Postponement for greener skies: the potential for sustainable aviation fuel on-site blending at airports

Martin Oetzel
Kühne Logistics University, Hamburg, Germany
Puay Guan Goh
NUS Business School, National University of Singapore, Singapore, Singapore, and
Kai Hoberg
Kühne Logistics University, Hamburg, Germany

Received 31 January 2025
Revised 9 October 2025
Accepted 11 October 2025

Abstract

Purpose – Sustainable Aviation Fuel (SAF) is crucial for aviation decarbonization, but its current pre-blending process at refineries presents challenges, including fixed blending ratios, higher transportation costs and long lead times. This study explores the potential of an innovative technology that enables on-site SAF blending at airports. By postponing blending to the point of use, this approach offers customization opportunities. However, the precise benefits and trade-offs of this concept remain unclear. The research aims to assess the impact of on-site blending on fuel price, lead time, carbon emissions and supply chain costs.

Design/methodology/approach – This empirical study evaluates the effects of SAF postponement using case analyses of Singapore-Seletar and Maastricht airports. The analysis incorporates cost modeling, lead time assessment and carbon impact calculations to quantify the implications of shifting blending downstream to airport sites. Data sources include industry reports, airport-specific logistics information and SAF supply chain parameters. A comparative analysis is conducted to determine optimal airport conditions for SAF postponement, highlighting key enablers and barriers to implementation.

Findings – The results indicate that on-site SAF blending can create competitive advantages by reducing supply chain costs and lowering carbon emissions. The benefits are contingent on airport-specific factors, such as Hydroprocessed Esters and Fatty Acids availability, logistics infrastructure and regulatory conditions. The findings suggest that certain airports, particularly those with strategic locations and favorable cost structures, are better suited for adopting SAF postponement. By shifting production downstream, airports can achieve greater flexibility in SAF blending ratios while minimizing logistical inefficiencies.

Originality/value – To the best of the authors' knowledge, this study is among the first to empirically examine the feasibility of postponing SAF blending to the airport level. While existing literature focuses on SAF production and distribution, the concept of downstream blending has not been systematically analyzed. The research provides new insights into how mass customization principles can be applied to SAF supply chains, potentially reshaping fuel logistics in the aviation industry. By identifying critical factors for successful implementation, this study contributes to both academic discussions and practical decision-making in sustainable aviation fuel management.

Keywords Postponement, Aviation fuel, SAF, Blending

Paper type Research article

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report revealed the urgency and requirement of drastic actions to limit global warming to 1.5 °C and reduce fossil fuels (IPCC, 2022). The aviation industry is responsible for 2% of the global emissions of greenhouse gases (GHG) (IATA, 2022a). The principal reduction of emitted GHG needs to come from the uptake of sustainable aviation fuels in the aviation industry. At least 1.8

Logistics Research
Vol. 18 No. 1/2, 2025
pp. 87-109
Emerald Publishing Limited
e-ISSN: 1865-0368
p-ISSN: 1865-035X
DOI 10.1108/LORE-01-2025-0012

gigatons of carbon must be removed from the atmosphere in 2050 to meet decarbonization goals (Scheelhaase *et al.*, 2019; IATA, 2022c). The established Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) organization has raised global interest in Sustainable Aviation Fuel (SAF). Since the SAF production volume and availability of SAF have increased in the fuel market, CORSIA includes the usage of SAF in its decarbonization strategies. (IATA, 2021).

Meeting these decarbonization goals in aviation will depend on the use of SAF at scale, as it can be adopted by conventional aircraft without modifications (Martinez-Valencia *et al.*, 2023), and the adoption of new aircraft technology is also expected to be slow (Abrantes *et al.*, 2021).

While various measures to accelerate the adoption of SAF have been proposed, such as policy measures including carbon pricing, incentives, loans and regulation (Martinez-Valencia *et al.*, 2023; Mousavi and Bossink, 2017), adoption of new aircraft designs (Abrantes *et al.*, 2021), developing the supply chain of the SAF fuel is also necessary to stimulate demand (Mousavi and Bossink, 2017). A lack of collective action, investment and leadership among biofuel companies, airlines and policymakers has led to slow adoption of SAF (Dodd and Yengin, 2021), while a stakeholder analysis revealed that to increase the use of SAF, lowering the production cost is necessary (Ahmad and Xu, 2021).

A common approach for manufacturing SAF is based on synthesized paraffinic kerosene produced from hydroprocessed esters and fatty acids (HEFA) that use feedstocks such as bio-oils, animal fat or recycled oils. However, the global manufacturing capacity is very limited, and the blending ratio between HEFA and the conventional Jet A-1 fuel is limited to 50%. Normally, the SAF fuel is pre-blended at the manufacturing site at a 20% ratio and shipped to the airport (bp, 2023; Pavlenko and Kharina, 2018). However, this pre-blending at the refinery has several key disadvantages. First, the selected blending ratio cannot be altered - customers who would like to have a different SAF blending ratio would need to order directly from the manufacturer, and an airport operator typically does not provide different tanks with different SAF blending ratios for its customers. Accordingly, airlines or private jet operators are restricted to the pre-selected 20% SAF ratio, although they would wish to use higher SAF ratios. This situation mirrors a classic manufacturing context where customers have no ability to customize a product to their specific needs. Second, the pre-blending leads to a situation where the blended SAF (that contains 80% of conventional jet fuel) is shipped in a special container of a certain grade (for example, stainless steel or mild steel) from the refinery to the airport. This is a high-effort process given that the conventional jet fuel is normally shipped in bulk directly to airports using pipes or tanker vessels. Accordingly, the transport costs and carbon emissions can be very high compared to the traditional approaches. In addition, long replenishment lead times and volatility of demand from central pre-mixing refinery locations increase inventory needs and planning effort.

To overcome this challenge of pre-blending, Singapore-based company FlyORO has developed a modular biofuel blending system called AlphaLite that allows precise on-site blending at airports. Its advanced pneumatic-driven process technologies guarantee customized, precise-manufactured SAF that is certified according to the highest quality and safety standards. This approach relates to the well-established concept of postponement that was first introduced by Alderson (1950). Companies like Hewlett–Packard (HP) and Benetton have introduced postponement to enable responsive mass customization by decentralization and product differentiation point a further downstream (Billington *et al.*, 2004; Feitzinger and Lee, 1997; Yang and Burns, 2003). So far, these postponement strategies often do not specifically consider sustainable operations but are driven by cost and lead time reductions. However, we aim to understand if a postponement strategy can be used for SAF manufacturing directly on-site at airports.

Against this background, this paper examines postponement as a strategic design choice for SAF supply chains. We focus on how shifting the decoupling point (DP) downstream to the airport – by postponing the blending of SAF until the point of use – affects supply chain cost, lead time and carbon efficiency. In doing so, the study addresses the trade-off between global sourcing of pre-blended SAF and local sourcing of HEFA for on-site blending, linking classical postponement theory with emerging sustainability constraints. Specifically, we analyze and compare two alternative supply chain configurations: (1) a baseline scenario in which SAF is pre-blended at the refinery and transported to the airport and (2) an on-site blending scenario in which only the synthetic blended component (SBC; HEFA) is shipped and final blending occurs at the airport.

Figure 1 illustrates the mechanisms by which the postponement of SAF blending is achieved, the benefits of doing so, and the assessment of the benefits. First, lower volumes of pre-blend SAF affect transportation cost and CO_2 emissions. Second, postponement enables local HEFA sourcing, which enables more flexibility in sourcing from diverse sources. Finally, flexible SAF ratios enable the potential for HEFA fractions compared to standard pre-mix SAF ratios.

For our analysis, we selected two airports in different regions and with different characteristics that we visited to get the required insights: the Selatar airport in Singapore that serves smaller-sized private and business jet airlines and Maastricht airport in the Netherlands that serves cargo, passenger and private jets. While the cost of logistics and the cost of sources of HEFA and Jet A1 vary by location, this allows us to understand the trade-offs between cost, blend ratios and distance. Against this background, we raised two research questions to investigate the impact of postponing SAF blending downstream.

RQ1. Does the postponement of SAF on-site blending significantly improve the supply chain costs, lead time and carbon emissions?

RQ2. Does the postponement of the on-site blending activities significantly affect the SAF price per liter?

The structure of the remainder of the paper is as follows. Section 2 provides a short literature review on strategic postponement. Section 3 provides an overview of the research context around sustainable aviation fuel, its pathways and on-site blending. Section 4 outlines the methodology and the data collection. Section 5 analyzes the cost, carbon emission and lead time impact of the two alternative strategies at the two airports. Section 6 discusses the results, and Section 7 presents the conclusion of this research.

