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Research Article

## Operational Feasibility of the Boeing 777x at Clark International Airport: A Comprehensive Review of Specifications and Requirements

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### Abstract

Clark International Airport is strategically positioned as a key aviation hub in the Philippines, with growing potential to accommodate next-generation wide-body aircraft such as the Boeing 777X. This study investigates the operational feasibility of integrating the 777X at Clark by assessing infrastructure compatibility, environmental compliance, ground handling efficiency, and economic viability. Utilizing a case study approach and descriptive-analytical method, data were gathered through interviews, site observations, and technical document analysis. Findings reveal that while Clark's 3,200-meter runway meets length requirements, critical gaps exist in pavement strength, taxiway width, apron capacity, and ground support systems, posing limitations for the 777X's higher maximum takeoff weight and extended wingspan. Economically, the 777X offers long-term benefits through reduced fuel costs, increased passenger and cargo capacity, and improved turnaround times. However, these advantages hinge on significant infrastructure investments. The study recommends targeted upgrades in runway reinforcement, taxiway expansion, and GSE modernization, alongside environmental enhancements such as sustainable aviation fuel (SAF) integration and noise monitoring improvements. Practical strategies include leveraging public-private partnerships and aligning development with regional growth goals. These insights provide a roadmap for enhancing Clark's competitiveness as a regional aviation hub capable of supporting next-generation aircraft.



## 1. Introduction

The Boeing 777X, as shown in Fig. 1, represents the latest advancement in wide-body aircraft engineering, integrating innovations in aerodynamics, propulsion, and materials science to meet the growing demand for long-haul operational efficiency and environmental sustainability. Among its standout features are its high-aspect-ratio composite wings with folding wingtips, the GE9X engines featuring TAPS combustor technology, and an airframe constructed from lightweight carbon-fiber composites (Ma & Elham, 2024; Foust et al., 2012; Haselbach & Newby, 2015). These enhancements collectively reduce fuel consumption, lower emissions, and enhance overall performance. The folding wingtip design allows the aircraft to maintain compatibility with standard Code E airport gates when retracted, thereby reducing the need for extensive airport retrofitting (Boeing, 2020; Petrescu et al., 2017).

As global air travel rebounds post-pandemic, airports are being challenged to modernize infrastructure in line with evolving aircraft technologies and international standards. In Southeast Asia, where competition among regional hubs is intensifying, airports like Singapore Changi and Kuala Lumpur International have proactively expanded their capabilities to handle next-generation wide-body aircraft (Bardai et al., 2017; Chang et al., 2020). In the Philippine context, Clark International Airport, located within the Clark Freeport Zone, is increasingly being positioned as a next-generation aviation gateway. While recent infrastructure expansions have extended the runway length and improved terminal facilities, a comprehensive technical evaluation of the airport's readiness to accommodate advanced aircraft, such as the Boeing 777X, remains lacking.

Current research on wide-body aircraft integration tends to focus on general airport compatibility, often omitting the specific operational and infrastructure demands posed by the Boeing 777X. The aircraft's extended wingspan of 71.8 meters, maximum takeoff weight (MTOW) of 351,500 kg, and enhanced environmental compliance features require more than just surface-level compatibility checks (Boeing, 2023). Critical aspects such as runway pavement strength (PCN), taxiway geometry, apron layout, and ground handling systems must be evaluated in detail (Sun et al., 2022; Stet et al., 2009). Environmental considerations are equally important. Although the 777X is equipped with emissions- and noise-reducing technologies that meet ICAO Chapter 14 and CO<sub>2</sub> standards, the airport's systems for monitoring noise, managing fuel spills, and integrating sustainable aviation fuel (SAF) infrastructure remain underdeveloped (Bergesen et al., 1998; Bugayko et al., 2022; Yang, 2024).

This study addresses these knowledge and infrastructure gaps by presenting the first dedicated feasibility assessment of integrating the Boeing 777X into Clark International Airport. The central research question guiding this investigation is: *To what extent is Clark International Airport equipped to accommodate the technical, operational, and environmental requirements of the Boeing 777X?* To answer this, a multi-dimensional case study framework was applied, combining site observations, technical document review, and interviews with aviation professionals.

The study's strength lies in its interdisciplinary approach, merging airport infrastructure benchmarking with sustainability analysis and operational feasibility. In contrast to previous studies that primarily focused on highly developed hubs, this research provides insights from an emerging Southeast Asian airport context, thereby filling a critical void in academic and industry literature (Quimba et al., 2024; Disimulacion, 2021). By aligning aircraft-specific requirements with localized airport realities, the study not only contributes to scholarly knowledge but also provides practical guidance for airport planners and policymakers.

Despite its comprehensive scope, the research has limitations. It is based on current infrastructure and operational data and does not account for projected traffic growth, long-term business models of airlines, or in-depth passenger experience analysis. These areas warrant further investigation in future studies, potentially through simulation modeling or comparative benchmarking with other regional hubs.

Ultimately, this research offers several important contributions. First, it delivers a data-driven feasibility analysis of the Boeing 777X tailored to the Philippine aviation landscape. Second, it informs infrastructure investment strategies that align with ICAO regulatory frameworks and sustainability objectives. Third, it supports Clark's broader ambition of positioning itself as a competitive, next-generation aviation hub. In doing so, the study bridges the gap between advanced aircraft design and airport operational readiness in emerging markets.



**Fig. 1.** Boeing 777X in Flight with Extended Wingspan (Boeing, n.d.)

## 2. Method

### 2.1. Research Design

This study employed a case study approach, descriptive-analytical method, and applied research design to evaluate the operational feasibility of the Boeing 777X at Clark International Airport. The case study approach enabled an in-depth, contextual analysis of Clark's infrastructure, including runway dimensions, taxiway configurations, ground handling capabilities, and environmental considerations—characteristics that make the case study ideal for investigating complex, real-world challenges (Crowe et al., 2011; Ratnasari & Sudradjat, 2023). Drawing from multiple sources of evidence, such as on-site observations, technical documentation, and interviews with airport personnel, the method allowed for triangulation, enhancing the validity and reliability of findings (Adeyinka-Ojo et al., 2014; Bell & Warren, 2023).

The descriptive-analytical method systematically documented and assessed Clark's infrastructure compatibility with Boeing 777X specifications by benchmarking key parameters, such as runway length, pavement strength, taxiway width, and ground handling efficiency, against international standards and ICAO guidelines. This process highlighted existing infrastructure conditions and revealed operational gaps requiring strategic upgrades. Meanwhile, the applied research element grounded the study in practical outcomes by focusing on the development of real-world recommendations for infrastructure reinforcement, policy refinement, and operational optimization. This integration of theory and practice is a defining feature of applied research, especially in aviation planning contexts where actionable insights are critical (Butvilas & Zygmantas, 2011; Bell & Warren, 2023). Through this multi-method framework, the study bridges conceptual analysis with practical aviation infrastructure planning, offering a comprehensive foundation for future upgrades to accommodate next-generation aircraft, such as the Boeing 777X.

### 2.2. Sampling

This study employed purposive sampling, a non-probability sampling method, which is well-suited for selecting individuals with specialized knowledge relevant to the research focus. Participants were carefully chosen based on their roles in airport management, infrastructure planning, and airline operations, ensuring that each had direct experience or decision-making authority related to Clark International Airport's readiness for wide-body aircraft such as the Boeing 777X. These included airport officials, civil and aeronautical engineers, and personnel from airline ground operations. A minimum of 10 participants was targeted to achieve data saturation, ensuring that recurring themes and insights could be identified without redundancy.

### 2.3. Data Collection Methods

This study employed a combination of primary and secondary data sources to comprehensively assess the operational feasibility of Clark International Airport for the Boeing 777X. Primary data were gathered through interviews and on-site observations, providing firsthand insights into operational challenges, ground-handling processes, and infrastructure constraints. Interviews were conducted with airport officials, engineers, and airline

representatives, utilizing a semi-structured format to allow for flexibility in discussing key concerns, such as runway compatibility, taxiway clearance, and turnaround efficiency.

Additionally, on-site observations were conducted to document the real-time conditions of the airport's runway, taxiway layouts, apron space, and ground handling operations. These observations were systematically recorded using standardized checklists based on ICAO standards and Boeing 777X specifications, ensuring accuracy and consistency. Secondary data were sourced from technical manuals, ICAO guidelines, airport planning documents, and academic studies to provide a broader contextual understanding. Boeing technical manuals detailed the aircraft's operational requirements, while ICAO guidelines benchmarked Clark's infrastructure compliance with international aviation standards. Government reports, case studies of airports accommodating wide-body aircraft, and environmental assessments were also reviewed to identify best practices and benchmarks relevant to Clark's expansion and operational strategies. By integrating primary and secondary data, this mixed-method approach ensured practical relevance while maintaining alignment with established aviation standards, providing a robust foundation for assessing the airport's readiness to accommodate the Boeing 777X.

#### **2.4. Data Analysis**

This study employed a combination of descriptive statistics, comparative analysis, SWOT, and gap analysis to comprehensively evaluate Clark International Airport's readiness for the Boeing 777X. Descriptive statistics were used to summarize quantitative data on runway dimensions, taxiway width, apron area, and ground handling capacity, establishing an objective baseline for infrastructure assessment—an approach commonly adopted in policy evaluation, infrastructure planning, and institutional performance studies (Batubara et al., 2023).

A comparative analysis was conducted using benchmarking matrices, aligning Clark's infrastructure with ICAO Annex 14 standards and operational requirements observed in leading regional hubs, such as Singapore Changi Airport and Kuala Lumpur International Airport. This method follows established frameworks used in infrastructure evaluations and regional competitiveness assessments (Mashuri & Nurjannah, 2020; Gusti et al., 2023).

