting) societal aspects. This applies to structural integrity as well. In [31], it is mentioned that there could be cases in which "a cost-benefit analysis can show that efforts to improve fatigue prediction are not really worthwhile", for example in cases in which the failure is not critical and/or the simple replacement of the failed component is not expensive. In [5], the trade-off between

safety and economic aspects in order to identify the threshold for the first inspection is discussed, while pointing out how the determination of the threshold (and of the inspection interval) is not just a matter of safety, but also of inspectability, and related technologies and costs. Though economic factors will remain a significant driver, motivating aircraft design decisions only on economics will eventually not fit current, upcoming, and future regulations, which are increasingly based on sustainability aspects in a broad sense, encompassing economic, environmental and societal considerations. In this new context, "companies need to move beyond ecodesign and circular design to a more sustainable design philosophy and practice, once that adopts a collaborative systems approach to satisfying societal needs in an environmentally, socially, ethically and economically responsible way" [34].
One example which will require such transition regards the topic of critical raw materials. Based on European Critical Raw Materials Act and following supply chain risks identified during the COVID pandemic and from 2022 due to war in Ukraine, restrictions on the use and the recovery of critical materials will eventually drive design decisions also in the aviation sector. Structural integrity practices and CE practices from other sectors will be fundamental to avoid negative impact related to the availability of critical raw materials, impact which is to be expected if aviation product development will keep on having a primarily economic-driven focus.

A case in which aviation economic considerations can be used as enablers in other sectors regards business models. In other sectors, a major obstacle to accept alternative business models to ownership lies on the consumer behaviour. In the aviation sector, business models which do not include ownership are fully accepted: passengers buy a service, airlines may buy a product (aircraft), but in general they lease it. Not only: aviation developed a culture in which the whole sector relies on non-ownership models without compromising on safety requirements (another perceived obstacle in other sectors). Though the aviation "product" is owned by a specific party, maintenance and repair are usually organised through a different, OEM authorised, provider, in full compliance with instructions provided by the OEM (and secondarily by the owning party), thus without risk of losing warranty or airworthiness. This aviation practice fits design for product integrity principles [36], positioning aviation MRO closer to a "closed-loop, closed-source" concept (in which OEM are in full control of the integrity of the product throughout its life cycle), and farther away from "open-loop, open-source" concept (in which end-users have complete freedom on the product). This is exemplary of how aviation is already functioning as a highly circular system, thus delivering also societal value (despite the unawareness of the sector itself).

A non-technological challenge limits the exchange between sustainability and CE, and aviation and structural integrity. First of all, the exchange stumbles upon the meaning of concepts such as "product", "consumer", "end-user". This is first a consequence of the intricacies of the air transport system; proper terminology needs to be developed and shared within the aviation sector. But this also connects to a more general issue preventing structural integrity to achieve a larger sustainable and societal impact: a language barrier. As previously mentioned, in many decades of research, structural integrity has fallen into an extreme specialisation. This means that, despite best efforts, interactions on structural integrity across different engineering fields are more and more limited. On top of this, the highly technical language used in the structural integrity publications create a barrier in terms of accessibility for experts from other fields of research, and also from politicians and other groups who cannot grasp the value, not only societal but also economic, of the results of structural integrity research. Cross-industrial initiatives, such as EIT and IF-CEED, are essential to reinstate the dialogue and to disseminate technical and non-technical knowledge across different sectors and towards policy-makers.

Another barrier that prevents structural integrity to deliver societal impact is the difficulty to quantify very concepts of societal value and sustainability. Research is being performed to develop indicators and metrics from universally accepted definitions of those concepts. But the only way to truly embed sustainability in engineering requires a change in mindset, towards adopting a Life Cycle Thinking mindset, as it is foreseen that "it will become more critical for the designer to set out to clarify and understand the actual aims and potential consequences, both direct and indirect of the new design […] and take this into account in the assessment of the overall benefits" [32]. Life cycle thinking is a mindset already embedded, though limited to technological and some economic aspects at times, in structural integrity experts. This mindset needs to be nurtured, further trained, and also expanded towards including environmental and societal values. This will be a major step towards sustainability in aviation, and towards ensuring that the entire set of sustainability and circularity requirements will be accounted for in aircraft design, as they will be essential in the future decision making and regulations.

In addition to the fulfilment of regulations, the -perceived- distance between the aviation sector and sustainability is also becoming an issue with regard to attracting to and retaining young engineers and researchers in the aviation sector. The desire of younger generations to have a broader (also social) impact and their involvement in the sustainability causes, creates a disconnect with aviation, including towards the field of structural integrity. Building awareness and broadening the mindset as described in this paper can be beneficial not only to see more of structural integrity research and results applied in aircraft structures, but also to generate a renovated interest in the discipline for the future generations of engineers and researchers.

CONCLUSIONS

This paper has presented arguments to show how structural integrity is a fundamental enabler of sustainability in aviation. Within the aviation sector, structural integrity has evolved to fulfil requirements (safety, economics) which are not directly visible as related to sustainability; on the other hand, sustainability in its true meaning encompasses environmental, social and economic aspects in a holistic way, and directly links to structural integrity practices. Even the definition of “damage tolerance” given in [5] as “aviation’s application of a universal method for maintaining anything prone to damage or decay”, connects directly to sustainability. Beyond the links between structural integrity and sustainability in aviation, connections with sustainability, circular economy and sustainable product design have been indicated.

The goal of presenting the connections between structural integrity and sustainability is to create awareness within the aviation sector of the unexploited potential of structural integrity in the transition to sustainability in aviation. On the other hand, research in the sustainability domain clearly shows the need to develop practices and approaches which are already existing in aviation structural integrity. A mutual exchange of aviation practices shall thus be encouraged with other sectors, to enable all sectors to achieve climate neutrality targets as soon as possible. The transition of the aviation sector towards sustainability will be an opportunity for structural integrity to introduce so-called “low-hanging fruits” in terms of knowledge, models and technologies, to develop research in new areas, and even (potentially) to renew itself. Embracing its qualitative character and emphasizing its contribution to sustainability, will shine a new light on the field of structural integrity, providing a new mission to its research community, a mission that goes beyond a pure technological goal. As result, this new image will attract young talent to a field of research which now has been proven to deliver technological, economic, environmental and societal value.

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