2. Strategic postponement in supply chain management

Postponement in supply chain management refers to delaying product customization until customer demand is better understood, thus reducing risks and costs associated with product

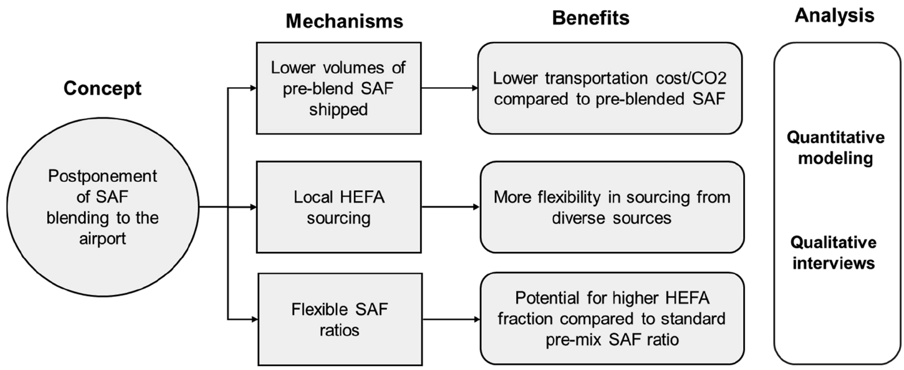

Figure 1. Mechanism through which postponement of SAF blending achieves benefits. Source: Created by authors

differentiation (Ferreira *et al.*, 2014). Initially introduced by Alderson (1950) and later expanded upon, this concept serves as a strategy for enhancing mass customization (van Hoek, 1996). Alderson's groundbreaking work emphasized meeting market needs cost-effectively, while Bucklin (1965) developed a methodology for integrating postponement, advocating for the use of semi-finished goods inventory to manage speculation. Zinn and Bowersox (1988) furthered this by establishing a framework for positioning activities along the supply chain. Postponing activities can result in reducing inventory, transportation and storage costs (Yang *et al.*, 2004).

Notable implementations of postponement include Hewlett–Packard's modular production approach, aligning product design, manufacturing and distribution to reduce customization costs (Billington *et al.*, 2004; Feitzinger and Lee, 1997). Similarly, Benetton enhanced responsiveness by postponing the dyeing process in their garment production, leading to reduced inventory and waste (Yang and Burns, 2003). These examples illustrate how postponement can lead to significant efficiency gains in supply chain operations.

2.1 Types of postponement

Zinn and Bowersox (1988) identified five types of postponement – labeling, packaging, assembly, manufacturing and time – and highlighted their role in discrete manufacturing, distinguishing between form (labeling to manufacturing) and time postponement for distribution cost savings. Bowersox and Closs (1996) expanded this typology into form, time and place categories, with form postponement delaying product form and function changes, time postponement waiting for customer orders to move goods and place postponement involving strategic goods positioning. Pagh and Cooper (1998) categorized postponement into four types: bundled manufacturing, unicentric, deferred assembly and deferred packaging, each corresponding to different supply chain stages, from upstream to decentralized warehouses. Brown *et al.* (2000) introduced product and process postponement, with the former allowing downstream product characteristic customization and the latter managing inventory and the push-pull boundary within the supply chain.

Waller *et al.* (2000) explored the interaction between market-oriented supply chain management and postponement, building on Zinn and Bowersox's (1988) typology to develop strategies considering supply chain members and value-adding activities. Yang and Burns (2003) discussed manufacturing process postponement, noting its impact on economies of scale and uncertainty. They described various postponement strategies from engineering-to-order to make-to-stock for managing uncertainty and customization. Finally, Yang *et al.* (2004) examined postponement at the management level, detailing strategies to handle uncertainties through product development, purchasing and production postponement, aiming to meet customer needs while managing financial liabilities and inventory.

2.2 Drivers for adapting postponement strategies

Decision factors for postponement strategies vary based on product characteristics, market demands and manufacturing processes, with an integrated approach often being most effective (Pagh and Cooper, 1998). Product-related postponement is driven by the product's life cycle, value density and design features, which influence customer service focus during introduction/growth phases and cost/risk management in maturity/decline phases (Zinn and Bowersox, 1988; Pagh and Cooper, 1998). Mass customization also prompts diverse and adaptable design considerations (Brun and Zorzini, 2009).

Market-driven postponement hinges on demand uncertainty, where greater unpredictability necessitates more flexible postponement strategies to manage lead times and delivery (Yang *et al.*, 2004). Manufacturing-driven postponement considers economies of scale and expertise, capacity, market fit and forecasting precision (Pagh and Cooper, 1998; Kisperska-Moron and Swierczek, 2011), with location, quantity and distribution networks prompting modular process adjustments (Guericke *et al.*, 2012). Manufacturing postponement can take the form of form/functional postponement, where final processing and manufacturing are conducted upon customer orders, and include customer and country-specific requirements (van Hoek and van Dierdonck, 2000).

While postponement strategies have generally been applied to modular manufacturing (Prataviera *et al.*, 2022; Van Kampen and Van Donk, 2014), with fewer applications on process industries (Van Kampen and Van Donk, 2014), process industries can also benefit from the use of postponement. For example, Bandaly and Hassan (2020) show how dairy products can benefit from postponed blending of the final dairy recipes from base recipes, while wine can also benefit from postponement by being shipped in bulk and bottled at regional distribution centers (Twede *et al.*, 2000). To the best of the authors' knowledge, postponement has not been applied to SAF.

In the SAF context, two postponement mechanisms are most important. First, design postponement enables customers to finally customize a product, and the extent and cost of customization depend on the implementation by the manufacturer. The SAF context exemplifies this mechanism by demonstrating how the on-site blending allows for a variable ratio that was not previously feasible, similar to a bag manufacturer offering extensive customization on colors and features. Second, the postponement of the on-site blending enables a streamlined logistics process. Instead of shipping pre-fabricated SAF at high cost, postponing the blending process to the airport reduces costs, similar to a manufacturing setup where region-specific power plugs are added at the final distribution stage rather than shipping a product with multiple plug options.

3. Research context: sustainable aviation fuel

The conventional aviation fuel market accounts for approximately 6% of the world's refinery fuel production and exceeds 81 billion gallons annually. It is estimated that 20–30% of Airlines' operation costs are caused by jet fuel. Most purchasers rely on long-term negotiation since the aviation industry is price-sensitive. The market can be distinguished into two fuel types: aviation gasoline and kerosene. These types differ mainly in carbon number composition (Baumi *et al.*, 2020; Holladay *et al.*, 2020; bp, 2022b). Aviation gasoline, also known as AVGAS, only accounts for about 1% of the aviation fuel market and is commonly used for smaller spark ignition aircraft (Baumi *et al.*, 2020; bp, 2022a). Jet A and Jet A-1 kerosene account for most of the aviation fuel market and are internationally standardized fuel types, differing mainly in their freezing points (Holladay *et al.*, 2020; bp, 2022a, b).

The conventional fuel infrastructure at airports usually consists of six steps (see Figure 2). An Oh and ICAO (2011) survey showed that fuel handling starts at the refineries where Jet A-1 fuel is made of crude oil. Once the fuel is produced, it needs to be transported to the airport. The mode of transportation may vary depending on the airport's infrastructure, location and size. Pipelines, ships, bulk truckloads or trains can deliver the fuel. The survey found that airports use pipelines the most. Airports typically have fuel farms where the jet fuel is stored; these fuel farms are usually located near or on the airport property. The final step in the supply chain is the delivery of fuel to aircraft by trucks or hydrant systems (Oh and ICAO, 2011).

3.1 Sustainable aviation fuel

SAF is a promising plane fuel alternative with the potential to reduce carbon emissions in the commercial airline industry by up to 80% (IATA, 2022d). Sustainable fuel development is

Figure 2. Conventional airport fuel supply chain. Source: Adopted from Oh and ICAO (2011)

distinguished into drop-in and non-drop-in SAF. Renewable *drop-in SAF* is an alternative to conventional kerosene. It is a synthetic blended liquid fuel consisting of two components Jet Fuel (Jet A-1) and SBC. It has chemical and physical similarities to conventional fossil-based jet fuel and can be used in existing aircraft and engine types (Neste, 2022). In contrast, *non-drop-in SAF*, such as hydrogen is incompatible with existing aircraft, requiring extra investment for new redesigns. Figure 3 illustrates the stylized SAF supply chain.

3.1.1 Technical certification for aviation fuel. The American Society for Testing Materials (ASTM) standard number D1655 is the most used standard to ensure that jet fuels are suitable around the globe. The ASTM convention guarantees that the fuel is suitable for any engine type when mixed. ASTM regulates crucial standards for composition, volatility, fluidity, combustion, corrosion, thermal stability, impurities and additives. After kerosene is derived from crude oil, it must undergo rigorous testing to ensure that it meets the international ASTM D1655 standard. Once all the tests are successfully completed, jet fuel is entitled to be sold in the aviation fuel market (ASTM International, 2022).

3.1.2 Synthetic blended components. SBC is a synthetic liquid fuel used as a renewable drop-in kerosene. It is produced from various biogenic feedstocks and has the same characteristics as conventional Jet A-1 kerosene derived from fissile fuels. Over the years, nine possible production pathways have been identified to produce SBCs from different feedstocks. The market's three most promising SBCs are Fischer-Tropsch (FT) fuels, Hydroprocessed Esters and Fatty Acids (HEFA) fuels and Alcohol-to-jet (ATJ) Synthetic Paraffinic Kerosene, while HEFA-SAF is the most promising pathway to meet short- and medium-demand, with a blending ratio of 50% by ASTM (Starck *et al.*, 2014).

Facilities need to undergo a rigorous and long-lasting testing process to be eligible to produce SBC and sell it under the ASTM standards. Europe has the largest SBC capacity and mandates drive the demand. Current demand exceeds supply. Neste Corporation is one of the current market leaders in the production of HEFA and produces more than half of the available volume worldwide. Most of their production facilities are in Europe (van Dyk and Saddle, 2021). Figure 4 illustrates the projected capacity of SAF and reinforces the significance of HEFA production; the volume is expected to increase significantly until 2030.

