Capstone Assignment: Sustainability and CORSIA Implementation

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Abstract

In a world where carbon emissions are increasing, and many actions are being implemented to decelerate them, the aviation industry has arisen as one of the main sectors to develop solutions to reduce emissions. Despite accounting for 2.5% of total global emissions, the aviation industry is one of the fastest-growing sectors in terms of CO2 emissions. This abstract is a starting point for the importance of complying with new regulations and developing solutions to reduce carbon pollution. This work gathered information from different solutions, like Sustainable Aviation Fuel (SAF), hydrogen-powered aircraft, and Air Traffic Management (ATM) optimization options. In addition to other possibilities, like fleet renewal, the created analysis could assess the airlines to invest in different solutions. Analysis of the information presented in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was also conducted. Operational information provided by the Brazilian Agência Nacional de Aviação Civil (ANAC), alongside social and economic perspectives, was also part of the analysis. The project also provided additional considerations and recommendations for future studies, as airlines are developing more efficient procedures and implementing new technologies.

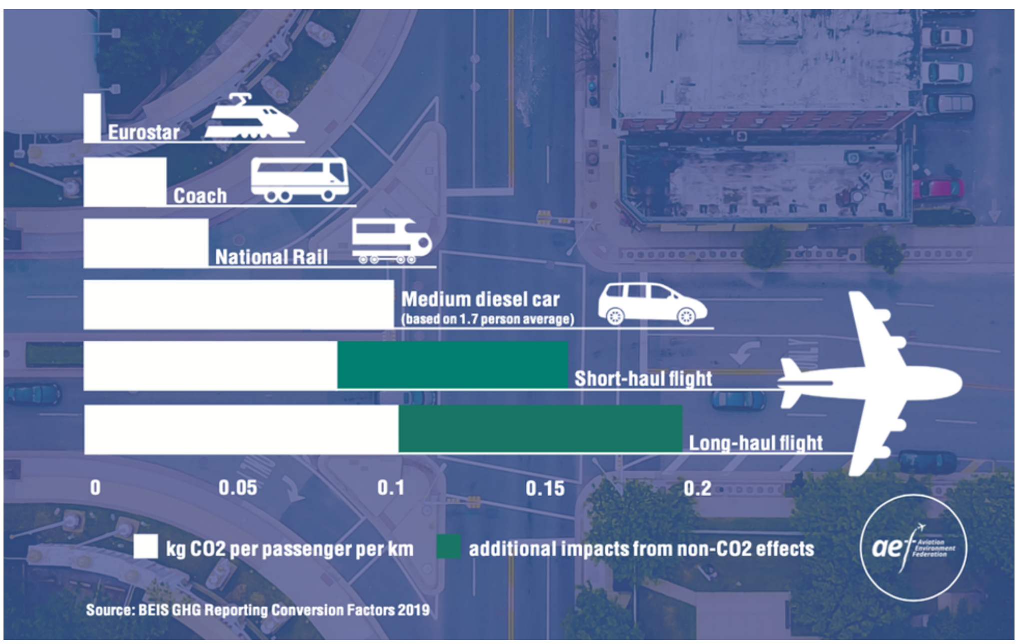
Keywords: environmental, social, governance, carbon emission, Brazil aviation, linear programming, optimization.

Introduction

The aviation industry has rapidly grown over the years, as more passengers are willing to travel to different destinations due to leisure and business activities. Parallel to the increment in the number of flights and transported passengers, there has been a higher demand for fuel consumption and gas emissions, especially CO2 and other polluting gases, like nitrous oxides (NOx) and sulfur dioxide (SO2), increasing global warming (Transport and Environment, n.d). In total, the quantity of gases generated by operating the aircraft, per passenger and kilometer, is greater than any other transportation means. However, not only the flight itself is responsible for the emissions and the pollution generated by the aviation industry, as the aircraft on the ground also has a great share.

Figure 1

Quantity of CO2 *generated per passenger and per km in different transportation systems.*



Note. By BEIS GHG Reporting Conversion Factors, 2019, Department for Business, Energy & Industrial Strategy, United Kingdom.

To solve this problem, many aviation organizations, including the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA), are joining forces to achieve net-zero carbon emissions. That means that the goal is a balance between what is generated and what is removed, in terms of greenhouse gases. Some possible solutions have been evaluated for the past years, and many more are being discussed to accelerate the net-zero goal. Some of them involve technological innovation, especially related to jet engine efficiency. Sustainable aviation fuel, or SAF, could also reduce CO_2 emissions by 80% (Aviation Benefits Beyond Borders, n.d). In addition, operational and market-based solutions associated with airport infrastructure can help in goal achievement.

In this context, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was established by ICAO as a global market-based measure to address the rise in CO_2 emissions from international aviation. Developed in 2016, CORSIA aims to cap net CO_2 emissions from international flights to the 2019 levels by requiring airlines to purchase carbon offsets to cover any emissions above this baseline. The scheme is an essential part of the broader strategy to achieve net-zero carbon emissions in the aviation sector.

The goals of CORSIA are not only to limit the increase in CO_2 emissions from international aviation but also to promote the development and deployment of SAF and new technologies. By creating a financial incentive for airlines to invest in cleaner technologies and fuels, CORSIA supports the industry's net-zero ambition. However, there are significant risks associated with airlines' exposure to the carbon offsetting market. As the demand for carbon credits is projected to rise sharply in the coming years, the cost of these credits is expected to increase, potentially leading to substantial financial burdens for airlines. The volatility in the carbon credit market can also create economic uncertainty, making it challenging for airlines to plan long-term investments and operational strategies.

