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Vertical and Horizontal Flight (In)Efficiency and Optimisation of Flight Trajectories – A Literature Review

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Review
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ABSTRACT

A review of recent academic and professional literature on flight efficiency reveals that vertical and horizontal inefficiencies persist as significant challenges to the performance and sustainability of the air traffic management (ATM) system. While these inefficiencies have been widely studied, there remains a lack of comprehensive insight into their full range of impacts, as well as the underlying factors that hinder effective optimisation efforts across different operational contexts. To address this gap, this study examines and synthesises the current body of research related to vertical and horizontal flight (in)efficiency. The review synthesises findings from diverse sources, identifying recurring themes such as fuel consumption, environmental impact, monetary effects, ATM operational constraints and trajectory optimisation strategies. Additionally, the analysis underscores key differences in methodological approaches and thematic priorities between vertical and horizontal efficiency studies. The results contribute to a more holistic understanding of flight (in)efficiency and aim to inform the future development of integrated, context-sensitive models that can improve operational efficiency and support the sustainable evolution of the ATM system.

KEYWORDS
air traffic management; vertical flight efficiency; horizontal flight efficiency.

1. INTRODUCTION

Flight efficiency has become a central topic of research within the domain of air traffic management (ATM) on a global scale [1-3]. In the European context, the fragmented nature of ATM service provision has been identified as a significant contributor to operational inefficiencies in flight trajectories [4]. The concept of flight efficiency is inherently complex and remains without a universally accepted definition. As noted by Fuller et al. [5], flight efficiency is a broad construct subject to varying interpretations, with perceptions differing across aviation stakeholders. In this regard, only air navigation service providers (ANSPs) may approach flight efficiency from a comprehensive, system-wide perspective. An alternative definition, presented in [6], frames flight efficiency as the discrepancy between actual and optimal, unobstructed aircraft trajectories, assessed from gate to gate. Such deviations are associated with increased flight time, fuel consumption and operational expenditures. Moreover, additional fuel burn due to inefficiencies carries substantial environmental implications, primarily through elevated carbon dioxide (CO_2) emissions.

From a performance monitoring and regulatory perspective, the International Civil Aviation Organization (ICAO) has defined key performance indicators (KPIs) for flight efficiency within the framework of the Global Air Navigation Plan (GANP) [7]. The GANP offers strategic guidance for the development of the global ATM system and is aligned with both the Global Air Traffic Management Operational Concept (GATMOC) [8] and the Manual on Air Traffic Management System Requirements (Doc 9882) [9]. Of the eleven key performance areas (KPAs) identified, the efficiency KPA is directly relevant to this field of research. It includes four specific KPIs: two concerning horizontal flight segments, namely the comparison between planned en-route distance and an ideal reference trajectory, and the comparison between actual en-route distance flown and the ideal trajectory; and two concerning vertical flight segments, specifically the occurrence of level-offs during climb and during descent. ICAO's performance-based methodology, outlined in the Manual on Global Performance of the Air Navigation System [10], promotes a structured process involving the assessment of current performance, identification of operational deficiencies and the formulation of improvement targets. These indicators are vital for monitoring ATM system performance and support data-informed decision-making, strategic prioritisation and efficient resource allocation, while ensuring the preservation of safety standards [11].

At the regional level, specifically within Europe, enhancing the efficiency of ATM is a central objective of the Single European Sky (SES) initiative. Regulation (EC) No. 549/2004, adopted by the European Parliament and the Council of the European Union, established the foundational legal framework for SES [12]. As part of the second legislative package, the Performance Scheme was introduced through Regulation (EU) No. 691/2010, which set out key performance indicators (KPIs) for monitoring and improving ATM performance [13]. These measures were further refined by Regulation (EU) No. 390/2013 [14], with an emphasis on environmental performance and the facilitation of localised performance monitoring. Commission Implementing Regulation (EU) 2019/317 [15] further defines flight efficiency as a core component of ATM performance within the SES framework. It introduces specific KPIs for setting performance targets and monitoring within the KPA of "environment," applicable at both the Union-wide and local levels. For the horizontal flight dimension, the regulation defines the KPI average horizontal en-route flight efficiency of the actual trajectory (KEA). In addition, it establishes two supporting indicators for monitoring: horizontal en-route flight efficiency of the last filed flight plan trajectory (KEP) and horizontal en-route flight efficiency of the shortest constrained trajectory (KES). These indicators are applied at both the local level and within functional airspace blocks. With respect to the vertical dimension, the regulation introduces the monitoring indicator vertical flight efficiency of the actual trajectory between the top of climb and the top of descent, which is defined at both Union-wide and local levels. At the local level, additional monitoring indicators are specified, namely vertical flight efficiency of the descent and vertical flight efficiency of the climb. Within the institutional framework of the United States, the Federal Aviation Administration (FAA) employs [16] several indicators to evaluate flight efficiency. For vertical flight dimension, a primary metric is the distance at level flight – descent for jet arrivals at major airports, which quantifies the number of nautical miles flown in level segments between top-of-descent and touchdown. In terms of horizontal flight dimension, the FAA utilises metrics such as flown versus filed airborne time and the average distance flown between key city pairs, whereby deviations between actual and planned airborne time or distance serve as indicators of en-route efficiency performance.

This research paper aims to examine and synthesise recent scientific and professional literature concerning vertical and horizontal flight trajectory (in)efficiency. The primary objective is to conduct a thematic synthesis of existing studies by organising the literature into thematic areas that reflect the complexity and multidimensional character of the field. This thematic approach enables a more nuanced and integrative examination of the factors influencing vertical and horizontal flight efficiency across various phases of flight and operational environments, rather than treating them as entirely separate domains of research. Ultimately, the findings are intended to support the development of integrated, scenario-specific models that enhance operational performance and contribute to the long-term sustainability of the ATM system.

