

A Game Theoretic Approach in Modelling the Competition of Aviation Fuel Production Firms considering Book-and-Claim

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Amongst all efforts to decarbonize the aviation industry, sustainable aviation fuel has proven to be the most popular technologically matured innovation that could pose a significant impact on mitigating climate change. While optimization studies that aid stakeholders in making decisions regarding production and using sustainable aviation fuel has been on the rise, the current pool of literature does not look into the competitive dynamics of the aviation fuel production firms. A simultaneous game theoretic mathematical optimization model is developed to understand the Cournot dynamics of the competition of conventional and sustainable aviation fuel production firms. A Fuzzy Cournot Optimization Approach is used to solve the model. This model aids production firms in making decisions based on anticipated market behaviour considering its highly competitive nature. An illustrative case study is carried out to understand the behaviour of the optimization model. Scenario analysis including varying the prices and considering book-and-claim strategy are also done. Results demonstrate strategies by both conventional and sustainable aviation fuel production firms that satisfies the equilibrium of both parties, each having a profit of USD 13,730.11.

1. Introduction

The International Air Transport Association (2025) has reported a 3.3 % increase in the total demand of air transportation for March 2025 compared to March 2024. While the aviation industry is one of the fastest growing industries on the planet and provides economic growth, one of its biggest challenges is to control its environmental impact, especially the combustion of fossil fuels during airborne operations (Dray et al., 2022). While studies have explored the possibility of having electric-powered aircraft, they are currently limited to short distances (Rohacs and Rohacs, 2020). Battery cell technologies are currently fitted to be utilized by the automotive industry rather than the aviation industry. Amongst all efforts to achieve carbon neutrality in the aviation industry, sustainable aviation fuel (SAF) is currently the most technologically matured innovation that can significantly contribute to the decarbonization of the sector (Xu et al., 2025). Moreover, more research and development are required for electric-powered aircraft (Dray et al., 2022) and they are impossible to commercialize in the near future (Trinh et al., 2021). That said, more and more airlines are starting to use SAF because of its significance in reaching environmental goals and its availability. In fact, its production has significantly increased throughout the years as governments around the world have been pushing for its implementation to decarbonize the aviation industry. Over the past six years, SAF production has risen from 1.9 M to 15.8 M gallons (Ozkan et al., 2024). Nonetheless, this is not yet enough to fully adopt SAF, and conventional aviation fuel (CAF) is still needed to fulfil the fuel demand of the aviation industry. CAFs are kerosene-based fuels that are widely used to power aircraft because of their market availability and cost-effectiveness. Nonetheless, due to their chemical composition, consumption of CAFs results in large CO₂ emissions, having a greater negative impact on the environment.

Decision support systems have been successful in aiding individuals and organizations in complex decision making (Triantafyllou, 2024), especially for optimizing costly processes that require cost minimization (Nanibabu et al., 2024). Optimization studies related to SAF in the current literature concentrate on the supply chain of sustainable aviation fuel and the innovation of the fuel components. Studies have considered looking into decision support systems regarding the locations and quantities of each process in the supply chain of

sustainable aviation fuel, minimizing the total cost and assessing the environmental life cycle (Masum et al., 2023). Optimization studies have also been conducted in different production pathways of SAF, optimizing economic benefits through process integration (Ambrosio et al., 2023). Studies that use multi-criterion decision analysis have also been done to aid decision making in the different pathways that are being considered. For instance, Neuling and Kaltschmitt (2018) assessed the SAF production pathways based on the technical, economic, and environmental performance of SAF. Furthermore, Ahmad et al. (2021) modelled the production pathways of SAF based on its technical, economic, environmental, and social performance. Optimization studies regarding the adoption of SAF have also been conducted. A game-theoretic study has been conducted by Uy et al. (2024), which looks into the government-industry interaction of SAF production firms, aiding the decision makers on which pathway to choose considering government incentives.

