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Low-carbon benefits of aircraft adopting continuous descent operations

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HIGHLIGHTS

- Continuous descent operations (CDOs) are a promising strategy to reduce fuel consumption compared to the conventional step-down approaches.
- A method to estimate the potential fuel consumption and emission reductions through CDOs is proposed.
- Implementing CDOs at seven major Chinese airports can reduce fuel consumption by 139 kg per flight, consequently reducing aircraft emissions.
- The long-term effects of CDO adoption on aircraft emissions are estimated based on future scenarios.

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ABSTRACT

Continuous descent operations (CDOs) can significantly reduce fuel consumption compared to the conventional step-down approaches by minimizing level-off segments and enabling engines to operate at idle or near-idle during descent. However, accurately quantifying the potential environmental benefits of CDOs is empirically challenging and depends on factors such as airspace structure, traffic density, and aircraft performance. To address this challenge, we propose a straightforward method to estimate the benefits of applying CDOs. We validate the proposed approach by leveraging quick access recorder data from movements at seven major airports in China. The results show that CDOs can reduce fuel consumption by an average of 139 kg per flight, decreasing CO_2 and other emissions during the descent phase. This can contribute to improving air quality around airports. Looking forward, we estimate that the nationwide adoption of CDOs in China could cumulatively reduce CO_2 emissions by approximately 67.6 Mt. in the period 2025–2050 considering air traffic demand forecasts and expected technological advancements. Overall, this study highlights the critical role of CDOs in promoting sustainable aviation, providing a robust basis for policymakers to support the global adoption of CDOs for the net-zero transition of the aviation industry.

1. Introduction

Climate change has become a critical global issue, garnering increasing attention due to its far-reaching environmental, economic, and societal impacts [1,2]. As global temperatures rise and extreme weather events become more frequent, the need to identify and mitigate the anthropogenic factors driving climate change is becoming more urgent [3]. The transportation sector is a significant contributor to greenhouse gas emissions, being responsible for approximately 24 % of global energy-related CO_2 emissions [4]. The sector's reliance on fossil fuels for powering vehicles, ships, trains, and aircraft leads to the release of vast amounts of CO_2, methane, and nitrous oxides into the atmosphere [5–7]. The rapid expansion of transportation networks to meet global mobility demand has further exacerbated the sector's environmental footprint, making it a critical domain in the fight against climate change [8,9]. Notably, within the transportation industry, aviation has

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garnered increasing attention due to the strong increase in demand experienced over the past decades. This trend led aviation's contribution to climate change to become a pressing concern [10,11]. In 2018, aviation was estimated to account for 2.4 % of anthropogenic CO_2 emissions, and this percentage continues to rise as air travel increases [12]. In addition to CO_2, aircraft engines emit a range of non-CO_2 pollutants, including water vapor, sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) [13–15]. These emissions contribute to ozone formation in the upper atmosphere, which worsens global warming.

In recent years, policymakers and industry stakeholders committed to reaching ambitious targets of decarbonization for the aviation industry. To achieve these goals, numerous initiatives and measures have been implemented, focusing on reducing greenhouse gas emissions and noise pollution [16]. One of the most significant global frameworks in this area is the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was introduced to achieve carbon-neutral growth in international aviation [17]. Under CORSIA, airlines are required to offset emissions that exceed 2020 levels by investing in carbon reduction projects, thus promoting the industry's commitment to climate goals. Many airlines are also increasingly adopting sustainable aviation fuels (SAFs), which offer lower life-cycle carbon emissions compared to conventional aviation fuels (CAFs) [18,19]. Furthermore, NextGen in the US [20] and SESAR in Europe [21] aim to modernize air traffic management (ATM) through more precise and efficient flight operations, which improve fuel efficiency and reduce overall environmental footprints. Concurrently, innovative aircraft technologies, such as electric and hydrogen-powered aircraft, are being investigated, while policies promoting the use of greener transport modes are being implemented. Overall, these initiatives represent a multi-faceted approach to creating a more sustainable future for aviation.

A critical area where significant improvements in operational efficiency can be achieved is the terminal maneuvering area (TMA), namely the controlled airspace surrounding an airport where aircraft transition between en-route and approach/departure operations. In this area, a solution to reduce fuel consumption is to optimize aircraft approach through continuous descend operations (CDOs). During the approach phase of a flight, the conventional method used is the step-down approach where the descent is executed in a series of altitude levels or "steps" [22]. Pilots descend to a specified altitude, level off for a certain distance or time, and then resume descending to the next altitude step. This method is typically used in non-precision approaches or when air traffic control imposes altitude restrictions for airspace management. While it ensures terrain and obstacle clearance, the level-off phases require additional engine thrust, leading to increased fuel consumption and emissions. CDOs constitute an alternative to the conventional approach and consist of a smooth and uninterrupted descent path from cruise altitude at the top of Descent (TOD) to the runway [23], with minimal thrust adjustments and no level-offs. This modern approach leverages advanced navigation systems, such as performance-based navigation (PBN), to optimize the descent trajectory for fuel efficiency and reduced environmental impact. By eliminating the need for intermediate altitude clearances, CDOs can reduce fuel consumption, aircraft emissions, and noise pollution, contributing to enhancing flight efficiency [24,25]. With these benefits, CDO procedures align with the sustainable development goals (SDGs). Particularly, CDOs can contribute to SDG 12 (Responsible Consumption and Production) by enhancing fuel efficiency, reducing resource use, and minimizing aviation's environmental footprint, ultimately supporting sustainable operational practices. Additionally, CDOs can advance SDG 13 (Climate Action) by optimizing descent trajectories to reduce fuel consumption and greenhouse gas emissions, aligning with global climate goals such as the Paris Agreement and ICAO's CORSIA.

Despite its clear benefits, the adoption of CDOs in real-world operations presents several challenges. One significant difficulty is the need for precise coordination between air traffic controllers and pilots, particularly in busy terminal airspace where multiple aircraft may be descending simultaneously [26]. Ensuring safe separation while maintaining continuous descent can be complex, especially when traffic density is high or when weather conditions are unfavorable [27]. Furthermore, the variability in aircraft performance characteristics, such as heterogeneous descent rates and speed profiles, requires tailored CDO trajectories for different aircraft types, adding complexity to ATM [28]. Also, current airspace design, which is often based on traditional step-down approaches, may not always be suitable for CDOs [29], thus potentially requiring airspace restructuring or redesign. However, the increasingly sophisticated global navigation satellite systems (GNSS) may allow the successful adoption of CDOs by providing more precise positioning and trajectory guidance [30,31]. Specifically, satellite navigation enables aircraft to accurately follow optimized descent paths that minimize level-offs and thrust changes. It also supports the integration of CDOs with PBN procedures, which makes possible tailored descent profiles that accommodate varying aircraft capabilities and operational requirements [32].

Given the anticipated widespread adoption of CDOs, exploring the long-term potential benefits of these procedures is crucial. This study aims to provide a straightforward method to evaluate the benefits of adopting CDOs considering factors such as airspace structure, traffic density, and aircraft performance. The proposed modeling approach by leveraging quick access recorder (QAR) data allows estimating changes in fuel consumption and aircraft emissions before and after CDO implementation. To validate the proposed approach, we investigate fuel consumption benefits and emission reduction potentials using a large database of real-world QAR data from seven major airports in China. We find that CDO adoption can reduce fuel consumption by an average of 139 kg per flight, consequently resulting in a significant decrease in aircraft emissions. Furthermore, to evaluate the prospective benefits of a wide-scale adoption of CDOs, we estimate the environmental benefits of a nationwide adoption of CDOs in China from 2025 to 2050. The results quantify cumulative emission reduction in approximately 67.6 Mt. of CO_2. These findings ultimately inform policymakers, airport authorities, and airline operators on the effectiveness of CDOs in achieving environmental goals and promoting more sustainable aviation practices. In summary, the major contributions and highlights of this study can be summarized as follows:

- ➢ **Estimation methodology:** We propose a robust method for estimating the potential reductions in fuel consumption and aircraft emissions that can be achieved through the adoption of CDOs. This methodology provides a framework for evaluating CDOs' effectiveness across different operational contexts.
- ➢ **Quantitative impact analysis:** The proposed approach has been applied to data from seven major Chinese airports. The results indicate that adopting CDOs at these airports can reduce fuel consumption by 139 kg per flight on average. This substantial decrease can enhance operational efficiency and contribute to a marked reduction in aircraft emissions, demonstrating the CDOs' environmental benefits.
- ➢ **Long-term forecasts:** By simulating future scenarios, the present study estimates the long-term benefits of CDOs on sustainable aviation. These projections offer compelling insights into CDOs' potential to advance sustainability goals in the aviation industry over the coming decades.

