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Emissions of future conventional aircrafts adopting evolutionary technologies

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ABSTRACT

The current aviation sector has been shaken by COVID-19, but a few years prior, the industry was experiencing a time of prosperity never seen before. These years were marked by the introduction of new models and record sales. In particular, two cases stood out from the rest: the Boeing 737 MAX and the Airbus A320neo. Such overwhelming success in sales was partly because in essence, these are quite traditional and familiar aircrafts that featured improvements in some critical systems, notably in the use of newer engines. Current projections suggest that the pre-COVID growth rate of aviation will resume in a few years, which raises global concerns regarding the ecological burden of conventional aircraft and their resulting limitations. By reviewing the green technologies likely to be incorporated into conventional aviation over the next 30 years, we explore the limits of the industry's current approach. To this end, we reconstruct an already validated life cycle analysis model to assess a fleet of aircraft and analyze the impacts of these new technologies on emissions. Based on data from the literature, predictions are made for optimistic and pessimistic scenarios in a post-COVID world. The results are compared with the globally established targets set by the International Air Transport Association (IATA). Simulations show that a future based solely on conventional aircrafts using evolutionary technologies is of great concern. There is a need to promote a radical departure from the current aviation models to accommodate the growing demand for aviation with a green future.

1. Introduction

We are experiencing a unique moment in the aircraft manufacturing industry, a sector that was shaken by the COVID-19 pandemic (Mhalla, 2020; Nizetić, 2020). Prior to the pandemic, the commercial aircraft aviation industry was experiencing golden moments of high demand, which led to a significant aircraft production backlog (Price, 2018). The market perspective was that the demand for airplanes would continue to grow (Nizetić, 2020). This scenario of high demand prompted the development of new aircraft along with the modernization of older aircraft models to reduce fuel consumption and the environmental burden caused by air travel. One notable example was the Airbus A320neo (New Engine Option), a relatively simple modernization project that cost slightly more than \$1.3 billion. As the name implies, the main objective of this project was to adapt the frame of the highly successful A320 to accommodate two new engine options to improve fuel consumption performance (Mrzova, 2013; Sato et al., 2014).

Compared to other aircraft design projects that preceded it, the

A320neo project was not only simple but also commercially successful. In 2011 alone, the year after the program was launched, Airbus was awarded orders to supply 1226 units of the A320neo (Airbus, 2012). The aircraft was also well received by the public, in part due to the model's low environmental burden (Budd and Suau-Sanchez, 2016; Jupp, 2016b). Engine operation, particularly during flight, causes the dispersion of greenhouse gases as well as soil and water pollutants. Compared to the previous generation of the A320, it is estimated that the A320neo emits 50% less nitrogen oxide (NO_x) with 75% noise reduction and a 16% reduction in fuel consumption (Pratt and Whitney, 2020). This reduction in environmental impact through less pollution further increased the public's fondness for the model (Çabuk et al., 2019).

The A320neo project was so successful that it prompted a rapid response from Boeing, which launched the Boeing 737 MAX project (Leeham, 2019). However, the MAX was involved in two highly visible disasters, which was unusual for a new project (Tegler, 2019; Welch, 2020). The crashes of brand-new B737MAX aircraft representing the Lion Air and Ethiopian Airlines liveries led to the grounding of

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unprecedented proportions of aircraft (Sgobba, 2019; Travica, 2020). It is alleged that the B737MAX project was rushed to production so that deliveries could start not long after the introduction of the A320neo, well-positioning Boeing to compete (Johnston and Harris, 2019; NYT, 2019). Boeing's reaction illustrates the impact of the A320neo project, i. e., a classic airframe with a more sustainable footprint. This case is particularly important in aviation not only because the aircraft broke sales records and forced Boeing to make mistakes that were not typical of the company but also because it demonstrated that the public and airlines alike are eager to stick with classic airplanes while incorporating newer and more efficient technologies.

In comparison, more innovative projects were not as successful, such as the gigantic double-decker Airbus 380 and the highly advanced and composite-rich Boeing 787 Dreamliner. The A380 was discontinued in 2021, and it has been said that the complexity of the Dreamliner project meant a massive development cost of \$15 billion and cumulative losses of \$30 billion to build the initial run of 500 aircraft (Kesore, 2019; The Motley Fool, 2018).

In aviation, it appears that the most successful projects have been those consisting of incremental modernizations. However, extending the use of classic platforms raises long-term concerns about the industry's ability to maintain financial prosperity while reducing its environmental footprint. It is deemed too risky and costly to drop already established platforms to introduce entirely new concepts. By adopting incremental improvements, the industry benefits from existing aircraft certifications, a mature supply chain network, a trained workforce, manufacturing and sustainment infrastructure, common parts, and auxiliary equipment. For a large industry such as aviation, this strategy is quite concerning, as small changes can provide only small improvements and thus have limited ability to reduce the environmental burden of aircraft. In addition, the environmental impact of aircraft produced and sold today should be examined in terms of their life cycle because they are poised to remain in service for 20 or more years. One could argue for the need to change the paradigm of aircraft design to enable a green revolution. However, this is unlikely to happen in the short or medium term.

Unlike passenger cars, we cannot count on the short-term electrification of passenger airplanes. The first commercial electric passenger flights are forecast to be available no earlier than 2030 (Reuters, 2018). Furthermore, the success of commercial flights using electrical planes is hard to foresee considering the industry's resistance to changing from mass-produced classic platforms and the technical hurdles that would follow such change. For instance, there is much work to be done in terms of battery technology to store the amount of energy necessary to propel medium to large airplanes on nonregional routes (Trainelli et al., 2019, 2020).

In addition to electrification, to achieve sustainable aviation, another revolutionary technology being researched is a general change in aircraft configuration by eliminating surfaces that are not dedicated to lift generation. In a classic aircraft, we have a dedicated cylindrical fuselage to accommodate passengers and cargo. The fuselage is the aircraft's largest contributor to aerodynamic drag, but in a conventional design, it is responsible for only a small amount of the total lift. In the "blended-wing" concept, the entire plane has an aerodynamic function, as the cargo and passenger compartments are extensions of the wings. Even though this revolutionary concept introduces great gains in efficiency and passenger capacity (Muta'ali et al., 2020; Okonkwo and Smith, 2016), there are many issues with the feasibility of such a design, and hence, we are not aware of a reliable timeline for the introduction of this concept into commercial aviation.

Because we will have to live with conventional aircraft layouts for the foreseeable future, if the design of future aircrafts is not optimized from the early stages of the project for lower impact over its lifecycle, the environment will suffer greatly, and the growth of aviation might be limited by the environmental burden of the continuous use of such aircrafts. In this study, a model to assess the emissions of a fleet of conventional aircrafts is used and adapted to incorporate the

characteristics of a hypothetical fully optimized aircraft with evolutionary technologies to find the lower bound of the conventional aviation environmental footprint. Such a model would help identify the limits of the current approach to achieving sustainability. To the best of our knowledge, no previous study has tried to estimate the limits of the conventional design to reduce the environmental burden of this industry.