A SWOT analysis provided a qualitative framework to assess internal and external factors, identifying strengths such as a strategic location and potential for facility expansion, as well as weaknesses, including limited wide-body aircraft handling capabilities. Opportunities for future partnerships and infrastructure investments were highlighted, along with external threats, including regional competition and regulatory constraints. The flexibility of the SWOT analysis has been demonstrated across various sectors—from higher education and health services to banking and e-government—supporting its value in aviation infrastructure planning (Kuchler et al., 2020; Wong et al., 2014; Murudi-Manganye et al., 2021; Bharadwaj & Pradeep, 2023).

Gap analysis utilized compatibility assessment templates and cross-tabulation techniques to pinpoint deficiencies in critical infrastructure elements, such as inadequate taxiway clearance and limited apron space, and to quantify the alignment of existing conditions with Boeing 777X specifications. As in prior studies, the use of SWOT matrices and gap analysis supports the formulation of targeted recommendations and decision-making strategies in complex operational environments (Mashuri & Nurjannah, 2020; Gusti et al., 2023).

By integrating quantitative and qualitative tools, this multi-method analytical framework ensured a robust evaluation of Clark International Airport's capability to accommodate the Boeing 777X, supporting the formulation of strategic, data-driven recommendations for operational enhancements.

#### **2.5. Instrument Validity**

To ensure the validity of the research instruments, all tools—including structured interview questions, observation checklists, and compatibility assessment templates—were subjected to expert validation. Aviation professionals and academic experts in airport planning and aircraft operations were consulted to review the instruments for content relevance, clarity, and alignment with the Boeing 777X's technical specifications and ICAO standards. Revisions were made based on their feedback to eliminate ambiguity and ensure each item effectively measured the intended parameter. This process established content and face validity, reinforcing the accuracy and appropriateness of the data collection tools used in the study.

### 3. Results and Discussion

#### 3.1. Technical Specifications and Infrastructure Implications

The Boeing 777X incorporates advanced technical specifications (Table 1), positioning it as a next-generation wide-body aircraft tailored for long-haul efficiency and environmental sustainability. With an extended wingspan of 71.8 meters and a folded configuration of 64.8 meters (Fig. 2), its signature folding wingtip technology enhances aerodynamic performance while allowing the aircraft to remain compatible with airport gates designed for ICAO Code E standards (Boeing, 2020; Ma & Elham, 2024). This feature is particularly relevant for airports like Clark International Airport, where existing taxiways and parking aprons are optimized for current-generation wide-body aircraft, such as the Boeing 777-300ER. However, despite the reduced span when folded, the 777X's full wingspan still exceeds the design envelope of many taxiways and turning areas, requiring selective widening and reconfiguration to prevent clearance issues and operational delays (Stet et al., 2009).

The aircraft's overall length of 76.7 meters and Maximum Takeoff Weight (MTOW) of 351,500 kg enable it to transport high volumes of passengers and cargo across long distances without compromising efficiency. These characteristics, however, place increased demands on airside infrastructure. Although meeting the minimum length requirement of 3,000 meters, Clark's main runway must be evaluated for load-bearing capacity. The 777X's higher MTOW necessitates a reinforced Pavement Classification Number (PCN) to prevent premature surface wear and ensure structural integrity under frequent heavy-load operations (Sun et al., 2022; Sabahfar & Murrell, 2020).

**Table 1.** Boeing 777X Technical Specifications

Specification	Details
Wingspan	71.8 meters (extended) / 64.8 meters (folded)
Length	76.7 meters (777-9 model)
Maximum Takeoff Weight (MTOW)	Approximately 351,500 kg (777-9 model)
Engine Type	GE9X engines
Passenger Capacity	Approximately 384 passengers (typical 2-class configuration, 777-9 model)
Range	13,500 km (777-9 model)
Fuel Efficiency	10% lower fuel consumption compared to the Boeing 777-300ER
Noise Compliance	Meets ICAO Chapter 14 standards for noise reduction
Materials	Advanced composites (including carbon fiber-reinforced polymers for wings and fuselage)



**Fig. 2.** Boeing 777X Folding Wingtip Technology Enhancing Compatibility with Existing Airport Infrastructure (Boon & Pande, 2023)

The 777X is powered by state-of-the-art GE9X engines, which offer a 10% reduction in fuel consumption compared to the 777-300ER, achieving a maximum range of approximately 13,500 kilometers (Boeing, 2023; Foust et al., 2012). In addition to improved fuel economy, the engines produce 30% less NO<sub>x</sub> and comply with ICAO Chapter 14 noise standards, making the 777X one of the most environmentally friendly aircraft in its category (Bergesen et al., 1998; Bugayko et al., 2022). While these advancements reduce the overall environmental footprint, they still necessitate upgrades in Clark's environmental monitoring infrastructure. Current noise monitoring

zones may not accurately assess and mitigate noise generated during thrust-intensive phases such as takeoff, particularly during night operations or in densely populated surrounding areas (Abeyratne, 2003; Agarwal, 2009).

Constructed using advanced composite materials—such as carbon fiber-reinforced polymers in the wings and fuselage—the aircraft benefits from reduced structural weight and increased durability. This design also improves fuel efficiency and maintenance longevity, translating into higher airport operational throughput. However, to fully leverage these efficiencies, airports must possess the ground handling capacity to manage quicker turnaround times, including high-capacity refueling systems, wide-body-configured gates with dual-boarding bridges, and automated cargo and baggage loading equipment (Horstmeier & Haan, 2001; Tabares & Mora-Camino, 2017).

With a passenger capacity of approximately 384 in a typical two-class configuration, the Boeing 777X enhances the economics of long-haul operations (Boeing, 2020). For airports like Clark, this requires synchronized upgrades in terminal space, check-in counters, immigration processing areas, and baggage claim systems to avoid congestion and maintain a high-quality passenger experience (Schultz, 2018; Srisook & Panjakajornsak, 2017).

In summary, each of the Boeing 777X's innovative features has direct infrastructure implications. The aircraft's scale, engine power, and environmental performance metrics necessitate corresponding enhancements in runway strength, taxiway geometry, apron layout, ground support equipment, terminal capacity, and environmental monitoring. These interdependencies underscore the importance of aligning aircraft technological advancements with airport infrastructure modernization, particularly for airports aiming to serve as regional hubs for next-generation aviation (Frediani et al., 2019; Chang et al., 2020).

### 3.2. Clark International Airport Strategic Location

Clark International Airport, situated in the province of Pampanga in the Philippines, boasts a strategic geographical location within the Southeast Asian region, making it an ideal hub for both regional and long-haul flights. Its proximity to major cities such as Manila, Hong Kong, Singapore, and Tokyo provides airlines with access to key business and leisure travel markets. This location is further enhanced by the Philippines' role as a central point connecting major East Asian economies and growing markets in Southeast Asia (Homsombat et al., 2011; Chang et al., 2020). (Fig. 3) highlights Clark's strategic placement, offering direct access to international air routes in the Pacific and Asian regions. Compared to Manila's congested Ninoy Aquino International Airport (NAIA), Clark provides significant room for expansion, making it an attractive alternative for airlines aiming to reduce operational delays and optimize flight schedules (Disimulacion, 2021; Huynh et al., 2020).

Additionally, the airport's proximity to Subic Freeport Zone and other industrial areas supports cargo operations, positioning Clark as a logistics hub for both domestic and international freight (Homsombat et al., 2011). With its expansion plans and infrastructure improvements, including extended runways and upgraded terminals, the airport is well-equipped to accommodate next-generation wide-body aircraft, such as the Boeing 777X, further enhancing its competitiveness in the aviation industry (Bardai et al., 2017; Dela Peña, 2024). In summary, Clark International Airport's location, combined with its infrastructure potential and lower congestion levels, underscores its importance as a gateway for international connectivity, economic growth, and tourism development in the region (Chang et al., 2020; Suh & Ryerson, 2017).



**Fig. 3.** Geographical location of Clark International Airport in the Philippines, highlighting its strategic position for regional and international aviation connectivity (BCDA & IFC, 2018)

### 3.3. Airport Infrastructure Assessment

Table 2 provides infrastructure details at Clark International Airport, revealing a promising foundation for accommodating the Boeing 777X and highlighting critical areas requiring strategic upgrades to ensure full operational compatibility and long-term efficiency. Fig. 4, which offers an aerial layout of the airport, illustrates essential components such as runways, taxiways, aprons, and terminals. While these currently support wide-body aircraft like the Boeing 777-300ER, the larger dimensions and operational weight of the 777X demand infrastructure enhancements. As illustrated in Fig. 4 to 8, Clark International Airport’s primary runway measures 3,200 meters in length and 60 meters in width, meeting ICAO Code F requirements and accommodating the 777X’s takeoff and landing distance needs (Boeing, 2020). However, the existing Pavement Classification Number (PCN)—reported as PCN 66/F/B/W/T—falls below the recommended level for wide-body aircraft with a Maximum Takeoff Weight (MTOW) of 351,500 kg. According to ICAO guidance and ACN-PCN research, a minimum PCN of 80 is advisable for aircraft of this class to ensure structural integrity and reduce long-term surface degradation (Stet et al., 2009; Sun et al., 2022). Without reinforcement, frequent operations by the 777X could lead to accelerated pavement wear and costly maintenance cycles.



**Fig. 4.** Layout map of Clark International Airport highlighting the main runway, taxiways, terminals, and apron configurations' compatibility with wide-body aircraft such as the Boeing 777X (BCDA & IFC, 2018)

Clark’s taxiway system also presents a mix of readiness and constraint. As shown in Fig. 7, taxiways are 23 meters wide, compliant with ICAO Code E specifications and sufficient for the aircraft’s folded wingspan of 64.8 meters. However, the 777X’s fully extended wingspan of 71.8 meters requires expanded taxiway clearance and improved turning radii at key junctions to prevent wingtip clearance conflicts (Boeing, 2020; Ma & Elham, 2024). Select taxiway modifications—particularly at apron intersections and near high-traffic gates—are needed to ensure safe and efficient ground maneuvering.