The rest of this study is structured as follows. Section 2 reviews the environmental advantages of CDOs and the strategies for adopting these procedures. Section 3 introduces the methodology used for evaluating the reductions in fuel consumption and emissions achieved through CDOs, while Section 4 presents the data sources and information used to validate the proposed approach. Section 5 analyzes the numerical results from the case studies conducted at the selected airports and proposes future scenarios to assess the potential benefits of large-scale adoption of CDOs. Section 6 discusses the implications of these findings for policy and practice. Finally, Section 7 draws the conclusions.

2. Literature review

This section summarizes the environmental impacts of aviation and explores pathways toward sustainable aviation. Specifically, the section focuses on current research addressing the environmental, operational, and technological aspects of CDOs and their role in sustainable aviation frameworks.

2.1. Environmental impact of aviation

The aviation industry significantly contributes to global greenhouse gas emissions, accounting for approximately 2.5 % of annual CO_2 emissions [33]. However, its environmental impact extends beyond CO_2, encompassing a range of pollutants and effects that amplify global warming. Aircraft engines release NO_x, SO_x, PM, and water vapor at high altitudes, contributing to radiative forcing [34,35]. Furthermore, non-CO_2 effects, such as contrail formation and aviation-induced cirrus clouds, formed by aircraft at high altitudes under specific atmospheric conditions, have been shown to exert a warming effect comparable to or greater than that of CO_2 emissions from aviation emissions [36]. These combined impacts make aviation one of the major contributors to climate change. In addition to its global climate impact, aviation poses significant challenges to local air quality, particularly in urban areas surrounding major airports [37]. Pollutants such as NO_x, CO, and unburned HC are emitted during ground operations and the low-altitude phases of flight, such as takeoff and landing. These emissions contribute to ground-level ozone formation and PM formation, which adversely affect human health and local ecosystem [38,39]. Communities near airports often experience heightened exposure to air pollution, which exacerbates health issues such as cardiovascular diseases, hearing loss, cognitive impairments, sleep disturbances, tinnitus, and respiratory problems [40]. Furthermore, the noise pollution generated by aircraft operations disrupts ecosystems and reduces the quality of life of residents, adding to the sector's local environmental footprint [41]. Also in this case, the exposure of inhabitants to aircraft noise has been demonstrated to be associated with various adverse health effects, including sleep disturbances, cardiovascular diseases, and cognitive impairments in children [42].

The environmental impact of aviation is further exacerbated by the rapid growth in demand. Globalization, rising incomes, and the increased availability of air travel following industry deregulation and the advent of low-cost carriers have led to a surge in passenger numbers over the last decades. Cargo aviation also contributes significantly to this trend, with e-commerce and global supply chain demands fueling the expansion of freight operations [43]. The combined impact of increased demand and technological advancements in aircraft fuel efficiency and engine design that have not kept pace with the growth in air traffic makes aviation one of the fastest-growing contributors to climate change. More urgently, this trend is far from being exhausted. After the severe disruption caused by the COVID-19 pandemic, the air transport industry has rapidly recovered, with traffic rebounding to long-term growth in developed markets and expanding economies boosting new flight demand. Recent forecasts estimate an increase in demand by 2.2–4.1 % by 2050, with emissions in 2025 projected to be double or triple of 2019 under a business-as-usual scenario [44]. These dynamics stress the urgency of addressing aviation's environmental impacts to ensure the aviation industry sector aligns with its ambitious targets and global sustainability goals.

2.2. Sustainable aviation pathways

Over the last few years, researchers and industry stakeholders have proposed sustainable aviation pathways including plenty of strategies, technologies, and policies to cope with aviation's environmental impact. These pathways, summarized in Table 1 together with associated benefits and challenges, aim to address critical industry concerns (e.g., carbon emissions and noise pollution) while ensuring that the aviation industry continues to support global connectivity and economic growth. Among the others, key strategies include the development and adoption of SAFs, aircraft fuel efficiency improvements, new aircraft technologies (e.g., electric-powered or hydrogen-based aircraft), more efficient air traffic procedures, and modal shift initiatives [45]. SAFs derived from renewable resources (e.g., biowaste) or synthesized with carbon capture technology can drastically reduce life-cycle emissions [46]. Aircraft electrification and transition to hydrogen, though still in their nascent stages and marked by significant technological and cost challenges, have the potential to revolutionize short-haul flights by eliminating direct emissions [47–50]. ATM operational improvements, such as CDOs and dynamic route optimization, as well as measures to optimize ground operations, can reduce fuel consumption and emissions [51]. Lastly, modal shift initiatives aim to reduce aviation's environmental impact by incentivizing modal diversion toward greener transport modes [52,53].

Within this complex environment, policy and regulatory frameworks are critical for fostering sustainable aviation. Governments and international organizations (e.g., ICAO) play pivotal roles in establishing carbon offset schemes such as CORSIA, mandating clear emission reduction targets [54]. Airlines, on their side, are increasingly setting ambitious net-zero goals and trying to achieve that by renewing their fleet, retrofitting aircraft with lightweight materials, and investing in offset programs. However, achieving these goals necessitates global cooperation, consistent investments in R&D to overcome technological barriers, and the devising of new ways to ensure the financial sustainability of these interventions.

Beyond the mere technical innovations, the transition toward sustainable aviation requires systemic and regulatory shifts, including integrating air transport with multimodal mobility solutions and enhancing ATM systems. Emerging technologies, such as hydrogen-powered aircraft, are promising avenues, but they require substantial infrastructure investments. Urban air mobility (UAM) leveraging electric vertical takeoff and landing (eVTOL) vehicles could alleviate ground traffic congestion and redefine short-haul travel [55]. Overall, achieving sustainable aviation toward meeting its ambitious net-zero commitments hinges on carefully balancing company profitability, passenger experience, technological aspects, and environmental responsibility.

2.3. Continuous descent operations

CDOs are one of the measures aimed at improving operational efficiency. CDOs allow aircraft to descend to their final destination from cruise altitude in a controlled and continuous manner with minimal thrust, thus reducing fuel consumption, emissions, and noise pollution. Several prior studies have investigated the environmental advantages of CDOs, particularly in reducing fuel consumption and associated greenhouse gas emissions. For instance, Fricke et al. [56] found that CDOs reduced fuel usage by approximately 20 %–40 % per descent compared to conventional step-down approaches. The reduction in fuel consumption translates directly to lower CO_2 emissions [57]. Furthermore, using simulation data from Stockholm Arlanda Airport, Lemetti et al. [58] estimated that fuel consumption in TMAs can be reduced by 65 %, demonstrating the potential benefits of environmental measures targeting efficiency improvements acting in this area. Emission reductions through CDOs also have localized environmental impacts, especially in the vicinity of airports, where the concentration of pollutants is highest [59]. However, the extent of these reductions depends on variables such as traffic density, aircraft type, and weather conditions, which suggests the need for adaptable CDO strategies in diverse operational environments. CDO implementation is also a method for mitigating noise pollution, typically constituting a significant concern for communities

Table 1
Summary of sustainable aviation pathways.

Pathway	Description	Benefits	Challenges
SAFs	Fuels derived from renewable sources or with the use of carbon capture processes.	Reduced life-cycle carbon emissions.	High production costs and limited scalability in the short run.
Aircraft electrification	Use of electric propulsion for short-haul flights.	Zero direct emissions and lower noise pollution.	Limitations in battery technology constraints both the operating range and cruise speed. Potentially high operating costs in the short term.
Hydrogen-powered aircraft	Aircraft powered by hydrogen combustion or fuel cells.	Zero carbon emissions during operation.	Infrastructure and storage challenges.
Operational efficiency	Techniques such as CDOs and optimized routing.	Lower fuel consumption and reduced emissions.	Requires enhanced ATM systems.
Fleet modernization	Upgrading aircraft with efficient engines, lightweight materials, and aerodynamic designs.	Improved fuel efficiency and lower emissions.	High capital investment required and limited production capacity.
Carbon offsetting	Programs to offset emissions through afforestation or renewable energy projects, (e.g., EU ETS, CORSIA).	Immediate mitigation of emissions impact.	Limited direct impact on emission sources.
UAM	Deployment of eVTOL vehicles for urban and regional connectivity.	Lower urban congestion and emissions.	Regulatory hurdles and infrastructure requirements.
Modal shift and multimodal integration	Promoting modal shift or modal integration toward low-carbon transport modes.	Reduced dependency on air travel for short trips.	Coordination across transport sectors and capacity of alternative transport modes.

living in airport neighborhoods. Domínguez et al. [60] found that continuous descent profiles significantly reduced noise because aircraft engines operate at reduced thrust settings throughout the descent phase. This noise reduction is particularly beneficial at lower altitudes, where the greatest disturbances by aircraft operations for local communities originate. Tian et al. [61] suggested that CDOs could reduce noise levels relative to traditional descent methods, contributing to improved quality of life for residents near airports.

