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A new high-level life cycle assessment framework for evaluating environmental performance: An aviation case study

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ABSTRACT

Conventional Life Cycle Assessment (LCA) methods are able to assess environmental impact using significant resources (including time and data). However, due to the challenges associated with data collection these can still suffer from issues including representation accuracy, comparability, data availability, data quality, and uncertainty. This paper describes a new streamlined, high-level framework which seeks to solve these issues through rigorous and iterative application of existing standardised LCA methodologies whilst continually engaging with stakeholders. This new framework has been applied to an aviation case study, which seeks to investigate the potential environmental impact of implementing sustainable aviation fuel (including fuels based on used cooking oil, power to liquid technology, and hydrogen) and digitalisation of training regimes within a UK aircraft manufacturer. These are currently major areas of focus to enable the decarbonisation of the global aviation sector. The proposed framework allowed for efficient joint interpretation of results by different stakeholders, and therefore enabled effective strategic decision making without requiring the granular level of data detail demanded by conventional LCA frameworks. The case study has shown that each scenario offers potential reductions in global warming potential, fine particulate matter formation, and water consumption for an aircraft; but only when the associated supply chain is just as sustainable as the scenario in question. Overall, this research has shown that applying the new framework allows for rapid evaluation of decarbonisation technologies through rigorous environmental assessment to a degree accuracy which still enables strategic decision making, but without the use of unnecessary resources. Although this framework has been developed to work across product, platform, or system, further work should seek to apply it in different contexts as a LCA enabler within technological developments including exploration of other aviation decarbonisation pathways to achieve net zero.

1. Introduction

Ensuring that global mean temperature increases stabilize to, at most, 1.5 °C above pre-industrial levels means reaching net-zero carbon dioxide (CO_2) emissions by 2050 (United Nations, 2023). Despite the challenges that this transition poses, emissions reductions have been found through improving energy efficiency, changing to renewable sources of energy, and electrifying end uses of energy (Bergero et al., 2023). A large majority of countries, jurisdictions, and companies have announced net-zero emissions targets making use of emerging technologies and rethinking the use of resources (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2023). Global anthropogenic CO_2 emissions are generated by several broad sectors including utilities generation, industry, buildings, and transport. Despite recent trends, transport remains one the most challenging sectors to decarbonise due to the reliance on energy-dense liquid hydrocarbons (INTERNATIONAL, 2023a). This is particularly true in aviation where air travel has up to thirteen times more CO_2 per passenger than rail travel (RAIL, 2023). The International Energy Agency (IEA) estimates that in 2022 the global aviation industry contributed approximately 0.78 Gt CO_2, down from a peak of 1.04 Gt CO_2 in 2019 (INTERNATIONAL, 2023a).

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1.1. Aviation sector

Aviation is a key sector for the United Kingdom (UK) economy (Aerospace Growth Partnership, 2022), and the UK aviation sector is ranked among the largest in the world (Sustainable Aviation, 2018). This means that UK is, inherently, at the forefront of sector decarbonisation. The combustion products of traditional aviation fuel include several gaseous emissions which have significant potential impact on the global atmospheric environment. The largest non-CO_2 warming effects come from nitrogen oxides (NOx), water vapour and soot (Lee et al., 2021). Aircraft operation involves the emission of directly radiative substances, chemicals which may produce or destroy radiatively active substances (e.g. CO_2 or water vapour), and substances that trigger the generation of aerosol particles (Timmis et al., 2014). These emissions modify the chemical and particle microphysical properties of the upper atmosphere, which can directly lead to climate change impacts which in many cases are not well understood (Timmis et al., 2014; Gratton et al., 2021).

From life cycle and environmental performance perspectives, the sector is making significant drives to meet decarbonisation targets with technical innovations across the entire product life cycle (Keiser et al., 2023), with several key areas of focus (as defined by the Aerospace Technology Institute (ATI) (Aerospace Technology Institute, 2020)). These comprise energy efficient aircraft design (Nicolay et al., 2021; Sziroczak et al., 2020), optimising aircraft flight operations (Severis et al., 2019; Blanca-Alcubilla et al., 2020), optimising aircraft ground operations and facilities (Butt et al., 2020; Shen et al., 2016), sustainable aircraft production (Meng et al., 2017; Mami et al., 2017), sustainable through-life engineering services (Meng et al., 2017, TIMMIS et al., 2016), and exploiting alternative energy sources (Ribeiro et al., 2020; Bullerdiek et al., 2021). Existing LCA research in aviation largely deploy a conventional LCA framework which does not emphasise the role of stakeholders in the entire process, thus rendering a more resource inefficient outcome. In addition, this methodological gap found in the research in these areas have highlighted that two of the main pathways for operational decarbonisation of the sector are sustainable aviation fuel (SAF) and digitalisation, each are explored in the following sections.

1.2. Sustainable aviation fuel

A key challenge within the aviation sector's decarbonisation plan is that a large proportion of the aircraft fleet will remain operational into 2050. Therefore, a drop-in fuel is needed which has the appropriate energy density and is based on sustainable resources (Acquaye et al., 2012; International Civil Aviation Organization, 2022b). Several solutions to this problem have been developed under the umbrella of SAF. SAF is a very broad term but is typically defined as fuel which is produced from sustainable feedstocks and is very similar in its chemistry to traditional fossil jet fuel (which itself is typically kerosene based). The overarching aim of SAF is to reduce the life cycle greenhouse gas emissions from aviation fuels (Prussi et al., 2021, BP, 2022). In practice this falls into two categories called biofuels and electrofuels (efuels) (Bauen et al., 2020; Hutchings et al., 2023). Under the SAF umbrella, there are currently four major pillars each of which have their own availability, resource, and technical challenges. It is anticipated that due to the required scale of feedstock production using pioneering techniques, feedstock costs, and low yields that the cost of production may exceed traditional fossil jet fuel by as much as eight times (Pavlenko et al., 2019). This will undoubtedly be passed to the end user in an industry where cost control is paramount (Timmis et al., 2014; Pavlenko et al., 2019). The definition of each pillar is described below and are summarised in Table 1.