Moreover, the effectiveness of carbon offsets in truly mitigating emissions is subject to scrutiny. The quality and credibility of carbon credits can vary widely, and there is a risk that some offsets may not represent real, additional, or permanent emission reductions. This sets airlines at risk of investing in credits that do not genuinely contribute to their net-zero goals.

To sum up, while CORSIA represents a critical step towards reducing the aviation industry's carbon footprint and achieving net-zero emissions, airlines must navigate the complexities and uncertainties of the carbon offset market. Ensuring the credibility of carbon credits and managing the financial risks associated with rising costs will be crucial for the success of this scheme and the industry's sustainable future.

Problem Statement

The increased demand for carbon credits, driven by the growth in air travel, could lead to higher prices in the carbon market, further escalating costs for airlines. The problem is, airline companies are pressured to invest in sustainable practices and emission reduction technologies to minimize their reliance on purchasing offset. The implementation of CORSIA introduces a substantial and potentially volatile cost component that airlines must manage strategically to maintain competitiveness and profitability. The use of optimization through linear programming can result in determining the best practices for airlines to deal with this demand. Of particular interest is in reducing airline costs, maximizing efficiency, and minimizing dependence on buying offsets.

Project Goals and Scope

Our research project aimed to develop a framework and management strategy to be used by airlines to fully implement CORSIA guidelines. Doing so would assist in balancing the costs and increasing operational efficiency while reducing the maximum possible carbon credit market exposure. The main goal was to identify which technologies, procedures, and management strategies could provide the best outcome in terms of carbon emission reduction. Thus, setting a robust procedure to calculate the carbon emission based on new technologies and solutions was also considered.

The goal of this project was achieved by gathering data about emissions and implementation costs from different initiatives that could be developed by Brazilian airlines. Additionally, the associated mathematics was developed based on a conceptual framework to help the airline's decision-making process. Hereby, CORSIA requirements could be fulfilled when setting a financial target.

Definition of Terms

The project used terms that are mainly used by the industry when discussing carbon emissions and sustainability and are important to the complete understanding of the subject and the considered initiatives.

Airspace Optimization: The process of redesigning and managing airspace to improve flight efficiency, reduce fuel consumption, and minimize CO_2 emissions, often through more direct flight paths and optimized altitudes.

AOC (Air Operator Certificate): a document issued by a national aviation authority that allows an aircraft operator to perform commercial air transport operations.

APU (Auxilary Power Unit): a small gas turbine that mainly supplies electrical, and pneumatic power to start the engines and power the air condition system when on the ground.

APU OFF (Auxiliary Power Unit OFF): Initiative to reduce the use of the aircraft’s APU to generate power while the aircraft is parked at the gate. The use of ground equipment is ensured and provided by the airports.

Carbon Credits: Certificates representing the right to emit one metric ton of CO_2 or the equivalent amount of another greenhouse gas. Carbon credits can be traded in carbon markets and are used to offset emissions.

Carbon Offsetting: The process of compensating for carbon dioxide emissions arising from industrial or other human activities by participating in or funding schemes designed to make equivalent reductions of carbon dioxide in the atmosphere.

Climate Change: Refers to significant and long-term changes in climate patterns, both natural and induced by human activities. Global climate change is widely associated with global warming, primarily caused by increased concentrations of greenhouse gases in the atmosphere.

CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation): A global market-based measure developed by the International Civil Aviation Organization (ICAO) to address CO_2 emissions from international aviation. It aims to cap emissions at 2020 levels and requires airlines to purchase carbon offsets to cover emissions above this baseline.

ESG (Environmental, Social, and Governance): A framework used by organizations to consider environmental, social, and governance factors in their operations and investments, focusing on sustainability and ethical impacts.

GWP (Global Warming Potential): A measure of how much heat a greenhouse gas traps in the atmosphere over a specific period compared to carbon dioxide. It is used to compare the impact of different gases on global warming.

IEC (International Energy Agency): International organization attached to the Organization for Economic Co-operation and Development that supports and guides international politics related to energetic issues within 30 countries.

IATA (International Air Transport Association): The International Air Transport Association is a global trade organization for airlines. Founded in 1945, IATA supports the aviation industry with global standards, promotes policies that encourage safe, efficient, and sustainable aviation, and provides a range of services to its members.

ICAO (International Civil Aviation Organization): The International Civil Aviation Organization is a specialized agency of the United Nations, established in 1944, which sets international standards and regulations for civil aviation. ICAO promotes the safe and orderly development of international civil aviation worldwide.

IPCC (Intergovernmental Panel on Climate Change): The Intergovernmental Panel on Climate Change is an international scientific organization established in 1988 by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO). The IPCC is responsible for assessing scientific, technical, and socio-economic information relevant to understanding the risks and impacts of climate change, as well as potential mitigation and adaptation options.

Net-Zero Emissions: A state in which the total amount of greenhouse gases emitted is balanced by the amount removed from the atmosphere, resulting in no net increase in atmospheric CO_2 levels.

Operational Efficiency: The capability of an organization to deliver products or services most cost-effectively without compromising quality, often achieved through the optimization of resources and processes.

SAF (Sustainable Aviation Fuel): Biofuel used to power aircraft that has identical properties to conventional jet fuel but with a lower carbon footprint. SAF is considered crucial for reducing the aviation industry's greenhouse gas emissions.

