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Life Cycle Assessment and its Application to the Aviation Sector

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Abstract
Air transport plays an important role in multiple aspects of human lives, such as business and leisure. Air transport constitutes an important part of the global economy and, at the same time, has a crucial role in both domestic and international transport. It provides people and goods with connectivity that cannot be challenged by any other means of transport and therefore offers crucial services within the modern economy and society. On the other hand, it is the second biggest polluter among the transport methods. Therefore, there is a need to switch to more sustainable solutions within the aviation sector. To choose the right options, a Life cycle assessment can be a useful tool for evaluating environmental impact. Most of the studies concerned with the environmental impact of aviation focus on the pollutants emitted during the flight, ignoring other direct and indirect effects on the environment. The extraction of raw materials needed for the construction of aviation infrastructure, its manufacturing, operation and maintenance and fuel production is often ignored. In this paper, the first life cycle assessment methodology is explained, along with its benefits and the important role played by the mining industry within LCA. In the next part, we present a possible model for evaluating the overall environmental impact of air transport, divided into four main parts – production, operation, maintenance and liquidation, followed by the analysis of the social aspect of the impact evaluation.

Keywords
life cycle assessment, environmental impact, raw materials extraction, aviation sector, social assessment

Introduction

The rise of urbanization and industrialization led to an increased dependency of various sectors on fossil fuels. This dependency on current infrastructure resulted in considerable deterioration of the environment. It is vital to remember that the transport sector is one of the key contributors to the degradation of the environment. Globally, the transportation industry generates a sizable amount of environmental emissions (Siddiqui & Dincer, 2021). The growth in air traffic impacted local and global emissions of greenhouse gases (Pereira et al., 2014). Due to the advantages that air travel—both for passengers and cargo—offers in boosting the economy, lowering the carbon footprint of the airline sector is a difficult task (Hadi-Vencheh et al., 2018). When addressing this industry's sustainability issues, finding a balance between non-CO_2-related consequences and the impact of aviation emissions is a matter to take into consideration (Kucukvar et al., 2020).

The aviation sector must prepare for a large increase in air travel over the coming decades, as well as the lofty goal of minimizing environmental effects. Even with a 2% annual increase in fuel economy, it is predicted that worldwide emissions from international aviation will be almost 70% greater by 2025 than they were in 2005. According to the International Civil Aviation Organization, emissions may increase by 300% to 700% by 2050. Climate change and achieving the goals established by the Intergovernmental Panel on Climate Change are both enormous challenges. Due to their outstanding mechanical qualities, low weight, and favourable fatigue behaviour, composite materials have seen an increase in use in the aerospace and transportation sectors in recent years *(*Bachmann et al., 2017*)*.

In recent years, there has also been a rise in worldwide awareness of the need to cut greenhouse gas (GHG) emissions from aviation and consequently make the entire aviation industry more ecologically friendly. Currently, the aviation sector contributes 2.5% of the world's CO_2 emissions or roughly 820 tCO_2/a. Since rising living standards in emerging nations like China, India, and Brazil (and consequently accelerating travel activities), as well as sharply rising global trade flows, will encourage even more and longer flight operations per year, these emissions are most likely to increase in the years to come. In response to this trend, the worldwide aviation sector has created a demanding self-commitment pertaining to the growth of global CO_2 emissions from civil aircraft. This involves achieving carbon-neutral growth beginning in 2020 and achieving a 50% decrease in CO_2 emissions compared to the year 2005 by 2050. These lofty objectives are supported by more energy-efficient aircraft, improved flying procedures (such as the single European Sky), and sustainable aviation biofuels with much lower carbon footprints. According to this strategy, the market release of advanced biofuels for aviation is anticipated to result in the greatest CO_2 emission reduction (Neuling & Kaltschmitt, 2018).

Despite efforts to reduce CO_2 emissions significantly during the upcoming years, GHG emission values are anticipated to rise dramatically (Wang & Jiang, 2009). The aviation sector has established goals for lowering CO_2 emissions by 2050, some of which include improving climatic conditions, advancing economic development through greater connectivity, and utilizing clean, sustainable energy sources. Sustainable operations may be supported by the global aviation industry adopting the SDGs and establishing a positive business image (Elhmoud & Kutty, 2020).

Although technologies may improve living circumstances and hence contribute to sustainable development, they may also exacerbate sustainability issues. Therefore, it is ideal for decisions on alternative technologies to be made to minimize the latter. To guarantee that developing technologies are sustainable, it is essential to comprehend how they affect the environment throughout their full life cycles, especially at the raw material supply stage in clean energy technologies. Finding the "most sustainable" technology by analyzing environmental, economic, and social factors associated with technologies helps with decision-making. Numerous regional, national, and international frameworks and initiatives currently address sustainability, including environmental, economic, and social elements. More and more attention is being paid to the idea of life cycle sustainability assessment, which combines the approaches of life cycle assessment, life cycle costing, and social life cycle assessment (Thonemann et al., 2020). It is essential to adopt a life cycle viewpoint to prevent transferring the load across the various life cycle stages. Making decisions with the intention of promoting sustainable development is supported by analyses of the possible effects of goods and the identification of hotspots throughout their life cycles (Lehmann et al., 2013).

The ecological evaluation includes the following categories: solid wastes, water emissions, energy consumption, raw material consumption, land usage, toxicity potential, and risk potential. In this context, it is crucial to note that a product's purpose, not its physical attributes, serves as the foundation for a comparative assessment (Kicherer et al., 2007).