Despite the reductions in emissions and noise, implementing CDOs poses various operational challenges, particularly in congested airspace. High traffic volumes often require air traffic controllers to adjust descent paths, which can reduce CDO efficiency [62]. Controllers frequently prioritize maintaining safe separations between aircraft by using the step-down approach, resulting in lower environmental benefits of CDOs. Sáez et al. [26] showed that successful CDO adoption often required advanced ATM tools that can dynamically adjust descent paths to balance efficiency and safety. Weather conditions also complicate CDO implementation, as turbulence and adverse weather patterns can lead to altitude changes, which interrupts the continuous descents [63]. Advances in ATM and navigation technology are crucial for overcoming the operational limitations of CDOs. Automation tools, predictive algorithms, and communication systems have been identified as key enabling factors for successful CDO implementation. According to Sáez et al. [64], integrating the optimal control problem and the mixed-integer-linear programming model into ATM systems could allow for more precise descent management, even in complex airspace environments. Moreover, PBN allows for precise, flexible route planning that can support continuous descent profiles [65]. With the wider adoption of PBN and data-driven ATM tools, CDOs could become a standard practice in both high-density and low-density airspace, thereby resulting in significant environmental benefits.

In summary, while the benefits and challenges of CDOs are well documented, several areas of research still need to be addressed. A critical research gap is the lack of large-scale comprehensive studies that evaluate the environmental benefits of CDOs across diverse airspace structures and airports. Also, only a few studies have explored the long-term effects of applying CDO procedures on fuel savings and emission reductions. Addressing these gaps is a prerequisite for a data-driven approach in investigating CDOs and evaluating their full potential, ultimately providing a foundation for their broader adoption as part of sustainable aviation practices.

3. Modeling approach

While it is widely recognized that CDOs enhance fuel efficiency by allowing aircraft to descend continuously with idle thrust from cruising altitude, accurately quantifying the fuel savings and reductions in emissions linked to these procedures remains challenging. Currently, CDOs are primarily implemented during low-traffic periods, as the lack of level-off segments reduces control over arrival times, which can lead to congestion in the TMA. Therefore, collecting empirical flight operation data related to CDOs is difficult. This study proposes a straightforward approach for accurately estimating the fuel savings from applying CDOs.

Fig. 1 illustrates a schematic representation of the conventional step-down approach (A-B-C-D-*E*-F-G) with level-off segments, as well as the CDO approach (A'-B′-C′-D′). In this example, the step-down approach includes three level-off segments (B—C, D-E, and F-G), with the respective distances indexed as D_1, D_2, and D_3. The corresponding fuel consumption required for each level-off segment is denoted by f_1, f_2, and f_3, respectively. To quantify the fuel savings from applying the CDO procedure, the flight status (i.e., idle thrust setting and, thus, fuel consumption) during the descent phases of both the CDOs and step-down approach are considered equivalent, which is $\widehat{AB} = \widehat{A'B'}$, $\widehat{CD} = \widehat{B'C'}$, and $\widehat{EF} = \widehat{C'D'}$. The additional cruising distance of operating CDOs (A-A') is represented by D^*, where $D^* = D_1 + D_2 + D_3$. The corresponding fuel consumption for A-A' is denoted by F^*, and the fuel saving of operating the continuous descend approach instead of the step-down approach can be calculated as $\Delta F = F_1 + F_2 + F_3 - F^*$. This method reflects the practical scenario of the continuous descend approach in which air traffic control instructs the pilots to descend to an initial altitude h_1. Before the aircraft reaches h_1, a subsequent instruction is issued, directing the pilots to descend further to altitude h_2 ($h_1 > h_2$).

Based on this principle, the method for evaluating the fuel savings that can be achieved using CDOs considers the parameters in Table 2. For a given flight, let I indicate the set of level-off segments experienced, with each segment indexed by i; thus, the number of level-off segments is denoted by $|I|$. The total fuel consumption ($\mathscr{F}$) and flight distance (D^*) of these level-off segments can be calculated using the following two equations:

$$\mathscr{F} = \sum_{i=1}^{|I|} F_i \tag{1}$$

$$D^* = \sum_{i=1}^{|I|} D_i \tag{2}$$

where F_i and D_i are the fuel consumption and flight distance of level-off segment i. To better investigate fuel consumption within each level-off

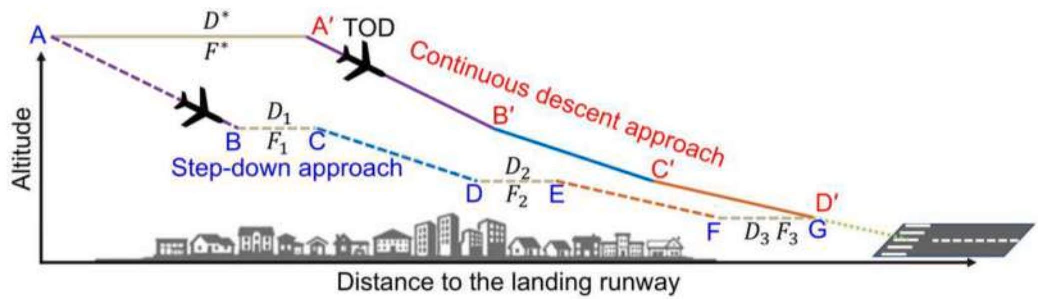

Fig. 1. Step-down approach trajectory (dashed line) and CDO trajectory (solid line). The reduction in fuel consumption when using the continuous descend approach with respect to the step-down approach is calculated as $F_1 + F_2 + F_3 - F^*$.

Table 2
List of notations.

Sets with indices	
I	Level-off altitudes, indexed by i
J_i	Trajectory points (latitudes and longitudes) at level-off altitude i, indexed by j
K	Pollutants produced by aircraft engines, indexed by k
Variables and parameters	
F_i	Fuel consumption for level-off segment i
$\mathscr{F}$	Total fuel consumption for all level-off segments
D_i	Flight distance for level-off segment i
D^*	The additional cruising distance when operating CDOs
$\overline{f}^i_{j,j+1}$	Average fuel flow between points j and $j+1$ at level-off altitude i
$\tau^i_{j,j+1}$	Time interval to fly between points j and $j+1$ at level-off altitude i
$d^i_{j,j+1}$	Distance from point j to point $j+1$ at level-off altitude i
F^*	Additional fuel consumption for longer cruising distance D^* when operating CDOs
$\overline{f}^*$	Average fuel flow at TOD altitude
$\overline{v}^*$	Average ground speed at TOD altitude
ΔF	Fuel savings when adopting CDOs
EM_k	Amount of aircraft emissions of pollutant k
F	Fuel consumption
E_k	Emission index of pollutant k

segment, we further divide each segment into different portions. Let J_i be the set of trajectory points in level-off segment i, indexed by j; therefore, the number of intermediate points in level-off segment i is represented by $|J_i|$. Accordingly, F_i and D_i can be more precisely estimated as:

$$F_i = \sum_{J=1}^{|J_i|-1} \overline{f}^i_{j,j+1} \tau^i_{j,j+1} \tag{3}$$

$$D_i = \sum_{J=1}^{|J_i|-1} d^i_{j,j+1} \tag{4}$$

where $\overline{f}^i_{j,j=1}$ represents the average fuel flow between point j and point $j+1$ at level-off altitude i, and $\tau^i_{j,j+1}$ is the time interval to fly between the two adjacent points j and $j+1$ at altitude i. The notation $d^i_{j,j+1}$ represents the distance from point j to point $j+1$. The distance $d^i_{j,j+1}$ can be calculated based on the longitude and latitude of points j and $j+1$.

The additional fuel consumption F^* due to the additional cruising distance (D^*: A-A' segment) when operating CDOs can instead be estimated using the average values at TOD altitude.

$$F^* = \frac{D^*}{\overline{v}^*} \overline{f}^* \tag{5}$$

where $\overline{f}^*$ and $\overline{v}^*$ denote the average fuel flow and ground speed at TOD altitude, respectively. Therefore, the fuel savings from the CDOs can be obtained as the difference between fuel savings due to avoiding level-off segments and additional fuel consumption due to the longer cruising distance. By adopting our notation, we have:

$$\Delta F = \mathscr{F} - F^* \tag{6}$$

The air pollutants generated by aircraft engines mainly include CO_2, H_2O, SO_x, NO_x, CO, HC, and PM. Let K be the set of different air pollutants (indexed by k), the amount of aircraft emissions of pollutant k (EM_k) can be calculated as follows:

$$EM_k = F \bullet E_k \tag{7}$$

where F represents the fuel consumption and E_k denotes the emission index of pollutant k, defined as the mass of the pollutant emitted per unit of fuel consumed (i.e., kg of pollutant per kg of jet fuel burned). According to the Airport Air Quality Manual [66], the emission indices for CO_2, H_2O, and SO_x are 3.15 kg/kg of fuel, 1.25 kg/ kg of fuel, and 1 g/ kg of fuel, respectively. In contrast, the emission of some pollutants such as NO_x, CO, and HC are related to fuel flow. We compute these emissions using the BFFM2 method [67] and the ICAO Engine Emissions Databank (ICAO EEDB) [68] by multiplying the fuel flow with the respective flight time and emission factor. The emission index for PM is also related to fuel flow and, therefore, PM emissions are calculated based on the Airport Air Quality Manual [66] and ICAO EEDB [68].