The apron layout, as visualized in Fig. 7, accommodates existing traffic but poses challenges for high-volume wide-body operations. The limited number of Code F parking stands and shared ground servicing zones may lead to congestion and extended turnaround times during peak periods. Expanding apron space and introducing dual-boarding bridge configurations at primary gates would improve passenger flow and reduce aircraft ground time, especially for long-haul departures (Saggar et al., 2021).

Fig. 6 further illustrates that Clark’s runway is limited by a lack of high-speed exit taxiways, which increases runway occupancy time and restricts throughput during peak operational windows. Constructing additional high-speed exits could significantly reduce taxiing delays and improve airfield efficiency. Ground Support Equipment (GSE) availability is another bottleneck. The 777X’s operational requirements—including greater fuel volume and

cargo handling—necessitate high-capacity refueling trucks, tugs, and automated cargo loaders. The current shared-use model can lead to handling inefficiencies. A dedicated GSE for wide-body aircraft is recommended to minimize delays and streamline turnaround processes (Horstmeier & Haan, 2001; Tabares & Mora-Camino, 2017).

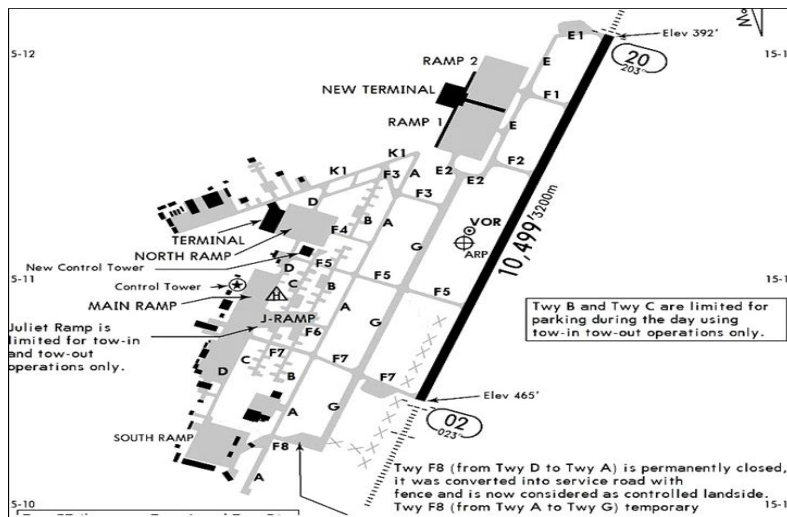
Finally, terminal infrastructure must be scaled to support the 777X's larger passenger load—approximately 384 passengers in a two-class configuration. Without upgrades, existing terminal layouts may experience pressure at check-in counters, immigration screening, and baggage handling. Expansion of passenger processing facilities, particularly with dual boarding bridges, will be critical in sustaining service quality and maintaining competitive turnaround times (Schultz, 2018). In conclusion, while Clark International Airport meets several baseline criteria for handling next-generation wide-body aircraft, including the Boeing 777X, infrastructure gaps—particularly in pavement strength, taxiway width, apron space, and terminal processing capacity—must be addressed. By implementing these targeted enhancements, Clark can solidify its position as a future-ready hub capable of efficiently supporting advanced long-haul operations and regional growth.



**Fig. 5.** Exterior view of Clark International Airport's terminal building, showcasing its modern architecture and capacity to support future expansions for next-generation wide-body aircraft operations (BCDA & IFC, 2018)



**Fig. 6.** Current Clark International Runway (The Market Monitor, 2018)



**Fig. 7.** Taxiway and terminal layout of Clark International Airport, highlighting main ramps, runways, and restricted areas essential for evaluating aircraft movement and parking configurations for Boeing 777X operation (BCDA & IFC, 2018)

Designations RWY NR	TRUE BRG	Dimensions of RWY	Strength (PCN) and surface of RWY and SWY	THR coordinates RWY end coordinates THR geoid undulation	THR elevation and highest elevation of TDZ of precision APP RWY
1	2	3	4	5	6
02R	021° GEO 022° MAG	3200M X 60M	PCN 85 R/C/W/T	151027.7198N 1203328.2441E (42.62M)	THR 142.141M/ 466.341FT TDZ 142.172M/ 466.443FT
20L	201° GEO 202° MAG	3200M X 60M	PCN 85 R/C/W/T	151204.9015N 1203406.7568E (42.573M)	THR 119.922M/ 393.444FT TDZ 125.394M/ 411.397FT
02L	021° GEO 022° MAG	3200M X 45M	PCN 60 R/B/X/U CONC+ASPH overlay	151014.1215N 1203307.5427E (42.642M)	THR 147.469M/ 483.821FT TDZ 147.603M/ 484.261FT
20R	201° GEO 202° MAG	3200M X 45M	PCN 60 R/B/X/U CONC+ASPH overlay	151151.4994N 1203346.1227E (42.597M)	THR 127.713M/ 419.005FT TDZ 131.777M/ 432.338FT

**Fig. 8.** Runway specifications at Clark International Airport, detailing runway dimensions, pavement classification numbers (PCN), and threshold coordinates, essential for assessing suitability for Boeing 777X operations (BCDA & IFC, 2018)

As illustrated in Fig. 4 to 8, Clark International Airport has a 3,200-meter by 60-meter runway, compliant with ICAO Code F length requirements. However, the current Pavement Classification Number (PCN)—PCN 66/F/B/W/T—is below the required threshold to safely support the Boeing 777X’s Maximum Takeoff Weight (MTOW) of 351,500 kg. ICAO recommends a PCN of at least 80 for aircraft of this weight class. Similarly, taxiway width, currently 23 meters, meets ICAO Code E standards but falls short of optimal clearance for the 777X’s extended 71.8-meter wingspan. These discrepancies emphasize the need for reinforced pavement and taxiway modifications, supported by the layout diagrams and specifications in Fig. 5 to 8.

**Table 2.** Summary of Clark Airport Infrastructure vs. Boeing 777X Operational Requirements

Infrastructure Component	Current Status at Clark	Boeing 777X Requirement	Gap Identified
Runway Length	3,200 meters	3,000+ meters	Compliant
Runway PCN	PCN 66	PCN ≥ 80	Needs upgrade
Taxiway Width	23 meters	≥23 meters (folded) / 36m (extended)	Turning radius limited
Apron Space	Moderate, limited wide-body bays	High volume wide-body operations	Requires expansion
Gate Configuration	Single bridge per gate	Dual bridge for 384 pax	Needs upgrade
GSE Availability	Shared & outdated	Specialized, high-capacity	Needs procurement

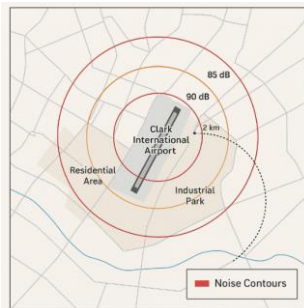
### 3.4. Environmental Impact Assessment

In (Table 3), the Boeing 777X introduces significant environmental advancements over older wide-body aircraft, primarily through enhanced fuel efficiency and reduced emissions. These improvements are achieved through design innovations such as high-bypass GE9X engines and advanced combustion technologies, which contribute to lower particulate matter and carbon emissions (Yang, 2024; Durdina et al., 2021). However, to fully accommodate the aircraft’s operations while minimizing environmental risks, Clark International Airport must enhance its current environmental management systems. Noise remains a key concern during takeoff, landing, and ground operations. Although the 777X, powered by GE9X engines, meets ICAO Chapter 14 noise standards—the most stringent to date—it can still produce moderate to high noise levels, particularly during thrust-intensive phases (Bergesen et al., 1998; Boeing, 2023).

**Table 3.** Environmental Impact Assessment for Boeing 777X Operations at Clark International Airport

Environmental Factor	Current Status	Boeing 777X Impact	Recommendations
Noise Levels	Noise monitoring system in place, but limited to specific zones near runways	The GE9X engines are quieter than older models, as they comply with ICAO Chapter 14 standards (Boeing, n.d.).	Upgrade noise-monitoring systems to cover larger areas, implement buffer zones, and optimize flight paths to minimize the impact on residential areas.
Takeoff and Landing Noise	Moderate to high noise impact on nearby communities during peak hours	Takeoff and landing noise remains a key concern, especially during reverse thrust and peak operations	Enforce restrictions on nighttime operations; optimize takeoff thrust and landing paths to minimize exposure.
Ground Emissions (NOx, CO2)	Emissions primarily from taxiing, engine idling, and refueling activities	10% lower fuel consumption and 30% reduction in NOx emissions compared to older models (Ramakrishnan, 2024)	Invest in sustainable aviation fuel (SAF) infrastructure; transition to electric or hybrid ground support equipment (GSE) to reduce emissions.
Air Quality (CO2, PM)	Moderate impact from current ground activities and aircraft operations	GE9X engines emit significantly lower CO2, improving air quality compared to earlier models	Implement air quality monitoring systems and promote the use of SAF to reduce ground-level pollutants.
Fuel and Chemical Runoff	Potential risk of spills during refueling and maintenance	No direct increase due to 777X-specific requirements, but higher operational traffic may pose a greater risk	Install spill containment systems and ensure proper drainage; conduct regular inspections of fuel storage and handling areas.
Sustainability Programs	Minimal SAF usage and limited offset programs	The 777X’s fuel efficiency aligns with international sustainability goals (CORSIA)	Collaborate with airlines to expand SAF usage and integrate carbon offset programs to achieve long-term environmental sustainability goals.