To address this research gap, the rest of this article is structured as follows: Section two discusses the importance and challenges of considering the entire life cycle in design studies for a greener airplane and how technological improvements should be incorporated into commercial aviation to obtain the best effective reductions in the sector's real environmental footprint. In section three, we perform a qualitative review to determine what key technologies on different fronts could be incorporated into a greener conventional aviation project. Finally, in section four, we perform numerical analyses of emissions and simulate scenarios where we introduce the green technologies identified in section three into the industry in a manner similar to what is recommended in section two.

2. Conventional aircraft designs and a greener industry

As discussed in the introduction, aircraft design will most likely continue to adopt the existing layout (a long tube with wings powered by combustion engines) in the foreseeable future. Therefore, in this section, we discuss the importance of optimizing the design in the early stages of a project and considering the entire life cycle in the environmental studies of such aircrafts. We also discuss how the implementation of new technologies affects the industry footprint and the need for concerted action among industry leaders in the implementation of those technologies to obtain significant results.

2.1. Design of greener conventional aircrafts

Under the term "eco-design", product development philosophies aimed at minimizing environmental impacts, such as design for the environment (DFE) and design for recycling (DFR), have proliferated across various industries (de Aguiar et al., 2017; Ferrer and Whybark, 2001; Liu et al., 2002). The design phase of an aeronautical project is crucial for the development of more eco-friendly aircraft. It is at this phase that critical parameters, such as part design, material selection, manufacturing techniques, assembly processes, and the use and disposal of the aircraft, are defined. For this reason, the best techniques for reducing the environmental impact of the final product should be adopted at the beginning of the project (Graedel and Allenby, 2010; Knight and Jenkins, 2009). Although most of the impact is during product usage, product development determines and locks the design, design defines usage, and usage drives the environmental impact (Fig. 1).

Green marketing in aviation often leads to the interpretation that the eco-friendliness of an aircraft is determined by the source of energy used in its power plant. However, this interpretation is erroneous because even electrically powered aircraft would need rigorous assessments of millions of parts made from various materials with their own environmental impacts. The development of a conventional commercial airplane lasts approximately six years and involves the design of up to 6 million parts (Sim et al., 2018). Once a commercial aircraft is acquired and brought into service, it stays in use for a long time, often more than 20 years (Flüthmann et al., 2020). For complex products with long life cycles, it is important to consider all the different steps in the development process, from product design to market introduction, to ensure the delivery of an eco-friendly product. One strategy to improve the environmental impact of an aircraft is to perform a product breakdown with a thorough analysis of each component. For example, the environmental footprint due to the material extraction of an airplane is the sum of the footprints due to the material extraction of each component. The design

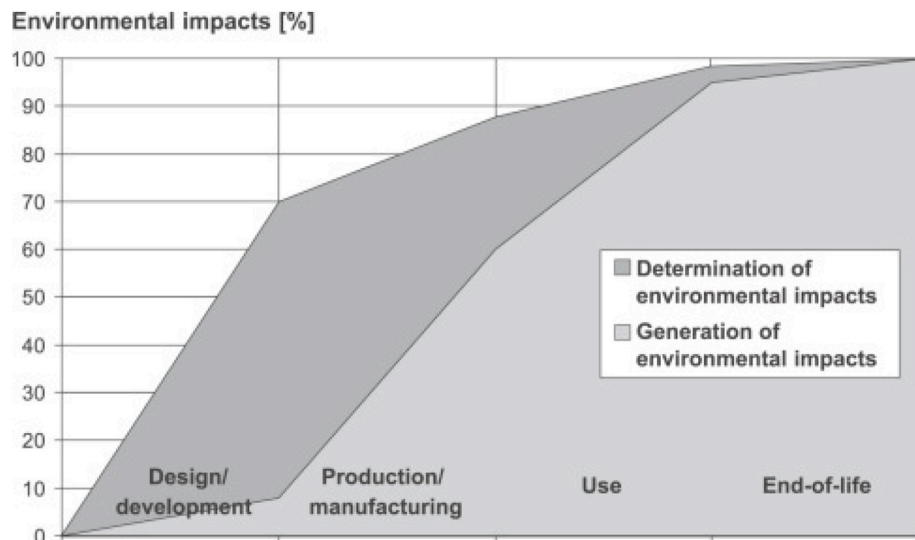


Fig. 1. Environmental impacts in each phase (Rebitzer, 2002).

of each part must be studied individually, and if possible, the use of renewable materials should be preferred (Vieira and Bravo, 2016a, 2016b).

The design and material choice of a part determine its recyclability. In the design phase, it is important to assess whether the recycling process can be cost-effective using conventional technology. Each component of the aircraft has its own impact from its extraction, processing, fabrication, and assembly to disposal at the end of its useful life. Therefore, when designing a new project, integrated design must be carried out, including product life cycle analysis (LCA), which is a rigorous approach used to evaluate the environmental footprint (Calisir et al., 2020). Typically, the operator and passengers are not aware of the efforts to reduce the use of nonrenewable resources. In new conventional airplane projects, considerable engineering effort must go into the development of the most efficient airframe and a mechanically sound design using fewer nonrenewable materials.

2.2. The need for collective industry action

In the initial design phases of an aeronautical project, LCA is crucial to determine the environmental burden of the aircraft. However, the efforts of just one player in the industry might not be sufficient. As previously discussed, an aircraft as a final product is composed of myriad subproducts or parts that may fail or have a longer life than the whole. Once in service, the aircraft undergoes several cycles alternating usage, storage, and maintenance, and these cycles repeat until the aircraft is no longer competitive or its repair is no longer justifiable. An aircraft may reach the lifespan that was expected in the initial design, so withdrawal from service is natural. However, predictions can be wrong. The user may stop the exploitation of a model earlier for a variety of reasons. It may be too expensive to keep the product operational, or the competition may downgrade the product's value due to the existence of more modern and economical aircraft.

In any of the situations above, the operator is at a significant disadvantage if it continues to exploit an outdated aircraft (De Brito et al., 2009; de Oliveira Junior et al., 2020). A strategic analysis of the airline may determine that it should be removed before or after the time originally planned. Therefore, the so-called "end of life" (EOL) for an airplane model may vary drastically due to wear and tear or due to strategic decisions by the operator. The time of equipment retirement is variable, and the fate of the aircraft parts depends on their market potential. Some parts can gain a new life if they are in good condition, can be removed intact from the retired airplane, and are sold in the

second-hand market for another aircraft (Keivanpour and Ait Kadi, 2017; Kilpi et al., 2009). Second-hand parts are integrated into other planes because if a specific component of another aircraft fails, using a part in good condition from a plane that is retired is usually the most economical alternative. Likewise, it is possible to extend the use of an old aircraft by renovating its interior (Vink, 2016; Vink et al., 2012).