By implementing sustainable, carbon-neutral development strategies, industries in rising economies throughout the world have aimed to significantly cut greenhouse gas emissions (Alsarayreh et al., 2020). There is no exception in this case for the aviation sector. Compared to its activities in the late 1990s, the aviation sector has, among all other industries, reduced its carbon footprint by half. Aviation emissions, particle soot, lead contrails, and cirrus clouds are expected to decrease with the introduction of new technologies, including sustainable fuel alternatives and zero-emission engine designs (García-Olivares et al., 2020). Reducing aviation emissions will also reduce the effects of climate change, so advancing Sustainable Development Goal 13: addressing climate-related concerns (Elhmoud & Kutty, 2020).

Life cycle assessment

Life cycle analysis serves as a tool for monitoring and assessing all stages of production in terms of their impact on the environment. It helps us in detecting and, at the same time, reduce negative environmental impacts. Life Cycle Assessment is a global tool with a wide range of applications. LCA is currently being used in many countries in several areas of social practice. This method is also widely used in environmental education and various industries, for instance, paper, construction, automotive, chemical, energy, etc.

For the beginnings of the development of LCA, two main periods can be distinguished – 1970-1990 and 1990-2000 (Guinées et al., 2011). During the first period, key elements of environmental policies, such as pollution, resources, energy efficiency and waste management, came to the broader public's interest and the first studies concentrated on the production chain "from the cradle to the grave". However, a clear theoretical and methodological framework, as well as international cooperation, was absent in this period; thus, the results of the studies conducted were highly incoherent. The beginning of the 1990s saw the rise of the popularity of LCA, which was marked by increased international cooperation, standardization of a common theoretical framework, publishing of guidelines and organization of workshops and forums. "Code of Practice" was implemented by SETAC, ISO standards were adapted, and LCA continuously became part of policy and legislation documents (Bjorn et al., 2018; ISO, 2006).

ISO 14040 defines the LCA method as the collection and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle. Life cycle definition is understood as a product path from its design on paper, its design and properties in the development department, through production (including mining, cultivation, and processing of raw materials), its subsequent distribution, use by end consumers, to recycling of suitable materials and storage of parts product at the end of its life cycle to the landfill or its disposal in an incinerator (SETAC, 2021; Siddiqui & Dincer, 2021). In other words, the life cycle assessment method helps determine how a product's lifecycle affects the environment at every step (Bachmann et al., 2017). Through this method, the management is given the knowledge they need to obtain the environmental benefit per Euro invested when the eco-efficiency of items is determined. In another way, it enables management to contribute most to increased eco-efficiency and the sustainable growth of the business and society (Kicherer et al., 2007).

Due to its standardization, objectivity, holistic approach, and scientific acceptance, LCA is a widely used technique to analyze products from an environmental standpoint. LCA enables the systematic quantitative evaluation of products, commodities, and services with respect to the effects on the environment, human health, and resource consumption (Bachmann et al., 2017).

The Society for Environmental Toxicology and Chemistry (SETAC) has defined the LCA as an objective process for assessing the environmental burdens associated with a product, process or activity, where it identifies and quantifies the energy, materials and waste released into the environment while assessing and realizes opportunities for environmental improvements (European Union, 2017).

LCA is a methodology that examines the environmental impacts associated with a product, process or service "from the cradle to the grave" - from raw materials to the final disposal of waste. In particular, LCA has proven itself in environmental management as a tool to compare two or more alternatives in terms of their combined potential environmental impacts and the sustainability of the alternative. LCA may be divided into two groups: attributional studies and consequential studies (Kolosz et al., 2020). In contrast to attributional analyses, which focus only on a product's direct impacts, the consequential analysis also considers indirect effects.

Detailed processing and compilation of detailed data reports can be very extensive. The quality and explanatory power of LCA results are always a mirror of the quality of the input data. The analysis usually involves internal data collection, followed by analysis using powerful software and possible expert economic calculations.

Life cycle assessment procedure - The life cycle analysis process is very complex and demanding. LCA consists of two basic starting points:

1. anthropogenic load on the environment, which can be determined by counting sources and energy or the necessary inputs consumed at each stage of the product life cycle,
2. resulting in emitted pollutants and produced wastes or produced outputs.

Inputs and outputs are then assessed for adverse environmental impacts, in particular for the long-term sustainability of renewable and non-renewable resources, damage to human health, biodiversity loss, soil acidification, potential global warming, water pollution, air pollution and much more. With already-known assessments and calculations, appropriate measures can subsequently be taken to mitigate the environmental impact of the outputs (Muralikrishna & Manickam, 2017).

The traditional or process-based LCA methodology can be described by four interrelated phases, as shown in Figure 1: definition of objective and scope, inventory analysis of inputs and outputs, impact assessment and interpretation (SETAC, 2021). As the scheme suggests, there are several possibilities for applying LCA – policy making, development and improvement of products, strategic planning and marketing, and comparison of the impact of products or design choices assessment (Life Cycle Initiative, 2022). The arrows in Figure 1 indicate that the phases are correlated. Therefore, if there are unsatisfactory and missing parts in one phase, the other phases need to be reviewed and improved.