Clark’s existing noise monitoring systems are limited in coverage and may not adequately track impacts on nearby communities. Upgrading to real-time noise tracking systems, establishing buffer zones, restricting nighttime operations, and optimizing flight paths could mitigate these concerns (Abeyratne, 2003; Agarwal, 2009). As shown in Fig. 9, the noise contour zones extend up to 2 kilometers from the runway, with noise levels of 90 dB and 85 dB affecting both residential and industrial areas. These findings underscore the need for implementing upgraded noise monitoring systems and optimized flight paths to protect community health and comply with ICAO Chapter 14 standards (Bugayko et al., 2022; International Civil Aviation Organization, 2017).



**Fig. 9.** Noise contour map of Clark International Airport showing 2 km, 90 dB, and 85 dB impact zones, highlighting nearby residential and industrial areas within the affected range

Regarding air quality, the 777X achieves approximately 10% lower fuel consumption and 30% lower NO<sub>x</sub> emissions compared to its predecessor, contributing to cleaner operations and lower environmental impact (Boeing, 2023; Yang, 2024). However, emissions during taxiing, idling, and refueling continue to pose localized pollution risks, particularly in high-traffic operational zones. To address this, transitioning to sustainable aviation fuel (SAF), adopting electric or hybrid ground support equipment (GSE), and installing air quality monitoring systems in critical areas are essential steps in reducing Clark International Airport’s carbon footprint. These strategies align with international sustainability objectives and carbon offset mechanisms such as ICAO’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) (Bugayko et al., 2022; Pavlenko & Kharina, 2018).

Additionally, increased operational traffic heightens the risk of hydrocarbon and chemical runoff, especially during aircraft refueling and maintenance activities. To mitigate this, Clark must invest in advanced spill containment systems, efficient drainage infrastructure, and rigorous environmental inspection protocols (Agarwal, 2009). Collaboration with partner airlines to scale up the use of Sustainable Aviation Fuel (SAF) and implement carbon offset programs would further enhance environmental performance and institutionalize best practices in sustainable airport management (Durdina et al., 2021; Yang, 2024).

In summary, while the Boeing 777X offers significant environmental advantages, Clark International Airport must implement targeted mitigation strategies—including noise and emissions control, SAF integration, electric Ground Support Equipment (GSE) adoption, and runoff management—to maximize sustainability outcomes and operational readiness for next-generation aircraft operations (Bergesen et al., 1998; Abeyratne, 2003).

### 3.5. Ground Handling and Turnaround Time Efficiency

In Table 4, efficient ground handling and quick turnaround times are crucial for optimizing airport operations and maximizing profitability, particularly for next-generation wide-body aircraft such as the Boeing 777X (Horstmeier & Haan, 2001; Tabares & Mora-Camino, 2017). The assessment of Clark International Airport identifies key challenges in refueling, baggage and cargo handling, passenger boarding, and the availability of ground support equipment (GSE). A limited number of fuel trucks may lead to delays, especially during peak periods. Expanding the fleet with high-capacity fuel trucks and implementing simultaneous refueling techniques would improve efficiency and reduce turnaround times. Baggage and cargo handling also face delays due to outdated systems and manual processing. Upgrading to automated loaders and training personnel would streamline operations and reduce human error (Saggar et al., 2021).

**Table 4.** Ground Handling and Turnaround Time Efficiency for Boeing 777X Operations at Clark International Airport

Ground Handling Aspect	Current Status	Potential Bottlenecks	Recommendations
Refueling Operations	Existing fuel trucks are designed for wide-body aircraft, but limited in availability	Delays during peak periods due to limited fuel truck capacity and turnaround time	Increase the fleet of high-capacity fuel trucks and adopt simultaneous refueling methods to optimize scheduling.
Baggage and Cargo Loading	The current baggage handling system supports wide-body aircraft, but the equipment is aging.	Slow baggage/cargo loading due to outdated equipment and limited automated loading/unloading systems	Upgrade to automated cargo loaders and baggage handling systems, and train personnel to minimize handling time.
Passenger Boarding and Deplaning	Current gates accommodate wide-body aircraft, but are limited to dual boarding bridges.	Longer boarding times due to insufficient gates and a lack of dual boarding systems for high-capacity aircraft	Add dual boarding bridges at key gates and reconfigure gates to facilitate simultaneous boarding and deplaning operations.
Ground Support Equipment (GSE)	Limited availability of specialized GSE for the 777X’s increased cargo and passenger load	Delays due to shared equipment and insufficient high-capacity ground handling vehicles	Invest in high-capacity GSE, including tugs, catering trucks, and cargo loaders specifically designed for wide-body aircraft.
Apron Congestion	Limited apron space for multiple wide-body aircraft during peak hours	Delays in parking, refueling, and servicing due to congestion and inefficient parking layouts	Expand apron space and redesign parking layouts to optimize movement and simultaneous operations.

Passenger boarding and deplaning are hindered by a shortage of dual-boarding bridges, resulting in congestion and inefficient passenger flow. Adding these bridges and optimizing gate configurations would significantly improve turnaround times and passenger experience (Schultz, 2018). Ground support equipment shortages further contribute to inefficiencies, as the 777X requires specialized tugs, catering trucks, and cargo loaders. Investing in dedicated and automated GSE for wide-body operations would minimize delays and align with international best practices in aircraft servicing (Tabares & Mora-Camino, 2017; Sheibani, 2020). Additionally, apron congestion restricts aircraft movement during peak periods. Expanding apron space and redesigning parking layouts would alleviate bottlenecks and improve operational flow, particularly in high-traffic zones.

In conclusion, while Clark International Airport can technically accommodate the 777X, strategic upgrades in refueling systems, ground support equipment, baggage handling automation, and gate infrastructure are essential to enhance efficiency and position Clark as a competitive regional hub for wide-body aircraft operations (Schultz, 2017; Saggarr et al., 2021).

### **3.6. Economic Feasibility Analysis**

According to (Table 5), the Boeing 777X offers significant economic potential for Clark International Airport, resulting in operational cost savings, increased passenger capacity, and enhanced cargo revenue. With 10% lower fuel consumption enabled by GE9X engines and lightweight composite materials, the aircraft reduces fuel expenses, particularly for long-haul operations (Boeing, 2023; Foust et al., 2012). Optimizing turnaround times and streamlining ground handling will further enhance cost efficiency (Horstmeier & Haan, 2001; Schultz, 2017). The 777X's improved aerodynamics and engine performance make it an attractive airline option, allowing for reduced operational costs per kilometer flown. Encouraging its deployment on high-capacity routes could position Clark as a hub for fuel-efficient operations (Frediani et al., 2019; Bravo-Mosquera et al., 2022).

With a passenger capacity of approximately 384 in a two-class configuration, the 777X offers higher revenue opportunities for long-haul flights. Clark's strategic location and lower congestion than other regional hubs make it a competitive hub for attracting international carriers (Chang et al., 2020; Homsombat et al., 2011). Expanding route development programs and marketing efforts can further boost passenger traffic and airport revenue. The aircraft's larger cargo hold also presents an opportunity for increased cargo throughput. By partnering with logistics companies and cargo operators, Clark can capitalize on the growing demand for air cargo, particularly for perishable and time-sensitive goods (Srisook & Panjakajornsak, 2018).

To quantify these economic benefits, a cost-benefit analysis reveals that while infrastructure upgrades—including improvements to the runway, taxiways, apron, and gates—will incur substantial capital expenditures, these costs are offset over time by increased passenger traffic, enhanced cargo capacity, and reduced operational expenses. The potential for higher airport revenue and airline efficiency suggests a favorable return on investment (Bardai et al., 2017; Huynh et al., 2020). Additionally, the adoption of the 777X can stimulate job creation, both directly and indirectly. Direct employment opportunities include technical and operational roles such as aircraft handling, maintenance, and security. Indirectly, increased passenger and cargo flows can support ancillary industries, including tourism, retail, catering, and logistics, contributing to broader economic stimulation (Srisook & Panjakajornsak, 2017; Homsombat et al., 2011).

Moreover, the long-term deployment of wide-body aircraft, such as the 777X, supports regional development by positioning Clark as a key aviation gateway in Central Luzon. Enhanced connectivity may attract further investments in business parks, logistics hubs, and hospitality services. This aligns with the Philippines' broader infrastructure and economic decentralization goals, reinforcing Clark's role in national development (Disimulacion, 2021; Llanto, 2016). Government and private sector partnerships can help secure the necessary funding, ensuring the airport's long-term sustainability and profitability (Cruz et al., 2018; Fahriza et al., 2021).

Overall, the 777X can drive substantial economic growth for Clark International Airport, strengthening its position as a key regional and international aviation hub while delivering measurable socio-economic benefits across the region.

**Table 5.** Economic Feasibility Analysis for Boeing 777X Operations at Clark International Airport

Economic Factor	Current Status	Boeing 777X Impact	Recommendations
Operational Costs	Refueling, maintenance, and ground handling operations account for the majority of current costs.	A 10% reduction in fuel consumption lowers overall operational costs, particularly on long-haul routes (Boeing, n.d.).	Optimize ground operations to further reduce costs by minimizing turnaround delays and idle time.
Fuel Efficiency Savings	Existing aircraft (e.g., 777-300ER) provide moderate fuel efficiency	Boeing 777X offers significant savings due to GE9X engines, lightweight composite materials, and optimized aerodynamics	Encourage airlines to adopt the 777X for high-capacity routes to maximize fuel cost reductions.
Passenger Revenue Potential	Moderate passenger growth based on current flight capacity and regional demand	Increased capacity (384 passengers in a typical 2-class configuration) offers revenue potential from long-haul routes.	Expand marketing and route development to attract international carriers and boost passenger traffic.
Cargo Revenue Potential	Limited cargo operations with existing aircraft	Larger cargo hold of the 777X provides opportunities for increased cargo revenue.	Develop partnerships with cargo operators and logistics companies to maximize cargo utilization.
Initial Infrastructure Investment	Significant investments are needed for runway, taxiway, apron, and gate improvements.	Upfront investments are required, but long-term benefits include higher operational efficiency and increased traffic.	Secure government and private funding to finance infrastructure improvements and long-term operational benefits.