4. Empirical setting

To validate the effectiveness of the proposed approach in quantifying the benefits of CDO adoption, we consider a large database of real-world QAR data from seven major airports in China. Specifically, we focus on Beijing Capital (ZBAA), Guangzhou Baiyun (ZGGG), Wuhan Tianhe (ZHHH), Kunming Changshui (ZPPP), Shanghai Hongqiao (ZSSS), Chengdu Shuangliu (ZUUU), and Urumqi Diwopu (ZWWW) airports. These airports were chosen for their different strategic geographic location, air traffic volume, and regional airspace characteristics, which offer the chance to comprehensively assess the potential benefits of implementing CDOs. ZBAA and ZGGG are among the busiest airports in China (with an average of 596 and 483 inbound flights per day, respectively), handling high traffic density and being denoted by complex airspace management, thus making them representative of major international hub airports. ZHHH and ZUUU are instead important regional airports with growing traffic, reflecting mid-tier hubs that face unique challenges related to the need of increasing capacity and operational efficiency. ZPPP airport in southwestern China is characterized by a distinct air traffic flow pattern, often influenced by mountainous terrain and weather conditions. ZSSS and ZWWW provide insights into smaller airports in coastal and western regions, which differ in terms of air traffic congestion, infrastructure, and proximity to international flight routes. Fig. 2 illustrates the geographical locations of the selected

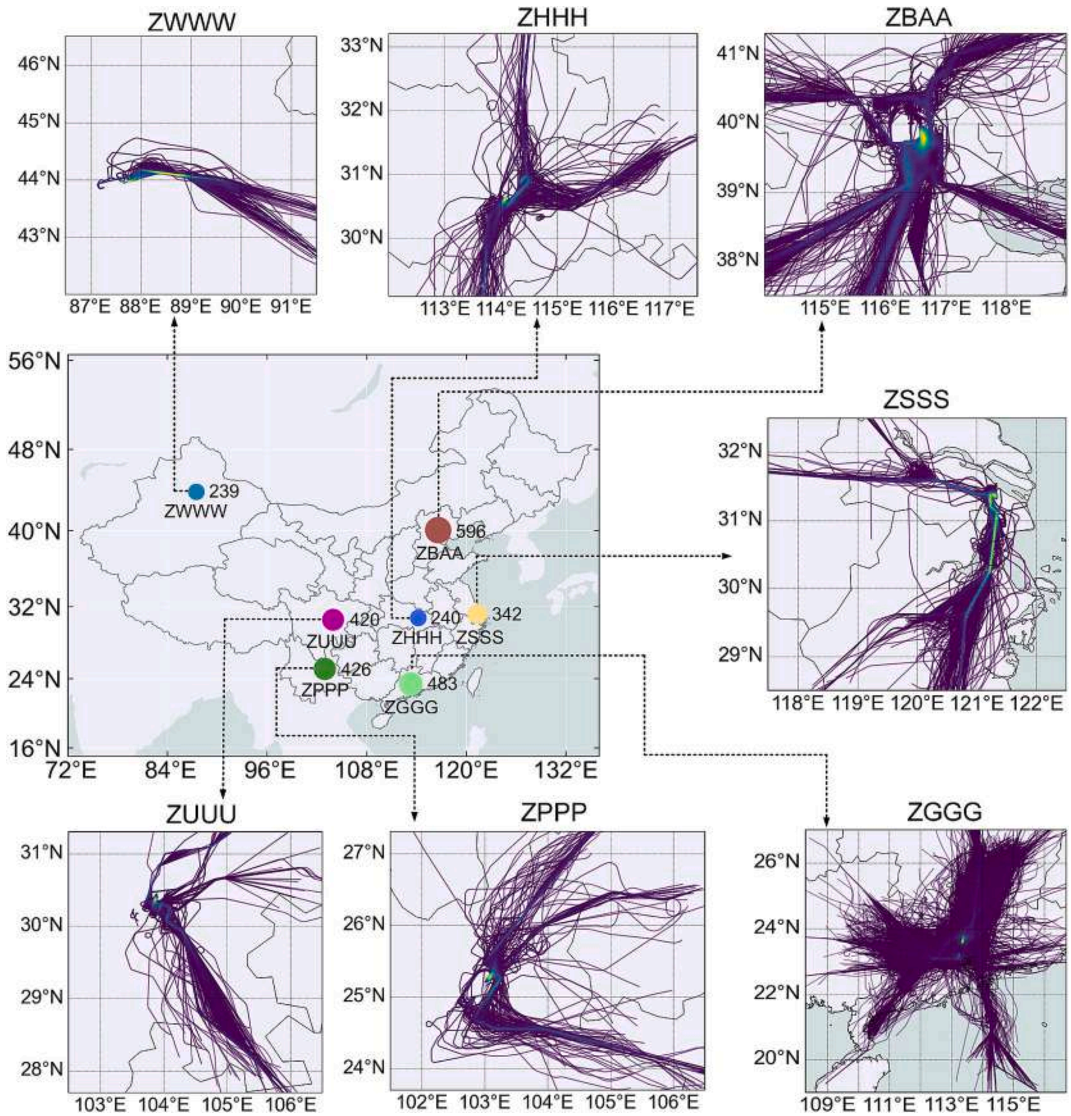

Fig. 2. Geographical locations of the selected airports and trajectories of inbound flights at different airports.

airports, highlighting their strategic locations across China. It also includes detailed visualizations of inbound flight trajectories and the average daily number of landings at each airport during June 2019, offering insights into their heterogeneous traffic patterns and operational characteristics.

The data used to feed the proposed modeling approach are QAR data

Table 3
Number of inbound flights operated by China Southern Airlines in June 2019 at selected airports by aircraft model. The most frequently used aircraft models were the B738, A321, and A320.

	ZBAA	ZGGG	ZHHH	ZPPP	ZSSS	ZUUU	ZWWW	Total
A20N	24	287	0	0	0	0	0	311
A21N	12	777	0	57	2	61	0	909
A319	36	669	0	4	0	38	0	747
A320	523	1093	6	19	31	10	18	1700
A321	962	659	1	40	152	18	8	1840
A332	194	234	22	65	64	27	0	606
A333	430	388	0	35	109	97	0	1059
A388	48	45	0	0	0	0	0	93
B737	4	390	23	24	2	5	0	448
B738	576	2333	263	60	157	46	176	3611
B744	0	2	0	0	0	0	0	2
B77L	0	50	0	0	0	0	0	50
B77W	16	184	5	0	69	19	0	293
B788	66	56	20	0	21	7	36	206
B789	33	199	0	0	86	0	1	319
E190	0	388	0	0	0	0	0	388
Total	2924	7754	340	304	693	328	239	**12,582**

including a range of parameters related to aircraft performance and flight operations, such as altitude, true airspeed, heading, vertical speed, and ground speed. QAR data also capture aircraft positions using latitude and longitude, engine performance metrics (e.g., thrust settings and fuel flow), and wind direction and speed. In this study, we consider a comprehensive dataset of QAR data of inbound flights operated by China Southern Airlines in June 2019 at selected airports. Specifically, a total of 12,582 flights, operated by 16 different aircraft models, were analyzed, (see Table 3). A comprehensive overview of the aircraft models and engine types is provided in Appendix (Table A1).

5. Results

This section summarizes the potential reductions in fuel consumption and emissions that can be achieved by implementing CDOs at selected airports. Additionally, future scenario simulations are used to evaluate the long-term benefits of the use of this procedure.

5.1. *Fuel reductions*

The estimates of potential fuel consumption reductions from applying CDOs to these analyzed flights are illustrated in Fig. 3. The fuel savings are influenced by both the flight volume and airspace configurations around each airport. Cumulatively, the major airports can achieve significant fuel reductions per day (e.g., 51 tons on June 2 for ZGGG). In contrast, ZHHH and ZWWW show relatively smaller potential savings, with peak reductions occurring on June 14 (2.8 tons) and June 3 (0.8 tons), respectively. Beyond demonstrating the fuel reduction benefits of adopting CDO procedures, this comparison highlights the potential for improving operational efficiency at single airports. Specifically, a larger gap between CDOs and step-down operations indicates lower operational efficiency, particularly on busy days [62]. Therefore, the summative benefits are aligned with the traffic density on different days. The operational mode which has a low traffic volume but a large optimizing gap, should be prioritized for future improvements. Such off-peak days have more space to improve environment benefits by CDOs which could be tough in those busy days. The exemplary operational performance observed at ZPPP on June 13, which has a high traffic density but a small gap for improvement by CDOs, may serve as a model for extending efficient practices to other days.