Literature Review

To identify important information that could be used to increase the work and set the best strategies, more than twenty bibliographical references were evaluated, and ten of them were selected. The literature provided good insights into the CORSIA goals and how different countries deal with regulation changes. Lastly, some of them provided details on the advantages and risks of not setting correct initiatives to reduce emissions.

The IATA report, *Net Zero Carbon by 2050*, directly addressed the aviation industry's commitment to achieving net-zero emissions by 2050. This document was used to understand the specific strategies adopted by the aviation sector, including technological advancements and the use of SAF. The presented roadmap provides a plan that complements the broader energy strategies outlined by IEA, making it an essential resource for developing a management strategy. By incorporating IATA's strategies, the project ensured that the proposed solutions were both feasible and aligned with industry standards and expectations.

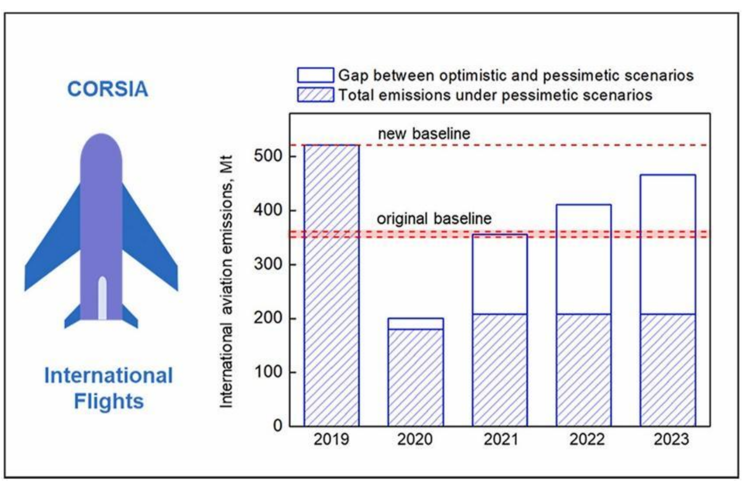
IEA's report, *Net Zero by 2050: A Roadmap for the Global Energy Sector*, also provided a detailed roadmap that is essential for understanding the broader context in which the aviation sector operates. This document was particularly relevant because it outlines the global path toward achieving net-zero emissions, highlighting the importance of improving energy efficiency. The insights from the IEA are fundamental to framing the aviation sector's efforts within the global energy transition, ensuring that the industry's strategies align with broader climate goals. The report's emphasis on investing in new technologies also underscores the need for innovation in the sector, particularly in the development and use of SAF.

Increasing the capacity and effectiveness of air navigation is one of ICAO's strategic goals. Improvements in aviation technology and airline operations decrease fuel usage and, thus, greenhouse gas emissions on the air-traffic. According to Lyle, C. (2018), in the aviation industry, it is anticipated that greenhouse gas emissions will rise rapidly soon, growing at a rate of about 3.5% annually and doubling in 20 years. Therefore, market-based measures are essential if the effects of greenhouse gas emissions must be reduced for international flights without established limitations on operations. Although the technical viability of some of these fuels has been established, there are still concerns about their full life-cycle benefits and the availability of sustainable feedstock (Lyle, C., 2018). There are significant obstacles related to the required investment, cost, and scaling up to a commercial level. Additionally, it is currently impossible to determine with certainty how much alternative fuels will contribute to reducing aviation emissions in the future.

The first program to address CO_2 emissions from a single industry globally was CORSIA, directing to airline industries which aims to achieve carbon-neutral growth in international flights starting in 2020. According to Zhang J. et. al (2021), the COVID-19 pandemic has caused a drastic decline in global aviation, with ICAO removing 2020 emissions from CORSIA's baseline. It is estimated that the total CO_2 emissions from global international flights decreased by 70 % from February to July 2020 when compared to 2019. The study suggests that the annual CO_2 emissions between 2021 and 2023 were far below the revised baseline even if the global aviation industry could embrace an optimistic recovery.

Figure 2

Gaps between optimistic and pessimistic scenarios, and total emissions under pessimistic scenarios. (Zhang, J. et.al).



One important definition provided by Fichert et.al (2020) was that domestic flights are not considered by CORSIA. That is also applicable to small operators, responsible for low carbon emissions, to small aircraft, that weigh less than 5.7 t. Rotorcraft aircraft, humanitarian, medical, and firefighting operations are also not considered. Military and governmental aviation were also excluded and must not be considered when evaluating carbon emission reduction. Lastly, the book mentions that offsetting requirements exist only for flights between participating states.