#### 4. Conclusion

This study assessed the operational feasibility of the Boeing 777X at Clark International Airport by evaluating critical areas, including infrastructure compatibility, environmental impact, ground handling efficiency, and economic viability. The findings indicate that while Clark possesses a foundational infrastructure capable of supporting wide-body aircraft, it requires targeted upgrades to accommodate the specific operational demands of the Boeing 777X and similar next-generation aircraft. Notably, the airport’s 3,200-meter runway meets the aircraft’s takeoff and landing requirements; however, the existing Pavement Classification Number (PCN) must be enhanced to support the aircraft’s maximum takeoff weight (MTOW) of 351,500 kg, thereby preventing long-term structural degradation. Additionally, while current taxiway dimensions meet folded wingspan requirements, further expansions and turning radius enhancements are necessary for the 777X’s extended wingspan operations.

The environmental analysis underscored the 777X’s technological advancements in reducing noise and emissions, yet identified that Clark’s existing monitoring systems and sustainability programs are not fully equipped to handle increased operational demands. Upgrades to real-time noise tracking, Sustainable Aviation Fuel (SAF) infrastructure expansion, and advanced air quality monitoring systems are recommended to align with ICAO and CORSIA goals. Furthermore, operational bottlenecks in refueling, baggage and cargo handling, and passenger boarding were identified, primarily due to the limited availability of high-capacity Ground Support Equipment (GSE) and single-boarding configurations. Investment in modern GSE, dual-boarding bridges, and automated systems is essential for reducing turnaround time and improving airport throughput. Economically, while the 777X presents opportunities for cost savings and revenue growth, primarily through increased capacity and fuel efficiency, these benefits hinge on substantial infrastructure investments.

This study provides a roadmap for infrastructure and policy development, offering stakeholders—airport authorities, civil aviation regulators, and airline operators—concrete data to support phased investments and strategic decision-making. Implementing the proposed upgrades will enhance Clark’s ability to handle the 777X and strengthen its competitiveness as a regional aviation hub capable of accommodating future generations of aircraft.

For future research, several avenues are recommended. Passenger experience and terminal processing capacity should be examined, particularly under high-volume wide-body aircraft scenarios. Comparative studies between Clark and other Southeast Asian hubs can yield insights into competitive positioning and best practices. Additionally, modeling long-term economic scenarios, including return on investment (ROI) timelines for

infrastructure upgrades, could support financing and policy advocacy. Investigations into regulatory readiness and alignment with international certification standards for newer aircraft technologies are also worth exploring. In sum, this research is a foundational study that bridges the gap between advanced aircraft design and regional airport preparedness, offering academic value and actionable guidance for infrastructure modernization and aviation sustainability.

#### **4.1. Practical Recommendations**

To accommodate the Boeing 777X and enhance operational efficiency, Clark International Airport must undertake critical infrastructure upgrades. This includes reinforcing the runway pavement to withstand the aircraft's higher maximum takeoff weight, widening taxiways to accommodate its larger wingspan, and expanding apron space to facilitate simultaneous operations of wide-body aircraft. These modifications will ensure that the airport meets the necessary safety and operational standards required for next-generation aircraft. In addition to airside improvements, investments in ground support and terminal facilities are essential. Procuring specialized ground support equipment (GSE) tailored to the 777X, implementing dual boarding bridges for faster passenger embarkation and disembarkation, and upgrading automated baggage handling systems will streamline ground handling and turnaround times. These enhancements will improve efficiency, reduce delays, and support the growing demand for international flights at Clark.

Environmental considerations must also be prioritized to align with sustainability goals and regulatory compliance. Expanding noise monitoring systems will enable a more comprehensive assessment and mitigation of aircraft noise in surrounding communities. Encouraging the use of sustainable aviation fuel (SAF) will contribute to reducing carbon emissions, while improving drainage systems and spill containment measures will enhance environmental protection and operational safety. From an economic perspective, securing financial support through public-private partnerships will be crucial in funding these necessary upgrades. Engaging government and private sector stakeholders in infrastructure development will ease financial burdens and stimulate growth by attracting international carriers and expanding route networks. These efforts will drive economic benefits and strengthen Clark's position as a key aviation hub. In conclusion, Clark International Airport has the potential to serve as a regional hub for next-generation aircraft, such as the Boeing 777X, provided that these strategic improvements are implemented. Enhancing infrastructure, optimizing ground operations, adopting sustainable practices, and ensuring financial viability will guarantee operational readiness and elevate the airport's competitiveness in regional and international aviation markets.

#### **Conflict of Interest**

The author declares that he has no known financial, professional, or personal conflicts of interest that could have influenced this study's findings, interpretations, or conclusions. The study was conducted independently, and all analyses and recommendations were formulated based on objective assessments and publicly available data. The authors declare that any affiliations or institutional relationships have not influenced the neutrality of this research.

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Research Article

## Energy Audit and Management in Shipping: A Case Study Onboard Ship

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### Abstract

The sectoral priorities of maritime transportation are expected to focus on reducing fossil fuel-based environmental pollution and shaping sustainable energy management. Despite the International Maritime Organization's (IMO) regulations in this context, the prioritization of energy efficiency and the improvement of its manageability in ships are still anticipated. This study thoroughly examines the energy efficiency and management of a reference chemical tanker, with a particular emphasis on performance and environmental efficiency. The analysis indicates that there is a need for defining energy efficiency targets and improving the optimization process. Based on the ship's load rate and energy consumption behaviors, parameters for energy efficiency rates have been developed, and the environmental impact of the ship can be evaluated using an entropy-based approach. According to histogram analyses, the first energy efficiency target is set at 8.80%, and the second target at 32.58%. Energy efficiency analyses indicate that environmental pollution is approximately 57%, while the entropy approach calculates the energy efficiency rate of the ship at 17.96%. This study should be evaluated as an example of energy audit assessment and exergy analysis for environmental impact assessment to gain energy management behaviour for ships. It provides a contribution to the energy management structure of ships. This study provides an approach for the holistic assessment framework of energy efficiency on ships. It reveals the environmental impact potential for the entropy-based consumption potential of energy consumption. It provides a framework for decision processes.



## 1. Introduction

Energy management and efficiency have become increasingly important in various sectors, including the maritime industry. The growing global awareness of energy consumption, its environmental impacts, and the economic burden of excessive energy usage can be seen as the main reasons for this change. In 2018, the International Maritime Organization (IMO) established an effective plan to reduce emissions from international shipping by half of the 2008 levels (IMO, 2023). This decision marks a significant step toward ensuring sustainability in the maritime industry and reducing pollution. Specifically, the IMO's decision to reduce the sulfur content in ship fuel from 3.50% to 0.50% outside the Emission Control Areas (ECAs) is an example of this commitment. Additionally, the NO<sub>x</sub> content in engine exhaust gases has been limited to 17.0 g/kW.h under Annex IV of MARPOL, which is a sign of the growing effort to reduce environmental pollution in the sector (Comer et al., 2024).

Effective energy management plays a critical role in managing energy-related environmental pollutants, such as emissions from chimneys, while ensuring that ships remain within these environmental boundaries. Regulatory actions on vessels have heightened the attention of policymakers in the maritime sector towards pollution caused by energy consumption. Another key factor emphasizing the importance of energy management in the maritime industry is the rising cost of bunker fuel. Compared to the 1980s and 1990s, bunker fuel prices have increased by 75%, now accounting for between 43% and 67% of a ship's operating costs (Schroten et al., 2024). This shift has led to greater emphasis on energy efficiency measures on ships, as fuel costs are expected to continue rising in the long term, creating an evolving managerial challenge (Sogut, 2023). This scenario, along with the regulations set by the International Maritime Organization (IMO), calls for a well-established managerial organizational structure. Indeed, sectoral obligations demand more effective measures, and in response to these challenges, there is an increasing emphasis on data collection regarding fuel consumption, CO<sub>2</sub> emissions, speed optimization, and the maintenance of propulsion systems. These efforts are shaped by plans such as SEEMP (Ship Energy Efficiency Management Plan), reflecting growing awareness of energy efficiency on ships (Çetin & Sogut, 2021). Shipowners, operators, and crews are increasingly recognizing the need to monitor and reduce energy consumption, striving to comply with both environmental regulations and economic objectives.