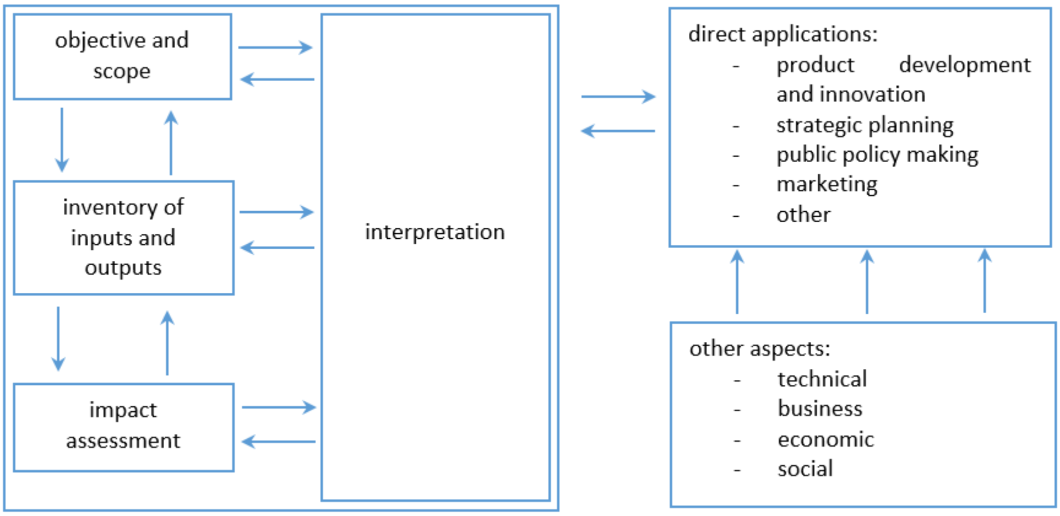

Fig. 1 LCA phases according to EN ISO 14040

Muralikrishna and Manickam (Guinées et al., 2011; Muralikrishna & Manickam, 2017; Jolliet et al., 2016) in the book Environmental Management describe the stages of LCA as follows:
Phase 1: Objective and scope - This phase defines how much of the product's life cycle will be taken into account and for what purposes it will be used. This step also describes the criteria used to compare the system and the specific times.
Phase 2: Input and output analysis - In this step, the inventory analysis provides a description of the required material and energy flows in the product life cycle, especially its interaction with the environment, raw materials consumed and emissions produced, or immissions.
Phase 3: Impact assessment - The details of the input analysis are used to evaluate the determined impact of the analyzed product. This step details the results of measurable indicators of all impact categories.
Phase 4: Interpretation - Life cycle interpretation involves critical examination, determination of data sensitivity and presentation of results.

In general, the life cycle consists of 5 main stages (Plevin et al., 2013; Bicer & Dincer, 2016):
Stage 1. Mining of raw materials - Pre-production is carried out by suppliers who usually draw on natural resources or raw materials and produce materials, components, and energy that serve as inputs for further processing.
Stage 2. Production - At this stage, the processing of input raw materials from suppliers, including energy consumption, into the final form of the product is included.
Stage 3. Transport - The transport of the product and the previous phase is provided by a specific company that sells the product to its wholesale or retail customers or directly to its consumers.
Stage 4. Consumption - The customer buys the product and continues to consume it. This phase is not directly controlled by the manufacturer but is strongly influenced by how the products are designed and the degree of the continuous interaction of the manufacturer.
Stage 5. Disposal / recycling - The product, which is no longer satisfactory due to obsolescence, degradation of components, or changed business or personal circumstances, is subsequently recycled or disposed of. All five previous stages affect the individual components of the environment.
Figure 2 briefly demonstrates the general life cycle of a typical product.

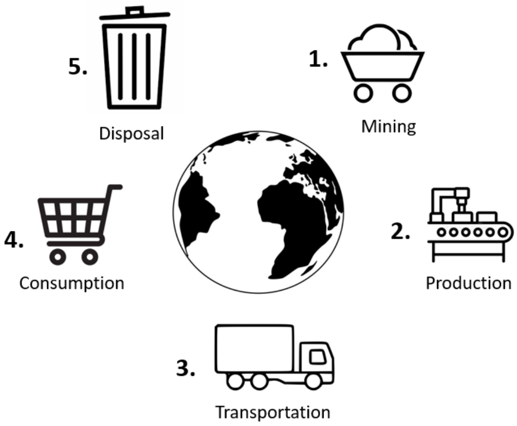

Fig. 2 Product's life cycle

Types of LCA - There are many types of LCA. As a rule, the more details we want to know about the process or product, the more complete and informative the analysis must be.

In the book Environmental management by Muralikrishna and Manickam (Guinées et al., 2011; Muralikrishna & Manickam, 2017) outline the following 5 types of LCA:

1. *Cradle-to-grave* is a type of life cycle assessment from the production (cradle) through the use phase to the disposal phase (grave). All inputs and outputs are taken into account for all phases of the life cycle.
2. *Cradle-to-gate* is an assessment of the partial life cycle of a product from production (from the cradle) to factory gate, i.e. before it is delivered to the consumer. The use phase and the disposal phase of the product are usually omitted in this type of assessment. This type of LCA "from cradle to gate" becomes the basis for environmental product declarations, for instance, the use of biofuels instead of fossil fuels during transport, cultivation in organic farming, etc.
3. *Cradle-to-Cradle* is a specific type of cradle-to-grave assessment where the end-of-life disposal step of the product is a recycling process. New, identical products (for instance, recycling textiles or clothing for fibres or fabric, etc.) or different products (for instance, glass wool insulation from collected glass bottles) come from the recycling process.
4. *Life cycle energy analysis* (LCEA) is an approach that takes into account all the necessary energy inputs of the product, not only the direct energy inputs during production but also all the energy inputs needed to produce the components, materials and services needed for the production process. LCEA determines the total life cycle energy input. In this case, it is also very important to know the energy source, whether from fossil fuels or renewable energy sources.