3.1.3 SAF and biofuels pricing. According to the International Air Transport Association (IATA), the current jet fuel price depends on crude oil prices. Compared to the price of crude oil, jet fuel is estimated to be 1.2 times more expensive (Hong *et al.*, 2019). The average jet fuel price for 2022 is \$142.1 per barrel (\$0.89 per liter. Biofuels are estimated to be 2–7 times more expensive than conventional jet fuel (Hong *et al.*, 2019). Consequently, the average SAF price will be between \$1.78 and \$6.23 per liter. The price volatility of crude oil and conventional jet fuel significantly impacts future investment in biofuels and SAF (Bardell and Ashton, 2018). Since it is impossible to fly with 100% SAF yet, SAF must be blended with jet fuel. These blending ratios range between 10% and 50%. The higher the blend ratio of SAF, the higher the fuel price. Nevertheless, this cost is anticipated to decline as technology advances and economies of scale are improved through commercialization (Bardell and Ashton, 2018).

For the purpose of the remaining analysis, we will refer to the HEFA as the component to be blended into SAF, since this is in predominant use today for SAF production.

3.2 SAF on-site blending

Singapore-based start-up FlyORO introduced its first solutions for on-site blending in 2022. The current AlphaLite modular biofuel blending system allows customized and precise on-site

Figure 3. Sustainable aviation fuel supply chain. Source: Adopted from CAAFI (2023)

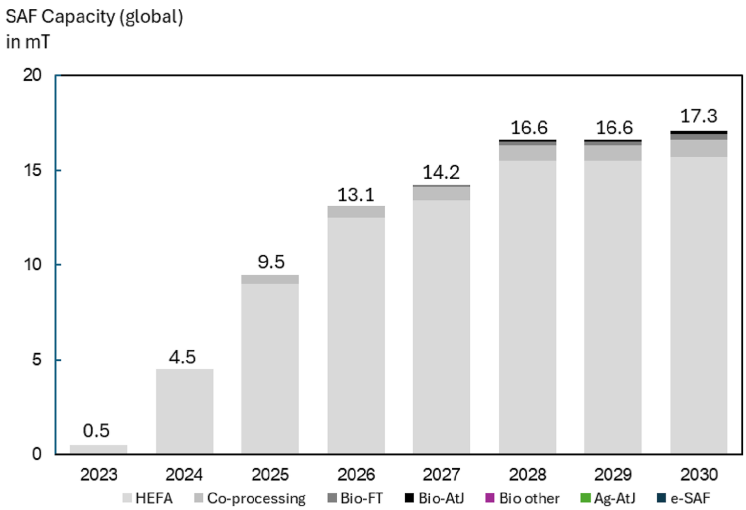

Figure 4. Global SAF capacity announcements until 2030. Source: Courtesy of SkyNRG (2024)

blending of SAF by ASTM D1655 quality standards (see Figure 5). One key benefit is that the design allows flexible utilization of already existing airport infrastructure and ties in with existing airport fuel storage. The latest technology enables a customized batch of up to 50% SAF blend within 20 min. The AlphaLite can blend up to 20,000 L at a time, and its design makes it easy to transport and integrate into the existing airport ecosystems. The easy handling of the system allows it to relocate, expand and stack multiple systems at any time. The AlphaLite blending can be installed with a solar panel to reduce further carbon emissions.

This allows airlines to benefit from a downstream blending concept. Crucial lead time can be eliminated and order flexibility increases. Airlines can also leverage jet to SAF price variability to optimize their SAF blend levels at specific points in time and maximize decarbonization goals. Therefore, the consolidated volume will be considered when aggregated by providing different lower-cost entry prices for more airlines to adopt. Customer can also customize their blend levels as needed.

Furthermore, airports can gain attractiveness as a lower-carbon fuel hub and increase their competitiveness. The airport carbon accreditation program encourages the reduction of CO_2 emissions. Fuel producers can produce SBCs and jet fuel in bulk and distribute these directly to the airport to focus on refining margins and trading margins. The cost of the on-side blending

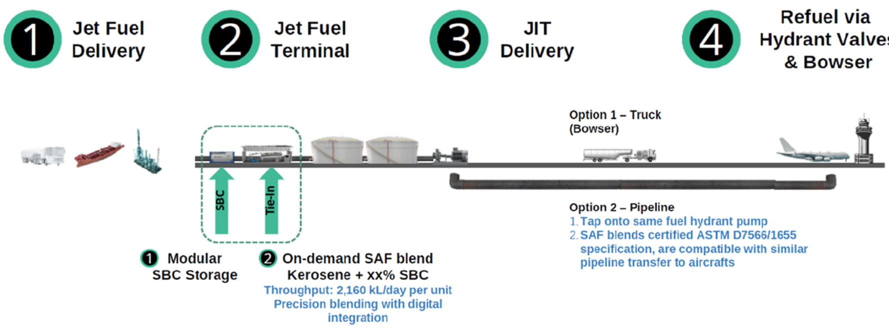

Figure 5. On-site blending of SAF using the FlyORO Alphalite system. Source: Courtesy of FlyORO (2023)

includes the FlyORO system, installation and maintenance, the operations, the certification of the blended fuel and the cost of uplifting the fuel. The cost of the system is currently offered on a per-use basis per litre of blended fuel in order to share risk and encourage adoption. The fixed cost and operating costs could be offset by the potential savings of bringing in SBC separately rather than pre-blended SAF in bulk, with an expected breakeven of on-site blending system within three years and also allow for the flexibility of allowing customized blend ratios for different airlines and even individual flights. Such a capability would likely also promote greater use of SAF in aviation.

4. Methodology

4.1 Research design

Data were collected in a combination of qualitative and quantitative approaches at FlyORO, as well as the airports in Singapore and Maastricht. This method allowed the researchers to acquire a broad understanding of airport supply chain operations, current cost structures and the identification of the involved stakeholders. Personal meetings, literature, internal records, websites and findings of relevant case studies were analyzed. Thus, the findings are derived from the collected data and contextualized. The meetings with FlyORO were crucial and captured in protocols. Further, internal records, websites and meetings supported the findings and increased validity. Credible websites were utilized to acquire the geographic and technical data required for numeric models and input values. Moreover, internal information, presentations and documents enabled an in-depth understanding of the on-site blending, its opportunities and the requirements for its viability.

The aim was to explore and analyze the effects of the two alternative supply chain scenarios (pre-blended vs. on-site blended) in a holistic manner: First, longitudinal secondary qualitative and quantitative data were gathered for each airport and the supply chain scenario for the three dimensions: cost, lead time and carbon emission. These three dimensions represent critical decision-making elements of the supply chain. Next, a quantitative model was used to compare the findings by calculating each supply chain scenario's overall cost, lead time and carbon emission. The effect on SAF prices was evaluated for the different blending ratios of HEFA and compared, considering the two supply chain scenarios.

4.2 Airports

The research was carried out at Seletar Airport in Singapore and Maastricht Airport in the Netherlands. These two airports vary in size, location and segment served. Thus, a scenario for each airport was set up to measure the result for the different supply chain operations and to be able to compare them.

4.2.1 Singapore Seletar Airport. Singapore Seletar Airport, with three three-letter code XSP, is a business and general civil aviation airport located in the northeast of the country. Seletar Airport is used for international aircraft charters, private flights, training flights and aircraft maintenance, such as repair and overhaul. Since July 1, 2009, Changi Airport Group has managed Seletar Airport and continuously modernized and improved it. (Seletar Airport, 2022). In 2014, Shell won the tender for the exclusive fuel supply and uplift rights (Seletar Airport, 2022). Jet A-1 fuel at Seletar airport is typically produced at the Shell refinery in Bukom Island, ASTM certified and shipped to Seletar Airport with 50,000-L trucks. At Seletar, the fuel will be stored and uplifted when needed. Since Seletar Airport does not have any underground pipelines for the fueling activity, the fuel will be transported in bowsers to the plane. Then, the fueling will be done manually. Moreover, the annual fuel consumption at Seletar Airport is 8–12 million liters. On average, a flight from Seletar Airport requires 8 to 10 thousand liters.

4.2.2 Maastricht Aachen Airport. Maastricht Aachen Airport, three-letter code MST, is a Dutch airport located in the south close to Belgium and the German borderline. From 2010 to

2021, passenger numbers fluctuated and peaked in 2019 at 435,980 transported passengers. Air freight is an essential segment of Maastricht Airport operations. In 2017, 86,770 tons, and in 2019, 110,823 tons of air cargo were transported from MST (CBS Statline, 2022). Maastricht Airport is managed and operated by Maastricht Aachen Airport BV and Shell Aviation is the Jet A-1 fuel manager. MST has two underground storage tanks, one for Jet A-1 fuel and the other for AVGAS. However, the exclusive uplift rights belong to an into-plane operator (ITP) and are executed by bowsers. Uplift activities can be fulfilled within 24 h prior to departure. Jet A-1 fuel supply is typically coming from the Shell plant in Wesseling/Cologne Godorf, due to its proximity. Moreover, Shell is responsible for the fuel supply. They will manage any fuel delivery and customer orders to the airport. Then, the fuel will be delivered by a bowser to the airplane and manually fueled.