A lot has been done in optimizing the supply chain of SAF, especially in the production side. Nonetheless, limited optimization studies on the adoption of SAF for end-users, specifically airlines, have been conducted. These include optimizing economic and environmental benefits in using SAF (Uy and San Juan, 2024a) and considering green product substitution strategies in further minimizing costs and maximizing environmental benefit to encourage airlines to use SAF, called book-and-claim (Uy and San Juan, 2024b). Moreover, an optimization study for the adoption of production firms to adopt SAF from CAF has also been conducted, looking into government incentives to encourage the production of SAF (Uy et al., 2024). While attention has been given to the adoption and usage of SAF, the competitive dynamics within SAF production remain unexamined. This is a crucial oversight, as understanding how SAF competes with CAF at the production level is key to identifying effective strategies for scaling SAF supply. Without addressing this gap, policymakers and industry leaders risk making poorly informed decisions that could lead to inefficient resource allocation, slow the transition to cleaner fuels, and compromise the aviation sector's contribution to global net-zero goals (Xu et al., 2025).

The nature and direction of this study leads to the development of a decision support system (DSS). A DSS involves choosing an alternative amongst a set of alternatives given a set of criteria and quantify its effect on the criteria (Tapia, 2021). Developing a DSS that involve competing production firms that produce substitutable products, with different sustainability characteristics can be carried out through Cournot game theory, such as in the study of Zhang et al. (2025). A Cournot game depicts an economics-inspired simultaneous decision-making process between two competing firms, assuming that one does not know the strategy of the other (Ibrahim and Zaibidi, 2023). This best illustrates the competing nature of SAF and CAF production firms. A Cournot game theory is modelled through multi-objective optimization, with two objective functions that are simultaneously optimized (Rao, 1987). While previous studies have relied on the traditional Pareto frontier to address similar optimization problems (Tang and Zhang, 2016), this approach often requires evaluating a set of trade-off solutions, increasing computational complexity (Jing et al., 2019). Since a final decision must still be selected from among multiple Pareto-optimal outcomes, the process can be inefficient in practical applications. Therefore, there is a need for a more direct solution method for game-theoretic Cournot problems—one that reduces computational effort while still capturing the essential dynamics of competition in fuel production.

2. Problem Statement

This study aims to address the aforementioned gap by developing a game-theoretic Cournot competition model to analyse how a SAF production firm and a CAF production firm determine production quantities, carrying out simultaneous decisions in a competitive environment that maximizes total profit. Given:

- Fuel demand, considering book-and-claim, that needs to be met by a SAF production firm and a CAF production firm, each of which has a different market price and expenses.
- The two firms individually simultaneously aim to maximize the total profit for a production period while deciding on the production level considering the market prices and expenses.

3. Model Formulation

3.1 Assumptions

The DSS that is developed assumes deterministic input parameters. Moreover, the DSS also assumes that the fuel produced will all be sold, leaving zero inventory. The Cournot nature of the problem also assumes that both firms have no foreknowledge on the strategy of each other, thereby making simultaneous decisions.

3.2 Objective Function

The profit-maximizing objective functions of the SAF and CAF production firms are respectively presented in Eq(1) and Eq(2). Expenses for the fuel production firms include feedstock costs, processing costs, carbon cost or credit, and capital recovery cost.

$$\text{Max Profit}_S = SP_S Q_S - FC_S Q_S - PC_S Q_S - CR_S Q_S - CE_S Q_S CT \quad (1)$$

$$\text{Max Profit}_C = SP_C Q_C - FC_C Q_C - PC_C Q_C - CR_C Q_C - CE_C Q_C CT \quad (2)$$

3.3 Constraints

Eq(3) ensures that the total production quantity of both CAF and SAF meets the demand. Eq(4) integrates the quantity of SAF that has been virtually purchased to be considered in production, which is based on the concept of book-and-claim. The capacity constraint of the fuel production firms is seen in Eq(5). Eq(6) ensures that the production quantity is non-negative.

$$\sum_i Q_i \geq TD \quad (3)$$

$$Q_S \geq BNC \quad (4)$$

$$Q_i \leq CAP_i \quad \forall \quad (5)$$

$$Q_i \geq 0 \quad \forall \quad (6)$$

4. Solution Approach

In a Cournot game theoretic model, the two entities simultaneously makes a decision, which is usually modelled through a bi-objective optimization model and solved through finding the Pareto front (Tang and Zhang, 2016). Studies have utilized an approach with a similar concept to the objective function in Eq(7), wherein it substitutes and simultaneously optimizes the original objective functions, having the decisions meet at equilibrium between the two objectives (San Juan and Sy, 2021). Each objective is represented by a value between 0 and 1 that is the ratio between the ratio of the attained improvement and the potential improvement. Originally, the attained improvement is represented by the difference between the worst possible value of an objective and the value of the actual simultaneous objective run. Since the worst possible value is zero in a Cournot duopoly game, then the attained improvement will be revised and represented by the value of the actual simultaneous objective run for the Fuzzy Cournot Optimization Approach. Similarly, the potential improvement originally represented by the difference between the best and worst possible value of an objective will be revised and represented by the best possible value, which assumes that the demand will be satisfied by solely the corresponding firm. This equation will then be linearized to assume that the final answer yields the global optimum. This leads to Eq(8) as the final objective function, with Eq(9) and Eq(10) serving as the linearizing constraints.