As it is possible to see, the LCA modeling of the conventional aviation sector can be highly challenging and complex. Several assumptions are necessary to handle all the different scenarios, as each fleet, and even each airplane, will be managed differently during its lifetime. However, one assumption that could be used to greatly simplify the LCA modeling of the commercial aviation section and make it much more straightforward is to consider that the changes in the sector occur homogeneously as a result of the collaborative action of the different industry actors. This is much more than a simple workaround; it is actually a considerably important factor for the sector to achieve actual meaningful results in its real environmental footprint reduction. This is because logically, even if more technologies being introduced into the aviation industry increases the potential for reducing emissions, the actual change in the footprint is greatly minimized if there is no collaborative action in its introduction by the industry. Henceforth, this article assumes that changes in airline fleets are made in a homogenous fashion and that technologies are simultaneously adopted by all fleets. Therefore, the predictions here are optimistic because they assume a scenario in which all players in the industry adopt green technologies in the development of next-generation conventional aircraft at the same time.

3. Green technologies for conventional aircraft projects

In the previous section, it is established that for the commercial conventional industry to be able to produce relevant impacts on the reduction of its environmental burden, the sector must adopt new technologies in a coordinated manner. In this section, we perform a qualitative review to identify trends in technologies in different areas that can be used to improve the life cycle of conventional aircrafts and are likely to be incorporated in future projects.

3.1. New materials and fabrication processes

To improve aircraft fuel consumption and reduce emissions, it is necessary to optimize the mechanical property-to-weight ratio. For this purpose, the trend is to design a new aircraft with the widespread use of

composite materials because such materials can have high tensile strength, ductility, shear strength, toughness, and impact resistance while being lightweight. A composite material is a mixture of two nonsoluble constituents, chemically different and with different physical properties, that acts at the macroscopic level as if it were just one material (Bosacka and Zienkiewicz-Strzałka, 2020; Ozkan et al., 2020).

Composites that make use of plastic materials as a matrix have the most applications in aeronautical projects (Bachmann et al., 2018; Bielawski, 2017). In this case, a polymeric resin is used as the matrix, which can be made of either a thermoplastic or thermoset polymer. The main characteristics of thermoset polymers are their high temperature and mechanical and chemical resistances. The most commonly used matrix in thermoset composites is epoxy, while the most common synthetic fibers are carbon and glass (Bachmann et al., 2018). Fiberglass has good tensile and compressive strength and good impact resistance and is easy to work with. It is relatively inexpensive and widely available. However, carbon fiber is generally stronger and more resistant to traction and compression, has greater flexural capacity than fiberglass, and is considerably lighter.

The use of more renewable materials is another expected trend in future aeronautical projects. This is already the case for the automotive sector, as some companies are carrying out development projects for car interiors using similar materials (Akampumuza et al., 2017). Promising results have been obtained in the development of new composites made entirely from renewable materials, such as polyethylene made from sugar cane, to be used as the matrix, while natural hardwood fibers are used as reinforcement (Bravo et al., 2015, 2018). These results show where it is possible to consider the use of such thermoplastic composites in applications with very high structural and thermal requirements, such as in mechanical gears. There is high potential in aviation to use such materials to make the cabin's interior lining, seats, and bins. Furthermore, for other parts of the aircraft, new sustainable composites of bio-epoxy combined with natural fibers were recently successfully developed and have the potential to be a greener alternative to replace traditional composite materials used in aviation (Vinod et al., 2021a, 2021b).

While the trend involves aeronautical projects incorporating more sustainable composites, it is inevitable that some parts of the airframe will continue to be manufactured using traditional metallic materials. In this case, the trend is to use manufacturing processes that have less impact on the environment, such as friction welding. This is a process where a rotating nonconsumable tool is positioned between two sheets or plates of materials to be welded, resulting in little distortion, great dimensional stability, and little residual stress (Kuritsyn et al., 2020). This process consumes little energy and produces minimal if any material waste. Thus, considering that it causes the minimal release of toxic gases into the atmosphere and does not require the use of shielding gases, this process has a lower environmental impact than other welding methods (Li et al., 2016). Furthermore, when using friction welding, even if the materials have different thicknesses, the resulting surface has excellent quality and thus optimal resistance to fatigue failure.

Another trend is for parts to be specifically designed to be made by additive manufacturing processes. This manufacturing process has many benefits for an aircraft's life cycle by enabling the design of lighter parts without the non-value-added portions that exist in parts made through traditional (subtractive) manufacturing (Niaki et al., 2019; Ghobadian et al., 2020). Additive manufacturing technology has been gaining traction in conventional aviation—notably, GE has made important efforts to employ more internal engine parts made with this technique (Kumar and Krishnadas Nair, 2017; Najmon et al., 2019).

3.2. Better maintenance management

The use of more additive manufacturing processes can also bring benefits in terms of maintenance. This manufacturing process makes it possible to not only design lighter parts using fewer materials but also

design single parts that replace modules that are traditionally built by assembling many parts. This provides the added benefit of simplifying assembly, disassembly and reassembly during maintenance.

In terms of maintenance management, another trend is to have a maintenance system controlled in real time by utilizing many sensors installed in the various systems of the plane (Ferrer et al., 2010; Karayianes, 2017; Metso and Thenent, 2020). These continuous monitoring systems greatly increase flight safety because as soon as an anomaly is detected, the compromised components are identified, and the maintenance officer is alerted. Owing to preventive maintenance actions, it is possible to reduce the cost of aircraft operations.

The data transmitted in real time are then stored in a large database so that it is possible to create and validate mathematical models. Other advantages are reductions in unplanned aircraft downtime, reduced maintenance downtime and costs, the early identification of operational problems, higher engine reliability, and increased time in the air. These systems can provide guidance for inspections and repairs to be made. The life cycle of the plane can also be increased by programming the system to make these operations as environmentally friendly as possible.

Notably, engines use these systems to collect data on temperature, pressure, and vibrations to detect operations outside the optimal parameters. For example, an engine condition monitoring system can help increase engine efficiency by allowing the operator to determine the optimal timing to flush the engine core. An optimized engine purge schedule can keep the exhaust gas temperature in the optimal range and consequently reduce fuel consumption.

3.3. New engine technologies

The current trend in terms of engine design is to combine an optimal design of the combustion chamber at high temperature with the largest possible diameter of the fan blades at the engine inlet. Regarding the optimal design of the combustion chamber, the use of advanced materials, such as ceramic composite materials, has the ability to make the engine lighter and able to withstand higher operating temperatures, as well as increase its lifetime and reduce the number of maintenance steps (Marsh, 2012). A project built in this way will have fewer requirements for cooling, needs less air for cooling, and uses more air for propulsion (Steibel, 2019). The use of a larger diameter of the inlet fan increases the ratio between the air that passes through the cold area and the hot area where fuel is actually injected and burned. This ratio in the total amount of propulsion driven mainly by a larger amount of cold air mass at a slower speed is called the “bypass ratio” (BPR).

For instance, Rolls-Royce is working with these concepts of an optimized combustion core coupled with a larger inlet fan diameter in its new engine for widebody aircraft called Ultrafan, where it forecasts a BPR of 15:1 (Rolls-Royce, 2021). This will be possible partially because of the addition of a gearbox that decouples the rotating speeds of the engine core and the fan. This technology enables the engine to operate with considerably fewer compression stages at its core and allows a larger frontal fan that turns at a slower but optimal speed that prevents the creation of shock waves at the blade tips (Ranasinghe et al., 2019).