Fig. 3h compares the total number of inbound flights at the selected airports (including also those not operated by China Southern Airlines) as a proxy for airport congestion with the average fuel savings per flight. The busiest airport with an average of 600 inbound flights per day (i.e., ZBAA) reports potential fuel savings from adopting CDOs of approximately 587 kg per flight. ZGGG follows with approximately 500 flights per day and an average fuel reduction of about 140 kg per flight. ZHHH exhibits a disproportionate relationship between flight volume and fuel reduction potential. Despite an average of 243 landings in June 2019, ZHHH shows a relatively low fuel reduction potential of 75 kg per flight. This discrepancy is due to operational procedures that constrain the efficiency of landing profiles. A similar situation is observed at ZUUU, which has a potential fuel reduction of 150 kg per flight. Ultimately, the results confirm that greater flight volumes lead to higher potential fuel savings. This pattern underscores the need for operational procedure optimization to enhance efficiency and economic performance.

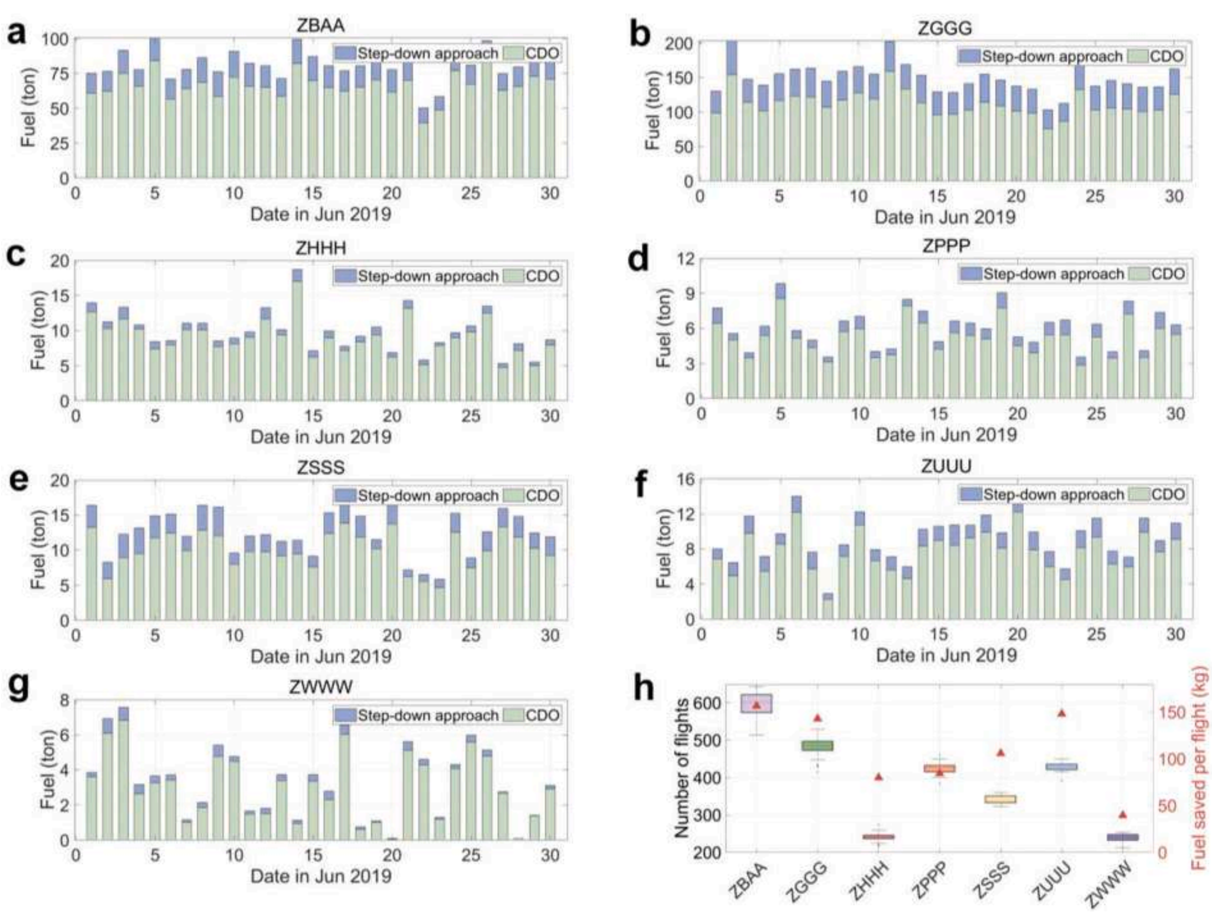

Fig. 3. Potential fuel reductions achieved through CDOs for inbound China Southern Airlines flights at airports ZBAA (a), ZGGG (b), ZHHH (c), ZPPP (d), ZSSS (e), ZUUU (f), and ZWWW (g). Subfigure h shows the average daily number of inbound flights (not only those operated by China Southern Airlines) and potential fuel reduction per flight at each airport.

Fig. 4 reports the potential fuel savings by time slot at the airports analyzed. The number of total inbound flights is used as proxy operational intensity, while the fuel reduction rate represents the extent of the benefits of applying CDOs. Overall, we observe notable variations in potential savings throughout the day. Traffic density is one of the vital factors influencing the conductions of the optimal profiles. In those scenarios with heavy traffic, the aircraft has to maneuver to maintain the separation requirement. Hence, the off-peak situations should be further explored to apply CDOs without the restriction by essential changes in the descent profile. Notably, unconventional scenarios often arise during morning hours at ZBAA, ZUUU, and ZPPP, particularly between 4:00 and 6:00. Despite low air traffic during these slots, the potential fuel savings exceed 30 %, which is in line with benefits achieved during busier periods. These outliers are likely attributable to emergency factors, such as severe weather conditions. These scenarios prove the opportunity for further optimization and integration of CDOs during non-peak hours. Furthermore, while an overall positive correlation between traffic volume and fuel savings is observed at ZGGG and ZHHH, significant divergences are evident at other airports. For example, during the 10:00–12:00 time slot at ZPPP, the greatest traffic flow (48 flights) coincides with the smallest potential benefits of adopting CDOs (10 %). This raises the question of whether these operational patterns could be adapted to other time slots at ZPPP. Future efforts should focus on these cases to develop decision-making tools as potential paradigms. The correlation between traffic flow and fuel saving metrics also demonstrates the economic benefits of implementing CDOs, especially at major airports.

5.2. Emission reductions

To evaluate the environmental benefits of CDO adoption, we analyze seven types of pollutant emissions: CO_2, H_2O, SO_x, NO_x, CO, HC, and PM [24]. Fig. 5 provides a detailed overview of potential emission reductions at selected airports. Since the emissions of CO_2, H_2O, and SO_x are directly proportional to fuel consumption, similar distribution patterns are observed for these pollutants. The median value of the average CO_2 reduction could reach nearly 436 kg and 380 kg per flight if CDOs are implemented for all flights at ZGGG and ZBAA, respectively. Considering the other pollutants, CO and HC show substantial potential for reduction, particularly at ZUUU, where decreases of 60 % and 37 %, respectively, are achievable. These reductions stem from the fundamental differences between the step-down approach and CDOs. The former requires aircraft to maintain level flight segments at various altitudes during descent, leading to prolonged engine operation at idle thrust or frequent throttle adjustments. This operational pattern disrupts optimal combustion, which results in incomplete fuel combustion and higher emissions. In contrast, CDOs involve a continuous descent profile, which minimizes thrust variations and reduces prolonged engine idling. This optimized descent trajectory enhances fuel efficiency and stabilizes combustion, thereby lowering CO and HC emissions. Consequently, CDOs hold significant potential for abating local air pollutants near airports and promoting broader environmental sustainability.