Fig. 3 Types of LCA shown in the product life cycle

Importance of the mining industry within LCA - A vital component of the economy, mining activities produce a wide range of goods, including electrical goods, construction materials, and automobiles. The mining and mineral processing business must supply Life Cycle Inventory (LCI) data related to its operations, i.e. data on the inputs and outputs linked with mineral extraction and subsequent refining, as LCA is used to assess the environmental implications of these products. It is in the mining industry's best interest to supply current, high-quality LCI data in order to maintain its competitiveness, given the sharp rise in consumer and manufacturing demand for life cycle information (Lesage et al., 2015).

The most comprehensive databases take into account the following mining-related activities: blasting, creation of the necessary mining infrastructure, use of chemicals in extractive processes, waste treatment, and energy usage during mining operations in the form of electricity, diesel, etc. Environmental inputs and outputs into the air, water, and soil are also taken into account. Mining infrastructure, blasting, land conversion, chemical inputs, and waste treatment are either entirely or only partially covered in less sophisticated databases. Even the largest databases sometimes leave out crucial information, including exploration and development activities, losses, location, and the elements that depend on the mining and processing methods and determine the kind of environmental discharges. Therefore, the mining sector is still responsible for providing more detailed information on its operations to raise the calibre of LCA results. Additionally, the majority of published mining LCA studies reveal that the evaluation of the mine operation receives the majority of the attention, while the extraction of mineral ore and the subsequent waste disposal part of the sector receive relatively less attention (Durucan, Korre & Munoz-Melendez, 2006).

In regard to energy efficiency, typically, a mix of diesel fuel to power mining equipment and transport material, electricity to power mechanical operations, and natural gas to provide heat energy during processing is utilized as the energy source for mining and processing raw materials (Farjana et al., 2019). Materials are often classified as being more or less energy-demanding throughout the processing/refining stage. Underestimating the average environmental consequences may result from doing an LCA that only considers expected emissions and energy usage in formal mining activities. If the operations are informal, accurately documenting these impacts might be difficult because the majority of LCAs on raw material extraction and processing rely on data supplied by significant mining corporations (Farjana et al., 2019)

The majority of published LCAs have included thorough information on the effects of raw material extraction and processing on the environment. The extraction and processing of raw materials have two drawbacks. In the first place, the research did not fully consider regional differences in mining techniques and exposure risk for adjacent communities. Due to regional circumstances and practices, some mining operations that account for a small portion of output are likely to contribute a disproportionate amount to total environmental consequences (Alvarez et al., 2018). Second, the underlying impact and midpoint approaches have built-in constraints. Studies rely on regional or global average components that are probably one or more orders of magnitude off from the real values because no LCA can do comprehensive fate and transit modelling for every emission to air, soil, and water (Porzio & Scown, 2021).

The lack of data about the locations of various waste streams released from mining and material processing operations exacerbates these difficulties. Additionally, not many researches examine the variations between average, marginal, and incremental sources of essential material inputs, as well as the ramifications for energy usage and emissions associated with mining and processing. The data and market predictions that are now available might fill what appears to be a clear vacuum in the literature (Porzio & Scown, 2021).

Benefits of life cycle analysis - The concept of the LCA environmental instrument has become widely accepted as a model for assessing the environmental impacts of products and services. This is evidenced by the adoption of life cycle assessment in legislation, product certification and sustainability standards. LCA is also used to describe the benefits associated with alternative products and services that contribute to climate change mitigation, both in the literature and in environmental policy-making reports (van der Meer, 2018).

The life cycle analysis approach enables product designers, service providers, government officials and consumers to make long-term decisions, taking into account all components of the environment (air, water, soil, biota). In many cases, LCA prevents the transfer of problems from one phase of the life cycle to another, from one geographical area to another, and from one environment (such as air quality) to another (such as water or soil quality). Many decisions in practice are already based on a lifecycle approach, such as consumer decisions when purchasing products through eco-labels or company reports on environmental issues, commercial design of products and services through lifecycle assessment studies, total product or management system calculations, government policy-making through the involvement of a wide range of stakeholders or through integrated product policy (IPP) approaches (Life Cycle Initiative, 2022).