Another trend in engine development is to design new planes that make use of open rotor engines. This technology makes it possible to achieve an even higher effective BPR than what is possible with traditional turbofans, resulting in a lower fuel consumption. However, there are some drawbacks that limit interest in their application, such as providing a lower cruise speed and being intrinsically noisier at the same trust setting (Abbas et al., 2013). The slower cruise speed of $M = 0.7$ to 0.75 makes these engines a more feasible solution for regional and narrow body aircrafts, where the typical travel distances are shorter and the flight duration increase is manageable (Jupp, 2016b; Dorsey and Uranga, 2020; Alves et al., 2020). In addition, the noise perceived by passengers can be minimized by an aircraft design with engines mounted at the rear of the fuselage, which is a configuration that is also more appropriate for smaller aircrafts. Even so, the use of additional sound

insulation and active noise suppression systems for the cabin might be required for optimal passenger comfort (Smith, 2016; Jupp, 2016a). Nonetheless, recent studies making use of advanced computational fluid dynamic tools have made advances indicating that it is possible to significantly reduce the noise generated by open rotor engines by optimizing the configuration and shapes of their blades (Smith et al., 2021; Jaron et al., 2018).

In a project of a new aircraft with open rotor engines, since there is no fan case that would protect the aircraft and contain the eventual release of one of the blades, manufacturers must consider the safety design philosophies of turboprops and demonstrate that such an event is extremely unlikely to happen while also ensuring that both passengers and critical systems are protected from blade release. To this end, shields specifically designed to protect the integrity of the aircraft from open rotor blade releases have been successfully tested (Seng et al., 2015).

3.4. Aerodynamic improvements

Aerodynamics also has a direct effect on the pollution generated during the lifecycle of commercial aircraft. The plane engines must provide enough power to overcome the drag force created by the plane's displacement in the fluid medium. The conventional "tube and wing" airplane model, due to the extended time it has been in use, has been improved in such a way that there is little room for substantial gains in drag reduction due to its shape. Specifically, according to Hollom (2019), the shape of the plane accounts for only 4% of the parasite drag of modern commercial aircraft. Fig. 2 reveals the total drag breakdown of a typical conventional aircraft and the breakdown of the parasite drag.

However, the majority of the drag created by an airplane at cruising speed is skin friction-induced drag. This is because the flow around the wetted area is turbulent under typical commercial flight conditions. Thus, a key element in reducing the drag created by a plane is to maintain laminar flow around the surfaces of the aircraft. This transition from laminar to turbulent flow occurs due to the growth of small disturbances in the flow boundary layer. Accordingly, delaying the transition from laminar flow to turbulent flow is a theoretically possible solution to implement on certain surfaces, such as the engine nacelle, tail and, notoriously, the wing. That said, it is almost impossible to do this on the surface of the main fuselage due to the extremely high Reynolds numbers.

There are three major strategies to extend the laminar boundary layer, namely, active, passive and hybrid control. The active stabilization of the boundary layer is called laminar flow control (LFC) (Risse et al., 2017). While working for the Fluid Mechanics and Acoustics Division of the NASA Langley Research Center, Ronald D. Joslin stated that "LFC is an active boundary-layer flow control technique (usually steady suction) employed to maintain the laminar flow (LF) state at chord

Reynolds numbers beyond that which is normally characterized as being transitional or turbulent in the absence of control" (Joslin, 1998). However, for this to be possible, the wing structure must be greatly modified to accommodate holes in the surface, suction chambers and ducts, thus reducing the amount of space available to store fuel, which, in turn, reduces the aircraft's autonomy. By using this alternative, there is also a substantial increase in the complexity of aircraft maintenance, which, when coupled with the increase in the weight of the aircraft, makes this alternative less viable in practice (Kehayas, 2007).

The preferred method is called natural laminar flow (NLF). In this method, the aerodynamic surface is designed to create a pressure gradient that dampens the instabilities of the boundary layer. The main phenomena causing instabilities are cross-flow instabilities, Tollmien-Schlichting instabilities and attachment-line transitions (Redeker and Wichmann, 1995). While the occurrence of these phenomena is strongly linked to the Reynolds number, the wing sweep angle also contributes to the instabilities. Hence, the airfoil must be designed in such a way that it avoids these phenomena, thus passively extending the laminar flow. This is easier to achieve on small aircraft, but Airbus has been making advances and has recently demonstrated the application of this technology in an A340 four-engine aircraft with wings modified so that the outer part is designed for NLF.

Another alternative is to use hybrid laminar flow control (HLFC), which combines aspects of LFC and NLF. More specifically, HLFC uses airfoil tailoring as well as suction, albeit the latter is used only on the frontal part of the wing (Neittaanmäki et al., 2004). Airbus has, in the past, explored this HLFC alternative using a modified A320 aircraft (Schmitt et al., 2001). For this, a laser-drilled titanium suction surface was applied to the vertical stabilizer. The system, which was designed to be used under conditions of high Reynolds numbers, such as at low altitudes, has a compressor in the passenger cabin connected to nine suction chambers. While tests have successfully demonstrated that laminar flow can be achieved using such a system, the system weight penalty on the aircraft canceled out most of the theoretical fuel economy gains (Schrauf, 2005).

3.5. The incorporation of sustainable fuels

Fuel is a key element of an optimal aircraft life cycle. The first aeronautical piston engines ran on gasoline; however, this fuel proved to be quite volatile in application. On the other hand, when diesel was tried as a solution, this in turn presented another problem: a very high freezing point. Today, kerosene is used in large commercial airplanes with turbofan engines due to a combination of characteristics. Suitable fuels for aviation are difficult to find because, among other factors, they must have highly specific volatility properties; safe storage must be possible, but at the same time, it must be possible for the fuel to be in the form of steam while it is applied in the airplane's engine. Furthermore, it

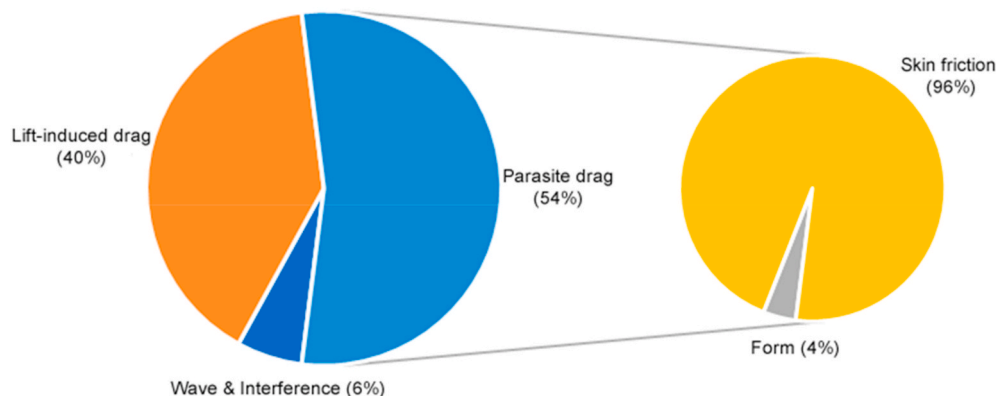


Fig. 2. Drag breakdown of total drag (left) and parasite drag (right) for a typical conventional commercial aircraft. Source (Schrauf, 2005; Hollom, 2019).

is necessary to have a very low freezing point because modern aircraft fly at high altitudes, at which ice crystals can form. Finally, the fuel must also have a high energy density to decrease the volume and total mass needed on the plane (Blakey et al., 2011).