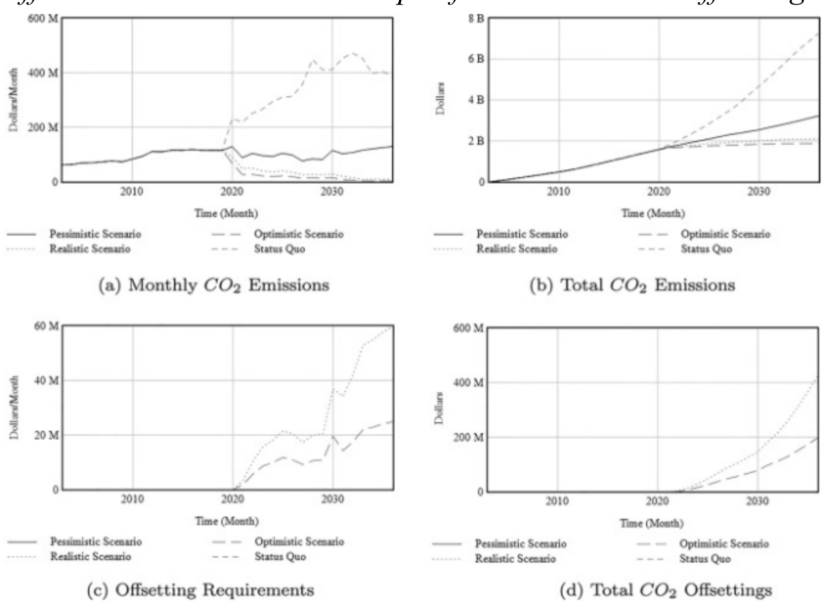
While there is a high expectation for the success of CORSIA, Warnecke et.al (2019) warns that it is critical to establish robust eligibility criteria. Additionally, these eligibility criteria should be restricted to new projects that are newly demanded. The warning is a response to the possibility of reducing emissions without revenue, as they could be discontinued due to the lack of earnings. The article provided a good insight into the lack of analysis on the downside of CORSIA development. That could be solved by the implementation of new initiatives that increase both revenue and efficiency.

CORSIA also created compliance complexities for aviation. If the ICAO designator and AOC holder cannot be readily established. According to studies, CORSIA compliance will then fall to the aircraft owner identified in the aircraft registration documentation (Labkon, Moss). This report examines the dangers related to each country's government's implementation of CORSIA. The paper concluded that although CORSIA has broad support, there are still some substantial risks and uncertainties associated with the plan. Any restriction concerning eligible offsets may increase the cost of compliance and thus create an economic burden for many operators under CORSIA.

Sharma et.al (2021) provided an insightful analysis of how airlines that operate in the United States could achieve net-zero emissions. The article develops an econometric simulation considering multiple financial and operational parameters to determine which affects carbon emissions the most. It also provided meaningful results on different possibilities and methodologies that could be used to minimize emissions. The article also delivered good predictions regarding optimistic and pessimistic scenarios, as a range basis that should be considered by CORSIA. The study can be used as a basis for the development of the Brazilian scenario.

Figure 3

Different scenarios were developed for emissions and offsetting.



The study by Alves et al. (2024) offered an in-depth analysis of the forest carbon market in Brazil, highlighting both the opportunities and challenges within this sector. This reference was crucial for understanding the role of carbon markets in achieving net-zero emissions, particularly considering Brazil's vast forest cover and biodiversity. The study's focused on the need for stronger regulations and the involvement of local communities underscores the importance of robust governance structures in the implementation of CORSIA. The insights were especially valuable for assessing the potential risks and benefits of engaging with carbon markets, particularly in regions with environmental and socio-economic challenges. By incorporating this reference, the project could better address the complexities of carbon markets and ensure that the proposed strategies are both effective and equitable.

Lastly, as a guiding article for methodological development, Chairat et.al (2022) described the necessary concepts to develop the marginal abatement cost curve (MACC). The text also mentioned that emission reduction initiatives should be chosen when the abatement costs are lower than those of other strategies. It is a great example of how the curve can be developed to select the Brazilian initiatives that have a larger potential to reduce emissions.

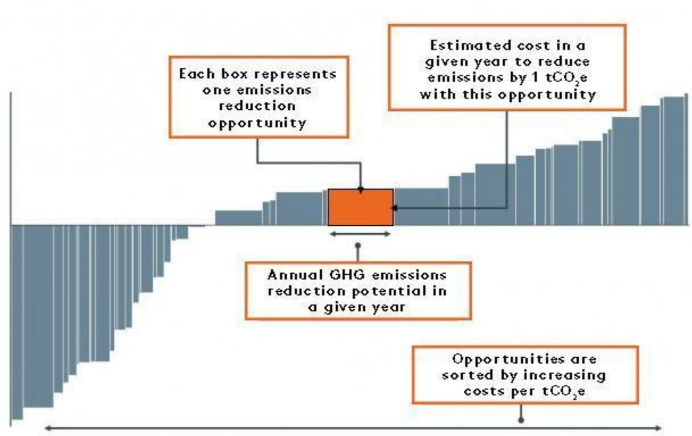
Methodology

The methodology was divided into four steps. The first one was data acquisition, in which historical and projected data on different initiatives were obtained. The main sources were the reports provided by the Brazilian Civil Aviation Agency (ANAC), the Department of Airspace Control (DECEA), IATA, and ICAO. To aid in the definition of the parameters used in the programming, the cost-effectiveness of different initiatives was considered.

The second step was the plot of the Marginal Abatement Cost Curve (MACC). The curve can be created by obtaining the abatement cost against the quantity of emissions reduced by different solutions. The most relevant outcomes, in terms of the cost per ton of CO_2, were indicated by boxes that represent the opportunities and their influence. The boxes located in the left part of the chart, usually below the reference line, represented the initiatives with the biggest potential gains.

Figure 4

Example of how a MACC is plotted.



Third was the selection of variables based on three of the best initiatives in terms of cost and carbon-avoidance capability. The calculated cost-effectiveness rates were used as part of a linear programming optimization. The main objective of the analysis was the maximization of CO_2 avoided by distributing resources between the solutions.

The constraints used in the model were set by regulatory and capacity limitations. For example, there is not going to be available SAF for all airlines in the first few years of use. Consequently, the project limited the value, as a constraint, to make it possible to optimize the objective.