1. Bio-jet fuels are typically referred to as hydrogenated vegetable oil (HVO) or hydro processed esters and fatty acids (HEFA). Biofuels are produced by the chemical processing of the triglycerides present in vegetable oils. The triglycerides require further deoxygenation which is achieved by hydrotreatment. This process produces a range of products which require further refining to obtain hydrocarbon fractions suitable for fuel production (Kubicka and Tukac, 2013; Xu et al., 2019; Hutchings et al., 2023; Shahabuddin et al., 2020).
2. Synthetic fuels (biofuels and efuels) are carbon-based fuels synthesised from hydrogen and a source of carbon (e.g. CO2 from the air for efuels or carbon from biomass for biofuels). There are number of potential pathways for synthetic fuels which include utilising the Fischer Tropsch (FT) and Alcohol to Jet Fuel (ATJ) processes (Hutchings et al., 2023; Doliente et al., 2020).
3. Hydrogen is a gas which can be burnt in engines to provide thrust or fed into fuel cells to produce electricity. It can be stored as a liquid at −253 centigrade or as a compressed gas at 350 to 700 Bar. It is envisaged that scale (10 times today's volume) production could happen using electrolysis of water with renewable power (green hydrogen) or through the reforming of natural gas, or biomass gasification both with carbon capture and storage (blue hydrogen) (Hutchings et al., 2023; Yusaf et al., 2024; Contreras et al., 1997).
4. Ammonia is a gas which can be burnt in engines to provide thrust or fed into fuel cells to produce electricity. It can be stored as a liquid at −30 centigrade or as a compressed gas at 10 Bar. It is currently produced at scale from hydrogen and nitrogen in the air. Future production could make use of green hydrogen (green ammonia) or using conventional processes with access to carbon storage (blue ammonia) (Hutchings et al., 2023; Otto et al., 2023).

There are a wide variety of potential pathways to create sustainable aviation fuels, including lots of small variations in sub-processes. There are eight (with continuing development of others) American Society for Testing and Materials (ASTM) approved pathways for non-fossil-fuel based jet fuels (Prussi et al., 2021, INTERNATIONAL CIVIL AVIATION ORGANIZATION, 2024). These range in technology readiness level (TRL) (Manning, 2023) from 5 to 9 as well as blend limits from 5% to 50% (Hutchings et al., 2023; Hosseinzadeh-Bandbafha et al., 2022).

As outlined by previous research (Doliente et al., 2020; O'Connell

Table 1
Existing SAF technology summary, partially adapted from (Hutchings et al., 2023) unless noted.

Pillar	CO2 generation by aircraft?	Feedstock/process availability	Typical process route	Low Carbon?	Blend (%) with kerosene	Required modification
Bio-jet	Yes	Scale and availability is a restriction (O'Connell et al., 2019)	HVO or HEFA (Kurzawska-Pietrowicz, 2023)	Process and feedstock dependent (Doliente et al., 2020)	50 +	Little (depending on blend level)
Synthetic	Yes	Availability and cost of feedstocks is a restriction	FT or ATJ (Kurzawska-Pietrowicz, 2023)	Feedstock dependent	0–50	Little
Hydrogen	No	Scale is a restriction	Blue, Green (most favourable) (Weidner et al., 2023)	Process dependent	N/A	Major (AIRPORTS COUNCIL INTERNATIONAL, 2021)
Ammonia	No	Scale is a restriction	Blue, Green through Haber (Singh et al., 2018)	Process and feedstock dependent (Singh et al., 2018)	N/A	Major (Otto et al., 2023)

et al., 2019; Ng et al., 2021; Shahabuddin et al., 2020), there are a number of advantages and challenges associated with alternative aviation fuels (including SAF, hydrogen, or ammonia). These vary between each type (as shown in Table 1), but they are broadly similar. Typically these challenges involve ensuring that the alternative feedstocks are secure, sustainable, economically viable, and sufficiently available with both time and location of demands (Hendricks et al., 2011; Su et al., 2015). This is particularly important as multiple sectors (including heating, chemicals, road transport, and electricity) are trying to decouple from fossil fuels simultaneously with aviation which could lead to supply competition (de Jong et al., 2017). Effective management of supply chains to manage the variety of macro and micro level uncertainties will be a critical step beyond the technical challenges of alternative fuel implementation (Khoo et al., 2019). Previous research has also highlighted the need for more detailed Life Cycle Assessment (LCA) of proposed technologies and pathways to aid selection of the lowest impact fuels as well as develop associated policy and technology (Bergero et al., 2023; Seber et al., 2022). However, the technical complexity of possible solutions (including using wastes and biomaterials as feedstocks, and using novel direct air capture technology) will have a direct impact on the complexity of completing a sufficiently accurate LCA study (Hutchings et al., 2023), a challenge noted across LCA studies (Finkbeiner et al., 2014).

There has, at the time of writing, been minimal use of these products and pathways but progress is being made toward full introduction. As has already been identified, Used Cooking Oil (UCO) is currently the only practical feedstock which can be used effectively (Doliente et al., 2020). The UK's Royal Air Force (RAF) has recently tested a Typhoon aircraft using a 46–48% blend of Kerosene and UCO based fuel (ROYAL, 2023), underlining the commitment to their Net Zero plan (ROYAL, 2021). This shows how important it is, as a supplier and manufacturer of aircraft, to understand how different fuels affect a product's environmental performance. Similarly there are plans to undertake commercial flights using UCO based fuel, made net-zero through biochar credits before the end of 2023, but this is dependent on production levels meeting the demand of this single flight (Clarkson, 2022). In the UK, about 250 million litres of UCO is produced each year but the majority already has use in the agriculture and manufacturing industries. Furthermore, any UCO that is considered waste is generally difficult or impractical to collect (Greenea, 2016). These means that conservatively, current levels of UCO might be able to provide approximately 0.3% of jet fuel used in the UK (Hutchings et al., 2023); clearly a major hurdle to overcome despite current success.