Kerosene, gasoline, and diesel are not sustainable fuels because they are obtained through the distillation of crude oil. The idea of using renewable fuels in aviation is not new, but it has been gaining interest recently (Koistinen et al., 2019; Wydra et al., 2021). The idea is to use biokerosene, which has chemical and physical properties similar to those of kerosene, a fossil fuel, as an alternative to optimizing the aircraft life cycle without the need for major engine modifications (Anand et al., 2016; Buchspies and Kaltschmitt, 2018).

Due to the similarity between the two fuels, it should be possible to use a mixture of biokerosene and kerosene. The transition toward biokerosene can be implemented with smaller proportions of biokerosene that would gradually increase over time. Of course, this depends on other factors, such as availability, legal issues, and price. Modern initiatives toward producing biokerosene focus on sources that provide higher productivity levels and initiatives using oils from jatropha, camelina, and microalgae. Fig. 3 shows the life cycle savings due to the utilization of three prominent sustainable fuels.

3.6. Improved operation

An aircraft idles for a substantial amount of time before takeoff with both engines running. However, much pollution could be avoided if the wheels of the plane had electromagnetic motors that could be powered either externally by electrical contacts between the runway and the plane or by power generation by the auxiliary power unit (APU) of the plane. The use of batteries in this case would make little sense, since they would only be used in a small initial portion of the flight, but the weight of the batteries would have to be carried throughout the process (Guo et al., 2014).

Another more technological approach is to use magnetic levitation (Maglev) in a cart that would propel the aircraft during take-off and help the aircraft come to a full stop during landing. (Rohacs and Rohacs, 2016). A simpler and more viable alternative includes the extended use of trailers at the airport. Instead of just moving the aircraft away from the finger so that it can move on its own from there, the trailer could be used to transport the aircraft to its initial takeoff position. It would also be possible to use trailers after landing to bring the plane to the passengers' disembarkation position. If none of these options is possible, the aircraft could possibly carry out the taxiing procedures with only one engine running. This has already been implemented by some airlines at some airports but has been restricted to certain climatic conditions (Re, 2012).

Another great way to avoid unnecessary consumption is to always use optimal routes between destinations. Before a flight, the pilot registers his or her plan, where he or she outlines the route planned for the aircraft. Aspects such as the altitude at which the plane will fly and the time at which it will pass through different sectors are agreed upon with air traffic control (Hrastovec and Solina, 2016). There is also the challenge of being able to pass through complex geographic areas, including passing through countries, in a straight line or as straight a line as possible (Lulli and Odoni, 2007). Therefore, there are major geopolitical obstacles to the creation of a global air traffic management system. When there are obstacles to sovereignty or political challenges, aircraft must fly longer paths than necessary; this is an important source of pollution. Making a flight plan is a complex exercise with many more variables than one can imagine (Rodríguez-Sanz et al., 2019).

4. Assessing emission reductions in the commercial conventional aviation sector

Section two establishes that the industry needs to act in a collaborative fashion with the incorporation of different technologies, which are qualitatively reviewed in section three. Here, we perform a numerical simulation to quantify the potential improvement in terms of the conventional aviation environmental footprint that is theoretically possible to achieve.

For this, we build a software that was coded in MATLAB according to an existing LCA model from the literature. This approach provides two main advantages: first, it is easy to validate the correct programmatic implementation of the model, and second, it becomes easy to make adjustments to the model's original parameters to take into account the improvements due to the incorporation of green technologies in the foreseeable future of conventional aircraft.

The base model used here is the one originally proposed by Johanning and Scholz (2014) because it permits the calculation of the environmental footprint for a fleet of conventional aircraft. Furthermore, this model is sufficiently detailed to the extent that a programmatic implementation of this model makes it possible to adjust the base parameters represent the improvements in a scenario where the technologies reviewed in section three are adopted by the industry.

The heart of our software contains all the same equations, parameters and logic of the original model, and all the details are available in Johanning and Scholz (2014). However, an adjustment was necessary while creating the programmatic version of this LCA model to ensure that in the software, it would be possible to add foreseeable improvements in the area of maintenance services. Therefore, in our adaptation of the model in a computational tool, maintenance was coded to represent the ABCD system used in aviation, where A is the lightest and

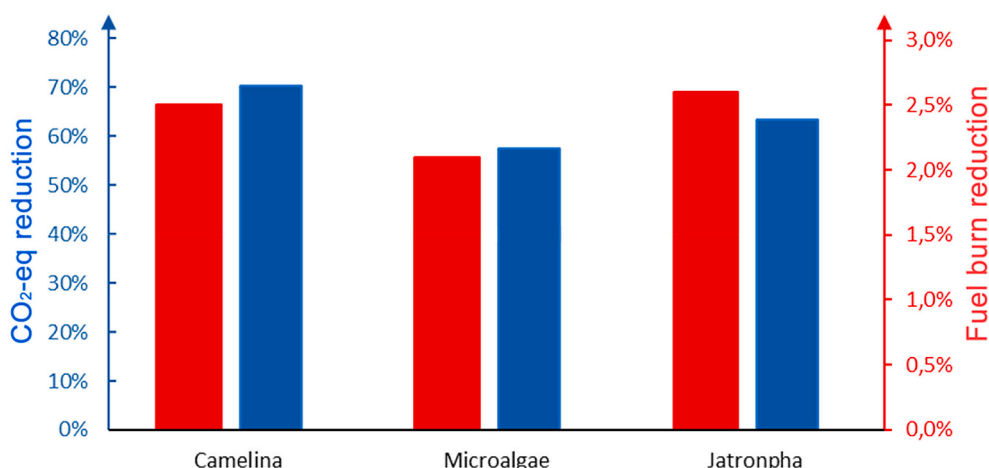


Fig. 3. Life cycle savings for three sustainable fuels for aviation: CO₂ equivalent and NO_x and fuel consumption savings. Source (Lokesh, 2015; Lokesh et al., 2014).

most frequent maintenance and D the heaviest and least frequent maintenance. Considering the information available in the literature (Kinnison and Siddiqui, 2012; Qantas, 2016), checks A, B, C, and D were defined as being made at intervals of 2, 7, 22, and 96 months, respectively, and the maintenance duration was considered to be 1, 2, 10, and 30 days, respectively. Checks C and D are heavy checks that require the replacement of airplane parts. It was established that 1% for C and 3% for D of the plane's empty mass must be replaced, and the new parts are manufactured using the same proportion of material as the plane's original constitution.