Lastly, a few financial scenarios were evaluated, when varying the maximum budget that the airlines could use to implement the different initiatives. Depending on the budget, the proportion of avoided CO_2 by each initiative changed. The programming was implemented and executed using LINDO® software, a powerful software for calculating linear programming. The whole methodology can be replicable, only adjusting parameters and constraints, depending on the resources and initiatives considered by each airline.

Data Collection

We used an integrated approach to evaluate the best emission mitigation strategies for the Brazilian aviation sector. The Marginal Abatement Cost Curve (MACC) was the main tool for prioritizing alternatives and complementing the analysis with linear programming. Applying these methodologies maximized CO_2 reduction based on cost, feasibility, and the impact of the proposed measures. The latter allowed for a more efficient allocation of resources and identified the most cost-effective options for the national scenario.

Building the Marginal Abatement Cost Curve

The Marginal Abatement Cost Curve (MACC) is an analytical tool normally used to compare the cost and potential of different Greenhouse Gases (GHG) mitigation measures. Each bar on the curve represents a specific measure, with the X-axis showing the abatement potential (in tons of CO_2 avoided) and the Y-axis indicating the cost per ton of CO_2 avoided (in US dollars or local currency). Measures with negative costs indicated net savings, while positive-cost measures showed the value associated with avoiding each ton of CO_2.

To build the MACC, data was collected from international sources such as IATA and ICAO. Additional data was also provided by ANAC (Brazilian Civil Aviation Agency) and the Department of Airspace Control (DECEA). Multiple initiatives and projects could be depicted in the curve, providing meaningful insights into the carbon reduction process.

Sustainable Aviation Fuel (SAF) is seen as an essential pillar for the decarbonization of the aviation sector. However, its availability and high initial cost are significant barriers to large-scale implementation. The inclusion of SAF in the MACC considered both the environmental impact and economic challenges.

Fleet Renewal, as the replacement of older aircraft models with newer, more efficient ones, such as the Boeing 737-8 MAX and the Airbus A320neo, can reduce emissions by up to 18%. Although this measure involves high upfront costs, it provides long-term benefits in terms of fuel savings and CO_2 reduction. Air Traffic Management (ATM) Optimization, represented by initiatives such as direct routing, optimized departure and landing procedures, and more efficient air traffic management. This measure offers immediate benefits, as they usually only require parameter changes in the flight systems.

Electrification of Ground Support Vehicles, especially investments in electric vehicles for ground operations at airports, such as refueling trucks and tractors. Green Airport Infrastructure is characterized by the implementation of renewable energy sources at airports and the improvement of energy efficiency. Hydrogen-powered aircraft, as a promising option for the future of the aviation sector, despite hydrogen-powered aircraft are still in the experimental phase and facing technological and infrastructure challenges.

Lastly, Carbon Capture and Storage (CCS): For emissions that cannot be avoided, the use of carbon capture and storage technologies is essential to achieving net-zero emissions. This measure has a high cost and depends on further technological development. The developed curve for the project took into consideration all the above-mentioned initiatives during a period going from 2024 to 2050. Some of them are already being used worldwide, and some still need investments and research to be ready. Therefore, they can only be used as part of the analysis in the future and are not going to be considered in the analysis.

Table 1

Collected information to develop the MACC.

Initiative	Cost per ton of Avoided CO2 (US$)	Abatement Potential (tons of CO2)	Period
SAF	200	80 millions	2023-2050
Hydrogen-Power	400	40 millions	2035-2050
CCS	300	30 millions	2040-2050
Fleet Renewal	150	15 millions	2023-2040
ATM Optimization	-20	10 millions	2023-2030

Green Airport	75	8 millions	2023-2035
Electric Vehicles	50	5 millions	2023-2030

Figure 5

Abatement Potential (Millions per tons CO2).