2. CONCEPTUAL BACKGROUND

According to Peeters et al. [17], horizontal flight efficiency (HFE), together with vertical flight efficiency (VFE), represents one of the two primary research domains within the broader field of flight efficiency. As defined by the Performance Review Commission [18], HFE is fundamentally described as a comparison between the actual trajectory length and the shortest possible distance between the origin and destination points. The achieved distance methodology, established by the Performance Review Commission [18-19], is widely employed to assess HFE. This approach calculates the average en-route additional distance relative to the achieved distance, which corresponds to a segment of the great circle distance between the arrival sequencing and metering area (ASMA) exit point of the departure airport and the ASMA entry point of the arrival airport (*Figure 1*). However, studies conducted by EUROCONTROL [20-21] have highlighted a key limitation of this methodology: it does not account for the optimal trajectory, as it overlooks meteorological conditions and the specific operational objectives of airspace users (AUs). In response to these limitations, EUROCONTROL has developed a complementary VFE indicator, which has been evaluated within the SESAR RP3 framework [22]. Similarly, scholars from the Federal Aviation Administration (FAA) have investigated the incorporation of wind data into the calculation of optimal trajectories [23]. European ANSPs are also actively engaged in enhancing the accuracy and representativeness of flight efficiency indicators. For instance, the UK's NATS has introduced the 3Di metric, designed to more accurately reflect the influence of ATM operations on fuel efficiency [24]. In a collaborative effort, BR&TE and CRIDA utilised real operational data to explore novel approaches for efficiency measurement, resulting in the proposal of an enhanced indicator by Calvo et al. that better captures fuel consumption dynamics [25]. Furthermore, several studies have contributed to the conceptual foundation and advancement of HFE metrics. Notably, López Leones et al. [26] proposed a comprehensive set of advanced, user-centric, cost-based efficiency and equity indicators. These indicators address multiple dimensions of efficiency, including horizontal and vertical performance, fuel consumption and flight cost, thereby integrating the perspective of airspace users into the evaluation process. The following operational concepts were not originally designed with flight efficiency as their primary objective, however, by enhancing safety, capacity, predictability and airspace flexibility, they frequently generate indirect improvements in both HFE and VFE. One such concept is performance based navigation (PBN). As generally defined in ICAO Doc 9613 [27], PBN is a navigation framework based on specified aircraft performance requirements for operations along air traffic services (ATS) routes, instrument approach procedures, or within designated airspace. It enables greater navigational accuracy, allowing for shorter and more direct routes, as well as safer and more efficient departures and arrivals. Another significant initiative is the flexible use of airspace (FUA) [28], which redefines airspace management by treating airspace as a single continuum rather than strictly segregating it into civil or military domains. Under this concept, airspace is allocated based on user requirements, thereby supporting the use of more direct routes and optimal cruising altitudes, ultimately contributing to improved flight efficiency. Free route airspace (FRA) is also a key development aimed at addressing efficiency, capacity and environmental challenges in ATM. By permitting aircraft to plan and fly trajectories that are not constrained by predefined airways, FRA helps reduce fuel consumption and emissions while enhancing overall flight efficiency [19]. As noted in [29], a notable improvement resulting from FRA and related initiatives is the reduction in route extension, defined as the difference between the flown route and the corresponding segment of the great circle distance, from 3.58 percent in December 2007 to 1.59 percent in August 2024. Additionally, several other concepts have been recognised for their potential to improve flight efficiency. Trajectory based operations (TBO), for instance, centre around a mutual agreement between AUs and the ATM system regarding the trajectory to be followed by an aircraft. This agreement is designed to align with AU preferences, particularly regarding minimising fuel consumption, as explored by Enea and Porretta [30]. Further innovations include dynamic airspace configurations (DAC), studied by Hind et al. [31], and integrated network management [32]. From the perspective of the FAA, the time-based flow management (TBFM) system optimises air traffic sequencing using time-based metrics rather than distance, as discussed by Chittargi and Martin [33]. Furthermore, the implementation of NextGen RNAV and RNP procedures has contributed indirectly to enhanced flight efficiency, particularly within terminal manoeuvring areas (TMAs), as analysed by Krozel et al. in their capacity estimation research [34].

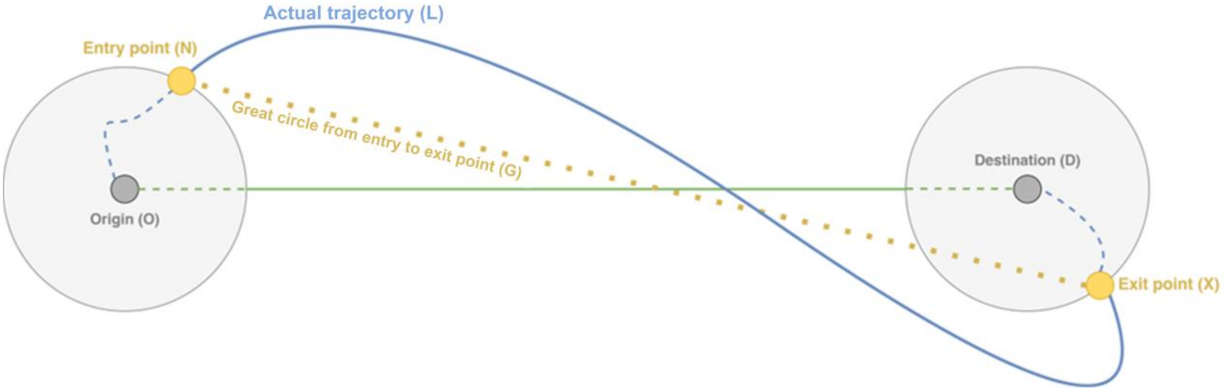

Figure 1 – The achieved distance methodology [19]

With regard to VFE, Peeters et al. [35] broadly define it as the extent to which the actual vertical flight profile aligns with the optimal vertical flight profile. The evaluation of VFE encompasses all flight phases, precisely climb, cruise and descent, each of which contributes differently to overall flight efficiency. In this context, EUROCONTROL's Performance Review Unit (PRU) has developed new performance indicators specifically targeting vertical flight efficiency [36]. The climb and descent phases are particularly critical due to their substantial altitude changes, which significantly influence fuel consumption and emissions. While the cruise phase is characterised by relatively stable altitude, climb and descent phases require dynamic altitude transitions that must be managed efficiently to minimise fuel burn and environmental impact. To address inefficiencies in these phases, continuous climb operations (CCO) and continuous descent operations (CDO) have been introduced as procedural solutions. According to ICAO Document 9993 [37], CCO (*Figure 2*) is defined as a flight operation technique supported by optimised airspace structure, standardised flight procedures and appropriate air traffic control (ATC) clearances.

As defined in [38], a normal descent refers to the flight phase in which the aircraft transitions from cruise altitude to either the initial approach fix (IAF) or the visual flight rules (VFR) pattern entry. This phase generally involves a progressive reduction in altitude in preparation for landing. According to ICAO Document 9931 [39], CDOs (*Figure 2*) are an aircraft trajectory management technique enabled by appropriate airspace design, standardised flight procedures and supportive ATC clearances. CDOs facilitate optimised descent profiles that employ low engine thrust and minimal aerodynamic drag, thereby reducing both fuel consumption and emissions. Extensive research has demonstrated the environmental and operational benefits of implementing CDOs. On the FAA side, Clarke et al. [40] analysed the implementation of optimised profile descent (OPD) procedures at Los Angeles International Airport. Similar to CDO, OPD represents an optimised vertical descent profile that allows aircraft to descend from cruise altitude using idle or near-idle thrust settings until reaching the vicinity of the landing runway.

