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Airline Fuel Loading Optimization Considering Sustainable Aviation Fuel

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With the efforts of different sectors to decouple the negative environmental impacts to the environment, the aviation industry has formulated different strategies to achieve net zero carbon emissions by 2050. Sustainable aviation fuel (SAF) contributes to 80 % of all efforts towards environmental sustainability. Despite its significance, no studies have considered SAF in fuel loading problems. In this study, a multi-objective mathematical optimization model is formulated for an airline fuel loading decision support system considering SAF by optimizing cost and environmental impact simultaneously. An illustrative case study is solved using the Efficiency algorithm to implement and test the model that uses less computational effort, yielding a total cost of USD 2,811,474 and a total environmental impact of 5,665,381 kg CO_2. Scenario analyses are done to validate and understand the behavior of the model. Results reveal important insights regarding decisions to be made that would balance out the economic and environmental benefits of the airline.

1. Introduction

The airline business is one of the major contributors to climate change with the increasing volume of passengers in the aviation industry (Sekartadji et al., 2023). With the Paris Agreement that was signed by different countries, various studies have been conducted to keep the stabilization of global warming below 2 °C of pre-industrial levels (Tian and You, 2022). Member airlines of the International Aviation Transport Authority committed to achieving net-zero emissions by 2050 (Vigeveno, 2021). In fact, sustainable aviation fuel (SAF) contributes to 80 % of all efforts towards environmental sustainability.

Studies that aim to innovate the production of SAF are increasing (Ambrosio et al., 2023), and the significance of SAF has been proven (Ramirez et al., 2023). That said, fuel loading problems must consider SAF. While all models that were developed were cost-centric (Alptekin and Gürsoy, 2023), this study considers both economic and environmental objectives, balancing the trade-offs between both objectives. As such, having both objectives considered in this study would benefit both the airline economically and the planet environmentally. Studies that only consider the economic aspect of the problem yield solutions that are not necessarily beneficial for the environment. The economic objective of previous studies considers location-based fuel costs (Okafor et al., 2020), cost of additional weight (Hassan et al., 2021), and discounted fuel prices (Hassan et al., 2021). This study has considered both location-based fuel costs and the cost of additional weight. This study also considers fuel-based fuel costs. This study considered fuel-based emissions for the environmental objectives.

While previous fuel loading problems only consider conventional aviation fuel (CAF) (Alptekin and Gürsoy, 2023), this study considers both CAF and SAF. This is important as SAF is already being used to mitigate the effects of climate change. Current models would not be able to solve fuel loading problems on SAF as they do not have blending considerations restrictions considering different fuel types.

As multi-objective optimization requires high computational effort, this study uses the Efficiency algorithm developed by Rollan et al. (2018). It is an operations research-based goal programming methodology that allows both objectives to be optimized simultaneously with less computational effort, identifying the best Pareto optimal solution without generating multiple solution points to generate the Pareto front (Caligan et al., 2022).

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2. System Definition

The optimization model that has been developed is based on economic and environmental objectives to decide on the amount of fuel to load per fuel type per flight. With a set of alternatives given a particular criteria, this study leads to the development of a decision support system (Tapia, 2021). The economic objectives are based on the total fuel costs, and the environmental objectives are based on the total environmental impact. The parameters that the optimization model would require include the cost of oil per fuel type per flight, the emissions of oil per fuel type, and the distance-based fuel consumption requirements (Zhu and Li, 2021). Trip fuel is based on the distance between airports considering the additional fuel burnt ratio. Taxi fuel is based on the taxi distance for both departure and arrival. Alternate fuel is based on the distance between the destination airport and the alternate airport. Reserve fuel is based on holding the plane in the air for 45 min during daytime or 30 min during nighttime at normal cruising speed. Contingency fuel is based on a fixed percentage as a parameter multiplied to the mission fuel. Extra fuel and discretionary fuel are given parameters. The constraints for the model include the blending constraints per fuel type and the fuel tank capacity of the plane being used.

3. Model Formulation

3.1 Assumptions

The input parameters for the mathematical model are considered per flight in a deterministic nature. The amount of fuel to be loaded into an aircraft is equal to the amount considering trip fuel, taxi fuel, alternate fuel, reserve fuel, contingency fuel, extra fuel, and discretionary fuel. The calculation of the fuel required is distance-based.

