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A System Dynamics Approach in Mitigating the Environmental Impact of the Aviation Sector

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Despite various efforts to mitigate the carbon emissions brought about by the aviation sector, its dynamic behaviour has portrayed no point of improvement with its current trend. While notable studies have presented solutions in aspects of aircraft technology, aircraft design, and aircraft fuel, the increasing demand for air travel has remained a threat to the little environmental improvement that has been done. This study aims to use a systems dynamic approach to understand the dynamic behaviour of the increasing carbon emissions from the aviation sector. A model was developed to perform simulation runs. until 2050. Solutions such as green airports, tariff intervention, sustainable aviation fuel, electric aircraft propulsion, and changing the travel behaviour of passengers were simulated. The results show that the fundamental solution, which has been tested also in Europe, is to change the travel behaviour of people, instead of just offsetting carbon emissions such as using sustainable aviation fuel or building green airports. In other words, the fundamental way to mitigate the increase of carbon emissions in the aviation sector is not to just offset the carbon emissions, but to attack the root cause of it, which is the increasing demand for air travel.

1. Introduction

The aviation sector has served an integral role in the everyday lives of individuals, sustaining jobs and trade to keep the economic rhythm running (Dempsey et al., 2021). Despite various crises the world encounters, the aviation sector, as one of the main modes of transportation, has stayed resilient over infectious diseases, terrorisms, and financial crises in economic, operational, and financial aspects (Cook et al., 2023) and has been one of the fastest growing industries in the world (Kioulepoglou and Makris, 2023).

While the aviation sector gives obvious economic and social benefits, the environmental impact brought about by the aviation sector has been detrimental to the planet. The aviation sector is responsible for 2.4 % of the carbon emissions caused by anthropogenic activities, 5 % of human-induced global warming, and 12 % of carbon emissions from the whole transportation sector (Klöwer et al., 2021). Failure to mitigate climate change in the aviation sector would lead to increased greenhouse gas emissions (Hasan et al., 2021).

Studies have investigated minimizing environmental effects in the operational context of the aviation sector, such as in the optimization of fleet assignments and fleet scheduling (Justin et al., 2022). Researchers have also proposed eco-friendly solutions for traffic flow management systems, such as in taxiway operations (Zhang et al., 2022), runway operations (Yin et al., 2021), and terminal control area (Barea et al., 2020). Nonetheless, operational challenges exist in carrying out these initiatives (Chen et al., 2024) and the resulting environmental contribution is relatively low when comparing with other solutions (Lange, 2021). Sustainable aviation fuel (SAF) has been investigated by various researchers as it is the most effective mitigation strategy out of all, contributing to 80% of all attempts towards environmental sustainability (Lange, 2021). Nonetheless, the biggest hindrance to the full implementation of SAF is its cost, which is 120%–700% higher than conventional aviation fuel (CAF). The electrification of aircrafts have been studied by several researchers (Schwab et al., 2021). The electric aircraft propulsion (EAP) is projected to be available by 2030 (Cai et al., 2022); however, it could only cater to 45% of current flights that do not exceed 500 miles (Schwab et al., 2021).

While notable studies have presented solutions in aspects of aircraft technology, aircraft design, and aircraft fuel, the increasing demand for air travel has remained a threat to the little environmental improvement that has

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been done (Hasan et al., 2021). The field of system dynamics studies qualitative or quantitative variables, relationships between them, and the systems they form. It is a method in understanding the dynamic and nonlinear behaviour over a time period of a complex system (Bayer, 2004). The problem of the increasing carbon emissions in the airline industry is perceived and is dynamic as it increases without any sign of being curbed. This study investigates the dynamic problem of increasing carbon emissions in the aviation sector.

2. Model Development and Simulation

To simulate the dynamic behaviour of the system modelled through a specific period, a stock flow diagram (SFD) was modelled in Figure 1. This is based on the following system definition. The increase in CO_2 emissions is caused by active flight operations (Timperley, 2020), operational aircrafts (Schwartz and Kroo, 2009), and operational airports (Sahinkaya and Babuna, 2021). These three are triggered by the passenger demand for air travel. In other words, the higher the demand, the more flights, aircraft, and airports there are that are active. The demand for air travel has two drivers: economic contribution of air travel that is gained by flights and the perceived travel convenience gained by the innovations in aviation. All hypothesized causations have a positive relationship, which indicates a never-ending increase in CO_2 emissions. The root cause of the carbon emissions is the demand for air travel, as it dictates the operational aircrafts, operational airports, and active flight operations, which would affect the carbon emissions from the aviation sector.