$$\text{Max } Z = \min \left\{ \frac{\text{Profit}_S}{\text{Profit}_{S(Q_S=TD)}}, \frac{\text{Profit}_C}{\text{Profit}_{C(Q_C=TD)}} \right\} \quad (7)$$

$$\text{Max } Z = \varepsilon \quad (8)$$

$$\frac{\text{Profit}_S}{\text{Profit}_{S(Q_S=TD)}} \geq \varepsilon \quad (9)$$

$$\frac{\text{Profit}_C}{\text{Profit}_{C(Q_C=TD)}} \geq \varepsilon \quad (10)$$

5. Illustrative Case Study

The developed DSS will be implemented as a case study to verify the model. The illustrative case study is based on a SAF production firm and a CAF production firm, simultaneously making production decisions while maximizing economic benefits. The input parameters for the model are shown in Table 1. The cost parameters were retrieved from the reports of Holladay et al. (2020), Pavlenko et al. (2019), and International Energy Agency (2022) as basis. The study of Neuling and Kaltschmitt (2018) are used as a basis for the carbon emissions. The carbon tax of 0.02 USD/kg-CO₂ is based on Singapore (National Environmental Agency, 2023). For this illustrative case study, a demand of 100 m³ and a book-and-claim demand of 20 m³ of fuel will be assumed.

The optimal fuel production quantities are presented in Table 2. Based on the total profit of each fuel production firm, the model balanced the production levels of both firms. Equilibrium was achieved in total profit through optimizing the production levels under market prices, expenses, and constraints, thereby satisfying the conditions of a Nash equilibrium and validates the solution approach used for the Cournot game-theoretic model. This approach could also be used in more complex models that also have the same Cournot nature.

Table 1: Parameters for SAF and CAF production firms.

Parameter	SAF Production Firm	CAF Production Firm
Selling Price (USD/m ³)	3,000 (Holladay et al., 2020)	1,100 (International Energy Agency, 2022)
Feedstock Cost (USD/m ³)	1,200 (Holladay et al., 2020)	500 (International Energy Agency, 2022)
Processing Cost (USD/m ³)	14,000 (Pavlenko et al., 2019)	300 (International Energy Agency, 2022)
Carbon Emissions (kg-CO ₂ /L)	1,700 (National Environmental Agency, 2023)	3,330 (National Environmental Agency, 2023)

Table 2: Solutions for SAF and CAF production firms.

	SAF Production Firm	CAF Production Firm
Total Profit (USD)	13,730.11	13,730.11
Production Quantity (L)	38.57	61.43

This shows depicts real-life situations on the production level of CAF and SAF. Due to the high costs and low profits of SAF, its production level is lower than CAF as there is no incentive for firms to produce SAF. The cost is a critical barrier in the adoption of SAF.

6. Scenario Analysis

Scenario analyses are carried out to understand the behaviour of the decisions in different conditions.

6.1 Varying SAF prices

One of the biggest barriers to the full adoption of SAF is its high costs and low profits. Figure 1 shows the Cournot equilibrium production levels of SAF and CAF considering the varying prices of SAF, which logically validates the solution approach that has been used. The inverse relationship between SAF and CAF shows the substitution effect of the fuels. When one becomes more expensive than the other, the fuel that costs lower would have more demand and produced more. This behaviour represents the characteristic of Cournot competitors adjusting their respective outputs based on market prices (Tang and Zhang, 2016). Identifying the critical price point is also essential to know at what price SAF should be set at. Figure 1 shows that the point wherein using SAF would not anymore be economically practical, when the selling price is higher than USD 2.9. This is true especially when no government subsidies are provided in a competitive duopoly setting. It is important for the government to provide subsidies for using SAF to decrease the cost in using it for environmental benefit as this is by far the most effective and most feasible innovation that could aid the decarbonization of the aviation industry.