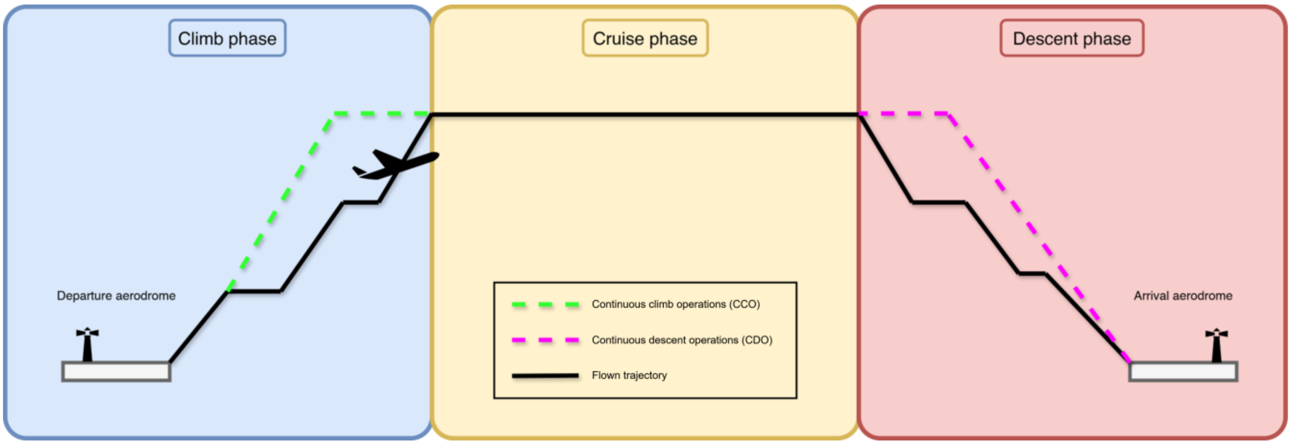

Figure 2 – Continuous descent operations and continuous climb operations concept

3. THEMATIC REVIEW OF RESEARCH AREA

Horizontal and vertical flight trajectories have been a subject of academic and operational interest since the earliest stages of aviation development. Researchers and practitioners have long recognised the critical role that trajectory optimisation plays in enhancing flight performance, safety and efficiency. Foundational studies such as those by Beaumont from 1943 [41] and David from 1944 [42] provide important context regarding the evolution of commercial aviation and the early challenges associated with efficient route design. An illustrative historical perspective is provided by Mason from 1936 [43], who noted: "The extension of air-routes throughout the world has been mainly due to private enterprise and individual daring. But such enterprise can only be fully effective if all countries are sympathetic to intercourse by air. When therefore we see on such a map the lack of modern communications across the northern frontiers of India, we have to take into consideration the political factor as well as the physical barrier." This early reflection underscores the enduring impact of political and geographic constraints on air route development, a theme that continues to influence contemporary airspace management and flight efficiency. Within this thematic review, the existing body of research is organised into several key domains: operational application and optimisation; environmental and economic impacts; capacity and system constraints; data, modelling and technology use; and strategic and geopolitical influences. These categories provide a structured framework for evaluating current knowledge and identifying areas for further research.

3.1 Operational application and optimisation

One of the most extensively studied segments within VFE research refers to the implementation and implications of CDO and CCO. Regarding operational application, Warren and Tong [44] investigated the potential of CDO procedures to mitigate the environmental and noise impacts associated with conventional aircraft approaches. They proposed a phased implementation strategy, categorised into near-term, mid-term and advanced stages, based on the progressive integration of flight management system (FMS) capabilities and ground-based automation systems. The environmental and economic impact of CDO implementation was further analysed by Wilson and Hafner [45] in a case study at Hartsfield-Jackson Atlanta International Airport, where annual fuel savings of approximately $30 million were reported. In a complementary study, Weitz et al. [46] evaluated the integration of airborne precision spacing (APS) with CDOs. Their findings indicated that APS could significantly improve aircraft spacing accuracy during CDO, although its effectiveness was contingent on the accuracy of trajectory prediction models. In addition, Toratani et al. [47] explored the potential to extend the temporal applicability of CDOs at Kansai International Airport in Japan. Using real-time simulations, the authors have developed optimised CDO procedures and vertical profiles. Their findings indicated that steeper descent paths generally yield greater efficiency, whereas shallower paths enhance aircraft controllability, highlighting the need to balance efficiency and operational manageability when designing vertical descent trajectories. Reynolds et al. [48] explored noise abatement strategies within UK airspace, emphasising CDOs as a central technique. Their work analysed trade-offs between environmental outcomes and operational flexibility, utilising modelling tools to assess noise levels, emissions, fuel burn and runway throughput. In a similar operational context, Tong et al. [49] developed CDO procedures designed for medium to high traffic volumes, specifically for simultaneous independent dual-runway operations at George Bush Intercontinental Airport. Their procedure, which spans from cruise altitude to instrument landing system (ILS) intercept, utilises low-thrust descents along a 2° flight path angle with staggered glideslope intercept altitudes to maintain vertical separation during parallel approaches. In relation to CCO integration, Pérez-Castán et al. [50] introduced a conflict-detection tool for ATC, based on the blocking-area concept, to assess the safe integration of CCOs within terminal airspace. By simulating 105 departure and arrival trajectories using both static and dynamic conflict analysis, they applied the tool to Palma terminal manoeuvring area (TMA) and confirmed the feasibility of integrating CCOs without compromising safety. Additionally, Errico and Di Vito [51] developed and validated a model for generating curved, continuous vertical descent profiles using the point merge (PM) system to support CDOs in TMAs. Their approach aimed to minimise level flight segments and improve arrival sequencing, with the goal of reducing fuel consumption, emissions and noise. Recent studies have emphasised the importance of both compliance with and deviations from CCO procedures. For instance, the International Federation of Air Traffic Controllers' Associations (IFATCA) [52] outlined the operational and environmental benefits of systematic CCO implementation, including reductions in flight delays, fuel usage and emissions. Additionally, compliance with CCO procedures has been further examined in empirical studies by Mori [53] and by Pasutto et al. [54], highlighting its relevance for enhancing VFE.

In the context of vertical optimisation during the en route phase, Park and Clarke [55] investigated vertical trajectory optimisation during en-route descent under the influence of altitude-dependent along-track and crosswind components. The authors formulated the problem as an optimal control task with operational and physical constraints, aiming to minimise both fuel consumption and emissions. The proposed method demonstrated close agreement with numerically derived optimal solutions. Their analysis also examined wind effects on vertical profiles for both the Boeing 737-500 and Boeing 767-400 aircraft types. Building on this work, Park et al. [56] developed a methodology for generating optimal trajectory option sets to facilitate in-flight trajectory negotiations during the climb and descent phases. Their approach identifies both user-preferred and alternative trajectories by analysing the structure of singular and boundary arcs, while incorporating aircraft performance constraints and flight dynamics. A general challenge with flight efficiency optimisation is the computational complexity of real-time optimisation of four-dimensional trajectories. This is further complicated by the limited availability of aircraft-specific parameters such as actual take-off mass and cost index, which are often absent from publicly accessible data sources [57]. In addition, Robinson and Kamgarpour [58] highlight that variability in observed fuel savings introduces further uncertainty into optimisation efforts, reinforcing the need for robust modelling techniques and accurate data inputs.

In contrast to VFE research, studies on HFE primarily examine deviations of actual flight trajectories from optimal or planned routes, with a particular focus on the en route phase. Dobruszkes and Peeters [59] conducted a global analysis of flight detours by comparing actual flight paths to great-circle distances, using a dataset comprising over 390,000 commercial flights. Their findings revealed that actual trajectories were, on average, 7.6 percent longer than the shortest possible route, with relatively greater detours observed in short-haul operations. Further contributing to this field, Dobruszkes authored a review article titled "Why do planes not fly the shortest routes? A review" [60], which outlines the interplay of technical, geopolitical and natural constraints underlying flight deviations. The review emphasises the heterogeneous nature of these detours and the varying degrees to which they may be avoidable. Advancements in data-driven trajectory prediction are exemplified by Schimpf et al. [61], who proposed a generalised deep learning framework for four-dimensional aircraft trajectory prediction. Their approach employs hybrid recurrent neural networks, integrating diverse meteorological data and flight plan information to improve prediction accuracy across various routes and time periods. From an optimisation perspective, Ng et al. [62] developed a practical algorithm that minimises both flight time and fuel consumption by integrating wind-optimal horizontal routing with fuel-optimal vertical profiling. Their method employs dynamic programming in combination with aircraft performance modelling based on BADA data and was applied to FedEx and UPS cargo flights operating between Anchorage and major airports. The results demonstrated fuel savings of up to 3 percent for domestic and up to 10 percent for international flights, with efficiency gains increasing with trip length, prevailing wind conditions and aircraft type. Additionally, Rosenow et al. [63] utilised the TOMATO simulation environment to evaluate multi-criteria optimised four-dimensional trajectories within European airspace. Their findings suggest that such optimised trajectories improve aircraft distribution and reduce air traffic controller workload. However, they also noted a potential increase in airspace complexity due to the greater variability of flight paths, thereby underscoring the need for adaptive airspace design and dynamic sectorisation strategies. Scenario specific optimisation has similarly been identified as a key consideration in HFE research. Durand et al. [64] stressed the importance of integrating conflict resolution tools to improve airspace safety and efficiency, particularly in complex traffic environments. Complementing this approach, Ghazi et al. [65] proposed a comprehensive methodology that includes all phases of flight, i.e. departure, cruise and arrival, allowing for a more complete and consistent assessment of flight efficiency. It is also important to view flight efficiency through the lens of different stakeholders. Airspace users prioritise fuel cost, route charges and schedule adherence, so an "optimal" trajectory is often the most cost-efficient one. ANSPs, on the other hand, focus on safety, capacity, predictability and equitable access at the network level. Consequently, AU optimal routes are not always aligned with ANSP optimal solutions, leading to trade-offs in busy or limited capacity airspace where efficiency must be balanced with fairness, workload and resilience.