The benefits of LCA studies can be listed as follows (van der Meer, 2018; Life Cycle Initiative, 2022; Muralikrishna & Manickam, 2017):

- environmental sustainability of products and production systems can be measured and managed throughout the varying life cycle phases

- determining the important environmental impacts of products during every part of the life cycle
- determination of environmental effects and hot spots that contribute to them at each stage of production processes
- helping decision-making process for potential improvement and investments
- comparing the sustainability of products in production and implementing improvements
- encouraging demand for products with the less adverse environmental effect
- guiding in the preparation of sustainability plans; managing risks and potential liabilities
- optimizing supply processes
- providing trust to stakeholders
- gaining competitive advantage
- assisting environmental management projects in decision-making and integration processes
- increasing return on investment

Using the LCA method can help in the following cases (Veeramanikandan et al., 2017; Guinées et al., 2011):

- finding the most accessible and efficient alternatives with a minimal negative impact on the environment,
- decision-making in industry, non-profit organizations or non-governmental organizations, which sets the direction and priorities in strategic planning, product design or process change,
- select important indicators of the organization's environmental performance, in particular in relation to the assessment of the state of the environment around the organization,
- Government initiatives will not only secure and strengthen the position of industry and the services sector in regional and global markets but will also ensure overall environmental benefits for society (balanced by economic and social aspects). Furthermore, governments can demonstrate global responsibility and support for the concept of sustainability by participating in various support programs and initiatives and implementing lifecycle approaches.
- consumers will be provided with more relevant information on purchasing, transport systems, energy sources, etc.,
- marketing with reference to the wording of environmental statements or eco-labels.

By determining the best available data and understanding the appropriate use of LCA, experts and researchers can help business managers, as well as governmental and non-governmental organizations, implement appropriate policies that will lead to effective environmental policies, including strategies to mitigate climate change and other environmental issues.

Traditional LCA can be extended by including the economic effects of the product. Economic input-output models focus on the economic aspect of the product's life. It represents monetary transactions between separate industry sectors, which are presented in the form of a matrix, where rows and columns represent industry sectors, and their intersection means an economic value of output from one sector and input to the other. Through EIO, it is possible to study the direct and indirect effects of changes to the economy and thus is often used to identify changes in the structure or nature of the economy. EIO can be supplemented by an additional column that represents the industry sectors' environmental output, thus creating a more complex life cycle assessment (Leisch, 2022).

A number of workable methods for calculating costs and performances have been developed to evaluate economic sustainability (Finkbeiner et al., 2010). Similar to an LCA, an LCC calculates all costs and benefits related to the product under investigation to quantify the economic elements over the whole life cycle. Potential economic hotspots can thus be found in this way (Melo et al., 2020). LCC operates within the same system limits while concentrating on products' financial implications (Kicherer et al., 2007).

It is important to consider both environmental and social product enhancement in the present context of sustainable development and responsible production and consumption (Huarache et al., 2020). The Social Life Cycle Assessment (S-LCA) is a frequently employed instrument for evaluating sustainability in the social sector (Thies et al., 2019). Using the S-LCA, social shocks are evaluated along the whole value chain of the product based on a chosen set of social qualities. In this life cycle stage, activities relating to the social component are included, from extraction through the final disposal stage (Elhmoud & Kutty, 2020).

An S-LCA is built on subcategories that are connected to various stakeholder groups through impact categories. These subcategories include topics or characteristics that are important to society, such as child labour, poor working conditions, corruption, or pay. They are divided into groups according to how they will have an influence, such as on human rights, health and safety, or socioeconomic effects. In order to assist a systematic effect assessment and interpretation by the stakeholders, impact categories are used to define subcategories within groups that have comparable consequences. The stakeholders are different social actors who are impacted by social consequences throughout the product life cycle, such as the local community, customers, employees, or society as a whole (Melo et al., 2020).

LCA application in the aviation industry

As in many other industries, the LCA methodology found wider popularity in the assessment of the environmental impact of the aviation industry. When we talk about LCA application to aviation, the concept should combine environmental, social and economic aspects of all direct and indirect activities that come together to create the end product that is being offered to the customer. It was suggested that the environmental assessment of aviation should focus not only on the transportation process itself but should rather take into account all the infrastructure and supply chains needed in the process. Multiple studies employing LCA methodologies were already conducted focusing on separate aspects of the aviation industry, such as aircraft, engine and components manufacturing, aircraft maintenance and operations, UAVs, and emissions emitted during aircraft operations or passenger services (Greenly, 2022).

Emerging aircraft technologies are receiving more attention as a result of worries about the future of aviation and the ongoing expansion of air transportation. Although emerging technologies, such as battery-electric propulsion systems, offer the potential to reduce in-flight pollutants and noise, environmental responsibilities may be transferred to other phases of the aircraft's life cycle, and new socioeconomic difficulties may materialize. The identification of key issue shifts and hotspots, as well as the formulation of early-stage action suggestions for aircraft development, call for a life-cycle-oriented sustainability evaluation. Contrary to road traffic, aviation-related CO_2 emissions are expected to double or triple until 2050 unless significant modifications are made due to the long lifespan of aircraft. The aircraft industry is also criticized for a number of other effects, such as noise pollution, particularly near airports. Auxiliary power units, ground support equipment, and fuel burn emissions from airport shuttle services are a few examples of sources (Melo et al., 2020).

Regardless of their extent, all LCAs must start with the extraction of raw materials. First off, the mining of raw materials, building, operation, maintenance and decommissioning of the airport are the primary components of an airport's life cycle that are being considered. The exploitation of raw materials has additional environmental effects (Porzio & Scown, 2021). The material and energy streams related to the construction of sealed areas at airports, such as the parking, runways, and other amenities, are included in these life cycle stages. The material and energy streams related to the development of the necessary buildings are also taken into account. Additionally, the airport's operation and maintenance life cycle stage involve the use of both power and heat as well as water. The airport's energy infrastructure, as well as its energy usage, needs to be taken into account. Also taken into consideration are the transportation options at the airport (Siddiqui & Dincer, 2021).