Given the strong presence of China Southern Airlines (in terms of the number of inbound flights) at ZBAA and ZGGG, we perform on data from these two airports a statistical analysis to examine the distribution of CO_2 reductions for each flight. The distribution was modeled using a

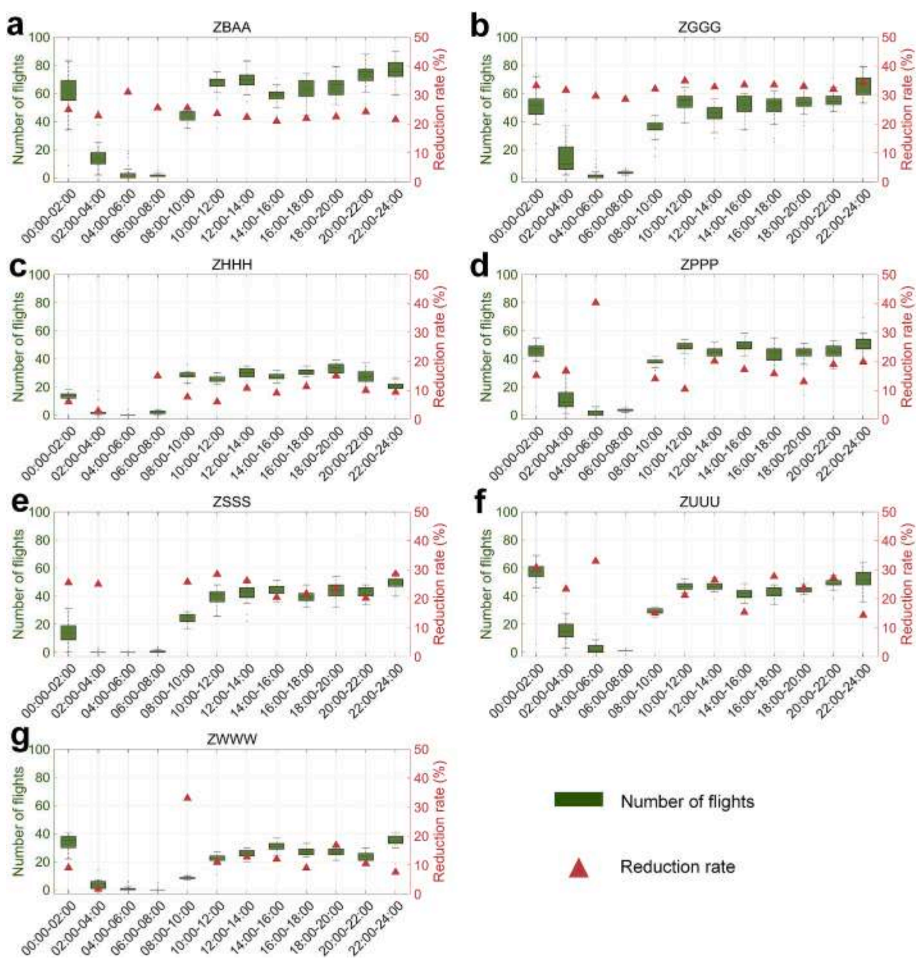

Fig. 4. Fuel reductions achieved by adopting CDOs for flights operated by China Southern Airlines in different time slots. The absence of points means that there were no landing flights operated by China South Airlines in the slot.

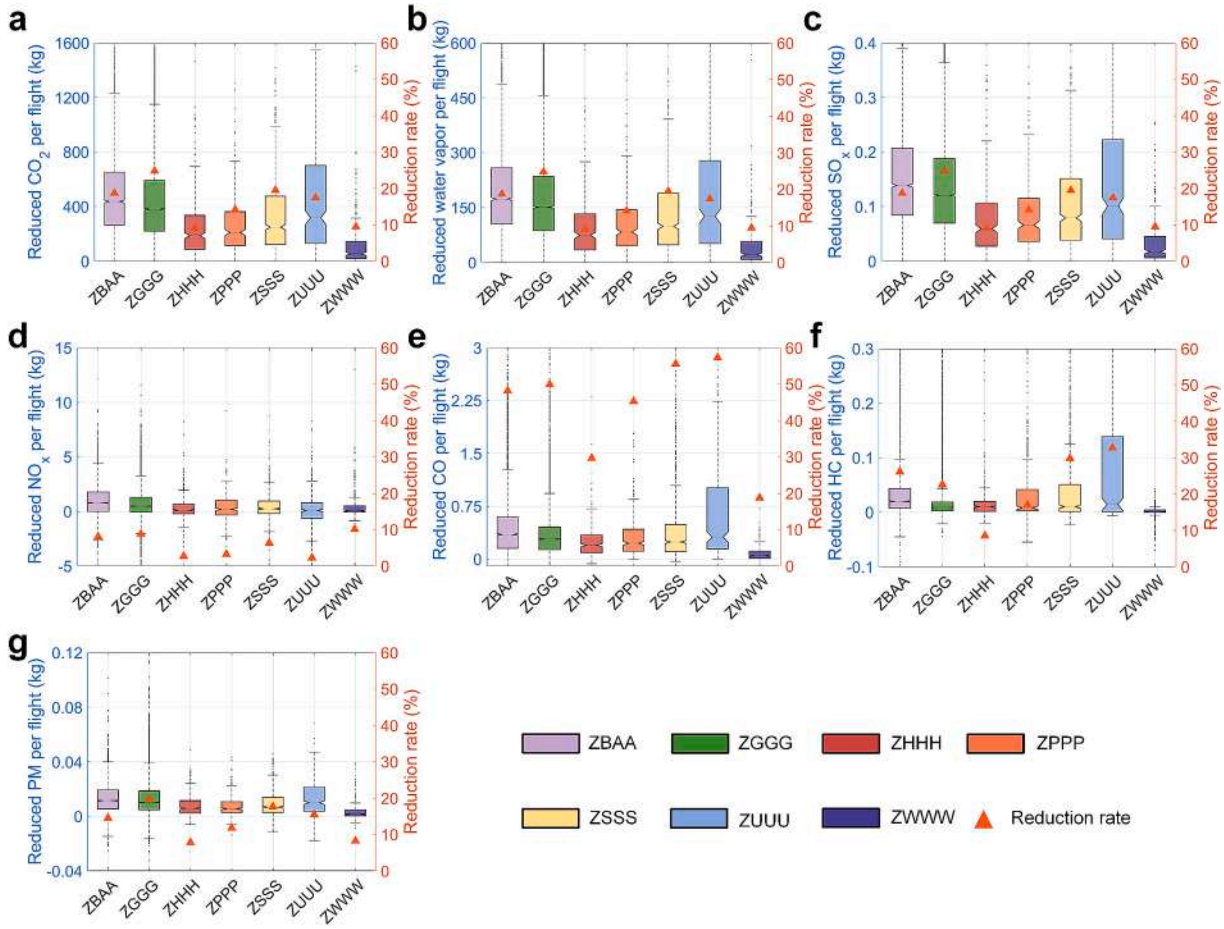

Fig. 5. Emission reductions per flight at the selected airports; a: CO_2, b: water vapor, c: SO_x, d: NO_x, e: CO, f: HC, and g: PM.

logarithmic exponential curve, as shown in Fig. 6. The maximum likelihood locations are identified as 281 kg and 214 kg of CO_2 per flight for ZBAA and ZGGG, respectively. These results can serve as benchmarks for operational efficiency, with two key optimization targets: reducing the maximum likelihood location and eliminating the tail of high values in the distribution.

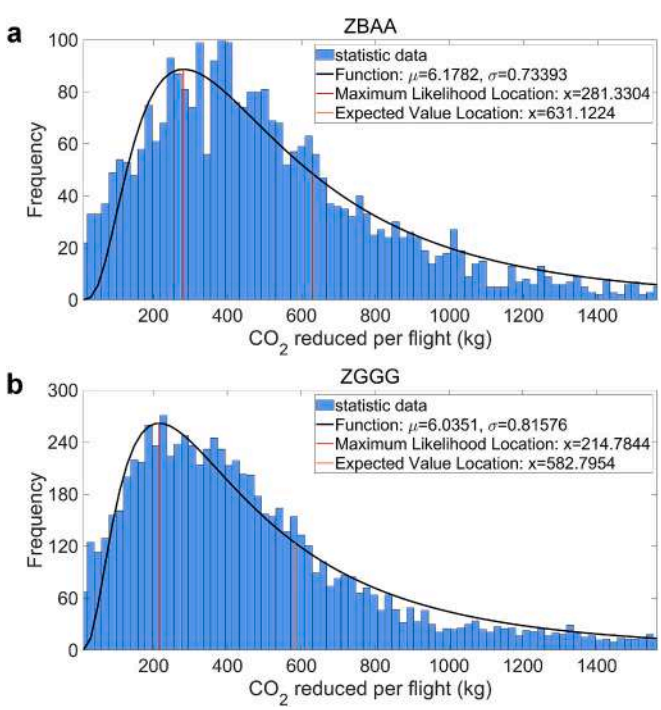

Fig. 6. Distribution of CO_2 reduction per flight at ZBAA (a) and ZGGG (b).

Advanced operational strategies, such as adaptive ATM systems, are essential to achieve further optimization through CDOs. The fitted curves offer valuable insights into developing intelligent tools. For example, real-time trajectory adjustments and machine learning-based predictions of optimal descent profiles could be used to dynamically minimize CO_2 emissions under various traffic conditions. Furthermore, aligning flight schedules with airport capacity constraints could help reduce excessive variations in operational efficiency.