3.2 Environmental and economic impacts

The environmental and economic impacts of flight inefficiencies have been extensively addressed within both VFE and HFE research domains [66-67]. In the vertical domain, procedure-based optimisation, particularly through the implementation of CDO, has been consistently linked to significant reductions in fuel consumption and greenhouse gas emissions. Turgut and Usanmaz [68], for example, analysed the effects of CDO procedures with varying flight path angles on fuel usage, nitrogen oxide (NOx) emissions and descent duration. Their findings revealed a strong inverse correlation between flight path angle and both fuel consumption and NOx emissions, primarily due to lower engine thrust and reduced exhaust gas temperatures. McConnachie et al. [69] reported that potential fuel savings per descent can range from 6 to 19 kilograms, contributing to significant annual reductions in CO_2 emissions. At high-traffic airports, this can equate to approximately 5,000 kilograms of CO_2 saved per flight, underscoring the substantial environmental and economic advantages of efficient descent procedures. Further studies by Fricke et al. [70], as well as Wubben and Busink [71], have shown that CDOs can reduce fuel consumption by 25% to 40% compared to traditional descent procedures. In relation to aircraft noise near airports, Thoma et al. [72] examined various approach procedures, including CDO, and found that noise and emission outcomes are highly sensitive to specific flight parameters. Their study highlighted a trade-off in which noise reductions near the airport vicinity often correspond to increased noise exposure at locations further away and vice versa. The benefits of optimising horizontal and vertical trajectories have been well documented in contemporary literature. These benefits include reductions in fuel consumption, emissions, noise exposure and flight time, contributing to more sustainable and cost-effective operations [73-74]. Despite these potential advantages, practical implementation remains constrained by several challenges.

The economic implications of flight efficiency improvements have also been explored in the context of vertical procedures. Xu et al. [75] have proposed a method for the economic evaluation of CCO, utilising aircraft performance data to estimate fuel and time costs based on a cost index (CI). Their results have demonstrated that CCO procedures offer substantial economic benefits compared to conventional climb profiles, primarily through reduced fuel consumption and time savings. Levy and Bassett [76] investigated the economic implications of inefficient level flight segments and recommended prioritising implementation at airports where the highest potential benefits can be achieved. Their findings indicated that airports in the New York City area, due to their high traffic volumes, are especially well-suited for targeted implementation. From an environmental perspective, Olive et al. [77] conducted a study aimed at quantifying environmental inefficiencies within TMAs for arriving aircraft. Using data from the OpenSky Network [78], they identified arrival procedures, point merge implementations and holding patterns. The OpenAP model [79] was applied to estimate fuel consumption and emissions based on flight trajectory data. Olive et al. introduced a novel methodology for evaluating inefficiencies in standard arrival procedures across five major European airports, enabling a comparative assessment of environmental performance. Additional studies have further examined the environmental impacts of aviation operations. For instance, [80] approached the issue from a trajectory optimisation perspective, while [81] evaluated descent procedures in TMAs using flight time as a proxy for vertical efficiency. In the context of congestion-related inefficiencies, [82] investigated the environmental effects of traffic delays at London Heathrow Airport, and [83] provided a broader analysis of fuel and operational inefficiencies across various airport environments. While the point merge system has been developed with operational performance as a primary objective, relatively few studies have focused specifically on its emission performance. Addressing this gap, Villegas Díaz et al. [84] analysed the environmental benefits of optimising CDO. Using real flight data recorder (FDR) inputs and simulated trajectories generated through the Chebyshev–Gauss–Lobatto pseudospectral method, the authors demonstrated the importance of optimising, rather than merely implementing, continuous descent profiles to maximise environmental benefits. Furthermore, Andraši et al. [85] evaluated the operational and environmental outcomes of implementing the continuous descent approach (CDA) in comparison to traditional step-down descent procedures at Split Airport. Their study provided empirical evidence of the benefits of CDA in reducing fuel burn and environmental impact in real-world operational settings.

Similar findings have been reported in studies related to HFE. Wind-optimal routing algorithms developed by Patrón et al. [86] and Murrieta-Mendoza et al. [87] have demonstrated fuel and cost savings ranging from 5 to 16 percent, contingent upon factors such as flight distance, prevailing wind conditions and specific aircraft performance characteristics. When considered across high traffic volumes, en-route inefficiencies can lead to significant cumulative costs for airspace users, underscoring the importance of trajectory optimisation in achieving both economic and environmental benefits. With the objective of minimising total fuel consumption, Hartjes et al. [88] studied the long-haul flight fuel efficiency of commercial aircraft formations and analysed the impact of wind field on the performance. On that front, in a recent study by Liu et al. [89], the authors developed a runway-to-runway 4D trajectory optimisation model to evaluate fuel saving potential in a TBO environment, considering travel time constraints, routing options and sector capacity limitations. Using the Shanghai–Beijing route as a case study, they assessed fuel efficiency under capacity constrained scenarios with fixed and flexible routes. Results showed clear trade-offs between flight time, distance and fuel burn, and demonstrated that airspace congestion reduces fuel saving potential, while flexible routing increases optimisation capability. They suggest expanding the approach to network-wide analysis and including additional operational factors such as weather and airport capacity in future work. In terms of horizontal dimension, Lovegren and Hansman [90] investigated the fuel-saving potential of optimising cruise speed and altitude profiles as a means to improve environmental performance in aviation operations. They analysed 257 U.S. domestic flights, using Piano-X aircraft performance data and NOAA atmospheric data to calculate actual cruise fuel burn and to generate optimised profiles, including optimal cruise climbs, step climbs (1000/2000 ft) and optimal/LRC speed schedules. Their results indicated that up to 3.5% cruise fuel savings (2.6% system-wide) could be achieved through full optimisation, with speed optimisation offering greater benefit than altitude optimisation. On that front, Delgado and Prats [91] analysed how cruise speed variations affect fuel consumption in conventional commercial aircraft. They examined the relationship between fuel burn and key operational parameters such as cost index, aircraft weight, optimal flight levels and flight length, and evaluated this through two example flight cases. Their results showed that reducing cruise speed can save fuel depending on cost index settings, typically up to ~7% for standard European flights, and up to 15% under high CI values, indicating that cruise speed management could serve as an efficient alternative to delay absorption strategies like holdings or rerouting.

3.3 Capacity and system constraints

While flight efficiency improvements are technically feasible, their operational realisation is bounded by a range of strategic and tactical constraints that span the airport, airspace and network levels. Strategic constraints include airspace design, regulatory structures, sectorisation and military restrictions, while tactical constraints arise from traffic interactions, air traffic control officer (ATCO) workload and conflict resolution requirements. Understanding the interplay between these constraints is critical to explain why high efficiency trajectories are not always feasible in day-to-day operations, even when optimal solutions exist theoretically. At the airport level, a central challenge is the trade-off between flight efficiency and runway throughput. Sequencing and merging are fundamentally a tactical activity, where ATCOs react dynamically to the evolution of traffic to safely organise aircraft in sequence for landing.