The following stages of the fuel life cycle are the manufacture of the feedstock needed for a certain type of fuel, followed by fuel production and transportation. According to Zhang et al. (2022), the comparatively advanced mining methods resulted in low energy consumption of fossil fuels during the feedstock stage. Due to its highly developed and straightforward collection and processing technologies, coal uses between 50 and 30 per cent less energy than natural gas or crude oil. The aircraft transportation sector requires fuels with high energy densities, making liquid hydrocarbon fuels the main supply source. Alternative aviation fuels must contain certain qualities such as good cold flow properties, thermal stability, and low freezing point. The fuel must be properly suited to the aircraft engine's existing design. Sustainable jet fuels should have minimal carbon emissions throughout their entire life cycles (Bicer & Dincer, 2016). The extraction of raw materials and processing of fuels, the production of material inputs, and facility operations are the life cycle phases and processes that are included for the generation of the reference flow in each system's baseline scenario (Young & al., 2019). CO2 emissions should be evaluated with other sustainability criteria, such as social implications, local food security, biodiversity preservation, soil impact, water and waste management, air quality, and direct and indirect land-use change (LUC) consequences. The production and transportation of auxiliary chemicals, the conversion process, and the storage, distribution, and combustion of fuel are all included in the boundaries for the LCA study of SAF. They also include the cultivation, harvesting, and transportation of the feedstocks, as well as the associated LUC. The crops used to produce energy should not interfere with the production of food or the ecology, harm the atmosphere, or result in deforestation (Bicer & Dincer, 2016; Michaga et al., 2021).

When we take electric aircraft into consideration, it takes much energy to mine and refine battery materials and manufacture battery cells, modules, and packs, and this might result in GHG emissions that are so high that utilizing electric aircraft instead of conventional ones would have less of a positive climate impact. Most of the studies related to the sustainability of batteries used in vehicles either reference prior research or use data from academic or commercial LCA material data sets, typically constructed using modelling instead of looking at the real energy used in the process of extracting and refining materials. As a result, no study on the life cycle of batteries has included any fundamental information about the mining or refinement of battery resources from actual manufacture. Additionally, it indicates that, depending on the database utilized, there may be as much as a 100% difference in the material values and actual availability of accurate information for the many speciality chemicals used in lithium-ion batteries (Melin, 2019). For example, prior battery LCAs have taken into account the risk of ozone depletion, acidification, eutrophication, and human toxicity. The majority of studies capture the appropriate locations and local grid mixes for raw material extraction and processing, but battery manufacturing has largely been modelled based on grid mixes and primary fuel choices appropriate for the location of the study rather than the most likely manufacturing location. This is the final criticism of battery LCAs (Porzio & Scown, 2021).

The stages of the aircraft's life cycle are also taken into account. This basically comprises building, running and maintaining aeroplanes. These facts cover the material, energy, and water fluxes related to the production process. Additionally, the total life cycle includes the transportation of commodities by both rail and road. Additionally, the energy needed to get deionized water needs to be taken into account when calculating power use. Moreover, the manufacturing facility's infrastructure could be taken into account, as well as the transfer of various aeroplane components from various production facilities. For this procedure, the amount of fuel used and the airborne pollutants are very important. There are three basic categories for where airborne emissions are located: low population density areas, stratosphere, and unidentified regions. The inventory data includes consumption of a chosen fuel, which in usual applications is jet fuel kerosene, as well as direct air emissions of gases, particulates, and heavy metals. The outcomes display the typical fuel usage and emission data brought on by a typical flight (Siddiqui & Dincer, 2021).

Although LCA has already been widely used for the assessment of separate components of the aviation industry, the representation of the full LCA for air transport, due to its high complexity and a high number of elements that need to be taken into account, is so far absent in the academic literature. In the following figure (Fig. 4), we present the elements' structure that should be considered if we wish to conduct the overall life cycle assessment of air transport.