1.3. Digitalisation

Although alternative fuel is the main focus of aviation decarbonisation efforts, digitalisation has emerged as a prevalent pathway for sustainability initiatives and is beginning to be incorporated into the aviation sector. Digitalisation is used as a sustainability pathway in aviation as it can reduce flight time and jet fuel burned, and improve efficiency among other benefits (Schmied-Kowarzik et al., 2022). The direct and quantified sustainability benefits of reducing flight time through digitalisation (e.g., flight simulation) are largely unknown, with a gap in the literature in this area being prevalent. Despite a reduction in jet fuel burned providing obvious environmental benefits, it is largely unknown if this will be outweighed by the resource intensity of the equipment and data storage required (Whitehead et al., 2015). The uncertainty around the energy consumption and resource intensity of digitalisation systems as well as that around the specific use of a digital system makes conventional LCA studies difficult (Whitehead et al., 2015; Gołębiewski et al., 2022). Digitalisation in the aviation sector is currently heavily dedicated to two sections of the product life cycle: maintenance and training (Schmied-Kowarzik et al., 2022): (i) maintenance (digital twins); a digital twin can be produced for the shop floor or a product to test maintenance solutions without using any physical resource, improving efficiency (ii) training (flight simulation); reduction in flight time as pilots are training on a flight simulator rather than a real plane burning fuel.

The sector is beginning to take advantage of the efficiency improvements digitalisation can provide; however, the adoption of digitalisation for sustainability purposes remains largely overlooked (Aydın and Kahraman, 2022). The RAF are beginning to embrace digitalisation through the RAFX and Astra projects which aim to explore digitalisation for the force, however both are in early stages with innovation being tested (ROYAL et al., 2022). A shift towards full automation for training and semi-automation for maintenance could also provide a large reduction in the environmental impact of an aviation product from cradle to gate (Aydın and Kahraman, 2022).

2. Life cycle assessment

2.1. Standard life cycle assessment methods

There are several standardized methodologies for evaluating the feasibility of decarbonisation including Environmental Impact Assessment (European Comission, 1997), Environmental Management System (UNITED and PROTECTION, 2021), and Carbon Footprint of a Product (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). Life Cycle Assessment (LCA), however, is currently the most widely used method to provide a general perspective for a given product by evaluating a wide range of environmental impacts throughout its whole life cycle (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). LCA has also become an increasingly critical lever within industrial product development as a strategic decision making tool, where solutions to address environmental impacts can be prioritized to best optimize a system given current financial, technological, and human resources (Jolliet et al., 2015; Pryshlakivsky and Searcy, 2021). ISO 14040 and ISO 14044 define LCA methodology, as shown in the four distinct stages in Fig. 1 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a).

The first stage, 'Goal and Scope', defines and establishes the rules and depth of a study. This includes selecting a functional unit, system boundary, and allocation procedure for a selected product. Stage two, 'Inventory Analysis', encompasses data collection and data quality evaluation. The third stage, 'Impact Assessment', aims to calculate the environmental impacts of the defined product using environmental indicators. Stage four, 'Interpretation', requires the assessor to draw conclusions based on the analysis and to carry out checks to ensure robust results. While interpretation is often listed as the last step in conducting an LCA, it should ideally occur at every step of the LCA

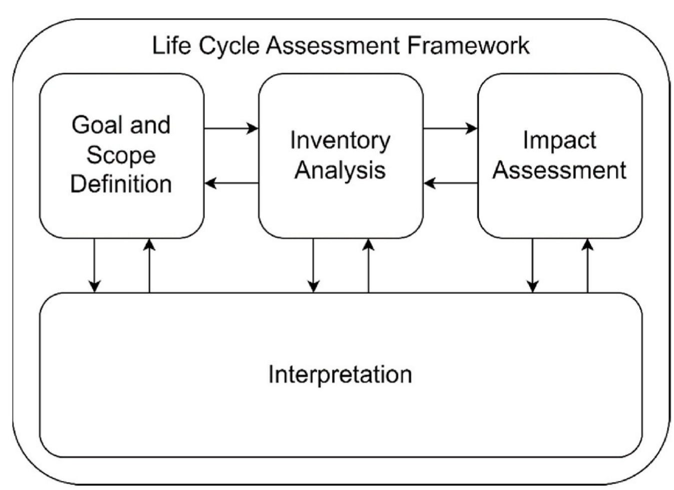

Fig. 1. LCA Framework, adapted from (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a).

methodology.

Although the standardised framework exists for conducting LCA, the technique used can be decided by the practitioner. Therefore, a range of techniques have been devised to increase the efficiency and effectiveness of completing an LCA study (Islam et al., 2016). As outlined by Islam et al. (2016), there are three principle LCA techniques which are process based, input output and hybrid. Process modelling is the traditional LCA technique which involves inventory compilation via process analysis, first introduced in the 20th century (Smith, 1969). This can be done either by simple process flow or through the more modern matrix method (Heijungs and Suh, 2002). For a simple product system this methodology works well but industrial processes tend to have multiple input and output streams. In this case, the allocation of material flow becomes a challenge due to the large amount of data required to fully satisfy the system boundary and the time required to process this. This issue can be reduced by using the matrix method of process modelling, but this still requires large amounts of time and data. Both of these method variations suffer from error truncation (the error caused by approximating mathematical process), which can seriously hamper long term decision for policy making or comparative assessments (Islam et al., 2016). Despite the accuracy that this method produces, ultimately this makes purely process based LCA studies undesirable in many cases. To counter this, an application of economic input output (IO) data to environmental process data was devised (Leontif, 1970). The key benefit of this technique is that it avoids the truncation error found in process orientated modelling because it considers the whole product supply chain within an economy. This normally makes the technique faster to conduct as IO data is already widely available through national databases (Islam et al., 2016). However, this results in a significant limitation on the IO technique as these databases do not always provide the detail required (Finnveden et al., 2009), both due to the scale of economic data and the fact that large sets of data do not tend to be updated on a regular basis (Islam et al., 2016). The concept of Hybrid LCAs (HLCA) was developed during the 1970s with the aim of combining the advantages of both Process and IO into a robust technique. Hybrid techniques are based on the principle that indirect energy consumption is equally important as direct energy consumption. This combination of techniques results a consistent approach but one where complex data management is required (Islam et al., 2016). This technique has been well used in a wide range of industrial sectors and contexts (Ibn-Mohammed et al., 2016; Bilec et al., 2006; Smith et al., 2019). There are four generally utilised HLCA techniques, namely tiered, integrated, path exchange, and matrix augmentation (Crawford et al., 2018).