European CCO/CDO task force in [92] noted that the traditional way of ensuring that runway throughput is maintained is to use racetrack holding patterns near the airport. A side effect of traditional racetrack holding patterns is that all arrivals in a holding pattern have no lateral separation and therefore need to be separated vertically by ATC through tactical clearances. Typically, aircraft will be cleared for descent 1,000 ft at a time, with each aircraft in the holding pattern being cleared to descend when the aircraft holding below has vacated the corresponding level. Moreover, European CDO/CCO task force notes that parallel runway operations can significantly constrain the implementation of fully optimised CDOs [92]. While CDOs are generally feasible during dependent parallel operations, independent parallel approaches often necessitate high-side/low-side configurations, which limit continuous descent. According to ICAO Doc 4444 [93], independent parallel approaches require aircraft to intercept the final approach track at ≤30°, include at least 1,900 m of straight and level flight before intercept, and be established in level flight for at least 3,700 m prior to glide path capture. These design requirements typically introduce a level segment near the final approach, reducing vertical efficiency. Moreover, ICAO separation minima [93] mandate 300 m vertical or 5,600 m radar separation until both aircraft are established on the localiser, which often forces one arrival to level off to maintain safe separation during simultaneous independent operations. On that front, Pérez-Castán et al. [94] demonstrated that achieving a CCO rate of 100 percent could lead to a 32 percent reduction in maximum theoretical airport capacity, highlighting the trade-off between environmental efficiency and throughput. Conversely, Sáez et al. [95] investigated the potential of enhancing support for CDOs by replacing conventional vectoring-based sequencing with required time of arrival (RTA)-based control along predefined arrival routes. Using both historical and simulated traffic data for Berlin-Schönefeld Airport in Germany, the study showed that assigning RTAs and fixed routes maintained safe separations, thus enabling environmentally efficient operations without compromising capacity. Additionally, ATCOs workload has been identified as a major limiting factor, particularly in high-density or mixed-operation airspace. On that regard, Efthymiou et al. [96] highlighted that the complexity introduced by CDO procedures may significantly increase controller workload, posing challenges for routine implementation. From a systemic perspective, Vempati [97] examined the influence of traffic volume and weather-related constraints on the feasibility of executing CCOs and CDOs. A case study focused on operations in the Houston area revealed that elevated traffic levels, whether due to congestion or adverse weather, substantially reduced the likelihood of flights executing CCO and CDO. In the context of VFE, Rosenow et al. [98] have identified the complexity of procedure implementation and emphasized the need for a phased integration strategy to accommodate existing system constraints. Jin et al. [99] also emphasised the importance of tailoring procedures to local conditions. They advocated for region specific evaluations and simulations to ensure practical feasibility and operational effectiveness. Moreover, network-level capacity measures can undermine local vertical efficiency improvements, highlighting the need to balance both strategically. For example, in [92] it is noted that limitations on achieving optimal cruising altitudes may result from strategic measures such as route availability document (RAD) constraints or network capacity initiatives, as well as tactical ATC interventions during flight. On that front, in European airspace, level-capping measures are frequently used to manage capacity, exemplified by the 4ACCs initiative [100], which introduced cross-border cruising level restrictions to reduce en-route delays. European CCO/CDO task force in [92] also notes that these constraints freed capacity in upper airspace but increased vertical inefficiencies for affected city pairs, illustrating a trade-off between capacity and fuel efficiency. Controllers may also restrict final cruising levels to prioritise traffic flows, sometimes leading to suboptimal profiles if further climb is not cleared when feasible. The effects vary across aircraft types; for instance, business jets are often more affected because their optimal flight levels are higher, and flying at lower capped levels significantly increases fuel burn. While level capping can indirectly reduce time spent in level segments during climb or descent, this does not reflect genuine efficiency gains, as flights cruise longer at less efficient altitudes.

Horizontal flight inefficiencies are heavily influenced by airspace fragmentation, regulatory constraints and the requirements of conflict resolution. Research by Nakamura and Kageyama [101] and Rosenow et al. [102] has shown that operational limitations such as sector boundaries, restricted military zones and rigid route structures frequently take precedence over wind-optimal or cost-optimal routing strategies. In Europe, these inefficiencies are often structural, stemming from fragmented national airspaces and legacy fixed routes. EUROCONTROL [103] reports that route extension due to airspace design remains a major contributor to horizontal inefficiency, particularly across FIR boundaries, and while free route airspace has mitigated some of these issues, transition zones between FRA and fixed-route structures remain inefficient. Beyond structural constraints, tactical ATC interventions during congestion or adverse weather often result in reroutings that lengthen trajectories [104]. These deviations can propagate through the network, creating secondary inefficiencies downstream. On the approach side, Jaekel, Hirte and Niemeier in [105] examined the approach efficiency in the TMA at four major European airports using horizontal flight inefficiency and vertical flight degree efficiency (VDE) metrics as well as multiple MM-type regressions to identify the determinants of inefficiency and gave out recommendations for increasing efficiency. The authors revealed a restriction of the study considering safety issues. Including the distance to neighbouring aircraft in our study would be an important extension of the study. The authors highlighted that expanding runway capacity may increase overall efficiency. To identify capacity limitations of ATC sectors among other things, Lazarovski [106] proposed and tested a new trajectory-based efficiency metric called partitioned efficiency indicator (PEI) that separates useful progress toward destination from lateral/vertical deviations, enabling deeper performance assessment, inter-area comparison and future 3D and emissions-based extensions. Building on the need to address capacity and flow constraints directly, another line of research introduced the enhanced demand and capacity balance (EDCB) model, which manages airspace congestion using traffic-volume capacity limits and alternative lateral/vertical trajectories that reflect airspace user preferences. The model applies a cost-based global optimisation (time, fuel, route charges) and, when tested in a 24-hour ECAC scenario, achieved ~70% delay reduction and ~11.7% cost savings compared to computer-assisted slot allocation (CASA), though fairness issues were identified for some flights. Future work aims to improve equity, incorporate uncertainty, and extend evaluation scope.

3.4 Data, modelling and technology use

Recent advancements in data availability and modelling capabilities have significantly influenced the evolution of flight efficiency research. For example, combining demand data repository (DDR2) planned trajectories with realised automatic dependent surveillance-broadcast (ADS-B) tracks allows for the systematic quantification of deviations between planned and actual trajectories, a crucial step for large-scale VFE/HFE benchmarking. More particularly, within the VFE domain, the use of high-resolution surveillance data sources, e.g. ADS-B and DDR2 has enabled more precise identification of level flight segments and enhanced the accuracy of fuel consumption assessments, as demonstrated in the study by Polishchuk et al. [107]. Recent research has moved beyond the use of single-source data toward multi-sensor fusion, integrating surveillance, meteorological and AU operational data to reconstruct trajectories with greater fidelity. For example, in [108] fusion of ADS-B data with Mode-S parameters enables the estimation of indicated airspeeds, Mach numbers and rate of climb with improved temporal resolution, thereby refining the detection of vertical inefficiencies and thrust regimes. When combined with meteorological reanalysis datasets, such as the fifth-generation ERA5 [109] reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF), which provides comprehensive coverage across European Civil Aviation Conference (ECAC) states, these approaches allow for the development of wind-adjusted performance baselines and support the generation of spatially resolved flight efficiency maps. Accurate estimation of fuel burn requires the integration of aircraft performance models, such as BADA, which was employed by Miller et al. [110] to evaluate performance-based metrics. However, several challenges persist, particularly related to the limited availability of aircraft-specific operational parameters in open-access datasets. Key variables such as actual aircraft mass, configuration and true air speed are often not recorded or disclosed, thereby constraining the accuracy of simulation outputs derived from performance models. For instance, variations in the assumed actual take-off mass (ATOM) can result in fuel burn discrepancies of up to 7 percent in aircraft trajectory simulations, as shown in [111].