3.2 Objective Functions

The economic and environmental objectives for the mathematical optimization model are presented in Eq.(1) and Eq.(2). The cost objective is obtained by getting the product of the cost per oil type per flight along with the amount of oil to be loaded into the airplane per oil type per flight. The environmental objective, which has not been considered in the literature, is obtained by getting the product of the carbon emissions per oil type and the amount of oil to be loaded into the airplane per oil type per fight.

$$Cost = \sum_i \sum_j C_{ij} \cdot x_{ij} \tag{1}$$

$$Impact = \sum_i \sum_j I_i \cdot x_{ij} \tag{2}$$

3.3 Simultaneous Optimization of Objectives

The two objectives of the mathematical optimization model were solved simultaneously by utilizing the Efficiency algorithm. The method maximizes the worst efficiency value to attain a balance in both objectives, represented by Eq.(3). The efficiency value is represented by the ratio of the attained improvement, the difference between the worst possible value of an objective and its value in the multi-objective optimization run, and potential improvement, the difference between the best and worst possible value of an objective. For instance, among a set of solutions for multiple objectives, the lowest value and the highest value are the best and worst possible values for a minimizing objective. This method has proven to be effective by studies on algal biofuel production (Solis and San Juan, 2021), biomass co-firing networks (San Juan et al., 2018), hybrid energy renewable systems (San Juan and Sy, 2023), and airport gate assignment problem (Uy et al., 2023). Presented in Eq.(4) is the final objective function of the mathematical optimization model, with the linearizing constraints presented in Eq.(5) and Eq.(6) to assure the global optimality of the solution obtained.

$$Max\ Z = min\{\frac{Cost_{worst}-Cost}{Cost_{worst}-Cost_{best}}, \frac{Impact_{worst}-Impact}{Impact_{worst}-Impact_{best}}\} \tag{3}$$

$$Max\ Z = Efficiency \tag{4}$$

$$Efficiency \leq \frac{Cost_{worst}-Cost}{Cost_{worst}-Cost_{best}} \tag{5}$$

$$Efficiency \leq \frac{Impact_{worst}-Impact}{Impact_{worst}-Impact_{best}} \tag{6}$$

3.4 Constraints

Eq.(7) ensures that the total amount of oil is within the bounds of the minimum and maximum percentage of each oil type for each flight. Eq.(8) defines the total oil loaded into an aircraft. Eq.(9) assures that the total oil loaded into an aircraft in each flight is within the fuel tank capacity. Eq.(10) defines the total required fuel for every flight elaborated in the system definition. The non-negativity constraints are presented in Eq.(11).

$$N_{ij} \cdot T_j \le x_{ij} \le M_{ij} \cdot T_j \quad \forall i, j \tag{7}$$

$$T_j = \sum_i x_{ij} \quad \forall i \tag{8}$$

$$T_j \le F_j \quad \forall j \tag{9}$$

$$\begin{aligned} T_j = {} & DF_j \cdot AC_j + FP \cdot T_j + DD_j \cdot GC_j + DA_j \cdot GC_j + DT_j \cdot AC_j + HT \cdot CS_j \cdot AC_j \\ & + CP \cdot \left(D_j \cdot AC_j + FP \cdot T_j\right) + EF_j + DF_j \quad \forall j \end{aligned} \tag{10}$$

$$x_{ij} \ge 0 \quad \forall i, j \tag{11}$$

4. Illustrative Case Study

The illustrative case study contains a total of 30 flights, with the fuel costs listed in Table 1. Flights wherein SAF is unavailable at its origin airport have their costs represented by a dash (“-“). These are retrieved from Global Air (2024), Aviation Fuel Prices (2024), Heathrow Airport (2021), Ahlgren (2021), Massy-Beresford (2023), and Jet A1 Fuel (2024). The carbon emissions released is 3,745 kg/m^3 for CAF and 260 kg/m^3 for SAF (Hamdan et al., 2022). The maximum blend of SAF that can be loaded into a flight is 50 % (Müller-Langer et al., 2020). More comprehensive data for the illustrative case study can be provided upon request.

Table 1: Cost for CAF and SAF (x10^3 USD/m^3)

Flight	SAF	CAF	Flight	SAF	CAF	Flight	SAF	CAF	Flight	SAF	CAF	Flight	SAF	CAF
1	1.33	0.86	7	-	0.55	13	7.77	2.59	19	2.44	1.80	25	10.59	3.53
2	-	0.55	8	-	0.55	14	5.42	0.88	20	-	1.77	26	2.44	1.80
3	-	0.55	9	1.33	0.86	15	9.35	1.87	21	2.56	1.76	27	-	1.77
4	-	0.55	10	-	0.55	16	-	0.55	22	2.44	1.80	28	2.56	1.76
5	1.33	0.86	11	9.35	1.87	17	10.59	3.53	23	-	0.55	29	-	1.62
6	-	0.55	12	10.59	3.53	18	5.42	0.88	24	-	0.55	30	2.44	1.80

The multi-objective solution, together with the single-objective solutions obtained, are shown in Table 2. The economic and environmental objectives, which are conflicting, are balanced out in the multi-objective solution. Specifically, economic and environmental components yielded values in the middle of both objectives when comparing the single and multi-optimization runs. When only cost is minimized, the environmental impact is relatively high. When only environmental impact is minimized, cost would not be economical for the airline.