Despite the range of LCA techniques available, each still has positive and negative attributes; typically, that studies either take a significant amount of time to complete or that data availability is limiting factor. This is directly opposed to the increasing drive within academic and industrial literature for detailed product based LCA studies particularly within the aviation sector (Rahn et al., 2024; Timmis et al., 2014; Kolosz et al., 2020; Vita et al., 2019). These studies require a large amount of resource (both time and data) to complete, but this should generate an accurate environmental impact assessment of a product or process. However, due to the challenges associated with data collection they typically still suffer from the same issues including representation accuracy, comparability, data availability, data quality and, uncertainty (Keiser et al., 2023; Arvidsson et al., 2023). This can make results interpretation difficult, which goes against the core principles of LCA as a methodology (British Standards Institution, 2006a). Other frameworks have sought to tackle these challenges by combining standard frameworks (e.g. life cycle costing) to add additional dimensions to analysis but data availability and data quality remain large obstacles (Wu et al., 2023; Mahmud et al., 2021).

To address these challenges, this paper presents a new, high-level LCA framework methodology which will enable completion of LCA studies without time intensive data collection through strategic iterations and continuous stakeholder engagement. This new methodology will then be applied to a case study about a manufacturer in the UK aviation sector across a baseline scenario and two exploring the implementation of sustainable aviation fuels and digitalisation respectively; given the noted focus and challenges of strategic and targeted decarbonisation efforts in these areas.

2.2. New Proposed High-level framework

LCA is a key pillar for strategic decision making because it offers an analytical way of assessing a product's environmental impact across a range of high- and low-levels and is therefore a critical tool in achieving accelerated product, sectoral, and global decarbonisation toward net zero. However, to complete LCA studies which produce useable results for a stakeholder, significant resources are typically required. In particular, emissions which fall outside of manufacturers immediate system boundary (e.g. cradle-to-gate) are challenging to account for due to the range of potential stakeholders involved.

Fig. 2 presents a new streamlined, high-level framework for LCA studies which seeks to limit the number of resources required through rigorous and cyclic application of existing LCA methodology whilst continually engaging with multiple stakeholders through joint interpretation, and strategic decision making. The proposed framework is outlined as creating an initial study, in partnership with the relevant stakeholders, from which a baseline scenario can be generated and from which comparative scenarios can be investigated. After result interpretation and strategic decisions following this, the study can be concluded once a desired accuracy level is reached. Furthermore, this framework can be used to scale a high-level study to a different product or platform. Once an initial iterative study has been completed, the differences between the platform of interest and the baseline product can be identified. These could be technical-, process-, material-, use-, or disposal-based. Due to the inherent knowledge gaps in this style of study, the accuracy is sufficient so that the results of the baseline study and subsequent scenarios can be scaled to different, but related business products, in order to aid strategic interventions without significant additional resource investment.

This framework was co-developed and co-designed with industry stakeholders as part of the aviation decarbonisation case study outlined in Section 3. As noted, LCA can be resource intensive and time consuming to complete on complex systems to a degree of accuracy which serves the purpose required. This approach is more advantageous to both stakeholders and practitioners through efficient engagement and joint iterative interpretation of results; contrasting with existing LCA methods which do not emphasise this approach. This results in the application of the described high-level LCA framework in this real and empirical case study to produce a valid and accurate LCA which can be conducted with minimum resource and maximum efficiency.

3. Case study methodology

3.1. Goal and Scope

Given the decarbonisation pressures facing the aviation sector, it was chosen as a case study to apply the newly developed framework. The LCA was conducted following ISO 14040 and ISO 14044 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006b), which as outlined, contain four main stages: determination of the goal, scope, and system boundary; inventory analysis; assessment of environmental impact; and interpretation of results. The objective of this study was to carry out an LCA of the key manufacturing and use stages of a typical platform from the defence aviation sector.

Fig. 3 presents the system boundary with a process flow diagram of the platform manufacturing process, including associated inputs and outputs, at a high-level as required by the new LCA framework. The

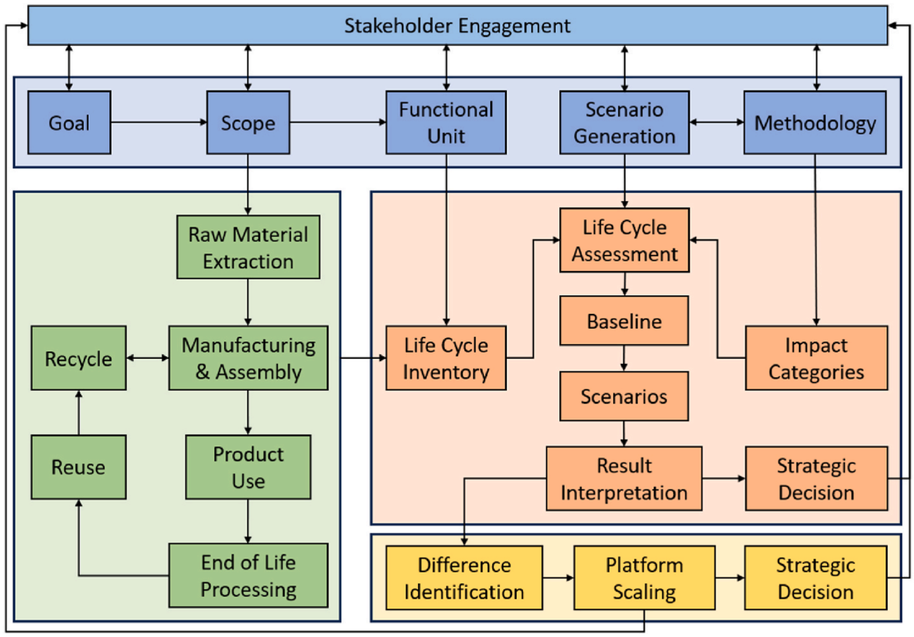

Fig. 2. Proposed High-level LCA framework (where blue = LCA scoping with stakeholders, green = life cycle data provided by stakeholders, orange = LCA results sharing with stakeholder engagement, yellow = scaling to other platforms to enable cross-business use of results). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