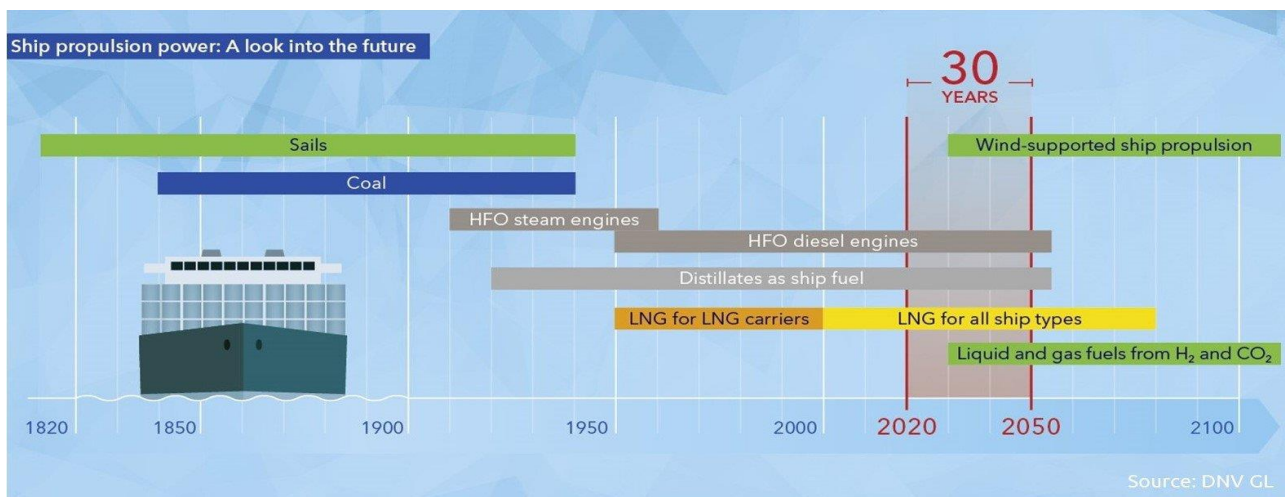
Among different types of vessels, chemical tankers stand out particularly in the context of energy management and efficiency. The share of chemical tanker capacity in ports has remained at high levels, around 46%, since late 2021, compared to approximately 42% before the outbreak of COVID-19. The congestion of chemical tankers has gradually increased since late 2020, particularly with rising congestion in East Asia and Europe. Additionally, disruptions caused by the war in Ukraine have intensified congestion in the Mediterranean and Black Seas. In Northwestern Europe, the gradual removal of Russian volumes transported by road has led to challenges in terminal capacity, struggling to accommodate recent increases in shipments. This mobility has drawn significant attention due to the high energy consumption associated with chemical tankers. These vessels operate predominantly in open seas and coastal areas, and due to high fossil fuel consumption and low efficiency, they contribute significantly to atmospheric pollution. The energy demand of chemical tankers is primarily driven by complex systems such as cargo transfer, heating, and inert gas systems, which increase fuel consumption and emissions. However, literature indicates that energy efficiency in these systems is addressed through various conceptual approaches. For instance, Baldi et al. (2014) proposed a method to analyze ship energy systems applied to chemical tanker operations. The analysis identified key energy flows and system inefficiencies, with exergy analysis highlighting potential waste energy recovery in exhaust gases, showing that up to 18% of engine power could be recovered. The results emphasized that propulsion was the largest energy consumer (70%), followed by auxiliary heat (16.5%) and power (13.5%). In contrast, Vasilev et al. (2025) examined the challenges of achieving compliance with EEXI, EEDI, and CII standards for tanker energy efficiency. Although the regulations improved efficiency, they found that only 14.8% of vessels met the EEXI standards, with smaller vessels requiring more significant power reductions. The study also showed that tankers operated at less than 60% of their engine power and 8% slower than their design speeds. Sogut (2024) used data from a two-stroke diesel engine to assess the impact of eight alternative fuels on energy and environmental sustainability. Entropy-based thermodynamic analyses for five operations were performed using two indices developed to evaluate environmental impact, assessing the decarbonization of the sector. It was found that the use of liquid hydrogen resulted in an 18% reduction in fuel load. In terms of energy management, particularly in chemical tankers, it is crucial to assess the efficiency of key equipment such as the main engine, diesel generators, boilers, and cargo systems. Given their contribution to overall energy consumption, the effectiveness of these systems directly impacts the vessel's operational costs and environmental footprint. During port periods, fuel consumption increases due to the operation of energy-consuming systems in chemical tankers, such as inert gas systems, cargo transfer systems,

and steam generators for cargo heating. This highlights the importance of implementing efficient energy management practices. Therefore, evaluating and improving energy efficiency in chemical tankers is of critical importance for the overall sustainability efforts of the maritime sector.

Currently, there is a limited amount of research regarding energy studies and the manageable framework for chemical tankers. Specifically, the necessity of a direct and sustainable institutional process for energy management on ships is an imperative requirement. This study conducts an energy audit based on a chemical tanker reference, evaluating the vessel's energy efficiency performance.

## 2. Shipping's Role on Energy Management for Decarbonization

Maritime transportation plays a crucial role as the backbone of global trade, but it also holds a significant share in carbon emissions. Globally, maritime transport accounts for approximately 2-3% of total CO<sub>2</sub> emissions, a proportion that is increasingly emerging as a growing concern. In this context, energy management is a critical element for the success of decarbonization efforts in the maritime sector. The IMO's target to reduce emissions from shipping by 50% by 2050 has further emphasized the importance of energy efficiency strategies and management practices in the industry (Trivyza et al., 2020). Indeed, as shown in Fig. 1, this transition process indicates that the sector's preference is increasingly focused on LNG.



**Fig. 1.** Sectoral Decarbonization Framework (Dekker, 2021)

Energy management in ship operations and maritime transportation aims not only to reduce fuel consumption but also to minimize environmental impacts. Ship owners and operators are taking steps to reduce carbon emissions by adopting environmentally friendly technologies and energy-efficient operational practices. One of the key elements of energy management is optimizing vessels to improve fuel efficiency. This involves various strategies, including optimizing the ship's speed, considering environmental factors such as wind and currents, implementing energy recovery systems, and utilizing next-generation, lower-emission engine technologies. Energy efficiency also provides economic benefits by reducing operational costs for vessels. Especially with rising bunker fuel prices, the savings achieved through energy efficiency offer a significant competitive advantage for ship operators (Yuan et al., 2023). Additionally, the use of low-carbon alternative fuels and improvements in ship design are crucial factors contributing to the decarbonization process in maritime transportation. For example, alternative fuels such as liquefied natural gas (LNG) and ammonia are playing a significant role in reducing emissions by replacing traditional fossil fuels. To meet the targets set by the IMO, innovative research and developed technologies in energy management and efficiency are accelerating the transformation process within the industry (Liu et al., 2024). Furthermore, it is emphasized that ship operators and industry stakeholders must take on greater responsibility for monitoring, reporting, and managing carbon emissions. Plans such as the SEEMP guide ship operators in achieving energy efficiency goals and systematizing monitoring processes. These plans help develop strategies for more efficient operations by monitoring a vessel's energy consumption. The maritime sector plays a vital role in achieving decarbonization through energy management. Efforts to reduce carbon emissions provide significant advantages in terms of both environmental sustainability and economic efficiency (Godet et al., 2023). This process requires the collaboration of all stakeholders in the industry and the development of innovative solutions.

IMO regulations play a significant role in shaping the manageability of energy in the maritime sector, which is based on fossil fuel consumption. Specifically, new regulations related to MARPOL Annex IV and the Reduction of Carbon Emissions in the Open Sea have made the adoption of various technological innovations mandatory in order to limit carbon emissions from ships and reduce environmental impacts (Akac & Anagnostopoulou, 2024). IMO's carbon emission targets for 2030 and 2050 have also directed ship operators towards energy efficiency-enhancing systems. While these targets have made technological change essential, it has become inevitable for ships to reassess how they manage energy and prioritize efficiency as a key step. Indeed, efforts to increase engine efficiency, transition to alternative fuel systems, and develop ship designs that promote energy efficiency can be seen as significant steps to comply with the regulations set by the IMO.

Energy Management Systems (EMS) on ships and the mandatory SEEMP within the industry are crucial for ensuring compliance with IMO and MARPOL regulations. However, energy management must be based on a disciplined process management approach. Such systems provide ship operators with significant advantages in monitoring, optimizing energy consumption, and improving performance (Wang et al., 2024). Moreover, low-emission technologies, energy storage systems, and the integration of renewable energy sources offer vital tools for ship operators to achieve sustainability goals in the face of pressures from IMO regulations. As a result of these regulations, the maritime sector has adopted a more transparent and innovative approach to energy efficiency and environmental responsibility (Jasmi & Fernando, 2018). Notably, in July 2011, the International Maritime Organization (IMO) introduced mandatory measures aimed at increasing the energy efficiency of international shipping during the 62nd session of the Marine Environment Protection Committee (MEPC 62) (Shi, 2016). One of the key outcomes of these decisions was the adoption of the first global energy efficiency standard for the maritime sector, known as the EEDI, which aims to reduce greenhouse gas (GHG) emissions. This index consists of technical requirements applied to new ships, setting a minimum energy efficiency level based on CO<sub>2</sub> emissions per ton-mile, depending on ship type and size. Additionally, the SEEMP is designed to enable ship operators to monitor and manage ship performance as an operational measure to cost-effectively increase energy efficiency. The primary objective of these mandatory regulations is to ensure the construction of ships that are 30% more energy-efficient than those built in 2014 by the year 2025 (Baroudi et al., 2021).

Sectorial expectations have been defined as improving energy efficiency and reducing fossil fuel consumption and environmental impacts on ships. Indeed, the largest source of greenhouse gases in maritime transport is the burning of fossil fuels to generate energy. However, energy efficiency on ships can be achieved through processes that include several simple steps, from the design phase to operation and monitoring stages. The IMO, by developing the concepts of EEDI and SEEMP during MEPC 62, aimed to enhance energy efficiency in both new and existing ships at the design and operational levels. These measures not only enable ships to operate more sustainably but also prioritize the reduction of operational costs and environmental pollutants. The IMO's energy efficiency processes focus on reducing fuel consumption and greenhouse gas emissions in the maritime industry. Key initiatives like the EEDI and SEEMP aim to enhance energy efficiency through design improvements and operational practices. These processes apply to both new and existing ships, encouraging sustainable design, continuous monitoring, and performance optimization. By implementing these measures, the IMO seeks to promote environmentally responsible shipping while reducing operational costs and the industry's overall environmental impact. All of these processes have, in fact, emerged as steps that support the change targeted by the IMO, as illustrated in Fig. 2.