On that front, a growing body of work explores hybrid modelling, combining data-driven machine learning (ML) with physics-based performance models to address gaps in available operational data. For instance, by assuming that actual flights follow quasi-fuel-optimal trajectories, the take-off mass of a flight can be estimated based on simple regression models trained on the optimal trajectory dataset as explored in research by Tassanbi et al. [112]. Similarly, hybrid trajectory prediction frameworks like the one presented in [113] that integrate ML models trained on historical surveillance data with physics-based estimation methods, such as residual-mean interacting multiple models (RM-IMM), can rapidly generate accurate short-term predictions for conflict detection, sequencing and scheduling. By leveraging data-driven forecasts as pseudo measurements within dynamic models, these approaches significantly improve prediction accuracy while remaining suitable for real-time air traffic control applications and improving flight efficiency. In recent years trajectory optimisation has seen a rapid growth due to artificial intelligence (AI) and ML, for example, the ATM-EXCITE project [114] supported by the SESAR 3 joint undertaking, aims to demonstrate the broad benefits of applying ML and AI within flight efficiency domain. For ATCOs, these technologies enable earlier detection of potential conflicts and facilitate more efficient tactical and strategic rerouting. For airlines, they offer the potential to reduce delays, lower fuel consumption and enhance overall cost efficiency. Passengers benefit from more reliable and smoother travel, while society gains through reduced environmental impacts. At the system-wide level, machine-learning-enhanced ATM trajectory optimisation improves safety, operational efficiency and coordination across both civil and military operations. On the ML front, Taguchi & Itoh in a study from 2025 [115] developed a hybrid optimisation model that integrates a neural-network–based fuel-consumption predictor with a genetic algorithm to generate fuel-optimal vertical climb trajectories. Their model evaluates climb profiles under operational constraints and identifies optimised trajectories for a Boeing 787, showing clear fuel-saving potential compared to standard climb procedures. Moreover, Gui et al. in [116] developed a data-driven trajectory optimisation model that uses Wasserstein-distance spectral clustering to learn patterns in historical trajectories, then generates candidate 4D paths and selects optimal, conflict-free trajectories through Pareto-based optimisation. Applied to the Guangzhou TMA, the model demonstrates significant operational benefits, including an estimated 30% increase in arrival capacity. Wind-aware and weather-responsive optimisation techniques, such as those proposed by Ghazi et al. [65] and Murrieta-Mendoza and Botez [117], have demonstrated the potential for significant fuel savings when environmental conditions are incorporated into route planning processes. Building on this, Chang et al. [118] introduced a multi-objective trajectory optimisation method grounded in optimal control theory. Their model incorporates wind force data obtained from an ensemble forecasting system [119], thereby enhancing the realism and responsiveness of the optimisation process. In addition, Liu et al. [120] investigated the causal relationships between en-route flight inefficiencies and a range of contributing factors. Their findings highlight the multifactorial nature of inefficiencies in the en-route phase. Despite these advancements, the real-time optimisation of flight trajectories under dynamic traffic and weather conditions remains a considerable operational challenge. As noted by Dalmau and Prats [121], the trajectory optimisation problem can be formulated as a multi-phase constrained optimal control problem, where a cost function is minimised while multiple constraints are imposed on the decision variables. This formulation reflects the inherent complexity of managing four-dimensional trajectories in real-world air traffic environments. Beyond traditional data and modelling tools, emerging digital infrastructure is reshaping flight efficiency analysis. The implementation of system wide information management (SWIM) facilitates real-time data exchange between ANSPs, AUs and meteorological providers, enabling trajectory predictions that incorporate updated intent and weather information [122]. Parallel to this, digital twins of airspace [123], virtual replicas of the operational environment updated in real-time are being developed to support what-if analyses, dynamic demand-capacity balancing and trajectory re-optimisation during flight. These technologies are expected to shift efficiency assessment from retrospective analysis toward continuous, predictive management of trajectory performance, opening new research pathways for both HFE and VFE optimisation in dynamic contexts.

Overall, the convergence of high-resolution surveillance data, performance models, meteorological datasets and advanced computational tools is laying the groundwork for fully integrated 4D trajectory management. However, operationalising these capabilities requires solving interoperability, data sharing and real-time computational challenges.

3.5 Strategic and geopolitical influences

Throughout its more than a century-long development, aviation has often been shaped by the need to bypass certain airspaces for political or safety reasons. One of the most notable examples of political reasons occurred during the Cold War, when Soviet airspace was largely inaccessible to foreign airlines. According to the 1944 Chicago Convention, overflight rights are negotiated bilaterally but generally guaranteed under Article 5, which obliges signatory states to permit the passage of foreign aircraft. However, since the Soviet Union did not sign the Convention, it retained the ability to deny such rights and, with only rare exceptions, prohibited non-Soviet carriers from traversing its territory for most of the Cold War period [124]. In a more operational sense, a flight from London to Tokyo would need to transit through Anchorage or a circuitous route through Dubai and Hong Kong. Flights from New York and Los Angeles to Tokyo also required a stop at Anchorage [125]. In recent times, literature increasingly recognises the significant role of strategic and geopolitical factors in shaping flight efficiency, particularly with respect to horizontal routing. Elements such as national airspace closures, military activity, underutilisation of available airspace, limitations in flexible airspace structures and the imposition of international sanctions have all contributed to persistent inefficiencies in horizontal flight trajectories. The impact of geopolitical disruptions on HFE was investigated by Majka et al. [126], who assessed the resulting increases in flight time, fuel consumption, carbon dioxide emissions and operating costs using established efficiency metrics [127–128]. Their analysis focused on the consequences of airspace avoidance resulting from the Belarusian airspace incident. Similarly, regarding the closure of Ukrainian and Russian conflict, studies by Chu et al. [129] and Ivannikova et al. [130] quantified the environmental and economic consequences of geopolitical disruptions, identifying substantial increases in flight path length, fuel burn and emissions on routes connecting Europe and Asia. At the broader, network-wide level, EUROCONTROL’s forecast for the period 2022–2028 [131] indicates that, following the closure of Russian and Ukrainian airspace to European carriers at the end of February 2022, a significant portion of traffic has been redirected along the south-eastern axis. Consequently, the volume of overflights has declined predominantly over the Baltic states, Scandinavian countries and Poland, while overflights have increased most notably across states in South-Eastern Europe. Airspace restrictions were further analysed by Ostroumov et al. [132], who estimated the effects of airspace closures by computing cumulative functions of affected areas based on trajectory deviations and changes in horizontal efficiency indices.

On a strategic level, Mihetec et al. [133] investigated the impact of transferring flexible airspace structures on flight efficiency. The authors developed a utilisation model that enables the dynamic allocation of flexible airspace structures between civil and military users. The model accounts for temporal, vertical and modular/sector-based dimensions of airspace organisation. Through scenario-based simulations, they demonstrated that the activation of flexible airspace structures leads to measurable inefficiencies in civil flight operations. However, by applying modular redesign strategies, these inefficiencies can be substantially reduced, by approximately 30% to 76% compared to the existing configuration.