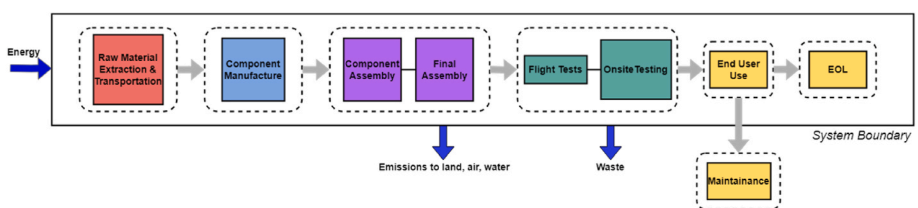

Fig. 3. System boundary and process flow diagram of aircraft manufacturing and use.

boundary can be considered cradle to grave, except for ongoing maintenance. The baseline of this study is an assessment of the current production, testing and use of an aviation platform of relevance to the industry stakeholders. Within this scenario, conventional kerosene based fuel is used for flight testing and end user use.

A material flow containing inputs, intermediate products, and outputs for each process is presented in Table 2. The primary materials considered during this study are carbon fibre composites, metals (including aluminium lithium, titanium), glass reinforced plastics, other general materials, and the fuel of choice of the end user. The selected functional unit (FU) for this study was unit of environmental impact per airframe, to enable easier strategic interpretation with key stakeholders as part of the high-level framework discussed in Section 2. Mass allocation was used within all analysis stages. Economic allocation could not be used due to the lack of financial information about the products and systems.

3.2. Scenarios

The new framework has been designed to allow for strategic, long-term designs to be made without the need for detailed data on a particular process or material. Therefore, two scenarios have been assessed beyond the baseline (described in Section 3.1) which relate to current areas of decarbonisation focus within the aviation industry as highlighted within the literature review. The first of these investigates the replacement of kerosene-based jet fuel with different substitution

Table 2
Generalised material flow of aircraft manufacturing and use, adapted from (Eurofighter GMBH, 2022).

Stages	Raw Materials, additives, and fuels	Intermediate Products	Products and co-products	Wastes
Component Manufacture	Aluminium, Titanium, Steel, Other Metals, Glass Fibre Reinforced Plastic, Carbon Fibre Reinforced Plastic, Natural Gas, Electricity	Machined Components for Fabrication	Machined Components for Airframe, Fabricated Components, Carbon Fibre Components	None
Component Assembly	Fabricated Components, Machined Components, Carbon Fibre Components, Other Materials, Natural Gas, Electricity	Airframe, Composite Components, Electrical Components	None	None
Final Assembly	Airframe, Composite Components, Electrical Components, Electricity	None	Aircraft	None
Testing	Natural Gas, Fuel, Electricity	None	Testing Regime	None
Training	Natural Gas	None	Training Regime	None
Use	Fuel	None	Used Aircraft	Aircraft

levels and types of SAF. The second of these investigates the digitalisation of flight training through different levels of automation. Both scenarios are summarised in Table 3.

3.3. Data inventory

The quality of environmental assessment results is directly related to the quality of data used to complete the life cycle inventory (LCI). This means that obtaining quality data is critical. A data inventory was primarily obtained from a leading aerospace company in the UK, relating to the manufacture and use of an aircraft. This data was supplemented by data from both Ecoinvent and literature. The primary data used to generate a LCI for aircraft manufacture cannot be disclosed due to data confidentiality, however the LCI for each scenario investigated can be disclosed and is shown in Tables 5 and 6. Although much of the data used in this study has been obtained directly from a leading manufacturer, supplementary data has been derived from Ecoinvent databases and literature. This secondary data has been regionalised to the UK where possible but in some cases remains an approximation due to database or knowledge limitation. Assessing the quality of data used within a LCI is challenging, but it is of paramount importance to ensure that data is up to date, geographically relevant, technically suitable and ultimately applicable to the scenario (Edelen and Ingwersen, 2016). The simplified pedigree matrix used to assess the quality of data used within this study, where each data source is assigned, a value based on its category, is shown in Table 4.

Utilising this methodology, the data used is assessed as follows (where a lower number indicates higher quality data).

1 Primary data: Reliability (1), Completeness (2), Temporal Correlation (1) – 4/9
2 Ecoinvent: Reliability (2), Completeness (2), Temporal Correlation (2) – 6/9
3 Literature: Reliability (3), Completeness (2), Temporal Correlation (2) – 7/9

As noted in Table 3, hydrogen is assumed to be a complete replacement for kerosene-based fuels. The data for hydrogen production is taken directly from Ecoinvent.

3.4. Life cycle impact assessment

This study was carried out using SimaPro v9.4.0 (PRÉSUSTAINABILITYBV, 2023) and databases within the programme including Ecoinvent v3.8 (ecoinvent, 2023). In order to evaluate the significance of potential environmental impacts, inventory data must be grouped into relevant impact categories (British Standards Institution, 2006a). As outlined by ISO 14044, this can be done through two mandatory (category selection and characterisation) and two optional (normalization and weighting) stages (British Standards Institution, 2006b, INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2010).

Table 3
Scenario summary.

Scenario		Pathway	Comments
Sustainable Aviation Fuel	Short Term	HEFA processed UCO at a 50% blend	50% blend
	Medium Term	FT processed Power to Liqud (PtL) using renewable electricity and captured carbon	100% blend
	Long Term	Liquid hydrogen	100% volume replacement
Digitalisation of Training	Semi-Automated	5 h simulation	50% replacement
	Fully-Automated	10 h simulation	100% replacement

Table 4
Pedigree matrix, adapted from (OPENLCA, 2022).