4.3 Measures

The investigation for this study was conducted in the framework that on-site SAF production is viable and established at the airport site. It was assumed that an overall stakeholder interest was given to the AlphaLite system. Furthermore, the installation of one AlphaLite system did not cause any disruption in the airport ecosystem.

The cost comparisons between conventional blending and postponement were made using the following calculation based on a standardized volume of 100,000 L, which takes up 5 isotankers, although usage volumes annually for Seletar and Maastricht airports vary. A 20ft ISO tank container has a max weight of 30,480 kg, and road transport is assumed to use a 40–44 truck. For both conventional blending and onsite blending, it was assumed that the airport would have access to Jet A1 as this is the current operations. Logistics cost in the case of postponement would include both the cost of transporting the HEFA to the onsite and also the onsite costs of blending, certification to ASTM standards and uplifting of blended fuel.

A key challenge in the evaluation is comparing the fixed 20% SAF blending ratio in the baseline scenario with the customizable SAF ratio enabled by postponement through on-site blending. Currently, we are not aware of any cases where a customer seeking a higher (or lower) SAF blending ratio has opted to order customized SAF (with a ratio different from 20%) directly from the refinery. Therefore, while we provide a sensitivity analysis on the cost implications of varying SAF blending ratios, we recognize that product-design postponement (see Section 2.2) represents a fundamental shift that requires further exploration and deeper understanding moving forward.

5. Results

5.1 Qualitative insights

Enabling the SAF blending at the airport is a product postponement since the final product is manufactured according to the customer's needs. Thus, the postponement strategy allows an individual SBC ratio in each batch. Eventually, it can be distinguished between two points of differentiation in the production process - one for the SBC and another for the blending quota.

For simplicity, we assume that nine different SBCs are available, and the blending ratio varies between 5% and 50%. As indicated above, this is currently not possible as customers are used to the limited 20% ratio on offer. If airports were to offer different SAF blending ratios, this would necessitate additional storage tanks, increase inventory holding costs and complicate inventory management. Using on-site blending, the final product is produced at the site and uplifted. Consequently, a reduction of SAF inventory is achieved. SBC inventory can be handled better by adopting made-to-order policies instead of make-to-stock due to its high costs (Yang and Burns, 2003).

Ultimately, the SAF product postponement reconfigures the supply chain; thus, the DP moves further downstream. Therefore, the SAF final product assembly, the blending activity at the plant, is shifted further downstream. Moving the blending operation onto the airport site results in a lead-time reduction and a high customer service level. The variability in SAF and Jet A-1 fuel prices allows the customers to leverage the SAF usage by adopting this information into their blend quota. Additionally, product postponement can reduce distribution, logistics and inventory holding costs (Graman and Bukovinsky, 2005; Yang and Burns, 2003).

Furthermore, a combination of make-to-stock and make-to-order is feasible for jet fuel at the airport. Conventional Jet A-1 fuel can be ordered in a make-to-stock operation, and SBCs can be operated in a make-to-order way. Since conventional Jet A-1 fuel is mainly used, the SBC supply chain can be integrated and aligned in the airport ecosystem and with inventory management (Kumar *et al.*, 2009).

5.2 Singapore Seletar Airport

5.2.1 Baseline model. In the Seletar Airport Baseline model, SAF supply management relies on conventional practices, with Shell delivering pre-blended SAF based on long-term contracts. This SAF, consisting of 20% HEFA and 80% Jet A-1 fuel, is imported into Singapore via ISO tank containers with 20,000-L capacities. It is currently produced in Finland through Shell's collaboration with Neste and transported to Singapore (Sieppi, 2021). To meet the limited demand, we consider shipments of 100,000 L per order.

The supply chain in this scenario involves six key processes, categorized as upstream, midstream and downstream activities. Upstream includes the production of Jet A-1 fuel and HEFA (Process 1) and SAF blending (Process 2). Midstream encompasses the freight transportation of ISO tank containers (Processes 3 and 4). Downstream involves delivery and storage at Seletar Airport (Process 5) and SAF uplifting (Process 6). The DP is before the SAF blending process in Finland because Jet A-1 fuel and HEFA are produced to stock, while SAF is manufactured on order to achieve the required blend (Sun *et al.*, 2008). The cost analysis considers transportation from Finland to Singapore with combined road and sea shipping. The road transportation costs total $150.08 and deep-sea shipping costs at $3,221.60 per container, resulting in an overall logistics cost of $16,858.40 per order. This long-distance setup has a significant impact on cost, carbon emissions and lead time, as we find later. The location of the SAF supplier in relation to Seletar Airport emerges as a crucial factor negatively influencing these aspects in the baseline model.

Within the Seletar Airport Baseline Model, pricing transparency for HEFA within pre-blended SAF was notably limited. Due to competition among a select group of SAF producers, comprehensive pricing data for varying blending ratios remained elusive. We estimate that HEFA cost based on the supplier of Seletar Airport at $8.48 per liter whereas the average Jet A-1 price per liter in 2022 from Finland is $0.86. However, note that the cost for Jet A-1 fuel as well as HEFA differ widely at different locations globally, e.g. Finland and Singapore.

In this model, with a SAF volume of 100,000 L per order and each SAF-powered flight consuming 5,000 L, the total flights amounted to 20. To assess the comprehensive SAF cost, we considered the delivery of pre-blended SAF from Neste in Finland. Logistic costs for transporting from Finland translate to $0.17 per liter. Additionally, the other costs are $0.14 per liter. All in all, the total cost per liter for the 20% SAF are $2.26 per liter. Table 1 summarizes the cost assumptions used throughout the analysis.

5.2.2 Postponement model. In the second scenario, a postponement model was employed, requiring only 20,000 L of HEFA to be delivered to the airport for a 100,000l order with a 20% SAF ratio. This HEFA was supplied from the Sinopec refinery in Zhenhai, China, which commenced HEFA production in April 2022. The choice of Sinopec was based on its proximity to Singapore, making it a suitable HEFA supplier.

The supply chain for SAF blending in this scenario involves seven key processes, categorized as upstream, midstream and downstream activities. Upstream activities included the production of HEFA SBC in Zhenhai (Process 1). Midstream processes covered the logistical activities from the port of Ningbo to Seletar Airport (Processes 2, 3 and 4), where

Table 1. Cost parameters for analysis

	Baseline model	Postponement model
	Singapore Seletar Airport	
HEFA cost per liter	(HEFA from Finland) $8.48	(HEFA from China) $3.87
Jet A1 cost per liter	(Jet A1 from Finland) $0.86	(Jet A1 from Singapore) $0.83
Logistics cost per liter	(from Finland) $0.17	(from China) $0.17
Other cost per liter	(blending in Finland) $0.14	(blending in Singapore) $0.33
	Maastricht Airport	
HEFA cost per liter	(HEFA from Finland) $8.48	(HEFA from France) $3.87
Jet A1 cost per liter	(Jet A1 from Finland) $0.86	(Jet A1 from Maastricht) $1.25
Logistics cost per liter	(from Finland) $0.17	(from France) $0.01
Other cost per liter	(blending in Finland) $0.14	(blending in Maastricht) $0.36

Note(s): Other costs include blending, testing, certification, uplift etc.
Source(s): Created by authors

on-site SAF blending occurred (Process 4). Downstream activities comprised storage and uplifting (Processes 6 and 7).

Within Process 5, a blend of 4,000 L (20%) of HEFA and 16,000 L (80%) of Jet A-1 fuel is required for one batch produced on the airport site. The AlphaLite blending system allowed one ISO tank container to produce five such batches. Jet A-1 fuel and HEFA are made-to-stock, while the delivery of HEFA and SAF blending at the airport site was made-to-order. The DP were located before HEFA shipment activities and before the blending activity at Seletar Airport (Sun *et al.*, 2008). The cost analysis considered road transport from the Sinopec refinery in Zhenhai to Ningbo Port and from the PSA Pasir Panjang Terminal to Seletar Airport, totaling logistics cost $3,370.02 per container accordingly resulting in a similar $0.17 cost per liter as from Finland for the HEFA. Jet A-1 logistic costs were negligible as Jet A-1 fuel was readily available at the airport. However, other costs for blending, testing and certification are higher for the postponement solution at $0.33 per liter.

5.2.3 Model comparison. Table 2 summarizes the cost comparison between the baseline model and the postponement model based on different blending ratios of SAF. Note that HEFA costs differ in different locations and affect the fuel costs. Certainly, with a higher SAF ratio, the cost increases due to the higher HEFA costs. In addition, logistics cost jumps for the postponement model as multiple containers are required for a given ratio.

Next, we focus on logistics cost, carbon emissions, lead time and SAF pricing (see Table 3). Comparing the logistic costs between the two scenarios shows a significant advantage for the postponement model with an 80% reduction in overall logistic expenses. While the logistics cost per container are very similar (even though the distance shipping from China is much shorter compared to Finland), the number of containers required to be shipped is much lower due to the postponement. As a result, carbon emissions for the postponement options also shrink significantly, both due to the shorter distance and the lower number of containers required (see also Appendix 1).

Finally, lead time is a critical factor in supply chain efficiency, showing that deep-sea shipping was the predominant contributor to lead time in both scenarios. However, shipping from China compared to Finland reduced the lead time from 31 days to 11 days. Despite requiring 48 h for ASTM clearance, Scenario II maintained a lower total lead time. As more locations of SAF and SBC suppliers become available (that do not have to offer pre-blending), this advantage will grow.