4. DISCUSSION

The thematic synthesis presented in this review highlights the multifaceted nature of flight efficiency research and the diversity of methodological approaches employed across the vertical and horizontal domains. A critical observation is the extent to which VFE and HFE research have evolved along parallel yet largely disconnected trajectories. While both domains are driven by similar performance imperatives, particularly regarding reducing fuel consumption, emissions and operational costs, their respective research traditions, data sources and practical constraints have led to diverging focal points and conceptual models. Specifically, VFE research has predominantly concentrated on the development, simulation of effects and validation of procedural improvements such as CCO and CDO. These studies often rely on controlled simulations or localised case studies of specific flights, emphasising the procedural feasibility and environmental and monetary gains of optimised vertical profiles. In contrast, HFE research has gravitated towards strategic analysis at the global, as well as regional level, frequently employing optimisation algorithms, large-scale trajectory data and policy-focused assessments. The emphasis here is less on procedural compliance and more on structural and even geopolitical influences on routing efficiency. To summarise these diverse methodological approaches and highlight their respective advantages and limitations, *Table 1* provides a comparative overview of the principal methods identified in the literature. This synthesis underscores the absence of a single, universally accepted framework, while revealing both complementarities and gaps between vertical and horizontal efficiency assessment methods. While efficiency represents a central performance dimension in the studies reviewed, it cannot be pursued in isolation from other KPAs defined by ICAO and SES, particularly safety, capacity, predictability, flexibility and environmental performance. Improvements in VFE and HFE may introduce trade-offs, such as increased ATCO workload, reduced tactical flexibility or constraints on runway throughput, as demonstrated in several CCO/CDO and FRA studies. Conversely, safety-driven or capacity-driven measures, such as separation minimum, holding procedures or level-capping strategies, may intentionally reduce efficiency to preserve system resilience. Future research should therefore adopt a more integrated approach that examines efficiency not as a standalone objective but as one element within a multidimensional performance framework, where trade-offs and interdependencies with other KPAs are explicitly evaluated.

Table 1 – Comparative overview of methodologies for evaluating vertical and horizontal flight efficiency

Methodology / Indicator	**Dimension (VFE/HFE)**	**Flight phase / Scope**	**Data source**	**Metric / Calculation**	**Advantages**	**Limitations**	**Operational maturity**	**Key references**
Route extension / Achieved distance	HFE	En-route	DDR2, Flight plans, ADS-B	Additional distance compared to great circle or "achieved distance" (ASMA exit–entry points)	Simple, widely adopted by PRC/EUROCONTROL; good for large datasets	Ignores wind, airline preferences, ATC instructions	Operational	[18–21]
ICAO KPIs (GANP/SES/FAA)	VFE+HFE	Climb, descent, en-route	ANSP reporting, surveillance data	Level-offs in climb/descent; planned vs. actual vs. ideal en-route distance	Standardised, globally comparable, regulatory relevance	Coarse indicators; lack operational/airline perspective	Operational	[7–16]
NATS 3Di metric	HFE + VFE	Climb, descent, en-route	Radar tracks, ATC data	Composite index scoring efficiency of entire trajectory	Captures ATM influence; incentivises efficiency in operations	Proprietary; usage only in United Kingdom	Operational	[24]
Advanced KPI proposals (Calvo et al., López Leones et al.)	HFE + VFE	En-route, gate-to-gate	ADS-B, operational data	Cost-based, fuel-based and equity indicators	More user-centric; integrates airline perspective	Not standardised, limited application beyond case studies	Research	[25–26]
CDO analysis	VFE	Descent (TMA)	FDR, ADS-B, simulations	Number, duration and altitude of level segments; idle-thrust descent/climb profiles	Direct link to fuel/emission savings; well-documented in case studies	Implementation constrained by ATC workload, traffic density, airport capacity	Operational / Trialled	[39–40], [44–49]
CCO analysis	VFE	Climb (TMA)	FDR, ADS-B	Level segments, climb profile adherence	Fuel savings, procedural clarity	Capacity impacts; sequencing constraints	Operational / Trialled	[50], [52], [53]
Wind-optimal trajectory modelling	HFE + VFE	Climb, cruise descent	Meteorological data (e.g. ECMWF, NOAA) + BADA/OpenAP	Optimised trajectory length/time vs. actual flown	Captures operational realism; significant potential fuel/emission savings	Computationally intensive; results sensitive to input data accuracy	Research / Early trial	[62], [65], [86–87], [118]
Trajectory-based operations (4D-TBO) optimisation	HFE + VFE	Gate-to-gate	Integrated flight & ATM data	Optimisation of full 4D trajectory with time, altitude and lateral constraints	Holistic framework; aligns with SESAR & NextGen	Still under research; complex to implement operationally	Research	[30], [121]
ML / AI trajectory prediction	HFE + VFE	All phases	ADS-B + weather + flight plans	Predicted vs. observed trajectory efficiency	Handles large datasets, adaptive to uncertainties	Requires clean, large-scale datasets; limited interpretability	Research	[61], [114–117], [120]
Spatial / Network hotspot mapping	HFE + VFE	En-route, TMA	ADS-B, DDR2, GIS layers	Efficiency mapped spatially	Identifies systemic bottlenecks	Method still emerging	Research / Conceptual	[134]
Uncertainty quantification	HFE + VFE	All phases	Model + input distributions	Confidence intervals, sensitivity	Adds robustness and comparability	Largely absent in current practice	Conceptual	[111]

The rationale to structure the literature synthesis around five core thematic areas was driven by the need to capture the complexity and multi-dimensionality of flight efficiency research. Rather than segregating the literature strictly by vertical or horizontal domains, the approach in this research paper facilitates a more nuanced and integrative comparison of how various factors shape efficiency across different flight phases and operational contexts. Despite that, both research domains encounter similar systemic challenges which present important avenues for future investigation and advancement. The integration of real-time data, which is especially highlighted in European ATM Master Plan [135], the uncertainty associated with weather forecasts and the complexity of trajectory prediction remain persistent obstacles to operational implementation. Moreover, the literature reveals a lack of consensus on standardised efficiency metrics, particularly for HFE, where deviations may result from a multitude of confounding variables, including military airspace, route charges and temporary restrictions. This lack of harmonisation hinders meaningful cross-comparison of results and limits the generalisability of findings across different regions and ATM systems. Another research gap found in analysed studies is the limited integration of VFE and HFE within unified modelling frameworks. Despite the obvious operational interdependence between vertical and lateral trajectory planning, few studies have attempted to develop holistic trajectory optimisation models that incorporate both dimensions simultaneously. Given the emergence of four-dimensional trajectory-based operations (4D-TBO) as a cornerstone of next-generation ATM, this omission represents a critical research opportunity. Moreover, the development of integrated models capable of accounting for aircraft performance models, while incorporating real-time weather, traffic and system constraints, especially regarding VFE, should be prioritised in future research. Furthermore, regarding the real-world applicability, there is lack of integration and a clear gap between academic research and operational practice in domains of both VFE and HFE. Many simulation-based studies demonstrate significant potential benefits under idealised conditions; however, their transferability to real-world environments is frequently constrained by ATC capacity, airspace design and regulatory limitations. Bridging this gap will require collaborative research that engages ANSPs, airspace users, system developers and regulatory bodies. The granularity and availability of ADS-B data also present challenges, particularly when time intervals between data points affect the performance of estimation models and optimisation algorithms. Limited access to variables such as cost index and actual take-off mass further constrains model fidelity.