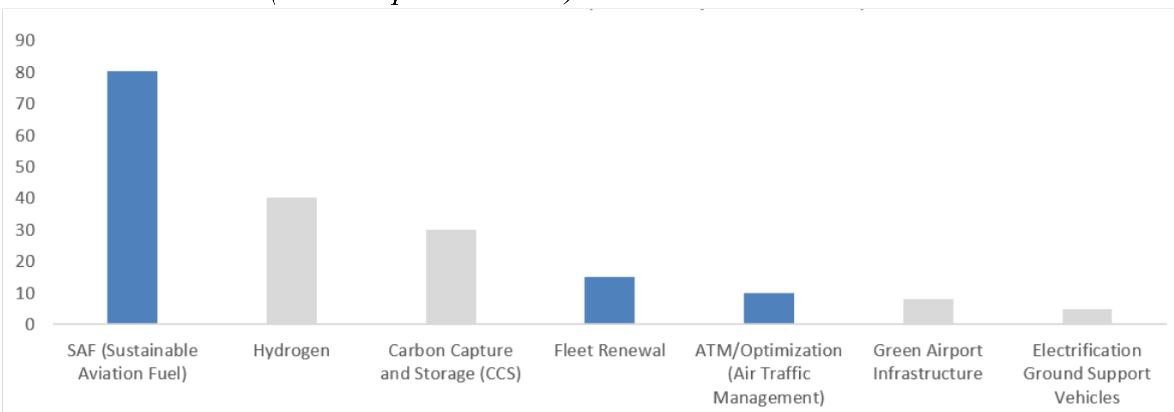


Figure 6

Cost per ton based on abatement measure

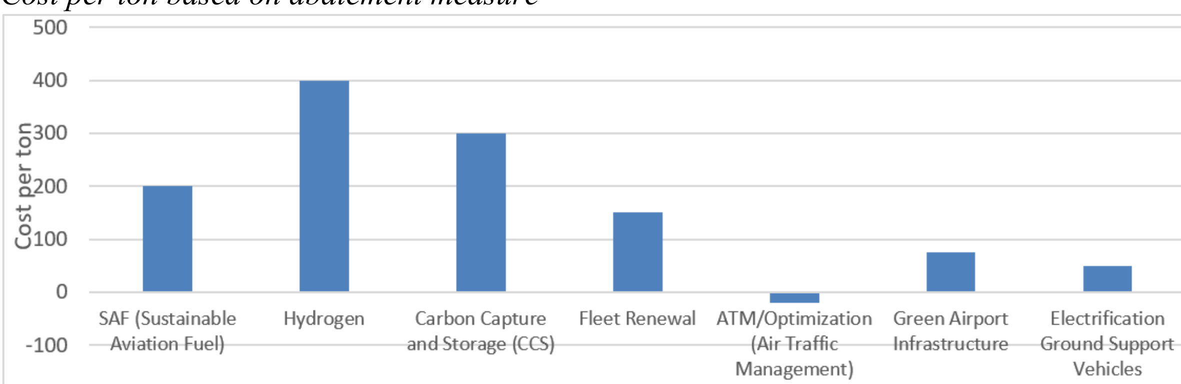
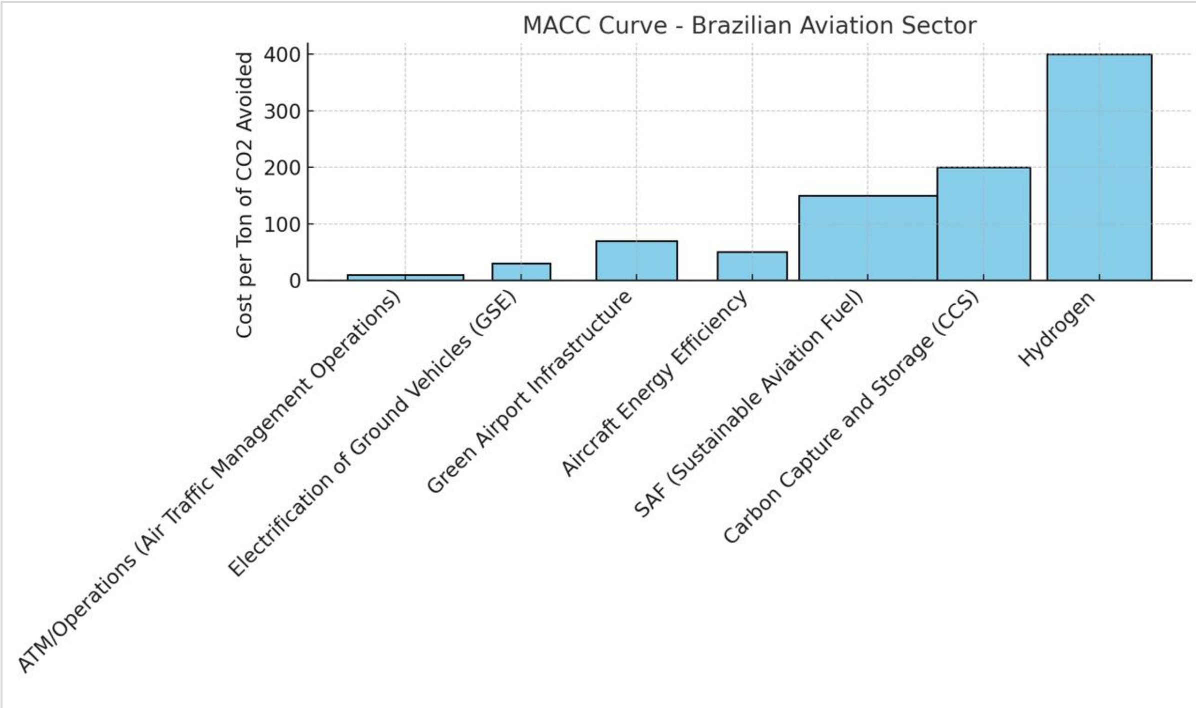


Figure 7
MACC Curve - Brazilian Aviation Sector



Note. Abatement Measure (Proportional to Abatement Potential)

Despite the MACC curve indicating several initiatives under development to reduce emissions, the Brazilian post-CORSIA scenario will not be characterized by all the initiatives outlined. Therefore, for this study, the three initiatives with the highest potential for emissions reduction were selected: SAF, fleet renewal, and ATM.

Data Analysis

As the next step of the project was linear programming, some additional information was necessary to develop the constraints. Regarding SAF, Chiappini (2024) stated that the annual production, based on 2024 numbers, is 1.8 billion liters, which could be converted to tons when divided by 1250. The conversion to CO_2 was given by multiplying a kilogram of fuel by 3.16. In addition, the Brazilian production of SAF could be approximated to 0.02%. After the calculation, the maximum quantity of SAF available in Brazil was 910,080 tons. The value could then be divided by 3 when considering the biggest commercial airlines, resulting in 303,360 tons per airline.

The maximum quantity of avoided CO_2 was calculated based on a reduction of 100kg of fuel consumption when considering international flights. The quantity of flights analyzed is based on the sum of the 10 busiest Brazilian airports (DECEA, 2023). The airports were Guarulhos, Brasília, Galeão, Salvador, Porto Alegre, Fortaleza, Manaus, Recife, Viracopos, and Confins, and the total number of flights was 109,230. After converting the fuel saving to the total quantity of avoided CO_2, the result was 11,506 tons per airline.