Finally, analyzing SAF pricing, it was evident that the postponed production strategy led to lower SAF prices compared to the baseline approach. The cost difference was substantial, with Scenario II offering more cost-effective SAF. This cost difference was primarily attributed to the HEFA price, which played a dominant role in determining the SAF price. As the HEFA

Table 2. Cost comparison between conventional blending and postponement in Seletar Airport

Ratio	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Cost of conventional blending										
Ave PriceJetA1	$66500.00	$63000.00	$59500.00	$56000.00	$52500.00	$49000.00	$45500.00	$42000.00	$38500.00	$35000.00
Ave PriceHEFA	$42392.66	$84785.31	$127177.97	$169570.62	$211963.28	$254355.93	$296748.59	$339141.24	$381533.90	$423926.55
Total cost SAF	$108892.66	$147785.31	$186677.97	$225570.62	$264463.28	$303355.93	$342248.59	$381141.24	$420033.90	$458926.55
SAF cost per l	$1.09	$1.48	$1.87	$2.26	$2.64	$3.03	$3.42	$3.81	$4.20	$4.59
Ave logistics cost	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77	$30854.77
Logistic cost per l	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31	$0.31
Total cost (SAF + Logistic)	$139747.43	$178640.08	$217532.74	$256425.39	$295318.05	$334210.70	$373103.36	$411996.01	$450888.67	$489781.32
Total cost per litre (SAF + Logistic)	*$1.40*	*$1.79*	*$2.18*	*$2.56*	*$2.95*	*$3.34*	*$3.73*	*$4.12*	*$4.51*	*$4.90*
Postponement cost										
Ave PriceJetA1	$78850.00	$74700.00	$70550.00	$66400.00	$62250.00	$58100.00	$53950.00	$49800.00	$45650.00	$41500.00
Ave PriceHEFA	$19350.00	$38700.00	$58050.00	$77400.00	$96750.00	$116100.00	$135450.00	$154800.00	$174150.00	$193500.00
Total cost SAF	$98200.00	$113400.00	$128600.00	$143800.00	$159000.00	$174200.00	$189400.00	$204600.00	$219800.00	$235000.00
SAF cost per l	$0.98	$1.13	$1.29	$1.44	$1.59	$1.74	$1.89	$2.05	$2.20	$2.35
Ave logistics cost	$36120.02	$36120.02	$36120.02	$36120.02	$39490.04	$39490.04	$39490.04	$39490.04	$42860.06	$42860.06
Logistic cost per l	$0.36	$0.36	$0.36	$0.36	$0.39	$0.39	$0.39	$0.39	$0.43	$0.43
Total cost (SAF + Logistic)	$134320.02	$149520.02	$164720.02	$179920.02	$198490.04	$213690.04	$228890.04	$244090.04	$262660.06	$277860.06
Total cost per litre (SAF + Logistic)	*$1.34*	*$1.50*	*$1.65*	*$1.80*	*$1.98*	*$2.14*	*$2.29*	*$2.44*	*$2.63*	*$2.78*

Source(s): Created by authors

Table 3. Key metrics comparison for Singapore Seletar Airport for 100,000l order for 20% SAF

Scenario	Shipment volume (in liters)	Containers shipped (ISO 20')	Total logistics cost (in US$)	Carbon emission (in tons CO2)	Lead time (in days)
Baseline model (Blending in Finland)	100,000	5	16,858	16.8	31
Postponement model (Blending in Singapore)	20,000	1	3,370	0.88	11

Source(s): Created by authors

portion in SAF increased, the price also rose. Overall, regardless of the blending ratio considered, the postponed SAF production strategy proved economically advantageous. The price difference between the scenarios ranged from $0.06 per liter for a 5% blending ratio to $2.12 per liter for a 50% blending ratio. This demonstrated that postponed production not only reduced costs but also made SAF more competitive in terms of pricing and delivery lead time.

5.3 Maastricht Airport

5.3.1 Baseline model. In the baseline model for Maastricht airport, an Oil Major is the Jet A-1 fuel supplier that sources SAF from Neste due to their close collaboration. The pre-blended SAF was transported from Neste's plant in Porvoo, Finland, to Maastricht, the Netherlands. The supply chain involved the same six processes as outlined in Section 5.2.1 for Singapore and can be categorized as upstream, midstream and downstream activities. These included the production of Jet A-1 fuel and HEFA, blending at the Neste plant, freight transportation, storage and SAF uplifting. Again, using a basis of 100,000 liters and 5 isotankers for cost comparison, the total logistic cost for this amounted to $17,283.91 annually, taking into account road transportation and shipping costs. The total lead time for SAF in this scenario was five days, with deep-sea shipping being the dominant contributor.

5.3.2 Postponement model. In the postponement model, HEFA is delivered from the Total Energy refinery plant in Le Mède, France, to Maastricht Airport. The total lead time for SAF in this scenario was three days, with ASTM approval contributing significantly to lead time. The Jet A-1 fuel price at Maastricht Airport was $1.25 per liter, based on Flyoro estimates, which is significantly higher compared to sourcing from the refinery. All other assumptions have been documented in Table 1.

5.3.3 Model comparison. In comparing two scenarios at Maastricht Airport, significant differences emerge between the baseline model and the postponement model. Table 4 summarizes the cost comparison between the two scenarios based on different blending ratios. See Appendix 1 for the carbon emissions comparison.

Logistics cost of trucking HEFA from France to Maastricht is much lower than the cost of transporting SAF from Finland to Maastricht and is almost negligible. However, other fixed costs of operations, such as uplifting and ASTM certification are significantly higher. This meant that for low blending ratios of SAF, it was not cost-effective to incur the cost. The postponement model in this case was more cost-effective at least 40% of blend ratio, which would allow almost the entire isotanker of HEFA to be used in the 100,000 L of SAF, with a cost parity between the two scenarios happening at a 15% blend. Below 15% blends, the postponement scenario is less cost-effective than the baseline scenario.

Differential pricing of SAF prices can affect the analysis. Notably, the dominant price factors differed. In the baseline scenario, the HEFA price contributed 47% of the total cost, whereas in the postponement scenario higher Jet A-1 fuel accounted for more costs. Overall, the pre-blended SAF was more economical per liter at a low blending ratio. Certainly, more care on supplier prices needs to be considered going forward.

Table 4. Cost comparison between conventional blending and postponement at Maastricht Airport

Cost of conventional blending										
Ratio	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Ave PriceJetA1	$66500.00	$63000.00	$59500.00	$56000.00	$52500.00	$49000.00	$45500.00	$42000.00	$38500.00	$35000.00
Ave PriceHEFA	$42392.66	$84785.31	$127177.97	$169570.62	$211963.28	$254355.93	$296748.59	$339141.24	$381533.90	$423926.55
Total cost SAF	$108892.66	$147785.31	$186677.97	$225570.62	$264463.28	$303355.93	$342248.59	$381141.24	$420033.90	$458926.55
SAF cost per l	$1.09	$1.48	$1.87	$2.26	$2.64	$3.03	$3.42	$3.81	$4.20	$4.59
Ave logistics cost	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24	$152271.24
Logistic cost per l	$1.52	$1.52	$1.52	$1.52	$1.52	$1.52	$1.52	$1.52	$1.52	$1.52
Total cost (SAF + Logistic)	$261163.90	$300056.55	$338949.21	$377841.86	$416734.52	$455627.17	$494519.83	$533412.48	$572305.14	$611197.79
Total cost per litre (SAF + Logistic)	*$2.61*	*$3.00*	*$3.39*	*$3.78*	*$4.17*	*$4.56*	*$4.95*	*$5.33*	*$5.72*	*$6.11*
Postponement cost										
Ratio										
Ave PriceJetA1	$118750.00	$112500.00	$106250.00	$100000.00	$93750.00	$87500.00	$81250.00	$75000.00	$68750.00	$62500.00
Ave PriceHEFA	$19350.00	$38700.00	$58050.00	$77400.00	$96750.00	$116100.00	$135450.00	$154800.00	$174150.00	$193500.00
Total cost SAF	$138100.00	$151200.00	$164300.00	$177400.00	$190500.00	$203600.00	$216700.00	$229800.00	$242900.00	$256000.00
SAF cost per l	$1.38	$1.51	$1.64	$1.77	$1.91	$2.04	$2.17	$2.30	$2.43	$2.56
Ave logistics cost	$164485.89	$164485.89	$164485.89	$164485.89	$164971.77	$164971.77	$164971.77	$164971.77	$165457.66	$165457.66
Logistic cost per l	$1.64	$1.64	$1.64	$1.64	$1.65	$1.65	$1.65	$1.65	$1.65	$1.65
Total cost (SAF + Logistic)	$302585.89	$315685.89	$328785.89	$341885.89	$355471.77	$368571.77	$381671.77	$394771.77	$408357.66	$421457.66
Total cost per litre (SAF + Logistic)	*$3.03*	*$3.16*	*$3.29*	*$3.42*	*$3.55*	*$3.69*	*$3.82*	*$3.95*	*$4.08*	*$4.21*

Source(s): Created by authors

Second, when comparing lead times, deep-sea shipment is a significant time factor in the baseline scenario, with trucking contributing minimally. Delays primarily result from the approval time required for the ASTM certificate at Maastricht Airport. Trucking adds an additional 10 h to the process. However, in the postponement scenario, ISO tank containers are delivered more quickly, assuming that the ASTM approval time remains low. Table 5 summarizes the findings.