Indicators	1	2	3
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out fluctuations	Representative data from only some sites ($\ll$50%) relevant for the market considered or > 50% of sites but from shorter periods
Temporal Correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set

These impact categories can be split by resources (inputs) and emissions (outputs). Similarly, when each impact category is defined, an indicator is chosen within the relevant environmental mechanism; typically at either 'midpoint' or 'endpoint' level (British Standards Institution, 2012). This study performed an environmental impact evaluation using ReCiPe 2016 (Huijbregts, 2016), calculating key midpoint categories including Global Warming Potential (GWP), Fine Particulate Matter Formation (FPMF), and Water Consumption (WC) as well as endpoint categories including Human Health (HH), Ecosystems (E), and Resources (R). This range of categories should generate sufficient information to understand the accuracy and efficacy of conducting an LCA study using the high-level framework as well as understand the change in environmental impact if each scenario is implemented.

4. LCA results

The midpoint results for the SAF and digitalisation scenarios, calculated using the ReCiPe methodology, for the GWP, FPMF, and WC midpoint impact categories are shown in Figs. 4 and 5 respectively. The actual quantitative values cannot be given for reasons related to data confidentiality, therefore are only given here on in as relative percentage contributions away from the baseline scenario. This is further elaborated in Section 5.

The analysis of the SAF scenario showed that the different levels of a 50% blend of UCO HEFA potentially offers a near 25% reduction in GWP, when compared to the baseline scenario. Similarly, PtL could offer a near 70% reduction in overall GWP. It is likely that these reductions would rise to be much closer to a 100% reduction from the baseline scenario as more detailed analysis would give a better understanding of the operational emissions. Each SAF scenario indicates a reduction in FPMF, except for hydrogen. This would likely change due to the lack of operation emissions included in this study. WC does not significantly reduce over the baseline scenario for each SAF scenario, but dramatically increases for the scenario involving hydrogen.

The analysis of the digitalisation scenarios showed that the percentage reduction in GWP from the baseline scenario for semi-automated and fully-automated is 1.37 and 4.73 % respectively. The percentage reduction in FPMF from the baseline scenario for semi-automated and fully automated is 0.88 and 3.32 % respectively. The percentage reduction in water consumption from the baseline scenario for both semi-automated and fully automated is 1.04 and 4.01 % respectively. This indicates significant reduction in the key impact categories for both the scenarios from the baseline, as well as between the scenarios themselves. The fully automated scenario gives 4-fold reductions in environmental impact, due to the elimination of jet fuel use in the training phase of the life cycle.

Table 5
Life cycle inventory of SAF scenario (material data sourced from Ecoinvent unless noted).

Lifecycle sub-section	Raw Material, Fuel, Additives	Unit	Value	Process Source
Used Cooking Oil Production				
Inputs				
UCO Rendering	Natural gas, high pressure {GB}| market for | Cut-off, S	m3	0.0381	(International Civil Aviation Organization, 2022a; Seber et al., 2014; Lopez et al., 2010)
	Used vegetable cooking oil {GLO}| market for | Cut-off,	kg	1	
	Electricity, high voltage {GB}| market for | Cut-off, S	MJ	0.15	
Jet Fuel Production	Natural gas, high pressure {GB}| market for | Cut-off, S	m3	0.195	
	Rendered Oil	kg	1	
	Electricity, high voltage {GB}| market for | Cut-off, S	MJ	0.22	
Outputs				
UCO Rendering	Rendered Oil	kg	0.73	(International Civil Aviation Organization, 2022a; Seber et al., 2014; Lopez et al., 2010)
Jet Fuel Production	Jet Fuel	kg	0.494	
	Diesel	kg	0.232	
	Naphtha Propane Mix	kg	0.07	
Power to Liquid Production				
Inputs				
Carbon Dioxide DAC	Heat, district or industrial, natural gas {RER}| market group for | Cut-off, S	kWh	1500	Schreiber et al. (2020)
	Anionic resin {RER}| market for anionic resin | Cut-off, S	kg	3.75	
	Electricity, high voltage {GB}| market for | Cut-off, S	kWh	500	
Syngas Production	Carbon Dioxide DAC	kg	1.38	
	Water, decarbonised, at user {RER}| water production and supply, decarbonised | Cut-off, S	kg	1.13	
	Natural gas, high pressure {GB}| market for | Cut-off, S	m3	0.588	
	Electricity, high voltage {GB}| market for | Cut-off, S	kWh	8.82	
Jet Fuel Production	Syngas	kg	1.9	de Jong et al. (2017)
	Electricity, high voltage {GB}| market for | Cut-off, S	MJ	0.45	
Outputs				
Carbon Dioxide DAC	Carbon Dioxide DAC	kg	1000	Schreiber et al. (2020)
Syngas Production	Syngas	kg	1	
	Oxygen, gaseous	kg	1.5	
Jet Fuel Production	Jet Fuel	kg	214	de Jong et al. (2017)
	Diesel	kg	677	
	Gasoline	kg	399	
	Propane	kg	4.92	

The normalised endpoint results for the SAF digitalisation scenarios, calculated using the ReCiPe methodology, for the HH, E, R endpoint impact categories are shown (as percentage contributions) in Figs. 6 and 7 respectively. The analysis of the SAF scenarios indicates that all investigated SAF options significantly reduce overall impacts across all endpoint indicators. The exception to this is for E and R of the hydrogen scenario. The reductions must be interpreted with care because some effects from combusting these fuels is not accounted for. Similarly, the analysis of the digitalisation scenarios indicates that increasing the amount of digital training within a life cycle offers reductions in impacts across all endpoint indicators, which are very similar to those found in the GWP midpoint indicator. This would suggest that the majority of impacts are generated by using traditional kerosene-based fuels.