The quantity of avoided CO_2 for fleet renewal was calculated based on the proportion of the conversion of the Boeing 737-800 to the Boeing 737-8 MAX and Airbus A320 to the Airbus A320neo used by the Brazilian airlines. The CO_2 reduction for the 737-8 MAX was stated as 13% (Boeing, 2024), and for the A320neo was measured as 18% (Iba, 2021). The total emissions reduction when renewing the 737-8 MAX and the A320neo Brazilian fleet was calculated as 326,945 tons of avoided CO_2. Per airline, the obtained value was 108,982 tons.

After calculating the maximum allowable carbon emission that could be avoided, it was possible to set a linear programming analysis to identify which initiatives could be more efficient in terms of avoiding CO_2. This study was developed to provide a comprehensive understanding of how to optimize a predefined budget, to maximize the avoided CO_2 emissions.

Objective

As mentioned in the project, the main objective was to reduce carbon emissions. Therefore, the function that represents the main goal was described as the maximum amount of carbon avoided by an airline in Brazil, considering the three selected initiatives. The objective function that models the research is:

$$Max\ (X1 + X2 + X3)$$

Where X1 was the amount of carbon avoided through SAF use (in tons), X2 was the amount of carbon avoided through fleet renewal (in tons), and X3 was the amount of carbon avoided through airspace optimization (in tons).

Linear Programming Constraints

Each initiative had a maximum achievable value which was previously calculated using public data, and the constraints are modeled based on the analyzed values.

After evaluating the maximum quantity of SAF available for each main Brazilian airline over one year, it was found that the obtained value was 303,360 tons. For the model, it was not possible to extrapolate the number, as it was a production constraint. Therefore, the first constraint could be written as:

$$X1 \leq 303{,}360$$

When analyzing fleet renewal, the model considered the proportion of more efficient aircraft that are flying in Brazil. Based on data provided by the Brazilian airlines, there was an approximated proportion of 3.75% of Boeing 737-MAX 8 and 5% of Airbus A320neo, when comparing the Brazilian fleet to the global number of aircraft in the selected models. Applying the previously mentioned carbon emission reduction of 13% for the 737-8 MAX and 18% for the A320neo, the resulting value that represented the avoided carbon was 108,982 tons per airline. Therefore, the second constraint was:

$$X2 \leq 108{,}982$$

The third constraint was based on the carbon emission reduction based on the Air Traffic Management Optimization (ATM) for the 109,230 international flights that were operated by ten Brazilian airports in 2023. As the calculated avoided carbon emission per airline was 11,506 tons, the constraint was written as:

$$X3 \leq 11{,}506$$

As previously mentioned, multiple values were going to be selected for the budget consideration. Each variable had an associated cost for carbon reduction, and the sum of these costs could not exceed the available budget. The costs per ton of carbon were selected because of the MACC and Table 1 results, which were US$200 per ton of avoided CO_2 considering SAF, US$150 per ton of avoided CO_2 considering fleet renewal, and - US$20 per ton of avoided CO_2 considering ATM optimization.

To represent the budget value, the letter B was used, and in the results section, all budget considerations were provided. Therefore, the fourth constraint could be represented as:

$$200 \cdot X1 + 150 \cdot X2 - 20 \cdot X3 = B$$

The next constraint was responsible for ensuring that there was a minimum quantity of avoided CO_2 per flight, on average. As previously analyzed, the maximum number of analyzed flights was 109,230, which means that there is not enough SAF for all flights and that the reduction initiatives were not efficient for all operations. Calculating 15 tons as the average quantity of fuel that is loaded in Brazilian aircraft to perform international flights, mainly in the Americas, only 20224 flights could be loaded with SAF.

In addition to SAF, it was also possible to assume that not only newer aircraft models could be used in international flights. Therefore, 30000 flights were considered. Lastly, despite 109230 was the number of international flights, there were some operations with no carbon reduction due to bad weather and contingencies. Therefore, 65000 flights were considered.

The minimum desired quantity of avoided CO_2 per flight is, for the assignment, 2.5 tons. The developed constraint considering the quantity per flight is then written as:

$$0.00005X1 + 0.000033X2 + 0.000015X3 >= 2.5$$

Lastly, as a consideration of the project, all three initiatives should have been considered, and it was not allowed for an initiative to represent no value of avoided CO_2. Therefore:

$$X1, X2, X3 > 0$$

After the constraint definition, the model was ready to be simulated. After the calculation, in which the budget was varied, the outcomes could be acquired. Lastly, data interpretation aided by the use of charts and tables were described, as possible to visualize in the next sections.

Results

As the core of the analysis was the linear programming used to optimize the quantity of avoided CO_2, the main results were obtained after the use of the software LINDO®. The first result that was possible to obtain was the maximum needed budget to achieve the maximum of avoided carbon emissions when considering all initiatives and previous calculations.

Table 2
Maximum budget calculation.

	Avoided CO2 (tons)	Cost (US$) per ton	Maximum Budget
SAF	303360	$ 200.00	$ 60,672,000.00
Fleet Renewal	108981.685	$ 150.00	$ 16,347,252.75
ATM	11505.56	$ -20.00	$ -230,111.20
Total	**423847.245**		**$ 76,789,141.55**

The maximum budget that should be allocated for carbon emissions initiatives was $76,789,141.55. Any value above this number could be considered a loss of investment, as they were not going to provide any benefits for the operation. As the maximum avoided CO_2 could not be increased when considering the case scenario, an extrapolation of the budget would only have been a good option if the airline had selected different initiatives, which were not considered in the study.