With our computational tool, the environmental footprint of the conventional aviation industry can be quantified for various polluting elements. Therefore, we first validate our tool by analyzing the results given in terms of emissions per revenue passenger-kilometer (RPK) by using the tool in a base scenario, and then we modify this scenario to accommodate the improvements foreseen in section three to measure the possible environmental footprint reduction of an optimized clean-sheet project of an aircraft in 2050. Second, we analyze the resulting carbon dioxide (CO₂) equivalent produced by the conventional commercial aviation sector considering its evolution up to the year 2050, i. e., considering fleet growth, the retirement of old aircraft, and the gradual forecasted introduction of the technologies during the period.

4.1. Potential reduction of emissions in an optimized industry scenario

In this section, two scenarios are simulated using our computational tool. The first simulation uses the same parameters as the example given in the case study of the article on which the computational tool was originally based. This is called the "base scenario", which is a simulation of an aircraft similar to the A320, having an empty mass of 41,244 kg. This mass of this aircraft includes 72% aluminum, 12% composites, and 7% steel. In this case, the baseline seating capacity is 180 passengers, the percentage of seats sold is considered to be 84%, and the average load factor is considered to be 78%. The typical flight is considered to be 1100 km long. Excluding landing and takeoff, each flight consumes 4100 tons of kerosene. Other important parameters for the simulation include 25 years of aircraft service and a hypothesized fleet of 20,000 aircraft. Takeoff and climb-out times of 0.7 and 2.2 min, respectively, are considered. An approach of 4 min and an average idle period of 26 min are also used. All the other details of the parameters used in the base scenario can be found in (Johanning and Scholz, 2014).

After performing the simulation of the base scenario, a second simulation is performed to quantify the possible improvements in emissions per RPK that are theoretically possible from the massive application of the green technologies. This scenario is called the "optimized scenario". In addition, for the tool to simulate this scenario, the necessary changes in the base parameters previously used due to the application of the different technologies qualitatively reviewed in section three must be identified. Therefore, the following discusses the impacts of these technologies on the parameters of the model. The changes in the model parameters of the base scenario due to the adoption of each technology and the values of these changes, as well as the references that justify the adoption of these assumed values, are presented.

In terms of materials, in the optimal scenario, it is expected that new aircrafts will make extensive use of composites. It is assumed to be possible to raise the percentage of composites in a conventional aircraft up to 53% (Mathijssen, 2017), so this value is used in the optimized aircraft scenario. This change affects the percentage of aluminum used by the same amount and also affects the empty mass of the aircraft. It is estimated that by replacing a metallic part with an equivalent composite part, there is a 40% reduction in the weight of the part (Mansor et al., 2019; Patel et al., 2018). The logic of this proportional weight reduction due to a change in the original material proportion used in the base aircraft was added to the software. The fuel consumption parameter used in the model is also altered due to variation in the weight, as it is

estimated that for each kilogram of weight lost, 0.03 kg of fuel is saved for each 1000 km traveled (Steinegger, 2017). Additionally, by using biobased versions of epoxy composites instead of oil-based equivalents, there is an important advantage in terms of net emissions due to CO₂ credits. This is accounted for in the model by reducing the corresponding emission factor by 39.2% (Bachmann et al., 2017; La Rosa et al., 2014).

In terms of better manufacturing methods, in the optimal scenario, it is possible to estimate that the industry can achieve a reduction of 50% in the original emission factors applied to the use of the production facilities module of the model (Atlas Copco, 2020; Rolls-Royce, 2015). Furthermore, technologies for better maintained management can reduce maintenance duration and increase the maintenance intervals of aircrafts. Therefore, these forecasted improvements are accounted for in the optimized scenario of the model by improving the timing parameters of maintenance in 33% over the ones originally used in the base scenario (Embraer, 2020).

In terms of new engines, the optimized scenario adopts an increased fuel efficiency of 25% because Rolls-Royce has indicated that their Ultrafan technology is expected to be 25% more fuel efficient than the current engines (Rolls-Royce, 2021). Furthermore, when possible, the option for an open rotor solution instead of a geared ultrahigh bypass engine is estimated to offer a 6% additional reduction in fuel consumption (ICCAIA, 2019). In our simulations, small narrow-bodies and regional jets are able to use open rotor engine.

As discussed previously in section three, the technologies for achieving aerodynamic improvements also influence the fuel consumption in the model. The value of the improvement used in the simulation was obtained by studies from Airbus concluding the future potential for a 4.6% reduction in fuel consumption with the application of the NLF technology while maintaining the conventional "tube and wing" concept (Airbus, 2017).

With respect to the incorporation of sustainable fuels, projections show that by 2025, 5% of the fuel used in airplanes will be sustainable and that this percentage will grow by approximately 1% per year from then on (EIA, 2020). Thus, in 2050, 30% of the fuel used for aviation will be sustainable. In the optimal scenario, we assume that camelina-based sustainable fuel is used. This is because the camelina crop has low fertilizer requirements and a high oil yield, making it one of the most sustainable drop-in fuels. Studies show that the net CO₂ emission of this fuel to the environment (considering biomass credits throughout its lifecycle) is 70% lower than that of traditional fuels (Lokesh, 2015; Lokesh et al., 2013). Therefore, the emission factor of the original model is reduced according to the proportion of sustainable fuel being used in the simulation. Furthermore, the use of sustainable fuel also has an effect on the engine performance used in the model, as it is also observed that camelina fuel has better performance than traditional jet fuel, reducing fuel consumption by 2.3% (Lokesh et al., 2014). This parameter was again adjusted to the proportion of sustainable fuel being used in the simulation.

In terms of improved operation for greener conventional aviation, Patrón et al. (2015) numerically studied the issue of reducing fuel consumption via the optimization of route parameters for various destinations. They studied different routes, including routes through complex geographic areas, and concluded that it is theoretically possible to reduce the fuel consumption of a route by 6% per flight on average. Furthermore, fuel consumption prior to takeoff during the taxiing phase is assumed to be zero in the model due to the use of the abovementioned electric trailer technology.

Now that the parameters for the base scenario and the necessary modifications to create an optimized scenario have been defined, both scenarios are simulated. Table 1 presents the results obtained using our software created in MATLAB along with the results of a reference for validation. The first column indicates polluting substances, and the second column shows the results obtained from Johanning and Scholz (2014). The third column shows the results obtained by our model of an A320 aircraft; the results are very close, validating our model. The

Table 1

Comparison of inventory analyses for the life cycle of a single-aisle aircraft (g/RPK). Reference data are from (Johanning and Scholz, 2014).

Substance	Reference	Base scenario	Optimized scenario
Crude oil	35	31.081	12.875
CO ₂	99	97.560	47.633
CO	0.07	0.064	0.030
HC	0.004	0.004	0.001
NO _x	0.5	0.451	0.030
CF ₄	9.8E-08	9.95E-08	6.34E-09
N ₂ O	4.00E-08	2.43E-08	1.41E-08
Hg	4E-11	2.43E-11	1.41E-11
Pb	9.5E-10	5.78E-10	3.34E-10

fourth column presents what could be obtained from a similar life cycle considering that all the prospective advances in technologies and techniques for a more sustainable aircraft are included in the model. It is possible to see that a significant decrease in the main polluting elements could be achieved.