5.4 Summary

With regard to RQ1, the empirical study has shown that the supply chain for postponed production can result in significantly lower supply chain activity costs and is affected by differences in fuel costs, the differential logistics costs of SAF sourcing and HEFA sourcing and blend ratios of SAF. For Seletar Airport, the on-site blending resulted in an 80% reduction of the relevant supply chain costs compared to pre-blended scenario. For Maastricht Airport, the cost difference depended on the blending ratios.

However, in both cases, there is a reduction in carbon emissions due to a smaller number of containers that need to be shipped, for example, 5 containers of 20% SAF blend to ship, versus 1 container of HEFA to be blended onsite. A total cost that takes into account both logistics cost and carbon pricing may therefore make onsite blending more cost-effective.

With regard to RQ2, while cost was a crucial driver for the implementation of postponed product production, postponement aims to reduce inventory and increase the service level. The empirical result indicates that with the on-side blending, storage could be significantly reduced. Moreover, the postponed SAF production increased the service level at Seletar and Maastricht Airport since the DP has been shifted downstream to the airport site. Thus, the SAF customization, the final assembly, took place at the last storage place of the SBC. That reduced lead time for ad-hoc SAF orders (Lee and Billington, 1994). Furthermore, SAF is a perfectly substitutable good and can be used in any aircraft engine once ASTM is approved. The postponement capacity is primarily determined by how closely the products are interchangeable. Perfectly exchangeable goods are highly consumer-driven and, therefore, suitable for postponement strategies. Fuel prices in particular play a crucial role in the demand for exchangeable goods; thus, postponement strategies must support a price decrease. Once the SAF postponement strategy reduces the price of the substitutional product, postponed production provides a benefit. It is more likely to be integrated successfully.

Table 6 provides a summary of the empirical study for the SAF cost. It can be concluded that the postponed production of SAF at Seletar Airport is more economical for different blending ratios and thus Seletar Airport offers an excellent ecosystem to integrate the postponement model successfully. In contrast, the final SAF price with a low SAF ratio for Maastricht Airport was lower for the pre-blended option and higher for the on-site blending. Hence, the postponed fuel price was higher; the postponed SAF production was only economical for higher blending ratios. The driver for the postponement was a price reduction and a resulting competitive advantage for the on-site blending technique. Another critical driver detected was the reduced lead time for the on-site production of SAF. 11 days instead of

Table 5. Key metrics comparison for Maastricht Airport for 100,000l order for 20% SAF

Scenario	Shipment volume (in liters)	Containers shipped (ISO 20’)	Total logistics cost (in US$)	Carbon emission (in tons CO2)	Lead time (in days)
Baseline model (Blending in Finland)	100,000	5	17.284	3.23	4
Postponement model (Blending in Maastricht)	20,000	1	486	0.87	2

Source(s): Created by authors

Table 6. Comparison of SAF cost per liter for airports and scenarios

		10%	20%	30%	40%	50%
Singapore	Baseline model	$ 1.79	$ 2.56	$ 3.34	$ 4.12	$ 4.90
Seletar Airport	Postponement model	$ 1.50	$ 1.80	$ 2.14	$ 2.44	$ 2.78
Maastricht	Baseline model	$ 1.79	$ 2.57	$ 3.35	$ 4.12	$ 4.90
Airport	Postponement model	$ 3.16	$ 3.42	$ 3.69	$ 3.95	$ 4.21

Source(s): Created by authors

31 days for Seletar Airport and 2 days instead of 4 days. Time has been identified as an additional crucial driver for the adoption of postponement (Pagh and Cooper, 1998). Nevertheless, demand uncertainty for on-site blending of SAF requires more supply chain postponement strategies. Forecasting will guarantee a shorter lead time (external factors not included). The lead time depends on accurate forecasting (Yang and Burns, 2003; Lee, 1998).

One aspect that is certainly very interesting is the opportunity to source HEFA from the cheapest available suppliers for the on-site blending. At the moment, pre-blended SAF is sourced in longer-term contracts at relatively high HEFA prices. However, the opportunity to source HEFA at cheaper spot prices from different suppliers and blend on-site will affect the fuel economics of the fuel.

6. Discussion

This section integrates the empirical findings with supply chain theory, outlines the key economic mechanisms that determine when on-site blending creates advantage and concludes with managerial implications for airports and policy makers.

6.1 Theoretical contribution

The empirical findings contribute to classical supply chain theory by extending the concepts of postponement (Alderson, 1950; Pagh and Cooper, 1998) and DP (van Hoek and van Dierdonck, 2000) into the context of process industries and sustainability transitions. Whereas traditional postponement theory focuses on product form and time differentiation for cost or service optimization, our findings reveal that environmental and carbon efficiency can emerge as additional strategic drivers. In particular, shifting the DP downstream to the airport introduces a new form of *green postponement*, where customization and emission reduction are jointly achieved.

To better situate our findings within established supply chain theory, Table 7 contrasts the characteristics of traditional postponement strategies – commonly applied in discrete manufacturing – with the novel SAF on-site blending postponement observed in this study. The comparison highlights how the shift of the DP downstream to the airport extends the postponement concept beyond cost and service optimization toward sustainability and carbon-efficiency objectives. The on-site blending approach reframes postponement as a sustainability-oriented supply chain lever. It introduces a triple-objective perspective, i.e., cost, service and carbon performance, thus extending the classical cost-service trade-off theory and highlighting how postponement can support both economic and environmental efficiency in process industries.

6.2 Economic factors

The comparative analysis between conventional pre-blending and on-site blending reveals that the economic and environmental viability of downstream SAF postponement depends on a small set of interrelated conditions. Three dimensions appear critical:

Table 7. Comparing traditional and on-site SAF blending postponement

Dimension	Traditional postponement	On-site SAF blending
Objective	Cost and responsiveness	Cost, responsiveness and decarbonization
Industry context	Discrete manufacturing (e.g., electronics, apparel)	Process industry (i.e. aviation fuel)
Decoupling point	Factory or distribution center	Airport site
Product customization	Final assembly/packaging	SAF blend
Key trade-off	Cost ↔ Service	Cost ↔ Service ↔ Carbon efficiency
Strategic implication	Postponement improves responsiveness	Postponement enables "green responsiveness" and local carbon competitiveness

Source(s): Created by authors

(1) *Relative logistics distance and cost between HEFA and pre-blended SAF supply sources.* When the HEFA production site is geographically closer to the airport than the SAF refinery, the reduced transport distance and lower shipped volume (HEFA instead of full SAF) generate cost and carbon savings that can offset local blending and certification expenses.

(2) *Local availability and price differentials for Jet A-1 and HEFA.* Since both components exhibit regional price variability, airports located near low-cost Jet A-1 suppliers or within reach of competitive HEFA producers can exploit arbitrage opportunities that favor on-site blending. Conversely, where local Jet A-1 is expensive or HEFA must be imported over long distances, pre-blending remains advantageous.

(3) *Scale of airport throughput*, which determines whether the fixed cost of installing and operating blending and certification equipment can be economically amortized. Larger airports with higher fuel turnover are more likely to achieve economies of scale, while smaller airports may face cost disadvantages despite the potential logistical and environmental benefits.

Together, these three dimensions define the boundary conditions under which on-site SAF blending becomes beneficial. They explain why Seletar Airport – characterized by shorter HEFA transport distances, competitive fuel prices and sufficient demand – achieves significant savings and emission reductions, while Maastricht Airport only reaches parity at higher blend ratios. Beyond cost considerations, on-site blending also offers flexibility advantages: it enables airlines with different sustainability mandates or carbon-pricing strategies to choose customized blend ratios, overcoming the storage and infrastructure constraints of fixed pre-blended fuels. These findings not only clarify when on-site blending is economically viable but also indicate what managerial and infrastructural conditions must be met to realize these benefits, as discussed next.

6.3 Managerial implications

The concept of postponement and on-site SAF customization overall appears promising. However, several factors need to be addressed and discussed before considering implementing a product postponement strategy. The right level of postponement needs to be evaluated carefully and the location of the HEFA and SAF production plant can influence this level. Additionally, crucial factors such as the right timing for product differentiation and the product DP need to be considered (Choi *et al.*, 2012). The prerequisites discussed here are the investment into on-site blending, the postponement strategy, increasing manufacturing capacities and taxes in the context of supply chain activities. However, certain implementation barriers around costs, technical requirements and supply chain must be overcome.

Regardless of the supply chain network and postponement implementation, the airport must make necessary *investments into the on-site blending* technology. FlyORO was investigating the system setup in airports with more than 500,000 passengers. Since currently only approximately 1% of all flights use SAF, a minimum demand is required to achieve economy of scale. The transportation of HEFA batches below 20,000 L is not economical at the Seletar Airport due to the long distance and lead time scenario, since it will be an LCL. Additional investments, such as fire-proven walls, might be needed if the AlphaLite blending system is near a building. That can become an obstacle, especially at airports with limited space (e.g. London City Airport).

The right level and *strategy of postponemen*t need to be aligned with the given airport ecosystem, demand and supply. Thus, the two presented supply chain postponement strategies for Seletar and Maastricht Airport may only apply to some airports. The on-site production of SAF emphasizes a production postponement strategy since the SAF will be customized at the airport. HEFA and SAF price uncertainty, supplier performance and overall supply availability would underline the use of a postponement. Especially, the HEFA and SAF purchasing price volatility significantly impacts the SAF consumer price. The increase in HEFA and SAF production plants will positively affect the supply network and reduce price volatility. Using the postponement strategy the airport can more easily source HEFA from cheap suppliers without bearing higher logistics costs and also can source from HEFA suppliers that do not have blending capabilities at their sites.