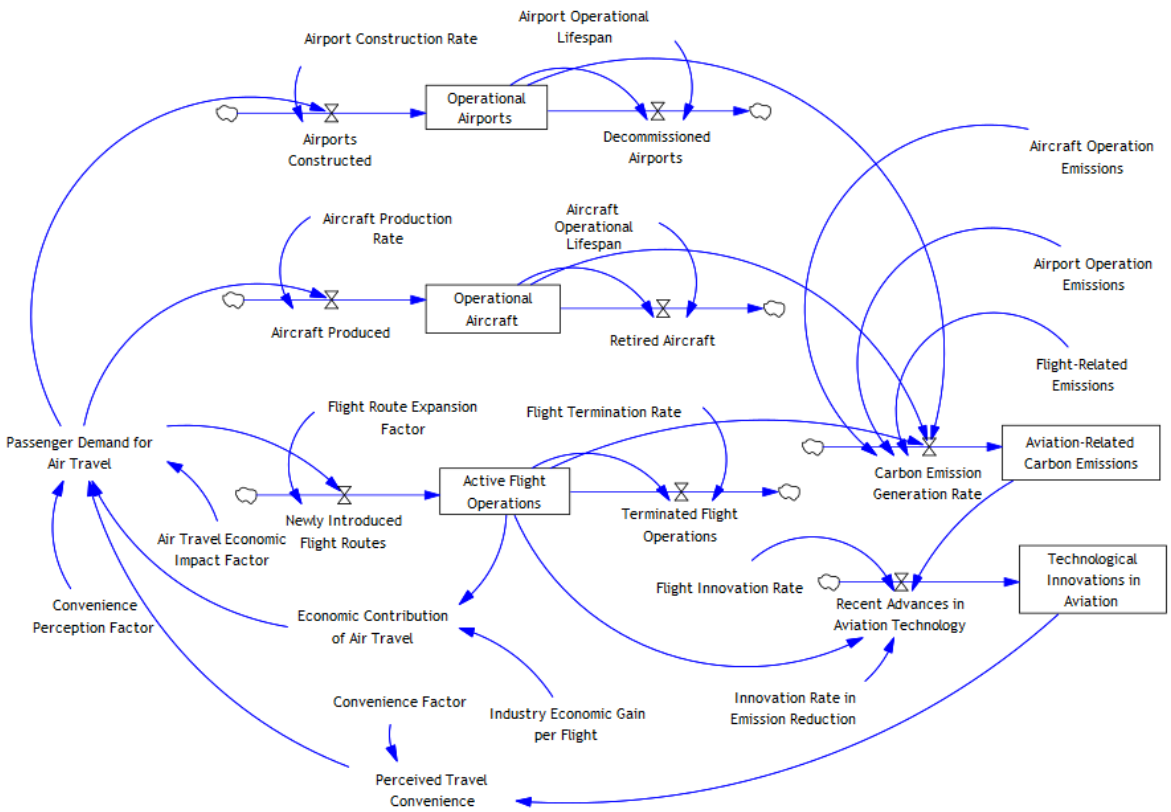

Figure 1: SFD for the aviation system

Figure 2a shows the simulated behaviour of the inflow of carbon emissions. The data used in the model is based on Uy et al. (2025a). The simulated trend for the model matches the real-life trend of the total aviation related carbon emissions (Bergero et al., 2023; Lee et al., 2021), which behaviourally validate that the data used in the model. The active aircrafts, active airports, and flights that are also increasing due to the increasing demand of air travel, shown in Figure 2b. Simulations are done without intervention of any strategies to mitigate carbon emissions in the aviation sector. Sensitivity analysis was also done with regards to carbon emissions generated and passenger demand for air travel to know what variables significantly contribute to their increase or decrease. Both showed a significant effect with regards to flight route expansion and termination factor, together with the convenience factor and convenience perception factor.

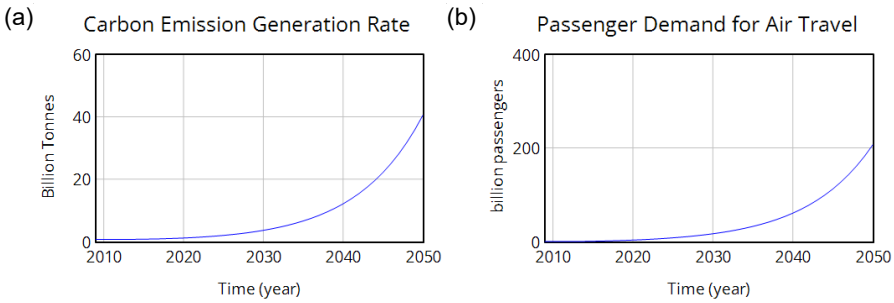

Figure 2: Base run for (a) carbon emission generation rate; (b) passenger demand for air travel