An aircraft of the future, incorporating much of the new technology presented here, may reduce the life cycle consumption of crude oil by 58.6%, dropping from 31.1 g/RPK to 12.9 g/RPK. We find a reduction of 51.2% in CO₂ (from 97.6 g/RPK in current aircraft to 47.6 g/RPK in the environmentally friendly aircraft of the future). CO emissions decrease from 0.064 g/RPK to 0.030 g/RPK, a 53.6% reduction. Carbon tetrafluoride (CF₄) is the substance whose emissions are projected to be reduced the most at 93.6% compared to base scenario. The other polluting elements (N₂O, Hg, and Pb) also show a considerable reduction of 42.2%.

In conclusion, comparing the typical traditional aircraft of today with the conventional aircraft of the future, simulations of aircrafts with a 25-year life cycle indicate a potential reduction of approximately half in the emissions of the project per RPK. This considers that all actions throughout the life cycle of future aircraft will incorporate actions and technologies that promote a reduction in the emissions of polluting elements. Overall, this is a highly significant reduction potential, as it indicates that if all current aircraft were replaced by these potential aircraft, the aircraft fleet could be doubled without significantly increasing the impacts on the environment.

4.2. Perspectives on the CO₂ evolution of the world fleet and current objectives

From these results, it would be interesting to consider the evolution of technological incorporations over time in the model. It is possible to develop a model to predict different scenarios in terms of CO₂ pollution evolution. However, for this to happen, the disruption in air traffic caused by COVID-19 must be considered because the pollution generated by airplanes was abnormally low in 2021. To do this, we reference the prediction for international aviation by CAT (Climate Action Tracker, 2020). Since the goal is to model the global aviation footprint, data from CAT was adjusted following the findings of the International Civil Aviation Organization (ICAO, 2019), which concluded that passenger transport accounted for 81.4% of the total CO₂ produced in 2018 and that international aviation was responsible for 60.37% of the total CO₂ emissions from passenger transport in 2018. According to Zaporozhets et al. (2020), the proportion of CO₂ generated by international aviation is historically stable and will likely vary very little over the coming decades. Therefore, according to the adjusted reference data in 2019, prior to the onset of the COVID-19 pandemic, the commercial passenger transport aviation sector produced 863.9 million tons of CO₂ (MTCO₂). The reference data also indicate that in the year 2050, in the best-case scenario, the commercial aviation sector will produce 1566.2 MTCO₂; in the worst-case scenario, it will produce 2085.1 MTCO₂.

These data are used as a reference to first validate the reliability of our computational tool. Once it has been validated, it can be adapted to

gradually incorporate the technologies discussed herein up to 2050 to assess the evolution of the CO₂ footprint of commercial conventional aviation. As the global passenger transportation fleet comprises airplanes of many sizes, in this study, the market is divided into five categories of airplanes: regional, small narrow body, large narrow body, small widebody and large widebody.

Jemiolo (2015) studied the characteristics of different airplanes and, for each of these five categories, defined what he called a “synthetic airplane”. Jemiolo was able to establish many linear relationships between various characteristics of each type of airplane and determined that each synthetic airplane exhibits several important characteristics, such as its operating empty weight, range, and average flight length, that best describes all of the airplanes in the corresponding seating category. Fuel consumption values were adopted using data from the literature (Biancardo et al., 2020; Amevoice, 2020) to consider the approximate average of various models in each seating group. Additionally, the average daily hours of utilization data for each airplane category were obtained from (Wyman, 2019), and the base fleet size and distribution among the different aircraft classes were acquired from (CAPA, 2021; Casanova et al., 2017), which revealed that in-service aviation peaked in 2019 before declining to the level of many years prior. Table 2 summarizes the characteristics of each of the five airplane categories.

Using these data, the model indicates that the amount of CO₂ produced by aviation prior to the pandemic was 850.2 MTCO₂, which is slightly less than the data used as a reference, i.e., a difference of -13.8 MTCO₂ or -1.6%. Furthermore, the results of our model indicate that widebodies are responsible for 36.6% of the total CO₂ emissions, while narrow bodies are responsible for 57.7% and regional aviation is responsible for 5.7%. These values are consistent with those observed by (Graver et al., 2019) of 41%, 53% and 6% for widebody, narrow body and regional aircrafts, respectively. Accordingly, these data validate our model with respect to the initial point of the simulation over time. In the future, according to Cooper et al. (2017), an average growth of 3% in the aircraft fleet from 2022 onward is expected. Therefore, this growth rate is implemented in the model with a tolerance of ±0.5% to consider uncertainty and to obtain the high and low growth scenarios, as in the case of the CAT forecast. The results from our simulations of these two scenarios are plotted in Fig. 4 over the data used as reference. As evidenced in Fig. 4, the evolution of the forecast emissions is quite similar between the two scenarios. In the case of the low growth scenario, our prediction starts marginally lower than the reference, but in the year 2030, the obtained results indicate 1115.4 MTCO₂, which is 39.7 MTCO₂ greater than the reference. This difference becomes negative from 2032 to 2043 and reaches a maximum negative difference of -39.7 MTCO₂ compared to the reference value of 1155.1 MTCO₂ in the year 2035. In the year 2050, our prediction is 1615.5 MTCO₂, whereas the reference is 1566.2 MTCO₂. At this point, the difference between our results and the reference is at its the highest, i.e., 3.15%.

A similar pattern can be seen for the high growth scenario, where the lines from the reference and from our computational tool are extremely close to one another. Initially, our MTCO₂ prediction is slightly higher in the year 2025, indicating 34.2 more MTCO₂ than the 908.4 MTCO₂ of the reference, or a difference of 3.8%. From 2026 onward, however, the lines become closer, and the difference is quite small at less than 3% until the year 2046. In 2050, the lines are at their greatest distance from each other, with our results indicating a value of 2227.5 MTCO₂ and the reference indicating a value of 2085.1 MTCO₂, i.e., a difference of 6.8%. This comparison with the reference validates our computational tool because it closely follows the reference, with the difference usually below 3%.

The validated tool can now be adjusted for the gradual implementation of aircraft in the future with the technologies discussed in this article. For this, we assume that all green technologies of the optimized scenario presented in the previous section will be only fully available within 30 years. Thus, according to the strategy defined in section two, gradual development and incorporation of the new technologies

Table 2

Categories of aircrafts and data used in the simulation (sources: (Jemiolo, 2015; Wyman, 2019; Amevoice, 2020; Biancardo et al., 2020; Casanova et al., 2017; CAPA, 2021))

Category	Seating group	Operating empty weight (t)	Average flight length (km)	Fuel consumption (kg/hr)	Average daily hours of utilization	Base fleet size
Regional	<100	12	460	1100	8,0	4253
Small Narrowbody	100–150	31	760	2100	9,9	3620
Large Narrowbody	151–250	51	1500	2700	10,8	12749
Small Widebody	251–450	116	6900	6500	12,8	2759
Large Widebody	>450	187	8100	11500	12,8	219