However, the *increase of manufacturing capacity* can also change entire supply networks. Initially, the new and increased production facilities for HEFA and SAF will reduce supply chain activity costs, lead time and carbon emissions. With new plants the routing of SAF will change. For example, Neste, the leading SAF producer, will open new SAF production facilities in Rotterdam and Singapore. Consequently, the supply chain cost, lead time and carbon emissions will reduce drastically for both supply chain scenarios at Seletar. Rotterdam can benefit from its relatively central European location. Thus, supply chain cost, lead time and carbon emissions will decrease for the Maastricht baseline scenario and central European airports. The introduction of two new HEFA and SAF production plants will increase the viability of product and production postponement for SAF on a global scale (with or without on-site blending).

The *role of tariffs* must be considered. The movement of goods across borders may be more complex and impose tariffs on the entire cost structure. Thus, the implementation of an HEFA and SAF supply chain network, distribution channels and supply chain emissions, along with the shipped quantity across borders, are affected by taxes (Mu *et al.*, 2021). Imposed tariffs are a significant fiscal constraint for HEFA and SAF entering and exiting a country. In addition, environmental taxes are raised for emitted emissions and cross-border supply chain activity can be exposed to the Value-Added Tax (VAT).

The *customer choice of individual SAF ratio* is a feature that is enabled by postponement and on-site blending. This allows customers to choose a higher or lower than the standard 20% ratio according to their interests and budgets. While cost per liter increases significantly with higher blending ratios, there might be many customers who would be willing to pay for this (e.g. high-wealth individuals for private jets). With the possibility to change the product design, this is now possible and much easier to do than having a particular blend made at the refinery and shipped across the globe, particularly, given uncertain demands.

Finally, the decision-making process also involves *managing multiple stakeholders*. Within the ecosystem, there are airlines, SAF providers, providers of jet fuel and providers of uplifting services, operating within the airport environment. Although providers of fuel or uplifting services may be different companies, they could also be contracted to provide a one-stop service to the airlines by coordinating all activities for fuel uplifting. Airports provide regulatory and safety oversight and in some cases may also be involved in the commercial provision of aviation fuel.

7. Conclusion

This paper presents an analysis of an on-site SAF blending solution and shows that it can reduce carbon emissions in the logistics, as well as improve the cost effectiveness of SAF adoption under certain conditions of supply locations, volume and blend ratios. While most prior research has traditionally addressed postponement for discrete manufacturing, this paper analyzes the use of postponement concepts in the process industry with respect to on-site blending and provision of SAF. The findings also indicate that to increase adoption of SAF through on-site blending, coordination among multiple stakeholders and the government may be needed.

Despite a research approach with data collection at multiple sites, this study may have several limitations. Firstly, the analysis of two SC strategies only considers three dimensions to measure the SC performance; however, external influencing factors are not considered in this analysis. According to Pounder *et al*. (2013), external components such as resource management, material handling, technological adaption and effective communication techniques along the SC have a crucial impact on SCM decision-making and the viability of SC executions. Furthermore, the empirical results from two different airports in developed countries cannot necessarily be generalized to the airport's fuel SC operation in any country. Airports' fuel SC infrastructures and operations may not be able to execute the assumed postponement strategies in developing countries (Choi *et al*., 2012).

The empirical research was conducted in a framework of a stable demand assumption for two airports and assumes high responsiveness and a certain SAF SC degree of flexibility. Nevertheless, SAFs have a high market risk for volatility regarding demand and price. In addition, feedstock limitations and possible demand restrictions due to the supply shortage of SAF are not considered when analyzing the two scenarios. Neither did this study take the emitted CO_2 emissions for the SBC and SAF production into account for the CO_2 dimension. The cost structure for the SC scenarios does not include global SC operation costs, such as customs duties, fees or any form of taxation. Lastly, the assumed values for calculating the three dimensions impacted the empirical results significantly. Gathering different data or other approaches regarding the data collection might have changed the model's estimation, sensitivity and analysis.

Further studies can be conducted on the cost-benefit analysis and decarbonization benefits of onsite blending at other airports. A framework can also be created to identify the sensitivity analysis for the factors of supply location, SAF cost versus jet fuel cost and different blend ratios. Doing so will also help to identify commercial and policy recommendations for stakeholders and governments to increase SAF adoption.

Supplementary material

The supplementary material for this article can be found online.

References

Abrantes, I., Ferreira, A.F., Silva, A. and Costa, M. (2021), "Sustainable aviation fuels and imminent technologies - CO2 emissions evolution towards 2050", *Journal of Cleaner Production*, Vol. 313, 127937, doi: 10.1016/j.jclepro.2021.127937.

Ahmad, S. and Xu, B. (2021), "A cognitive mapping approach to analyse stakeholders' perspectives on sustainable aviation fuels", *Transportation Research. Part D, Transport and Environment*, Vol. 100, 103076, doi: 10.1016/j.trd.2021.103076.

Alderson, W. (1950), "Marketing efficiency and the principle of postponement", *Cost and Profit Outlook*, Vol. 3 No. 4, pp. 15-18.

ASTM International (2022), "Standard specification for aviation turbine fuels", available at: astm.org (accessed 15 November 2022).

Bandaly, D.C. and Hassan, H.F. (2020), "Postponement implementation in integrated production and inventory plan under deterioration effects: a case study of a juice producer with limited storage capacity", *Production Planning & Control*, Vol. 31 No. 4, pp. 322-337, doi: 10.1080/09537287.2019.1636354.

Bardell, N.S. and Ashton, M.J. (2018), "Some issues affecting potential stakeholder uptake of sustainable aviation fuel within Australia: a case study conducted at Darwin International Airport", *Australian Journal of Mechanical Engineering*, Vol. 18 No. sup1, pp. 95-S107, doi: 10.1080/14484846.2018.1478700.

Baumi, J., Milani Bertosse, C. and Luisa Barbosa Guedes, C. (2020), "Aviation fuels and biofuels. Renewable Energy - resources", *Challenges and Applications*, September, doi: 10.5772/intechopen.89397.

Billington, C., Callioni, G., Crane, B., Ruark, J.D., Rapp, J.U., White, T. and Willems, S.P. (2004), "Accelerating the profitability of Hewlett-Packard's supply chains", *Interfaces*, Vol. 34 No. 1, pp. 59-72, doi: 10.1287/inte.0103.0054.

Bowersox, D.J. and Closs, D.J. (1996), *Logistical Management: The Integrated Supply Chain Process*, McGraw-Hill, New York, NY.

bp (2022a), "Avgas | Aviation fuel", available at: bp.com (accessed 10 October 2022).

bp (2022b), "Jet fuel | Aviation fuel", available at: bp.com (accessed 10 October 2022).

bp (2023), "How all sustainable aviation fuel (SAF) feedstocks and production technologies can play a role in decarbonising aviation | News and views | Air bp. Air Bp", available at: https://www.bp.com/en/global/air-bp/news-and-views/views/how_all_sustainable_aviation_fuel_SAF_feedstocks_and_production_technologies_can_play_a_role_in_decarbonising_aviation.html (accessed 16 November 2023).

Brown, A.O., Lee, H.L. and Petrakian, R. (2000), "Xilinx improves its semiconductor supply chain using product and process postponement", *Interfaces (Providence)*, Vol. 30 No. 4, pp. 65-80, doi: 10.1287/inte.30.4.65.11650.

Brun, A. and Zorzini, M. (2009), "Evaluation of product customization strategies through modularization and postponement", *International Journal of Production Economics*, Vol. 120 No. 1, pp. 205-220, doi: 10.1016/j.ijpe.2008.07.020.

Bucklin, L.P. (1965), "Postponement, speculation and the structure of distribution channels", *Journal of Marketing Research*, Vol. 2 No. 1, pp. 26-31.

CAAFI (2023), "Supply chain development", available at: caafi.org (accessed am 8. Oktober 2023, von).

CBS Statline (2022), available at: https://opendata.cbs.nl/statline/ (accessed 15 December 2022).

Choi, K., Narasimhan, R. and Kim, S.W. (2012), "Postponement strategy for international transfer of products in a global supply chain: a system dynamics examination", *Journal of Operations Management*, Vol. 30 No. 3, pp. 167-179, doi: 10.1016/j.jom.2012.01.003.

Dodd, T. and Yengin, D. (2021), "Deadlock in sustainable aviation fuels: a multi-case analysis of agency. Transportation Research", *Part D, Transport and Environment*, Vol. 94, 102799, doi: 10.1016/j.trd.2021.102799.

Feitzinger, E. and Lee, H.L. (1997), "Mass customization at Hewlett-Packard: the power of postponement", *Harvard Business Review*, Vol. 75, pp. 116-123, available at: http://mba.teipir.gr/files/Mass_Customization_at_HP_-_Thr_power_of_postponement.pdf (accessed 4 January 2023).

Ferreira, K.A., Tomas, R.N. and Alcântara, R.L.C. (2014), "A theoretical framework for postponement concept in a supply chain", *International Journal of Logistics Research and Applications*, Vol. 18 No. 1, pp. 46-61, doi: 10.1080/13675567.2014.945403.