Table 2: Solution of Singe-Objective and Multi-Objective Runs

Categories	Cost Minimization		Impact Minimization		Multi-Objective Optimization
Cost (USD)	$Cost_{best}$	2,584,041	$Cost_{worst}$	3,425,034	2,811,474
Impact (kg CO$_2$)	$Impact_{worst}$	6,781,190	$Impact_{best}$	5,251,776	5,665,381

The optimal fuel loading decisions are presented in Figure 1. The balanced muti-objective solution would yield a balance of choices in terms of SAF and CAF. There are flights wherein minimal SAF is used and there are flights wherein the SAF loaded is exhausted until the maximum possible to cover up for the high amount of carbon emissions produced by flights that only loaded minimal SAF because of its cost, such as flights 11, 12, 13, 14, 15, 17, and 18.

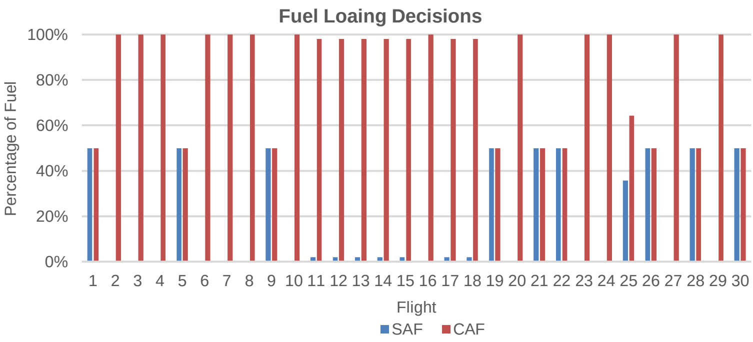

Figure 1: Fuel Loading Decisions

The behavior of the percentage of SAF decided to be loaded into a flight is investigated and presented in Figure 2. More SAF is usually loaded when the cost is lower as seen in the trend in the graph. When the price is high, less SAF is loaded, and instead CAF is loaded. SAF is also loaded in some cases even though cost is high because some flights are unable to load SAF. Not all airports have SAF available. This covers up the high environmental impact that CAF causes in flights where SAF is not available.

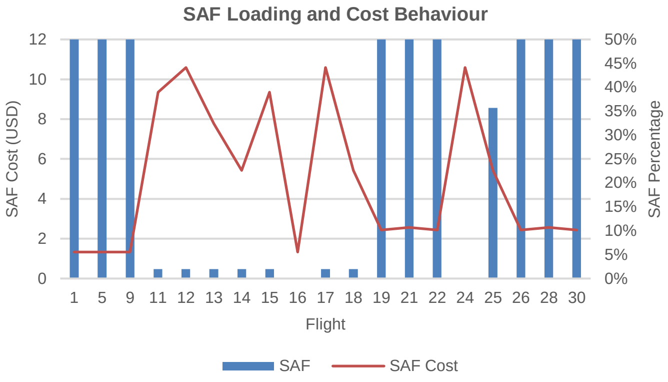

Figure 2: SAF Loading and Cost Behaviour

5. Scenario Analysis

Three scenario analyses are performed to show how the model would behave in different conditions.

5.1 Scenario 1: Comparison of Considering CAF Only and Both Fuels

As current models do not allow the consideration of SAF in their model (Alptekin and Gürsoy, 2023), a scenario analysis was made to compare the results when only CAF is considered together with the optimization model that was formulated. As seen in Table 3, although costs are lower, environmental impact was not lower when only CAF is considered. That said, the significance of using SAF for environmental benefits is evident.

Table 3: Solution of Scenario 1 and Base Run

	Only CAF	CAF and SAF
Cost (USD)	2,556,077	2,811,474
Impact (kg CO_2)	6,805,913	5,665,381

5.2 Scenario 2: Sensitivity Analysis on Adjusting SAF Cost

As the cost of SAF is one of the biggest hindrances in using SAFs (Tang, 2021), sensitivity analysis was done by adjusting the cost of SAFs by 20 % in both directions. Results presented in Table 4 show that decreasing the cost would encourage the airline to purchase more SAFs and vice versa. Decreasing the cost would lower the total environmental impact as well due to the additional SAF purchased when the cost decreases.