5.3. Long-term benefits

To investigate the prospective benefits of a wide-scale adoption of CDOs, we focus on the period 2025–2050 and simulate the environmental benefits of a nationwide adoption of CDOs in China from 2025 to 2050. We consider five key factors contributing to overall emissions from aviation: (a) air traffic growth, (b) technological advancements, (c) operational and infrastructure enhancements, (d) offsetting investments, and (e) SAF adoption. The evolutions of these five factors based on the Waypoint 2050 report [69] are illustrated in Fig. 7. Specifically, Fig. 7a reports the rate (a_y) of flight volume in year y relative to that in 2024. Fig. 7b-d shows the fuel reduction rates achieved through technological advancements, operational and infrastructural improvements, and offsetting investments, respectively. These three rates are denoted by b_y, c_y, and d_y. Lastly, Fig. 7e presents the adoption rate of SAFs, which is denoted by e_y. Detailed values for each factor are

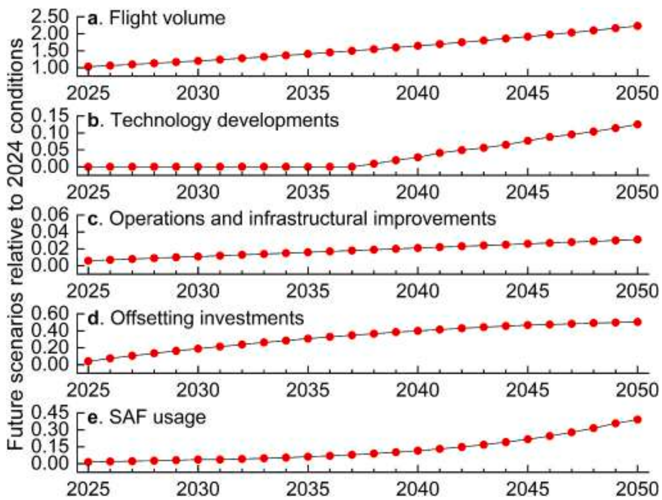

Fig. 7. Evolution of the five factors for the period 2025–2050. a: flight volume ratio relative to 2024 levels; b: fuel consumption reduction ratio deriving from technological advancements relative to 2024 levels; c: fuel consumption reduction ratio from operational and infrastructural improvements relative to 2024 levels; d: fuel consumption reduction ratio achieved through offsetting investments relative to 2024 levels; e: SAF adoption ratio relative to 2024 levels.

provided in Appendix (Table A2).

According to the Ministry of Transport of the People's Republic of China [70], the total number of inbound flights in 2024 is estimated to be 6.24 million. Given the average fuel consumption of 648.56 kg per step-down approach, the total fuel consumption for inbound flights in China in 2024 is estimated to be 4.05 Mt. This value is denoted as $\mathscr{F}_{2024}$. Therefore, the total fuel consumption for step-down approaches in year y can be formulated as follows:

$$\mathscr{F}_y = \mathscr{F}_{2024} \bullet a_y \bullet (1 - b_y)(1 - c_y)(1 - d_y) \tag{8}$$

SAFs play a crucial role in reducing aviation emissions, providing a cleaner alternative to CAF. Sourced from renewable materials such as waste oils, agricultural residues, and nonfood crops, SAFs can reduce life-cycle greenhouse gas emissions by up to 80 % compared to CAF. Focusing specifically on SAF effects (excluding life-cycle analysis), Table 4 presents the emission factors of SAFs relative to CAF ($\mathscr{R}_e$). Thus, considering future SAF adoption, the emissions of pollutant k in year y ($\mathscr{W}_y^k$) without CDO adoption can be represented as follows:

$$\mathscr{W}_y^k = \mathscr{F}_y(1 - e_y)E_k^f + \mathscr{F}_y e_y E_k^f \mathscr{R}_k \tag{11}$$

Fig. 8a illustrates the fuel consumption forecasts (including CAF and SAFs) for inbound flights in China between 2025 and 2050 under the assumption that all flights will operate the conventional step-down approach. Extrapolating our results for selected airports to the entire country, we can assume that adopting CDOs reduces fuel consumption by 21.5 % (approximately 139.3 kg on a per-flight basis). This assumption implies that selected airports, their airspace configurations, and the mix of aircraft models used are representative of the entire country. The estimated benefits from adopting at the country-level CDOs from 2025 to 2050 are depicted in Fig. 8b-h. Overall, in the period under analysis, we estimate that adopting CDOs in China could reduce CO_2 emissions by about 2.6 Mt. annually on average compared to the conventional step-down approach. The cumulative reduction in CO2 emissions in the period from 2025 to 2050 is quantified to be approximately 67.6 Mt. Significant benefits are also reported when considering other pollutants.

Table 4
Emission factors of SAFs relative to CAFs.

Emission	R_k	Reference
CO_2	1	Given that blended SAFs meet the same specifications as CAFs, the CO_2 emissions of SAFs are the same as those of CAFs [71].
Water vapor	1.1	SAFs increase water vapor emissions by 10 % compared to CAFs [72].
SO_x	0	SAFs completely eliminate SO_x emissions due to the absence of sulfur and aromatic compounds [73].
NO_x	1	SAFs produce similar NO_x emissions to those of CAFs [74].
HC	0.85	SAFs reduce HC emissions by 10 %–20 % compared to CAFs [75].
CO	0.85	SAFs can lower CO emissions by 10 %–20 % compared to CAFs [74].
PM	0.1	SAFs can cut PM emissions by up to 90 % compared to CAFs [73].

6. Discussions

This study demonstrates the substantial environmental and operational advantages of implementing CDOs, with particular reference to the Chinese context. The analysis of QAR data from seven major airports provides robust evidence of CDOs' potential to significantly reduce fuel consumption during aircraft approach, achieving an average fuel saving of 139 kg per flight. This translates into a significant decrease in CO_2 and other pollutant emissions, contributing directly to the ambitious climate goals of aviation. More importantly, we found that such reductions are particularly impactful in high-congested areas, where air pollution poses serious health and environmental risks. These findings confirm that the large-scale adoption of CDOs is a practical solution for contributing to mitigating the aviation sector's environmental footprint, ultimately contributing to the pursuit of both national and international climate commitments. In particular, the potential for a 21.5 % reduction in fuel consumption for CDO flights is a compelling case for the adoption of these procedures as part of a broader strategy for reducing aviation's carbon footprint. Our projections show that the nationwide use of CDOs in China could lead to a cumulative CO_2 reduction of approximately 67.6 Mt. from 2025 to 2050. Since air traffic continues to grow, particularly in highly developing regions such as China, adopting CDOs definitely offers a viable solution to balance operational efficiency with environmental sustainability.

From an economic perspective, the projected reduction in fuel consumption directly translates into cost savings for airlines, thus constituting a strong economic incentive for the adoption of CDOs. Furthermore, the implementation of CDOs may also reduce the burden on ATM systems by optimizing descent profiles, improving the overall flow of air traffic, and potentially reducing delays. A successful example in this regard is Brussels Airport where the implementation of CDOs has successfully improved efficiency and reduced environmental impact.

Despite the benefits, achieving a widespread CDO adoption poses several challenges. These include the need for significant changes in ATM procedures, the necessity to upgrade the existing infrastructure, and the establishment of coordination mechanisms between various stakeholders such as airlines, air navigation service providers, and regulators. Additionally, factors such as airspace complexity, aircraft technical performance, and different regional air traffic control systems can complicate the implementation of CDOs in diverse operational environments. Overcoming these challenges requires both technological advancements and collaborative efforts to standardize practices and ensure safety, efficiency, and sustainability in the adoption process. The findings also highlight critical implications for policy and practice in advancing CDOs. Governments and aviation regulators should integrate CDOs into national ATM strategies and provide incentives to encourage their adoption. Furthermore, the aviation industry should prioritize investment in the technologies and systems necessary to enable the seamless adoption of CDOs, such as advanced ATM tools and real-time flight trajectory optimization systems. For example, GNSS can facilitate precise and continuous descents, optimize flight paths, improve airspace utilization, and ensure seamless coordination between aircraft