3. Computational Experiments

3.1 Green Airports

Green airports have 30-50 % lower carbon emissions than normal airports (Parhamfar, 2024). An example of a green airport is Changi Airport wherein they operate with environmentally sustainable resources, such as using solar panels. It also operates a large indoor garden and has efficient energy systems as resources. This effort targets decarbonizing ground-based aviation infrastructure, decreasing the airport operations emissions. Assuming best-case 100 % adaptation, there is still a minimal decrease in the total carbon emissions generated from the base run as shown in Figure 3, where the maroon-coloured line represents the current scenario and the green-coloured line represents the simulated scenario. This run results in 7.96 % less carbon emissions than the base scenario.

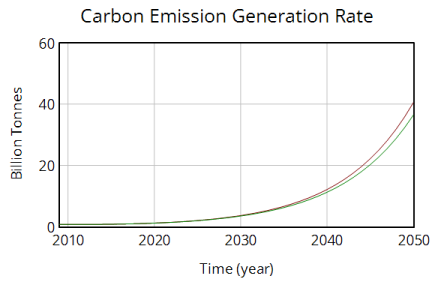

Figure 3: Adaptation of green airports run comparison for carbon emission generation rate

3.2 Tariff Intervention

This experiment extends the baseline with tariff intervention, attacking the economic contribution to air travel. This is a regulatory intervention imposed based on active flight operations to the customers of the airline sector. This influences a part of the demand for air travel, which is the root cause. This leads to a 15.36 % less carbon emissions than the base run, shown in Figure 4, where the maroon-coloured line represents the current scenario and the red-coloured line represents the simulated scenario. Tariffs could be in the form of frequent flyer levies, imposing increasing tariffs for each additional flight taken in a calendar year by the same individual. Moreover, carbon taxes proportional to flight emissions could also be imposed, especially on business class tickets and for flights that could be substituted by rail. Nonetheless, this is a short-term solution that brings minimal decrease in the carbon emission generation as the economic impact factor is not significant.

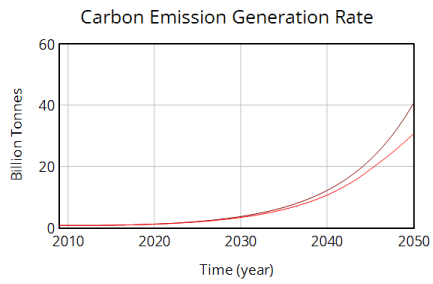

Figure 4: Tariff intervention run comparison for carbon emission generation rate

3.3 Sustainable Aviation Fuel (SAF)

Sustainable aviation fuels (SAF) have been investigated by various researchers as it is said to be an effective strategy, having an average of 70 % reduction in carbon emissions (Uy and San Juan, 2024). The adaptation of SAF targets the decreasing of the flight-related carbon emissions. While it is not yet being practiced, researchers have already tested a pure SAF flight and has been successful. Assuming full adaptation of SAF, there is a significant decrease of 38.37 % in the carbon emission generation rate in Figure 5, even before 2030, unlike the adaptation of green airports and tariff interventions wherein the difference from the base run could only be seen after 2030, where the maroon-coloured line represents the current scenario and the silver-coloured line represents the simulated scenario.

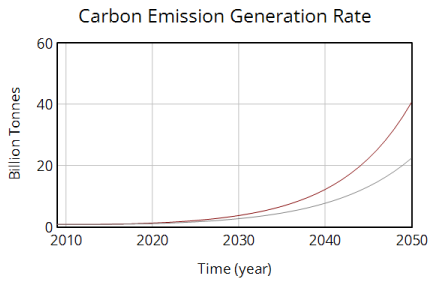

Figure 5: Adaptation of SAF run comparison for carbon emission generation rate

3.4 Electric Aircraft Propulsion (EAP)

The electrification of aircrafts have been studied by researchers not only because it reduces carbon emissions by up to 93 % than conventional aircrafts (Baumeister et al., 2024). The electric aircraft propulsion (EAP) could potentially cater to 45 % of current flights as EAPs can only work with flights that do not exceed 500 miles (Schwab et al., 2021). A simulation was conducted, with the run shown in Figure 6, where the maroon-coloured line represents the current scenario and the grey-coloured line represents the simulated scenario. This strategy attacks aircraft operation and flight related emissions, resulting at 47.29 % less carbon emissions than the base run, better than SAF adaption. Nonetheless, EAP has yet to become a technologically matured innovation and still needs time for development.