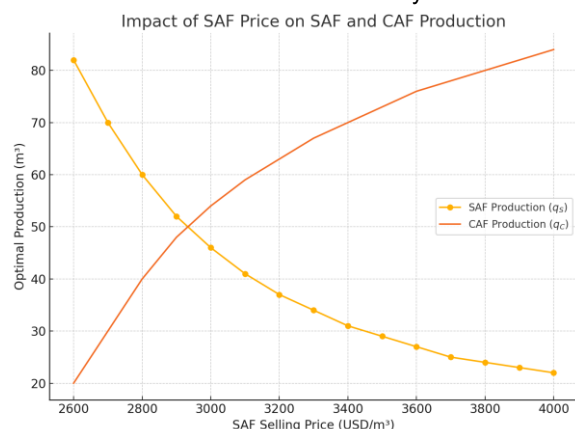


Figure 1: Impact of SAF price on SAF and CAF production

6.2 Varying book-and-claim demands

One promising strategy that encourages airlines to purchase SAF is through virtually buying it, pulling its costs as transportation is not needed to ship the fuel from the production firm to the airport especially if it is far. In the

point of view of the production firm, the book-and-claim demand would serve as a minimum SAF production level. Figure 2 shows the relationship between the book-and-claim demand and the production level of SAF and CAF. When the demand is low, it does not matter to the production level. Nonetheless, the virtual purchasing of SAF would come in useful at one point where the book-and-claim demand is higher than the Cournot production level of SAF. This pushes to increase the production of SAF. The increase in the production of SAF for the book-and-claim demand specifically would not affect the willingness to buy of an airline as this would be sold as CAF since the sustainability characteristics have been purchased by another airline already. This strategy is effective as proved in the study of Uy and San Juan (2024b) for the airline's point of view, and also for this study for the producer's point of view.

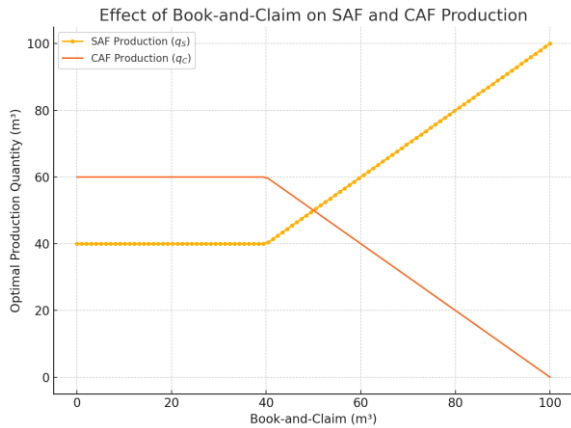


Figure 2: Effect of book-and-claim on SAF and CAF production

7. Conclusions

A Cournot game-theoretic optimization model has been developed on the decision-making for CAF and SAF production considering book-and-claim. The DSS maximizes profit for the SAF production firm and the CAF production firm. The Fuzzy Cournot Optimization Approach was used for this study, and the results show the validity of the approach. Results show that the approach satisfies the Nash equilibrium of the problem, representing its Cournot nature. Results also depict real-world relationships on the substitution effects of SAF and CAF considering the price variation, which reveals the need for government intervention on providing subsidies. The selling of SAF through virtual means has also been proven effective in the point-of-view of a production firm, which pushes the production of SAF higher than its equilibrium production level, which validates the efficacy of book-and-claim in SAF adoption. Future studies could use this solution approach to test a larger scale and a more complex Cournot game-theoretic problem, such as integrating three or more firms to the problem. A multi-period study can also be carried out with price fluctuations for a more realistic approach.

Nomenclature

i – index, fuel type (S - SAF, C - CAF)	
Q_i – decision variable, production quantity, m^3	
Profit _{i} – objective variable, profit, USD	
ε – auxiliary model variable, linearizing dummy variable for the Fuzzy Cournot Optimization Approach	
TD – parameter, total demand, m^3	PC_i – parameter, processing cost, USD/ m^3
BNC – parameter, book-and-claim demand, m^3	CR_i – parameter, capital recovery cost, USD/ m^3
CAP_i – parameter, production capacity, m^3	CT – parameter, carbon tax, USD/ m^3
SP_i – parameter, selling price, USD/ m^3	CE_i – parameter, carbon emissions, kg/ m^3
FC_i – parameter, feedstock cost, USD/ m^3	

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