After setting the maximum allowable budget, different scenarios were evaluated to compare how much could be avoided in terms of carbon emissions. US$10 Million, US$20 Million, US$50 Million, and US$77 Million were the considered budget values.

Table 3
Different scenarios analysis.

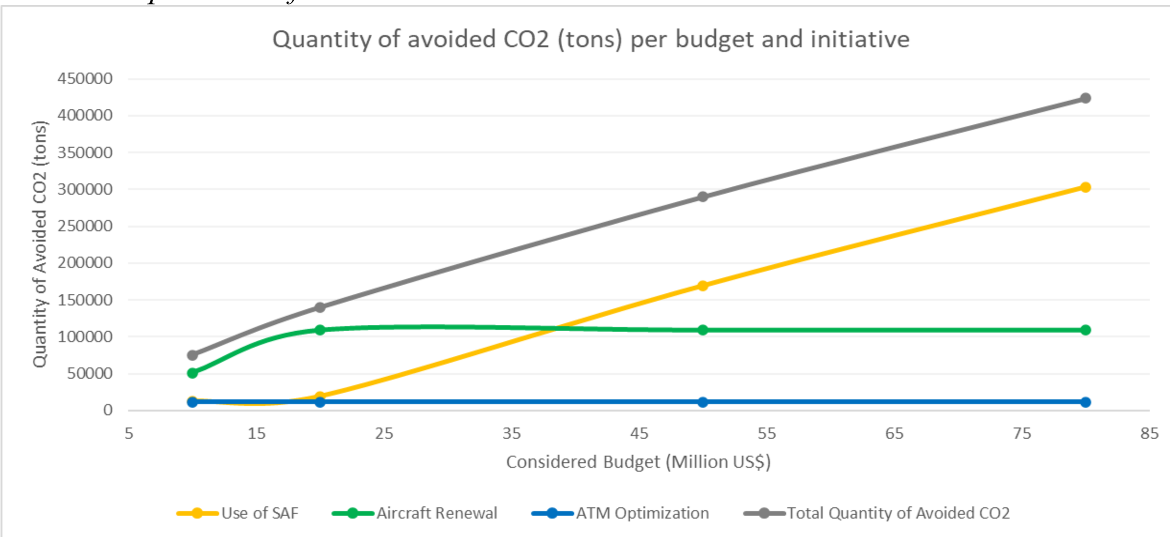
Budget (Million US$)	SAF (tons of CO_2)	Fleet Renewal (tons of CO_2)	ATM (tons of CO_2)	TOTAL (tons of CO_2)
10	12801	51133	11505	75439
20	19414	108982	11505	139901
50	169414	108982	11505	289901
77	303360	108982	11505	423847

As expected, the amount of avoided CO_2 tended to increase when the budget was higher. However, as previously stated, there was a maximum budget limit that should not be extrapolated, unless different initiatives or scenarios had been evaluated. The maximum amount of avoided CO_2 that could be achieved when considering the maximum budget was 423,847 tons. The analysis should be redone each year, as new initiatives arise, and changes in costs and quantities may happen.

Another possible interpretation from the table was that, when comparing different budgets, the quantity of avoided carbon emissions due to ATM did not change, and the same happened for fleet renewal for budgets higher than $20 Million.

Figure 8

Visual interpretation of the results.



As there were no costs to implement ATM initiatives, the optimization model tended to consider the maximum quantity related to ATM. As fleet renewal was the second highest cost, the model also tried to fully consider it before evaluating the SAF possibility. New constraints, especially related to payback analysis, implementation time, and others related to customer satisfaction could improve the model and generate a more diversified result.

Conclusion

The research showed for the analyzed period and market, that the MACC proved to be a robust tool to evaluate which initiatives would provide the desired outcomes. That happened because it allowed three initiatives to be identified and considered. The research also expanded the application of linear programming models to optimize the use of the selected initiatives. As a result, the model could supply the Brazilian airlines with insightful information on how much CO2 they could avoid emitting. In addition, a budget analysis provided additional information on the airline's capabilities.

With the completed analysis, the airlines could then develop a business case assessing all information, such as limitations, investment analysis, and the expected outcomes. The model was also proven to be replicable. Replicating the model means that for any given number of initiatives, the airline could use the MACC to get the ones that meet the expectations and, from there, use linear programming to optimize the results and find any limitations.

Recommendations

To further develop the model, some recommendations that can be followed are the importance of the airlines evaluating the period that is being analyzed, as well as the markets and the organizational situation. For example, if there are not any new ATM initiatives in the analyzed year, then it is not useful to replicate the model considering this initiative. It can be replaced by another one that is being developed in that period. In addition, the implementation costs and limitation analysis cannot be considered for every airline around the world. Each one should develop a model based on the characteristics that are part of their operations.

Aside from the model recommendations, it is also important to evaluate additional optimization methodologies, like hierarchy processes and simulations. Even a combination of multiple techniques could be applied to further develop the analysis. Lastly, automated solutions could be implemented to aid in the model calculation, by the simple input of cost and return parameters, aside from supply limitations and initiatives savings. This solution is considered to be easier and faster to obtain the proper results in a dynamic operation, even allowing the development of dashboards and better training.

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