To address the limitations, future research should incorporate data-driven models, human-in-the-loop simulations, operational trials and phased implementation strategies to better align theoretical models with operational realities. The re-routing consequences of the Russo-Ukrainian conflict and other airspace closures demonstrate that trajectory efficiency is susceptible to abrupt, large-scale disruptions. Future models should incorporate scenario-based planning capabilities to assess the robustness of routing strategies under different geopolitical and regulatory conditions. Lastly, airline business models and operational priorities, often underrepresented in the literature, also influence efficiency outcomes. For instance, the pursuit of time savings over fuel savings or the preference for operational flexibility over adherence to optimal profiles can affect the implementation and effectiveness of efficiency measures. Incorporating behavioural and economic considerations, alongside emerging technologies such as AI, big data analytics and ML, has the potential to enhance the realism and policy relevance of future flight efficiency research. Interoperability has a critical role as well, particular emphasis must be placed on the harmonisation of procedures, the establishment of standardised data exchange protocols, particularly for TBO as well as real-time optimisation and the seamless integration of systems across ATM environments. These elements are fundamental to enabling consistent, scalable and cross-border improvements in flight efficiency, both within regional frameworks and across the global aviation system. Future research efforts should prioritise the development of holistic models for both the estimation and optimisation of flight efficiency, integrating meteorological conditions, real-world operational constraints and advanced aircraft performance modelling.

While substantial progress has been made in quantifying and modelling flight inefficiencies across vertical and horizontal dimensions, several avenues remain underexplored. A more integrative and interdisciplinary approach, one that accounts for technological, operational, environmental and political variables, is essential for advancing the state of the art in flight efficiency and supporting the long-term sustainability of ATM.

5. RESEARCH GAPS AND FUTURE DIRECTIONS

Beyond the established methodological and operational challenges discussed earlier, several additional observations emerge from a broader examination of the literature and current developments in ATM. These perspectives highlight areas that remain underexplored but are increasingly relevant to the future of flight efficiency research and policy. First, most existing studies approach flight efficiency as a static or aggregated metric, typically focusing on single year analyses or mean performance indicators. However, flight efficiency is inherently dynamic, influenced by day of operation meteorological variations, evolving traffic patterns and gradual regulatory or infrastructural changes such as the expansion of FRA. Longitudinal analyses can reveal temporal trends, such as recurring seasonal inefficiencies linked to jet streams or persistent inefficiencies during peak traffic periods, which are obscured in static assessments. Incorporating temporal dimensions into efficiency evaluations could therefore support more targeted interventions and policy measures. While several studies have explored advanced modelling techniques and AI-based trajectory prediction, relatively few explicitly address the transformative role of emerging digital infrastructure, such as SWIM, digital twins or real-time network management systems. These technologies are likely to shift efficiency from a post operational performance indicator to an operational, real-time, variable that can be continuously monitored and optimised during flight. This evolution calls for new metrics that are compatible with real-time decision making and adaptable to rapidly changing operational contexts. Current research often focuses on average efficiency values at the airport, sector or network scale, but seldom examines where inefficiencies occur within the air traffic network. Spatial analyses could identify systematic “hotspots” of vertical inefficiency, such as sector boundaries or TMAs with recurring level segments, as well as horizontal inefficiency clusters near military airspace or geopolitical borders. Mapping inefficiencies spatially using network analysis or geospatial methods would provide valuable insight into structural weaknesses of the ATM system and inform localised efficiency improvements. On the organisational front, flight efficiency is often treated as a purely technical phenomenon, but the behaviour of operational stakeholders plays a crucial role. Airlines and AUs may select suboptimal routes to minimise en-route charges or to align with scheduling priorities. ATCOs may grant shortcuts selectively based on familiarity, workload or local practices, while national regulatory cultures can influence the persistence of procedural inefficiencies. These behavioural and institutional dimensions are underrepresented in the literature and suggest the need for greater integration of human factors and organisational studies within efficiency research. Furthermore, future research should increasingly account for the divergence between airline-centric and ANSP-centric definitions of efficiency, moving toward models that balance cost, fuel, capacity and environmental objectives.

A further underexplored dimension is the trade-off between efficiency and resilience. Operational deviations from optimal trajectories are sometimes deliberate, serving to maintain safety or continuity in the face of disruptions such as adverse weather, airspace closures or ATC strikes. For example, horizontal inefficiencies resulting from conflict-related rerouting may represent necessary resilience measures rather than performance degradation. Future research could examine efficiency and resilience as joint performance dimensions, developing metrics and models that account for both simultaneously. Finally, the literature generally lacks standardised approaches to quantifying uncertainty in efficiency assessments. Variability in input data, such as aircraft mass, meteorological fields or ADS-B resolution, can significantly affect fuel burn and emission estimates. Reporting deterministic efficiency improvements without confidence intervals or sensitivity analyses may obscure the true magnitude of observed effects. Establishing uncertainty quantification practices would improve methodological transparency and allow more meaningful comparison across studies.

6. CONCLUSION

The persistent challenge of flight inefficiency remains a critical issue undermining the performance of both European and global ATM systems. Despite decades of advancement and the implementation of various technical, procedural and regulatory initiatives, the optimisation of flight trajectories continues to be constrained by a complex interplay of social, technical, geopolitical and environmental factors. These constraints contribute to unnecessary fuel burn, increased greenhouse gas emissions and elevated operational costs, posing significant obstacles to the realisation of sustainable, efficient and resilient aviation operations.

This research paper provides a comprehensive literature review, thematically categorising scientific and professional literature on VFE and HFE in five distinct focus areas: operational application and optimisation; environmental and economic impacts; capacity and system constraints; data, modelling and technology use; and strategic and geopolitical influences. Rather than synthesising the literature solely by vertical and horizontal domains, this research paper synthesises it based on distinct focus areas, emphasising the complexity and multidimensionality of the research area. The thematic synthesis brings attention to well-established areas like procedural optimisation and fuel consumption analysis, while also highlighting emerging themes such as real-time data integration and geopolitical resilience. The review differentiates between general studies on flight efficiency and those specifically targeting trajectory optimisation, revealing an uneven distribution of research maturity across topics. While certain areas, such as the simulation and validation of CCO and CDO are well-researched and demonstrate clear environmental and economic benefits, others, particularly real-time trajectory optimisation, integration of diverse data sources and resilience under geopolitical disruption, remain underdeveloped. Key challenges identified in the literature include limited availability and granularity of data (ADS-B, cost index, actual take-off mass), methodological inconsistencies, a lack of standardised efficiency metrics and a notable disconnect between academic models and operational realities. Additionally, few studies adopt a holistic view that integrates vertical and horizontal efficiency, despite the growing importance of 4D-TBO in future ATM frameworks.

Given the anticipated growth in European air traffic and the increasing demands for sustainability, enhancing flight efficiency is no longer optional, it is essential. This imperative calls for future research to focus on developing integrated, real-world applicable optimisation models that account for operational, environmental, technological and behavioural factors. Such models should be capable of incorporating dynamic weather data, advanced aircraft performance modelling and strategic decision-making considerations. The incorporation of ML, AI and big data analytics holds considerable promise in improving model adaptability, predictive accuracy and policy relevance. Furthermore, narrowing the gap between academic research and real-world implementation will require interdisciplinary collaboration among ANSPs, AUs, system developers and regulators. Efforts such as human-in-the-loop simulations, operational trials and phased deployments could facilitate the translation of theoretical insights into actionable, scalable solutions.

Ultimately, advancing toward a more integrated, resilient and operationally grounded understanding of flight efficiency is critical, not only for enhancing the performance of regional ATM systems but for ensuring the long-term sustainability and adaptability of the global ATM system.

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