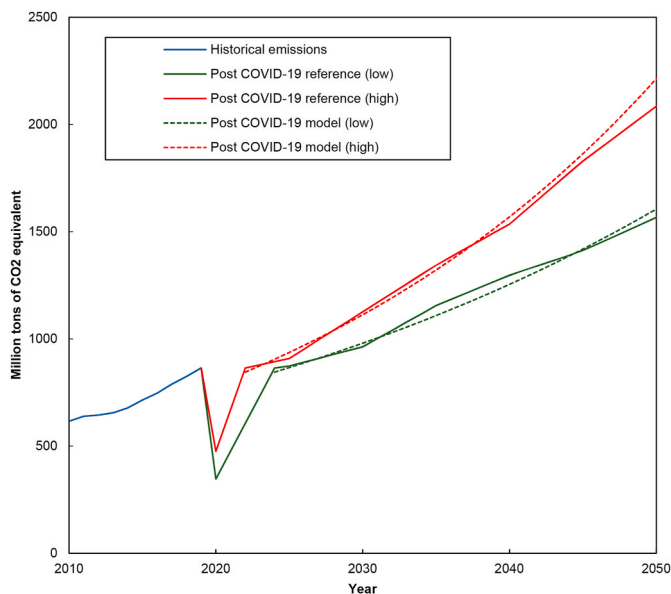


Fig. 4. Model CO₂ prediction for the aviation model with overlapping reference lines from the CAT prediction adapted for global aviation.

homogenously into newer aircraft was considered, with ten-year new engine generation launch cycles. For this, we use the prediction that in 20 years, 44% of the fleet will be replaced with newer and more efficient models (Boeing, 2019).

According to our projections, as indicated in Fig. 5a and b, at the lower end of the fleet increase, the CO₂ emissions in 2050 will be 1024.5 MTCO₂, which is 18.6% greater than the value in 2019. At the upper

limit of the fleet increase, the value in 2050 will be 1341.4 MTCO₂, which is 55.3% greater than that in 2019. Guaranteeing the same levels as in 2020 would be an ambitious result even considering a smaller increase in the aircraft fleet. However, efforts to reduce greenhouse gas emissions bear significant results. Specifically, we can save the equivalent of 743.6 MTCO₂ in the result with the largest fleet when compared to the initial projection of CAT, i.e., a reduction of 35.7%. In the scenario with the smaller fleet, we achieve savings of 541.7 MTCO₂, which is equivalent to a similar reduction of 34.6%, which is quite significant.

These results are interesting, as they can be compared with the objectives set by the International Air Transport Association (IATA) for the medium and long term: 1) increase fuel efficiency by an average of 1.5% per year; 2) achieve carbon-neutral growth, i.e., stabilize emissions at the levels observed in 2020 without halting the growth of the airline sector; and 3) attain levels of carbon emissions in 2050 that are half the levels of those reported in 2005.

The first objective was met for the period from 2009 to 2019, there is a high possibility that this trend regarding fuel efficiency will continue into the near future considering what can be assumed in terms of expected technological advances for conventional aviation. However, according to results of our simulations, the second IATA objective will not be achieved, as previously discussed. The third objective is even more difficult to attain since, according to the data and assumptions used in this study, this would be the equivalent of 283.0 MTCO₂ emissions by aviation in 2050. Our results indicate that without any electrification of international transport, in 2050, we would emit at best 741.4 MTCO₂ and at worst 1058.4 MTCO₂ more than the target. This is a substantial difference. In relative terms, this means that we would exceed the target by 162.0% and 273.9% in the best and worst cases, respectively. We conclude that there is an urgent need to reconsider hybrid or electric planes or adopt a revolutionary green design for planes intended for passenger transport.

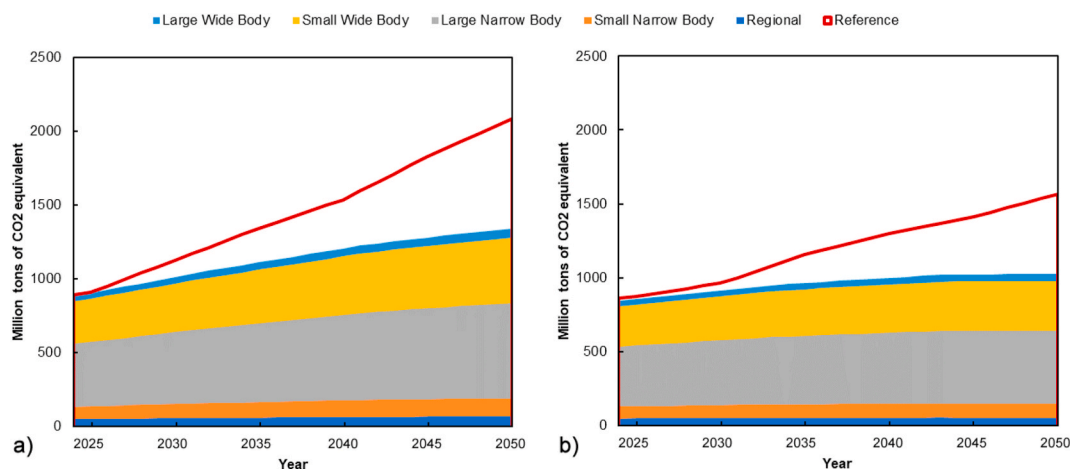


Fig. 5. Adjusted model that incorporates measures to reduce the pollution generated in conventional aircrafts with reference lines from the CAT prediction adapted for global aviation: a) high growth scenario and b) low growth scenario.

5. Conclusions

Current projections state that the growth rate of aviation before COVID will resume in a few years, which means that the ecological burden of conventional aircraft and their resulting limitations will become a critical global concern. In this article, we review the green technologies likely to be incorporated into conventional aviation over the next 30 years to explore the limits of the industry's current approach.

We built an LCA computational tool based on an existing LCA model in the literature. Then, after we validated the tool, a hypothetical future aircraft of traditional design with all the foreseen and possible advances to make it more environmentally friendly was considered. The simulations indicate that if all efforts are implemented, it will be possible to design an aircraft that generates half of the environmental impacts of current aircraft during its life cycle.

However, technological advances will gradually be integrated into aircraft in the years to come, and similarly, there will be a gradual replacement of old aircraft by aircraft with more environmentally friendly technologies. In this context, by using data obtained from the literature regarding the global fleet characteristics, we were able to forecast the evolution of CO₂ emissions from the aviation sector up to the year 2050.

In the best-case scenario, given the assumptions of industry-wide collaborative action and adhering to the conventional airplane design, the model predicted that it would be possible to almost stabilize the amount of pollution from the commercial aviation sector once the industry has recovered from the effects of the COVID-19 pandemic. However, in comparison with the goals set by IATA, it would be impossible to achieve the aviation pollution targets for 2050 with only conventional airplanes. Therefore, there is a pressing need to advance this research field and promote the entry in-service of hybrid and electric commercial airplanes, as the traditional model will soon reach its limitations.

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CRediT authorship contribution statement

Alencar Bravo: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Data curation. **Darli Vieira:** Conceptualization, Writing – review & editing, Project administration. **Geraldo Ferrer:** Conceptualization, Writing – review & editing, Supervision.

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.

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