5. Discussion

Throughout the SAF scenarios, it is evident from the results that across all investigated impact categories there is a significant reduction in environmental impact as the scenarios investigated become increasingly 'green'. This is likely a result of utilising waste products (in the case of use cooking oil) and producing fuel in a near carbon neutral manner (in the case of PtL). This trend of results continues across the endpoint categories, with a significant reduction in required resources across the scenarios due to the decreasing use of kerosene. However, the exception to this trend is the use of liquid hydrogen. In nearly all categories, the environmental impact equals or exceeds that of traditional kerosene. A number of literature studies suggest this should not be the case (Hutchings et al., 2023; Weidner et al., 2023), and in this study this is likely due to the assumptions made during modelling and the material selected from the Ecoinvent database. This material model is not aviation specific, and accounts for the vast amount of energy required to produce and store hydrogen in this manner. Although this result is not representative of a potential in-service scenario, it does clearly highlight that understanding the supply chain of any possible kerosene replacement is critical. Similarly, it shows that ensuring that this supply chain is just as sustainable as the product is paramount.

It is clear from the results that full automation for the training process in the life cycle is more effective in reducing environmental impacts than a semi-automated training regime. This is true for all environmental impact indicators investigated. This is due to the complete elimination of flight time during training practices which is extremely resource intensive. The results show that for some unreported environmental impact indicators, namely, marine eutrophication and terrestrial ecotoxicity, the semi-automated scenario has the highest environmental impact when compared with the baseline and fully automated scenario. For these indicators, the reduction in flight time is outweighed by the environmental impact of flight simulation and the associated data storage. It is unclear why this is the case for these indicators, and further research is needed to explore this. However, semi-automation has a lower environmental impact when compared with the baseline scenario for the remaining impact categories, including the key impact categories highlighted in the results section. Because of this, semi-automation is still beneficial to environmental impact reduction initiatives, but a decarbonisation scenario closer to full automation should be prioritized. This study focusses on exploring the impact of one form of digitalisation, flight simulation, in one part of the lifecycle, training. The results presented give a good indication of the environmental impact of reducing flight time while increasing computer and data storage use; however other forms of digitalisation that improve efficiency in varying stages of the lifecycle have not been analysed. It is clear from the literature that other prevalent technologies have the potential to further reduce environmental impact in the aviation sector alongside flight simulation.

Table 6
Life cycle inventory of digitalisation scenario (material data sourced from Ecoinvent unless noted).

Raw Material, Fuel, Additives	Unit	Value	Process	Process Source
Flight Simulator				
Airframe Assembly	%	0.05	Structure	
Computer, desktop, without screen {GLO}| market for | Cut-off, S	kg	1		
Display, liquid crystal, 17 inches {GLO}| market for | Cut-off, S	MJ	0.15		
Internet access equipment {GLO}| market for | Cut-off, S	m3	0.195		
Semi-Automated				
Tap water {Europe without Switzerland}| market for | Cut-off, S	kg	421.875	Data storage resource use	(Whitehead et al., 2015; INTERNATIONAL, 2023b)
Electricity, high voltage {GB}| market for | Cut-off, S	kWh	0.2851		
Electricity, high voltage {GB}| market for | Cut-off, S	kWh	0.77	Machine running	Gołębiewski et al. (2022)
Operation, computer, desktop, with liquid crystal display, active mode {GLO}| market for | Cut-off, S	hr	15	Operation	
Flight simulator	%	100	Structure	
Fully-Automated				
Tap water {Europe without Switzerland}| market for | Cut-off, S	kg	843.75	Data storage resource use	(Whitehead et al., 2015; INTERNATIONAL, 2023b)
Electricity, high voltage {GB}| market for | Cut-off, S	kWh	0.5702		
Electricity, high voltage {GB}| market for | Cut-off, S	kWh	3.08	Machine running	Gołębiewski et al. (2022)
Operation, computer, desktop, with liquid crystal display, active mode {GLO}| market for | Cut-off, S	hr	30	Operation	Operation
Flight simulator	%	100	Structure	Structure

These results have been generated using the new high-level LCA framework and are of similar magnitude to results generated by more detailed, resource intensive studies completed internally by the primary data supplier. This fulfils the goal of the new framework and indicates that it can be used as described through iterative stakeholder interaction to generate life cycle environmental impact hotspots across several decarbonisation scenarios. These can then be used to identify recommendations to aid strategic decision making.

6. Conclusions

Aviation is a critical but environmentally intensive sector, which has significant economic output globally. However, the depth and quality of data required to assess environmental impacts through robust LCA methods is difficult to obtain. Therefore, this study has developed a new framework for high-level LCA studies, which involves creating an initial study, in partnership with the relevant stakeholders, from which a baseline scenario can be generated and from which comparative scenarios can be investigated; as has been done during this study. After result interpretation and strategic decisions following this, the differences between the platform of interest and the baseline product can be identified. These could be technical-, process-, material-, use-, or disposal-based. Due to the knowledge gaps in this study, the accuracy is representative and acceptable that the results of the baseline study and subsequent scenarios can be scaled to different platforms in order to aid strategic interventions without significant additional resource investment. The core value added step in the new high-level LCA framework is the continuous co-development and collaborative process with the decision makers throughout the lifecycle, resulting in confidence and

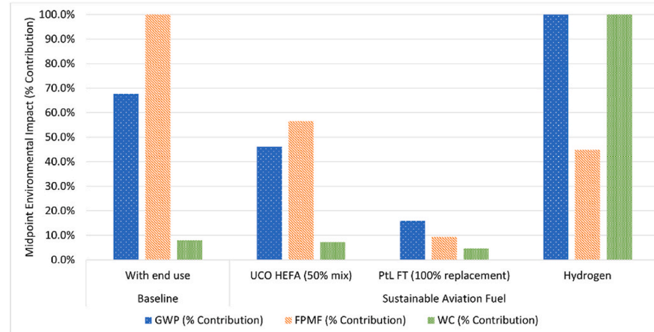

Fig. 4. Environmental impact assessment results (percentage contribution) for the SAF scenarios (GWP, ReCiPe Midpoint H – characterisation phase).