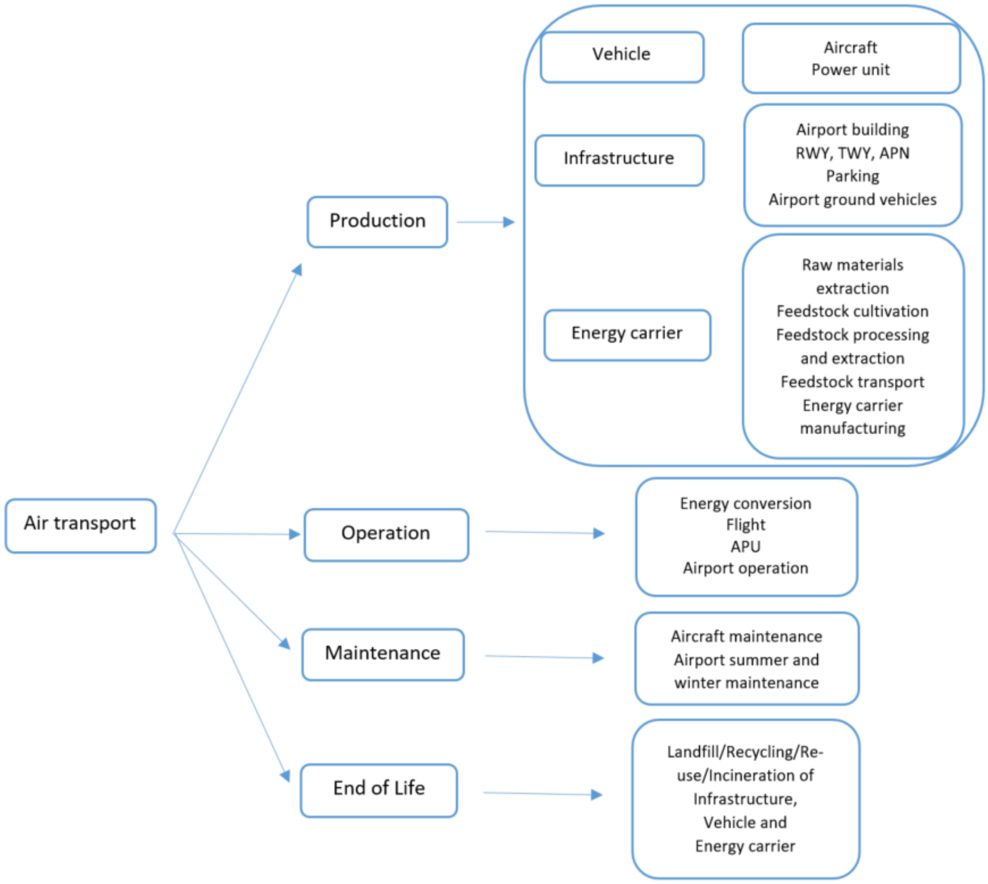

Fig. 4 Life cycle of air transport

When creating the LCA model for air transport, we need to look at several components which constitute the life cycle of every transport industry, namely production, operation, maintenance and disposal. As we can see from the scheme, air transport environmental impact assessment can be divided into four phases, each of which focuses on three main impact actors – vehicle, infrastructure and fuel or energy carrier. There are several key issues that need special focus. The first stage focuses on extracting the raw materials required for the construction of aircraft structures, the construction and exploitation of airports, and fuel production. It is important to include not only all the emissions emitted directly or indirectly during the production but to take into account also all the other direct and indirect environmental effects (for instance, effects of crude oil extraction, side effects of cultivation of feedstock for alternative fuels, impact of airport on the land use). In the operational phase, it is important to differentiate where most of the pollutants are emitted, as emissions at different altitudes have different types of environmental impacts. The third phase includes all the maintenance of the aircraft and airport area, where the environmental impact is not only about emissions and other pollutants, such as chemical substances used during the maintenance, that need to be considered. It is important not to forget about the last stage of LCA, as the disposal phase has a significant impact too.

The relevance of the operation phase may shift to the extraction of raw materials or increase the influence of the energy supply chain, for example, even though emissions from aircraft operation can be significantly reduced (e.g., by reducing the weight and subsequently the fuel consumption through the use of composite materials). Therefore, identifying environmental hotspots and their linkages with socioeconomic views is essential to determining the true improvement potential of future technologies in aviation. The extraction of raw materials for batteries involves crucial procedures, as is well-known from related sectors, and this must be taken into account in the sustainability evaluation (Melo et al., 2020).

Economic aspect - Both via its own operations and as a facilitator of other industries, the air transportation sector has a considerable economic influence (Lakshmanan, 2011). There are two levels of economic impact: the first level results from the creation of employment, income, and capital investment that "naturally" happens during the production of air transportation services, and the second level of impact is the dynamic economic "catalytic" or "spin-off" benefits, in particular the direct/inward investment including tourism development that is sparked by aviation. There are four separate categories for the effects caused by air travel: direct, indirect, induced, and catalytic (TRB, 2021).

The total number of jobs produced as a result of the region's air transport activity represents the direct contribution of the air transport industry to the national economy in terms of employment (jobs created) and GDP (income generated). The air transport activity includes activities that directly benefit air travellers, such as check-in, security services, luggage handling, on-site shopping, and catering. It also includes activities related to airport operations, aircraft maintenance, air traffic control, and aircraft repair. The total number of jobs in the area supporting the air transport industry, such as those associated with aviation fuel suppliers, facilities management and construction firms, vendors of goods sold in airport retail stores, and a wide range of other supporting activities related to the air transport services sector, are used to calculate the indirect contribution of air travel (Dimitrios, Mourmouris & Sartzetaki, 2017).

The revenue produced through the investments and consumption made by direct and indirect employees is referred to as the "induced impact." Induced contribution, therefore, accounts for the secondary effects on the economy, such as direct and indirect sales, and payroll effects are transferred to auxiliary industries via multiplier effects. Catalytic impact measures how much an air travel sector contributes to the national or regional economy in addition to any consequences that are directly or indirectly related to the air travel business. There are numerous and diverse sources of catalytic economic impact for air travel, encompassing the majority of business and tourism (Dimitriou & Sartzetaki, 2018).

Social aspect - Even though LCA was widely used for the assessment of the environmental impact of the industry, and subsequently, it was supplemented by economic aspects, social components are generally omitted from the impact assessment. The S-LCA methodology makes it possible to create an analysis of positive and negative social impact during the whole life cycle of the products, taking into account socially important themes or aspects as social indicators. Social aspects need to be observed and recorded along all the phases, from mining and processing raw materials to the final disposal. The resulting social impacts are seen as the effects of these activities on the stakeholders (CMU, 2022).