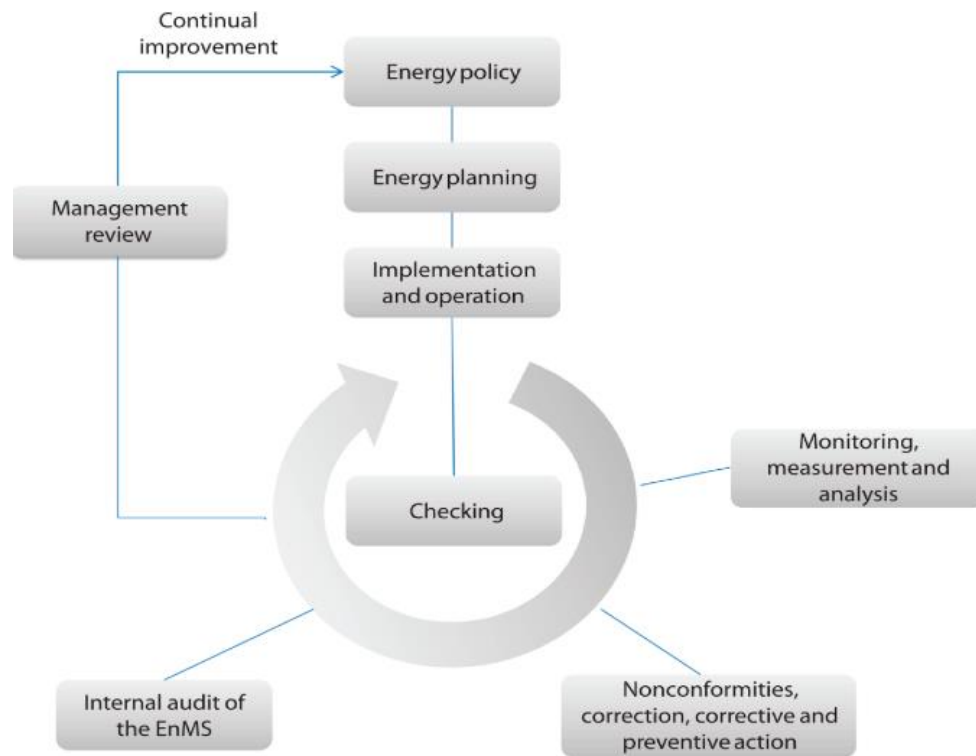


**Fig. 2.** IMO's Energy efficiency processes (KPMG, 2021)

### 3. Energy Audit and Management

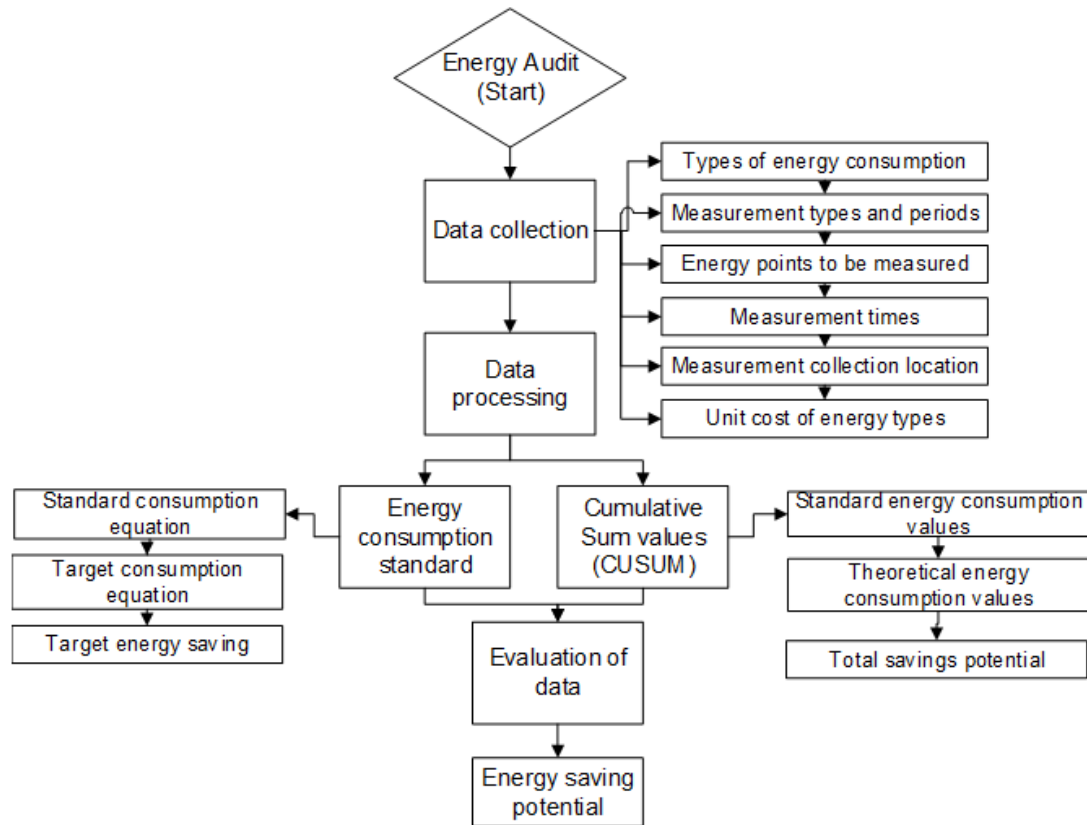
#### 3.1. Holistic Framework

Energy management on ships, in conjunction with the SEEMP, incorporates a structural perspective that contributes to the effective management of energy due to energy costs and environmental impacts. In ship operations, the priority is to develop a sustainable energy management model based on energy efficiency without causing operational disruptions. Regardless of whether a vessel has an institutional model such as the ISO 50001 Energy Management System, ship operators must establish an infrastructure to continuously monitor the points of highest energy consumption. These monitoring processes are based on minimizing risks that could affect operational processes and collecting energy data. In maritime operations, energy consumption is often monitored based on data derived from specific sailing conditions or previous operational habits, or according to institutional standards. However, this typically leads to an evaluation based on prior performance or specific sailing references, rather than the actual outcomes of ship energy efficiency. Maritime operations are influenced by numerous external factors, particularly weather conditions and routes, which can directly impact energy consumption and operational efficiency. Energy management should aim to achieve continuous improvement in energy consumption without compromising service and operational efficiency. In particular, the ISO 50001 Energy Management System provides an institutional framework that supports continuous improvement in energy efficiency under all circumstances. This system, as outlined in Fig. 3, aims to ensure the effective management of energy in ship operations, based on a cyclic process.



**Fig. 3.** Energy management system (EMS) cycle (International Organization for Standardization, 2011)

The ISO 50001 Energy Management System establishes the corporate energy management infrastructure in ship operations while defining the scope and boundaries of ship operations. In line with these definitions, the ship's significant energy consumers and current energy status should be analyzed. Within this framework, it is generally recommended to conduct a preliminary survey for ship energy management. The preliminary survey, also known as an energy audit, helps determine the ship's energy efficiency performance. The energy audit may vary depending on the ship's type and operational characteristics, but within the defined scope and boundaries, a detailed analysis should be conducted for significant energy consumers based on the types of energy used. As discussed in this study, an energy audit for a ship is examined in detail according to the methodology defined in Fig. 4.



**Fig. 4.** Flow schema of energy audit

An important phase in energy auditing on ships is the data collection process. This process forms the core data elements of energy management and must be approached with precision. Energy management must define the types of data to be collected, the structure of this data, collection points, and methods. Additionally, the characteristics of the data, types of measurements, and measurement periods and durations must also be specified. Data security and validity are of paramount importance during this process; therefore, calibration of measuring devices should be ensured, and data collection should be carried out on a regular schedule. During data collection periods, recurring behaviors and operational conditions play a critical role in energy consumption evaluations. Thus, sufficient data must be obtained for each selected period, and typically, the number of data sets should not be fewer than ten. In ship operations, energy management systems should continuously monitor and define the data collection process. For example, for weekly measurements, the collection period should be at least ten weeks, and for monthly measurements, data should be collected annually (UNIDO, 2015). In energy-intensive operations, such as those found in ship operations, data flow can be continuously monitored via SCADA (Supervisory Control and Data Acquisition) systems (Gnana et al., 2024). However, different methods may also be developed for non-production energy consumption data and low-energy-consuming structures. This allows the ship's total energy consumption to be accurately tracked, facilitating improvements in efficiency.

### 3.2. Energy Audit

In ship operations, data collection processes related to energy sources such as electricity and liquid fuels should be defined in a common unit. These data should be subjected to a conversion process before analysis or the monitoring system should be established in line with this structure. The data collected in ship operations are processed and analyzed using an energy consumption standard or cumulative total values approach. The energy consumption standard related to operational processes on ships are defined based on the difference between the current energy consumption of the operation or process and the target energy consumption, as well as the energy performance index. Ship operations are influenced by many variables, which can be classified into two main groups: specific and controllable variables. Specific variables are factors that directly impact the ship operations and determine energy demand. For example, factors such as the ship's speed, sailing time, the cargo it carries, and the route directly affect energy consumption. The standard equation that defines the relationship between

energy and these variables are dependent on them (Sogut, 2009). Controllable variables, on the other hand, include factors such as energy systems outside the ship, operational practices, system control, and maintenance standards. These variables are planned and optimized by ship management to minimize energy consumption. Generally, such standard equations are formulated as linear equations, demonstrating that energy requirements are dependent on specific variables. These equations are used to enhance operational efficiency in ship energy management and optimize energy consumption.

$$E = a + b(P) \quad (1)$$

E–Energy (kWh)

a and b–Constants

P–Variable or output

For ship energy efficiency and audit, three different linear equations commonly used in energy management applications related to energy consumption can be employed. However, the equation preferred in this study is the fundamental linear equation that directly evaluates the relationship between ship operations and energy consumption.