FlyORO (2023), "Overview of FlyORO Alphalite system", PowerPoint slides, FlyORO Technologies Pte. Ltd., unpublished internal presentation.

Graman, G. and Bukovinsky, D. (2005), "From mass production to mass customization: postponement of inventory differentiation", *Journal of Corporate Accounting & Finance*, Vol. 17 No. 1, pp. 61-65, doi: 10.1002/jcaf.20169.

Guericke, S., Koberstein, A., Schwartz, F. and Voß, S. (2012), "A stochastic model for the implementation of postponement strategies in global distribution networks", *Decision Support Systems*, Vol. 53 No. 2, pp. 294-305, doi: 10.1016/j.dss.2012.01.010.

Holladay, J., Abdullah, Z. and Heyne, J. (2020), *Sustainable Aviation Fuel: Review of Technical Pathways*, US Department of Energy, Bioenergy Technologies Office, available at: https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf (accessed 10 October 2022).

Hong, Y., Cui, H., Dai, J. and Ge, Q. (2019), "Estimating the cost of biofuel use to mitigate international air transport emissions: a case study in Palau and Seychelles", *Sustainability*, Vol. 11 No. 13, p. 3545, doi: 10.3390/su11133545.

IATA (2021), "Our Commitment to fly Net zero by 2050. IATA.Org", available at: https://www.iata.org/en/programs/environment/flynetzero/ (accessed 4 January 2023).

IATA (2022a), "IATA carbon offset program", IATA.Org, available at: https://www.iata.org/contentassets/922ebc4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf (accessed 29 December 2022).

IATA (2022c), "Annual Review 2022", available at: www.iata.org (accessed 4 January 2023).

IATA (2022d), "Net zero 2050: sustainable aviation fuels", available at: www.iata.org (accessed 9 October 2022).

IPCC (2022), "Climate Change 2022: impacts, adaptation and vulnerability: summary for policymakers", doi: 10.1017/9781009325844.001, available at: ipcc.ch (accessed 4 January 2023).

Kisperska-Moron, D. and Swierczek, A. (2011), "The selected determinants of manufacturing postponement within supply chain context: an international study", *International Journal of Production Economics*, Vol. 133 No. 1, pp. 192-200, doi: 10.1016/j.ijpe.2010.09.018.

Kumar, S., Nottestad, D.A. and Murphy, E.E. (2009), "Effects of product postponement on the distribution network: a case study", *Journal of the Operational Research Society*, Vol. 60 No. 4, pp. 471-480, doi: 10.1057/palgrave.jors.2602572.

Lee, H.L. (1998), "Postponement for mass customization: satisfying customer demands for tailor-made products", in *Strategic Supply Chain Alignment*, pp. 77-91.

Lee, H.L. and Billington, C. (1994), "Designing products and processes for postponement", Management of Design, pp. 105-122, doi: 10.1007/978-94-011-1390-8_6.

Martinez-Valencia, L., Peterson, S., Brandt, K., King, A.B., Garcia-Perez, M. and Wolcott, M. (2023), "Impact of services on the supply chain configuration of sustainable aviation fuel: The case of CO2e emission reductions in the U.S", *Journal of Cleaner Production*, Vol. 404, 136934, doi: 10.1016/j.jclepro.2023.136934.

Mousavi, S. and Bossink, B.A.G. (2017), "Firms' capabilities for sustainable innovation: the case of biofuel for aviation", *Journal of Cleaner Production*, Vol. 167, pp. 1263-1275, doi: 10.1016/j.jclepro.2017.07.146.

Mu, D., Ren, H. and Wang, C. (2021), "A literature review of taxes in cross-border supply chain modeling: themes, tax types and new trade-offs", *Journal of Theoretical and Applied Electronic Commerce Research*, Vol. 17 No. 1, pp. 20-46, doi: 10.3390/jtaer17010002.

Neste (2022), "Key benefits of SAF. Neste worldwide", available at: https://www.neste.com/products/all-products/saf/key-benefits (accessed 31 October 2022).

Oh, X. and ICAO (2011), "Fuel infrastructure at airports", available at: www.iata.org, https://www.icao.int/Meetings/EnvironmentalWorkshops/Documents/2011 -SUSTAF/19_Oh.pdf (accessed 17 October 2022).

Pagh, J.D. and Cooper, M.C. (1998), “Supply chain postponement and speculation strategies: how to choose the right strategy”, *Journal of Business Logistics*, Vol. 19 No. 2, p. 13, available at: https://togarsim.tripod.com/post/pagh.pdf

Pavlenko, N. and Kharina, A. (2018), *Policy and Environmental Implications of Using HEFA+ for Aviation*, Theicct, available at: https://theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-Paper_20180321_vF.pdf (accessed 16 November 2023).

Pounder, P., Bovell, G. and Pilgrim-Worrell, S. (2013), “A review of supply chain management and its main external influential factors”, *Supply Chain Forum: An International Journal*, Vol. 14 No. 3, pp. 42-50, doi: 10.1080/16258312.2013.11517320.

Prataviera, L.B., Moretti, E. and Tappia, E. (2022), “Coping with the postponement boundary problem: an empirical investigation in global food supply chains”, *The International Journal of Logistics Management*, Vol. 33 No. 2, pp. 687-711, doi: 10.1108/ijlm-10-2021-0508.

Scheelhaase, J., Maertens, S. and Grimme, W. (2019), “Synthetic fuels in aviation – current barriers and potential political measures”, *Transportation Research Procedia*, Vol. 43, pp. 21-30, doi: 10.1016/j.trpro.2019.12.015.

Seletar Airport (2022), “History and vision”, available at: https://www.seletarairport.com/history-and-vision.html (accessed 2 November 2022).

Sieppi, S. (2021), “Neste to enable production of up to 500,000 tons/a of Sustainable Aviation Fuel at its Rotterdam renewable products refinery”, *Neste Worldwide*, available at: https://www.neste.com/releases-and-news/renewable-solutions/neste-enable-production-500000-tonsa-sustainable-aviation-fuel-its-rotterdam-renewable-products (accessed 30 December 2022).

SkyNRG (2024), “Sustainable Fure Market Outlook 2024. June 2024 Update”, available at: https://skynrg.com/skynrg-releases-sustainable-aviation-fuel-market-outlook-2024/

Starck, L., Pidol, L., Jeuland, N., Chapus, T., Bogers, P. and Bauldreay, J. (2014), “Production of hydroprocessed esters and fatty acids (HEFA) – optimisation of process yield. Oil & gas science and technology”, *Revue D’IFP Energies Nouvelles*, Vol. 71 No. 1, p. 10, doi: 10.2516/ogst/2014007.

Sun, X., Ji, P., Sun, L. and Wang, Y. (2008), “Positioning multiple decoupling points in a supply network”, *International Journal of Production Economics*, Vol. 113 No. 2, pp. 943-956, doi: 10.1016/j.ijpe.2007.11.012.

Twede, D., Clarke, R.H. and Tait, J.A. (2000), “Packaging postponement: a global packaging strategy”, *Packaging Technology and Science*, Vol. 13 No. 3, pp. 105-115, doi: 10.1002/1099-1522(200005)13:3<105::aid-pts503>3.3.co;2-0.

van Dyk, S. and Saddle, J. (2021), *Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF): Technologies, Potential and Challenges*, IEA Bioenergy, available at: https://task39.sites.olt.ubc.ca/files/2021/08/Task-39-Progress-in-the-commercialisation-of-biojet-fuels-FINAL-August-2021.pdf (accessed 18 October 2022).

van Hoek, R. (1996), “VAL, the functional and spatial organization of businesses”, *Tijdschrift voor Economische en Sociale Geografie*, Vol. 87 No. 1, pp. 32-43, doi: 10.1111/j.1467-9663.1998.tb01535.x.

van Hoek, R.I. and van Dierdonck, R. (2000), “Postponed manufacturing supplementary to transportation services? Transportation Research. Part E”, *Logistics and Transportation Review*, Vol. 36 No. 3, pp. 205-217, doi: 10.1016/s1366-5545(99)00028-9.

Van Kampen, T. and Van Donk, D.P. (2014), “Coping with product variety in the food processing industry: the effect of form postponement”, *International Journal of Production Research*, Vol. 52 No. 2, pp. 353-367, doi: 10.1080/00207543.2013.825741.

Waller, M.A., Dabholkar, P.A. and Gentry, J.J. (2000), “Postponement, product customization, and market-oriented supply chain management”, *Journal of Business Logistics*, Vol. 21 No. 2, pp. 133-160, doi: 10.3390/en14164972.

Yang, B. and Burns, N.D. (2003), “Implications of postponement for supply chain”, *International Journal of Production Research*, Vol. 41 No. 3, pp. 2075-2090, doi: 10.1080/0020754031000077284.

Yang, B., Burns, N.D. and Backhouse, C.J. (2004), "Management of uncertainty through postponement", *International Journal of Production Research*, Vol. 42 No. 6, pp. 1049-1064, doi: 10.1080/00207540310001631601.

Zinn, W. and Bowersox, D.J. (1988), "Planning physical distribution with the principle of postponement", *Journal of Business Logistics*, Vol. 9 No. 2, pp. 117-136.

Corresponding author
Kai Hoberg can be contacted at: Kai.Hoberg@klu.org