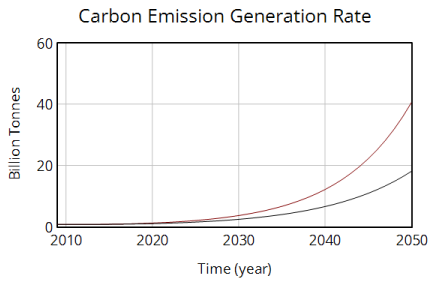

Figure 6: Adaptation of EAP run comparison for carbon emission generation rate

3.5 Travel Behaviour

While all previous solutions pose a decrease in carbon emission generation rate when compared to the base run, targeting the travel behaviour of passengers would directly attack the root cause of the problem, which is the passenger demand for air travel. This experiment involves the integration of an environmental awareness programme by non-profit organizations together with innovations in low-carbon travel alternatives, such as trains and buses. This has been done in Europe, especially in Sweeden where the flight-shaming campaign originated, and has shown significant results (Bhatta, 2024). This could also be done by requiring the amount of carbon emissions impact, that would be easy to understand to people (i.e., The flight that you are taking poses more than twice of the emissions that an average family emits per annum), to be made known to the passenger upon ticketing. Assuming the substitutional air travel percentage of short-distanced flights (Schwab et al., 2021), a simulation was conducted shown in Figure 7, bringing a significant difference shown when compared to the base run at 62.03 %, where the maroon-coloured line represents the current scenario and the blue-coloured line represents the simulated scenario. The low-carbon alternatives, when also as convenient as air travel, would encourage passengers to make the switch.

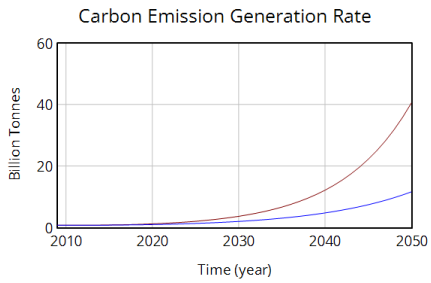

Figure 7: Change in Travel Behaviour run comparison for carbon emission generation rate

The SFDs of all computational experiments are shown in Uy et al. (2025b) Comparing all runs in Figure 8, targeting the passenger demand of air travel directly would be a fundamental and effective solution that gives the ideal results. While current studies suggest solutions that just offset carbon emissions (Hasan et al., 2021; Lange, 2021), long-term solution attacks the root cause directly, which affects the contributors to carbon emissions, operational airports, operational aircrafts, and active flight options. This point of attack may be used by policy makers as a basis when coining policies on sustainable travel, ensuring that the root cause is solved. At the same time, policymakers must ensure that this intervention does not merely shift the carbon emissions burden to another sector, but results in an overall reduction in emissions.

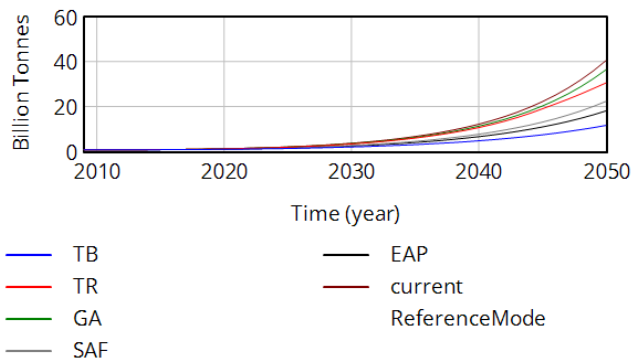

Figure 8: Comparison of all runs from the computational experiments

4. Conclusions

A system dynamics approach was used to analyse the increase of carbon emissions from the aviation sector. From the SFD that was constructed, it is demonstrated that the increase in carbon emissions is characterised by the increase in passenger demand in the aviation industry. Simulations were done on several solutions for the identified problem, which is the increasing carbon emissions in the aviation sector. These solutions include the transition to green airports, tariff intervention, usage of SAF, usage of EAP, and attacking the travel behaviour of passengers. Results show that a fundamental solution would need to attack the increasing demand in the aviation sector that would cause the demand to decrease, which is by the change in the travel behaviour of humans. While this study used hypothetical data, the data has been calibrated and verified to match the trend in real-life. Nonetheless, the researchers plan to extend the study to address the limitations of this study, exploring how human reaction would affect the solutions that should be imposed and including other non-CO_2 climatic effects. Moreover, the extended study would also explore on combining solutions to see potential interaction effects. Exploring the effects of different risk appetite on implementing solutions would also be investigated. Having the root cause and fundamental solution identified, researchers are recommended to further look into different ways on encouraging the change in the travel behaviour of humans, choosing a greener option rather than air transport. Moreover, future studies may also look into how to encourage airlines to take action voluntarily rather than wait for government intervention, which would bring a better outcome.

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