Table 4: Total SAF Purchased and Solutions of Scenario 2 and Base Run

	-20 % SAF Cost	Base Run	+20 % SAF Cost
Total SAF Purchased ($x10^{-3}$ m^3)	340,400	327,269	319,773
Cost (USD)	2,707,198	2,811,474	2,918,973
Impact (kg CO_2)	5,619,620	5,665,381	5,691,504

5.3 Scenario 3: Futuristic View on Removing Maximum Limit of SAF Loading

As of the current state, the maximum amount of SAF that is allowed to be loaded into an aircraft is 50 % (Müller-Langer et al., 2020). There are test flights that prove that the road to 100 % implementation of SAF is possible (Garcia, 2023). A scenario analysis is carried out to check how the model would behave when this happens in the future. Figure 3 shows that there are flights that would use 100 % SAF, especially when its cost is less. When compared to the base run in Figure 1, flights that can obtain cheaper SAF would load more, while the flights that have average to high cost would load minimally. Table 5 shows that removing the limit would allow significantly more SAFs to be used, having a better solution for environmental impact.

Table 5: Total SAF Purchased and Solutions of Scenario 3 and Base Run

Categories	No SAF Limit	With SAF Limit
Total SAF Purchased (x10^{-3} m^3)	527,027	327,269
Cost (USD)	2,886,364	2,811,474
Impact (kg CO_2)	4,969,224	5,665,381

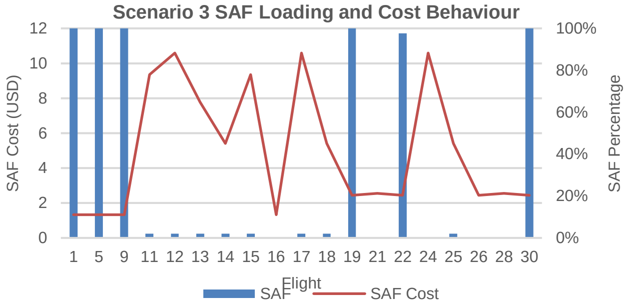

Figure 3: Scenario 3 SAF Loading and Cost Behaviour

6. Conclusion

A novel multi-objective mathematical optimization model was formulated for an airline fuel loading problem considering both CAF and SAF. The model has been designed to decide the optimal CAF and SAF to load into an aircraft considering economic and environmental objectives, which bridges the gap between not considering SAF and not considering environmental objectives. This study utilizes the Efficiency algorithm for less computational time than the conventional Pareto frontier. A case study and three scenario analyses were conducted to understand the model further. A balance is achieved in both conflicting objectives, prioritizing the use of SAF when the cost is low for environmental benefit and using CAF when the cost is slightly higher for economic benefit. The importance of using SAF can be seen as it allows room for environmental benefit. Thus, governments must look into policies and subsidies for SAF. It can also be seen that as the cost of SAF decreases in the long run, more will be purchased, resulting in both economic and environmental benefits for the airlines. Results show that aircrafts would also use 100 % SAF when available even though the cost stays status quo as this brings further reduction of carbon emissions. As such, the availability of SAF would help airlines lower their expenses as airlines can choose to load SAF in places where its more affordable. The study can be further improved by considering the concept of book-and-claim in the system, allowing virtual purchasing of SAF. Studies can also look into other optimization methodologies, such as genetic algorithms, and compare the results with this study. Additionally, government-industry interactions can also be studied on how incentives can encourage airliners to utilize SAF.

Nomenclature

i – index for oil type
j – index for flight
x_{ij} – amount of oil i loaded into a flight j, m^3
T_j – total amount of oil loaded into a flight j, m^3
C_{ij} – cost of oil i for flight j, USD
I_i – carbon emissions for oil i, kg CO_2
N_{ij} – minimum oil i for flight j, %
M_{ij}– maximum oil i for flight j, %
F_j – maximum fuel tank capacity for flight j, m^3
DF_j – flight distance of flight j, km
DD_j – departure taxi distance of flight j, km
DA_j – arrival taxi distance of flight j, km
DT_j – alternate airport distance of flight j, km
AC_j – fuel consumption for flight j, m^3/km
GC_j – ground fuel consumption for flight j, m^3/km
FP – additional fuel burn rate, %
HT – holding time, h
CS_j – cruising speed of flight j, km/h
CP – contingency fuel percentage, %
EF_j – extra fuel for flight j, m^3
DF_j – discretionary fuel for flight j, m^3

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