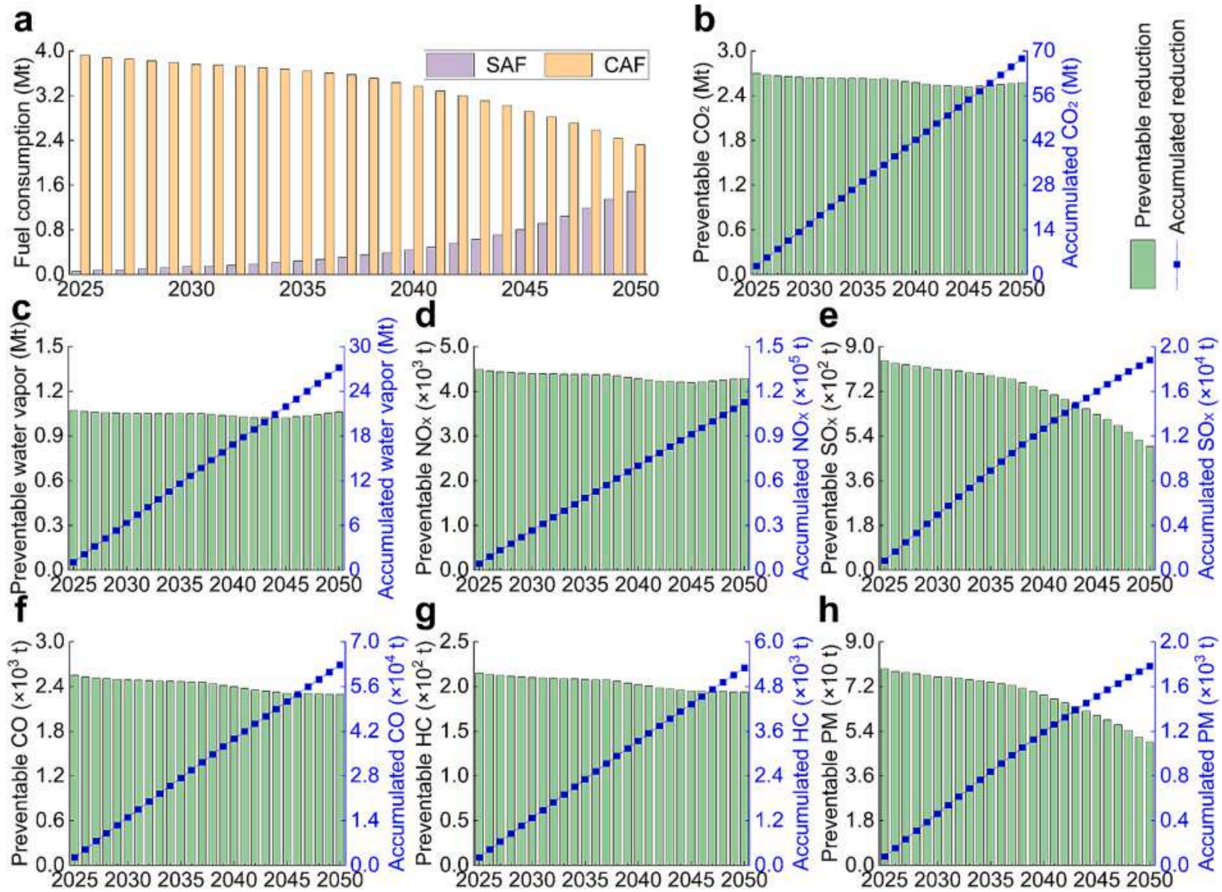

Fig. 8. Projected fuel consumption and emission reductions with the adoption of CDOs from 2025 to 2050. a: expected fuel consumption for the step-down approach; b: CO_2 reduction; c: water vapor reduction; d: NO_x reduction; e: SO_x reduction; f: CO reduction; g: HC reduction; h: PM reduction.

and air traffic control systems [76,77]. Predictive algorithms able to forecast air traffic flow and airspace congestion [78,79] are another tool to enable proactive management and dynamic descent adjustments to ensure smooth operations, reduce delays, and minimize fuel use and emissions. Point-merge operations can also complement CDOs by using predefined lateral paths to sequence aircraft efficiently, reducing the need for holding patterns or level-offs. This structured flow enables smoother transitions into continuous descent profiles, even in congested airspaces. Furthermore, pilot training and operational adjustments are necessary to accommodate the unique demands of CDOs. Adverse weather conditions and airspace congestion present additional hurdles that require the development of adaptive ATM systems capable of real-time adjustments. Policymakers should promote the overcoming of these barriers by fostering stakeholder cooperation and providing financial resources. Such initiatives will not only facilitate the adoption of CDOs but also establish a blueprint for sustainable aviation practices.

7. Conclusions and future research

This study highlights the significant environmental and operational benefits of using CDOs as a strategy to promote sustainable aviation. The results demonstrate that applying CDOs can reduce fuel consumption by 21.5 % per flight, leading to a substantial reduction in CO_2 and other aircraft pollutant emissions. From a long-term perspective, our projections indicate that the national adoption of CDOs in China from 2025 to 2050 could result in a cumulative CO_2 reduction of 67.6 Mt., corresponding to annual savings of approximately 2.6 Mt. per year. This makes these procedures a key tool for contributing to achieving the aviation industry's commitments toward carbon neutrality. The results of this study provide a strong basis for policymakers to support the global adoption of CDOs, which offer not only environmental but also economic advantages. Reducing fuel consumption indeed not only lowers the carbon footprint of aviation but also creates cost savings for airlines, ultimately contributing to the economic sustainability of this kind of measure in the long term. Furthermore, the improvements in air quality around airports, driven by reductions in local emissions, underscore the broader public health benefits of CDO adoption.

While this study offers a solid foundation for understanding the potential of CDOs, several areas deserve to be further investigated. Future studies could analyze the operational challenges and safety considerations associated with CDOs, particularly in complex airspace environments or during adverse weather conditions. Additionally, further research into the long-term effects of CDOs on ATM procedures and airport capacity would be valuable for comprehending the broader implications of CDO adoption. Exploring the integration of CDOs with other emerging technologies, such as automated flight systems, could provide additional insights into how these procedures can contribute to the decarbonization of aviation. Future works could also focus on refining the methods for assessing and optimizing CDOs' impact. This includes analyzing more airports and diverse operational conditions, as well as developing more advanced modeling techniques to predict the performance of CDOs under varying traffic and weather scenarios. Finally, exploring the environmental and economic impacts of CDOs at the global scale, including both fuel cost savings and pollutant reductions, will be crucial for guiding investment decisions and ensuring the successful scaling of CDOs.

In conclusion, while there are still technological and organizational challenges to overcome, this paper demonstrates that the implementation of CDOs represents a promising measure toward achieving the sustainability targets of the aviation industry. As the aviation industry continues to grow and face increasing pressure to reduce its environmental impact, CDOs constitute an effective and scalable solution that can deliver significant benefits in terms of fuel savings, emission reductions, and operational efficiency. Continued research and investment in enabling technologies and systems will be key to realizing the full potential of CDOs strengthening the aviation industry's sustainability credentials.

CRediT authorship contribution statement

Dabin Xue: Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Sen Du:** Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Bing Wang:** Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Wen-Long Shang:** Writing – original draft, Visualization, Validation, Investigation, Data curation. **Nicolò Avogadro:** Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Washington Yotto Ochieng:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

Appendix A. Appendix

Table A1
Comprehensive details regarding aircraft and engine types.

Aircraft		Engine	ID
A20N	A320-271 N	PW1127G	15PW104
A21N	A321-251 N	LEAP-1A35A/33/33B2/32/30	01P20CM132
A319	A319–131	V2522-A5	3IA006
A320	A320–231	V2500-A1	1IA001
A321	A321–111	CFM56-5B1	2CM012
A332	A330–243	Trent 772	2RR023
A333	A330–301	CF6-80E1A2	1GE033
A388	A380–841	Trent 970–84	01P18RR103
B737	B737–700	CFM56-7B24	3CM032
B738	B737–800	CFM56-7B26	8CM051
B744	B747–400	CF6-80C2B1F	1GE024
B77L	B777-200LR	GE90-110B1	01P21GE216
B77W	B777-300ER	GE90-115B	01P21GE217
B788	B787–8	Trent 1000-A	12RR055
B789	B787–9	Trent 1000-J2	12RR067
E190	ERJ 190–100 IGW	CF34-10E6	10GE131

Table A2
Detailed values of the ratio of the increase in flight volume compared to 2024 levels (a), the ratio of the reduction in fuel consumption due to technology developments (b), the ratio of the reduction in fuel consumption from operational and infrastructural improvements (c), the ratio of the reduction in fuel consumption achieved through offsetting investments (d), and the expected SAFs usage (e).

Year	a	b	c	d	e
2025	1.031	0	0.006	0.040	0.015
2026	1.063	0	0.007	0.075	0.020
2027	1.096	0	0.008	0.106	0.022
2028	1.130	0	0.009	0.135	0.026
2029	1.165	0	0.010	0.163	0.031
2030	1.201	0	0.011	0.189	0.037
2031	1.239	0	0.012	0.214	0.037
2032	1.279	0	0.013	0.238	0.042
2033	1.320	0	0.014	0.263	0.048
2034	1.362	0	0.015	0.285	0.054
2035	1.406	0	0.016	0.307	0.062
2036	1.451	0	0.017	0.329	0.070
2037	1.497	0	0.018	0.348	0.079
2038	1.545	0.009	0.019	0.366	0.090
2039	1.595	0.019	0.020	0.384	0.102
2040	1.646	0.028	0.021	0.400	0.115
2041	1.697	0.041	0.022	0.414	0.131
2042	1.749	0.049	0.023	0.430	0.148
2043	1.804	0.056	0.024	0.444	0.168
2044	1.859	0.065	0.025	0.456	0.191
2045	1.917	0.077	0.026	0.467	0.216
2046	1.977	0.088	0.027	0.474	0.245
2047	2.038	0.095	0.028	0.483	0.278

(*continued on next page*)

Table A2 (*continued*)

Year	a	b	c	d	e
2048	2.101	0.104	0.029	0.491	0.315
2049	2.166	0.114	0.030	0.498	0.357
2050	2.233	0.125	0.031	0.504	0.390

Data availability

Data will be made available on request.

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