As with the traditional LCA, the first step is the definition of the goal and scope for the analysis, and the second is the inventory analysis, therefore, the data collection. With the S-LCA, the important part is the identification of relevant stakeholders along with the indicators. In the following table, we provide the overview of key stakeholders that we identified would be important to consider when conducting social impact analysis as part of the wider life cycle analysis. Among the most relevant stakeholders for air transport, we identified aircraft manufacturers, airlines, airport operators, political decision-makers, passengers and the local community that lives near the production sites or airports. We listed the categories they are most interested in for all of the stakeholders. Subsequently, we created the stakeholder matrix (Figure 5), where we listed additional stakeholders that should be kept in mind while conducting S-LCA, and we sorted them into four categories along the power/interest axes. If they wish to follow the S-LCA, the last step is the evaluation and interpretation, where the interests and objectives of different stakeholders need to be taken into account.

Table 1 *Main stakeholders in the aviation*

Stakeholder group	Interests
political decision-makers	- legislation - taxation - standards - human rights - working conditions - health and safety
aircraft manufacturers and airlines	- customer satisfaction - safety - costs and revenues - situation on the market - competition
passengers	- high comfort - noise emissions - cost-efficiency - own well-being - safety - number of destinations
airport operators	- customer satisfaction - market behaviour - other market actors - costs and revenues - maximum traffic volume - maximum destinations served - safety - relations with airlines
local communities (in the vicinity of airports, mining areas, production sites)	- noise pollution - local safety issues - economic prosperity

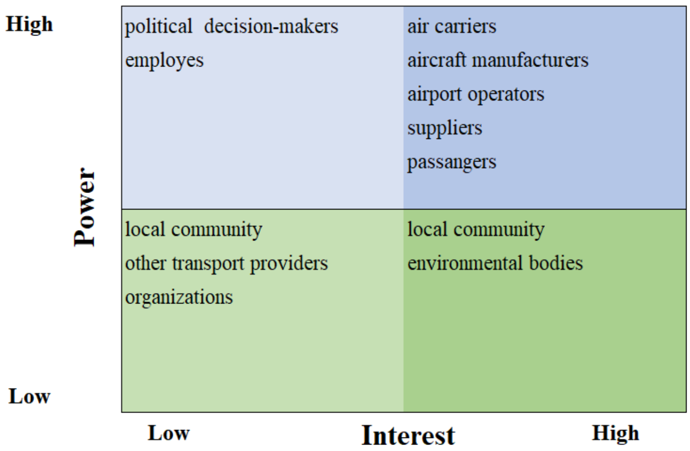

Fig. 5 *Stakeholder Matrix*

Social problems can also appear early in a person's life cycle. In addition to the issue of embedded GHG emissions, lithium-ion batteries are frequently linked to regional issues with localized resource exploitation, including both environmental and human issues. The batteries used in electric aeroplanes are made up of crucial and rare elements mined in developing nations with a high risk of corruption, child labour, and unfavourable working conditions. Particularly artisanal mining in the Democratic Republic of the Congo, with confirmed child labour and forced labour involved as well as environmental issues in the regions in South America where lithium is produced, has been the focus of attention (Melin, 2019). As an illustration, Similar to this, growing adequate feedstocks for biofuel production puts food production in competition and may cause issues with nearby populations (Melo et al., 2020).

Air travel and economic development are intertwined because aviation has a large direct and indirect impact on the economy and accelerates the economic cycle. According to conventional opinion, a useful instrument should be available to generate quantitative estimates of the socioeconomic impacts of air travel (Dimitriou & Sartzetaki, 2018).

Conclusion

In recent decades, we have witnessed numerous applications of LCA to support decisions in the context of environmental sustainability. Significant efforts have begun to facilitate the application of LCA and life cycle thinking in society from the regulatory and government level, through industry and manufacturing, to the citizen and consumer level. The main strength of LCA is its comprehensiveness in terms of life cycle perspective and coverage of environmental issues. This enables the comparison of the environmental impacts of product systems consisting of hundreds of processes, representing thousands of input sources and produced emissions that occur in different places at different times. Therefore, we can describe the LCA methodology as a valuable source of information for producers and consumers.

There is a crucial need to analyze the environmental impacts of air transport along the whole production, operational and supply chain. In the present paper, we first present the LCA methodology with its different types and process, as well as the benefits that can come from employing this method of environmental impact evaluation. At this point, we can say that while all the stages of the LCA should be equally important, most of the studies concentrate on the middle stages – production, transportation and consumption, while disposal and mining stages are very often neglected, even though, amount of emissions from these stages can cause significant differences when evaluating the sustainability of the products. In the second part, we present a possible structure which should be followed if we wish to conduct the complete LCA of the aviation industry as a whole, which is so far absent in the academic literature due to its complexity. We have created a model that considers all four phases comprising air transport – production, operation, maintenance and liquidation. Therefore, all direct and indirect environmental impacts are accounted for in this model. Moreover, it is highly important to take into account also a social aspect that has been omitted so far from the operations of air transport. Therefore, we identified the most relevant stakeholders along with their interests in the aviation sector and put them into the power/interest matrix. The most relevant actors with the highest interest/power ratio were identified as airlines, airport operators, aircraft manufacturers, suppliers and passengers. These are the groups that are the most important and whose interests should be taken into account when implementing new standards for air transport.

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