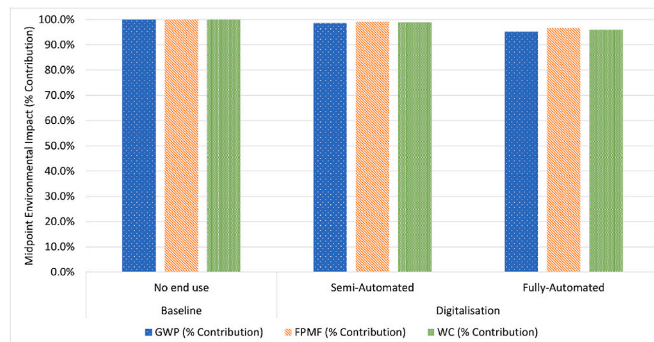

Fig. 5. Environmental impact assessment results (percentage contribution) for the digitalisation scenarios (GWP, ReCiPe Midpoint H – characterisation phase).

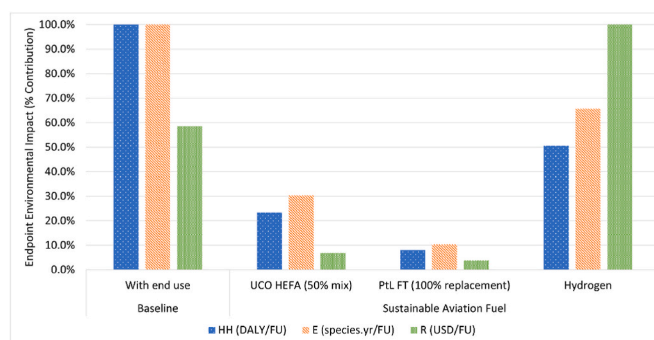

Fig. 6. Environmental impact assessment results (percentage contribution) for the SAF scenarios (HH, E and R, ReCiPe Endpoint H – normalization phase).

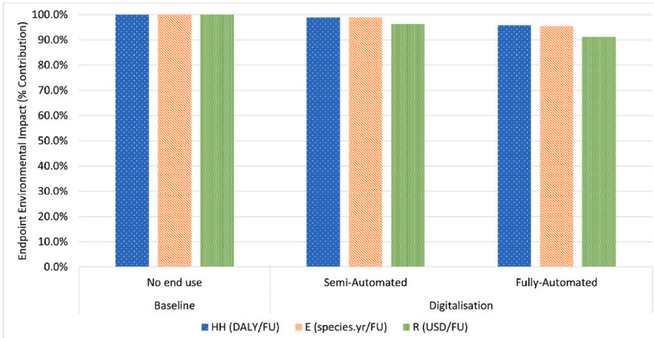

Fig. 7. Environmental impact assessment results (percentage contribution) for the digitalisation scenarios (HH, E and R, ReCiPe Endpoint H – normalization phase).

validation to the data inputs and result outputs.

This study has conducted a high-level LCA, using a new framework, to investigate the environmental impact of manufacture and use of a typical aircraft made in the UK. Further scenarios have been investigated to understand the potential environmental reductions associated with the use of SAF and implementation of training digitalisation. Although investigated using a novel framework, the effects of implementing these are as follows.

1. The first jet fuel replacement, produced through the established HEFA process using Used Cooking Oil as a feedstock. This fuel technology has been used in recent SAF flights and is currently the most readily available. This study has indicated that a typical blend level of 50% has the potential to reduce overall product CO_2 by up to 24%.
2. The second SAF scenario investigated the production of a PtL fuel, produced through the established FT process and making use of carbon dioxide captured from the air. This technology is not mature enough to have been used in commercial flight trials, but significant research and development is being conducted at The University of Sheffield (and globally) into scaling production. It is envisaged that this technology will serve as a complete replacement for traditional jet fuel, and this study has indicated that this fuel has the potential to reduce overall product CO_2 by up to 69%.
3. Finally, a third long-term scenario based on the use of liquid hydrogen has a completely different technology path was investigated using data available from industry standard databases. Similarly, to traditional SAF, climate friendly production of hydrogen is challenging. Therefore, this study serves to highlight, that without proper control over the production of a fuel there is a potential for climate impacts to increase (despite the higher specific energy of this fuel). Using current processing technology, this pathway has the potential to increase overall product CO_2 by up to 55%.
4. Semi-automated testing seeks to replace 50% of existing flight testing with computer-based system verification, making use of facilities such as data centres. This scenario has the potential to reduce overall product CO_2 by 1.37%
5. Fully automated testing aims to understand the effects of eliminating actual flight time during training regimes through the use of 100% flight simulation. This scenario has the potential to reduce overall product CO_2 by 4.73%.

In summary, this study has shown that using a novel high-level LCA framework, the environmental impacts of an aviation product can be estimated to sufficient accuracy to make informed, strategic decarbonisation decision. Two scenarios have been investigated, sustainable aviation fuels and training digitalisation, which have both shown that managed interventions within the supply chain, using increasingly available and accessible technologies could result in dramatic reductions in environmental impacts. This is a critical finding for the global net zero agenda, and highlights that most current net zero roadmaps are focussed on some of the most beneficial areas for environmental impact reduction. Future work in this area should focus on other aviation decarbonisation pathways, including the use of other sustainable aviation fuels and alternative power technologies. The developed framework is not product or sector specific, and therefore can be utilised to help assess any product, platform, or system through iterative stakeholder engagement where resource is an otherwise limiting factor. This is an important development for LCA methodology, which is quickly becoming a pivotal lever in strategic decision making to support decarbonisation. Future work should seek to apply this framework in different contexts as a LCA enabler to support technological developments that in turn will assist industry in moving towards net zero.

Data availability statement

The raw data used during this study are subject to a data use agreement, therefore are not publicly available.

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) license to any author accepted manuscript version arising from this submission.

CRediT authorship contribution statement

J.W. Whittle: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K. Callander:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **M. Akure:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **F. Kachwala:** Project administration, Funding acquisition. **S.C.L. Koh:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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