In energy audits, regression analyses based on energy consumption data are used to first determine the standard equation. This linear equation forms the basis for setting targets by considering the ship's energy consumption processes. For ship operations, this analysis can be extended to encompass all operational processes. The linear equation calculated based on target values will be in the same form as the standard equation. According to the target conditions, expected energy consumption on the ship should be calculated and compared with the current situation. Evaluations regarding unit energy consumption such as tons/consumption, rpm/consumption, knots/consumption are an important issues in ship management. However, for ships operating in a one-directional manner, energy consumption is typically defined through Specific Energy Consumption (SEC). On ships, SEC is usually expressed as the energy consumed per unit load or per variable. This can vary depending on the defined variable characteristic of the ship. SEC is an important parameter in measuring the ship's energy efficiency, and by calculating customized energy consumption values for each ship operation, efficiency targets can be achieved.

$$SEC = \sum \frac{E_c}{P_o} \quad (2)$$

SEC–Specific Energy Consumption (kWh/unit)

$E_c$ –Energy Consumption (kWh)

$P_o$ –Load, or variable (Unit)

In terms of energy audits on ships, the SEC value can be used as an indicator for the ship. An increase in the SEC value may indicate poor performance in ship operations related to energy sources and control issues in energy consumption. However, for such evaluations, energy management must conduct more comprehensive analyses to verify the validity of the defined framework. The energy efficiency performance of ships should be addressed not only with the SEC value but also through a broader data set and a systematic approach.

Another important parameter used to evaluate energy performance is the Cumulative Sum (CUSUM) graph. CUSUM is an analysis method that identifies potential energy savings using the least squares method and cumulatively sums them. These cumulative values help create a graph that reveals the energy-saving potential at the end of a specific period. The CUSUM graph shows the differences between the ship's target energy consumption and actual energy data, determining energy flow trends. The CUSUM graph is created using the cumulative sum of the differences between the ship's energy consumption data and the target consumption data. This graph visually presents the ship's energy-saving potential or changes in energy consumption. Negative regions or values indicate improvements in the ship's energy efficiency, while positive values signal a deterioration in energy consumption (Kedici, 1993).

To create a CUSUM graph, the cumulative sum of the difference between the ship's energy consumption and the target energy consumption must first be calculated. This calculation forms the basis of the ship's energy efficiency management and clearly highlights the differences between the targeted and actual energy consumption.

$$\sum \dot{E}_{c,total} = \sum \dot{E}_{c,con} - \sum \dot{E}_{c,target} \quad (3)$$

$E_{c,total}$ –Cumulative total

$E_{c, con}$  – Real consumption value

$E_{c, target}$  – Target consumption value

For defining the cumulative total savings potential, target consumption and costs are important parameters as key data. Accordingly, the potential target energy consumption.

$$\sum E_{target} = \sum E_{con} (1 - \alpha) \quad (4)$$

$E_{target}$  – Target consumption

$E_{con}$  – Real consumption

$\alpha$  – Energy efficiency rate

For energy audits on ships, the CUSUM graph is an important tool that allows for the examination of both target energy savings and energy savings costs for each collected data point (Sogut, 2009). This graph plays a critical role in achieving energy consumption goals and ensuring cost-effectiveness in ship operations. The CUSUM graph provides essential data for monitoring energy consumption and calculating potential savings, thereby enabling more effective energy efficiency improvements and cost management in ship energy management.

### 3.3. Exergetic Framework

In energy flows, the quantitative structure of the mass form is insufficient to define irreversibility and the environment. Energy is related to the environment in which it is located and the irreversibility rates vary accordingly. In energy system analyses, the maximum work that can be obtained for the environmental conditions in which it is located is expressed directly by exergy and the general exergy balance is as follows.

$$\sum (1 - \frac{T_0}{T_k}) \dot{Q}_k - \dot{W} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{dest} = 0 \quad (5)$$

$\dot{Q}_k$  is the heat transfer rate including to come over from boundaries of the process,  $E_x$  refers to the exergy flow rate of the system,  $\dot{E}x_{dest}$  refers to the exergy destruction rate depending on the limits of the irreversibility. The exergy flow passing through the system boundaries depending on the surrounding conditions defines the physical exergy flow and this is ( $\psi$ );

$$\psi = (h - h_0) - T_0(s - s_0) \quad (6)$$

$\psi$  – Flow exergy (kJ/kg)

$h$  – Enthalpy (kJ/kg)

$T_0$  – Surrounding temperature (K or °C)

$s$  – Entropy (kJ/K.kg)

Exergy flow rate directly refers to the enthalpy ( $h$ ) and the entropy ( $s$ ) flow rate at the surrounding temperature ( $T_0$ ) (Cornelissen, 1997). The potential of irreversibility rate of the process, which is the surrounding influence, depends directly on the amount of entropy generation. The Gouy-Stodola theorem refers to that the surrounding influence for entropy generation is directly due to the irreversibility in the process and depends on the exergy destruction rate (Moran et al., 2011; Dincer & Rosen, 2012):

$$\dot{E}x_{dest} = T_0 \dot{S}_{gen} \quad (7)$$

$\dot{E}x_{dest}$  – Exergy destruction (kW)

$T_0$  – Surrounding temperature (K)

$\dot{S}_{gen}$  – Entropy generation (kW/K)

All energy processes, energy is consumed feature and their system performance is a function of their efficiency based on the energy flow rate between input and output flows.. In particular, also in exergy analysis, similar of the energy efficiency, the efficiency of systems depends directly on the effect of the net work produced from the exergy flow rate. In fact, the exergy efficiency of a system is defined by the standard flow rate between the inlet and outlet conditions of the flow processes. For this condition, exergy efficiency is (Moran et al., 2011);

$$\eta_{Ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (8)$$

$\eta_{Ex}$  –Exergy Efficiency

$\sum \dot{E}x_{in}$  –Total Exergy input (kW)

$\sum \dot{E}x_{out}$  –Total Exergy output (kW)

$\dot{E}x_{dest}$  –Exergy destruction (kW)

All energy systems are subject to an assessment in terms of their operational issues and potential for improvement considering irreversibility rate. An important sustainability indicator for reducing environmental impact is the potential for improvement in entropy generation. Improvement potential (IP) is as given below (Van Gool, 1997):

$$IP = (1 - \eta_{Ex})(\sum \dot{E}x_{in} - \sum \dot{E}x_{out}) \quad (9)$$

IP–Improvement rate (kW)

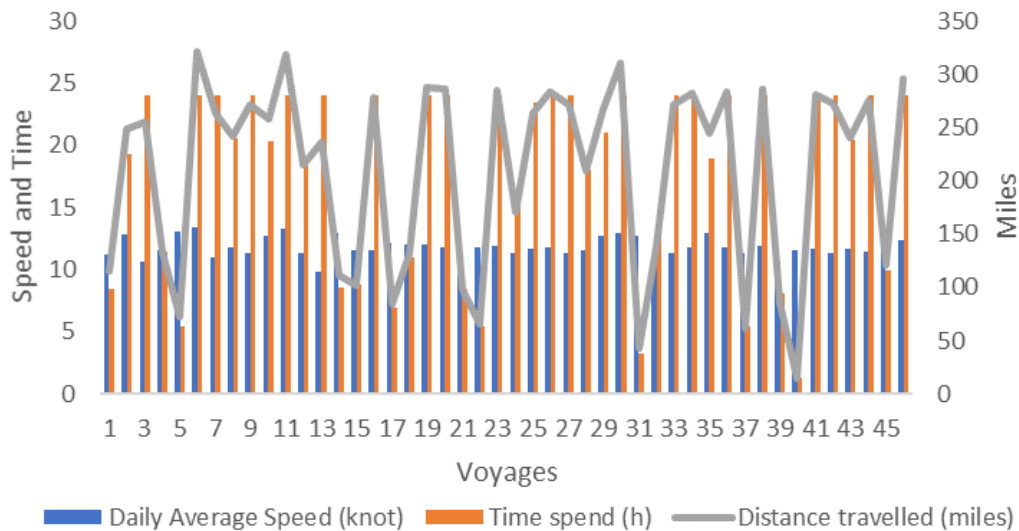
$\eta_{Ex}$  –Exergy Efficiency

$\sum \dot{E}x_{in}$  –Total Exergy input (kW)

$\sum \dot{E}x_{out}$  –Total Exergy output (kW)

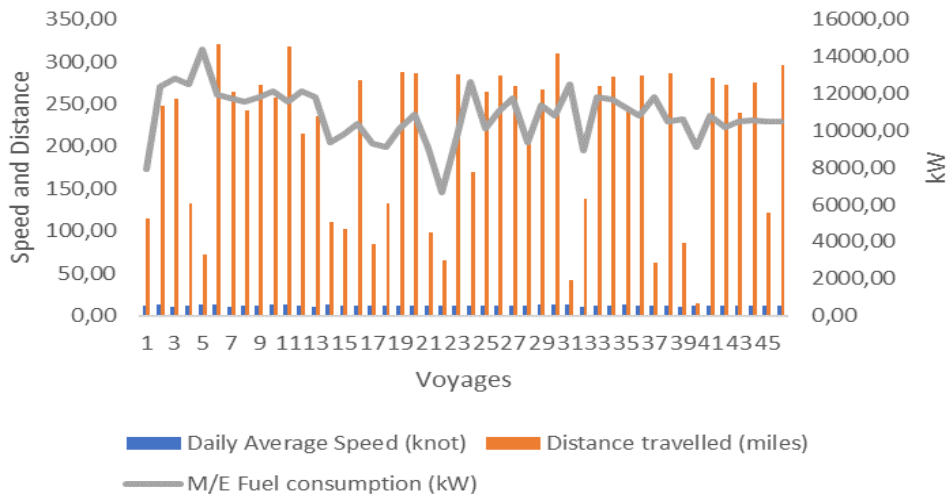
#### 4. Results and Discussion

In this study, the performance and environmental efficiency of energy management for a reference chemical ship were primarily considered, with a holistic assessment of energy consumption. The reference ship is a chemical tanker with a 6700 kW diesel engine, 180 meters in length, and a 37,000 DWT capacity, operating within the cabotage limits of Turkey. The ship's speed, distance, and daily values for 46 voyages are presented in Fig. 5.



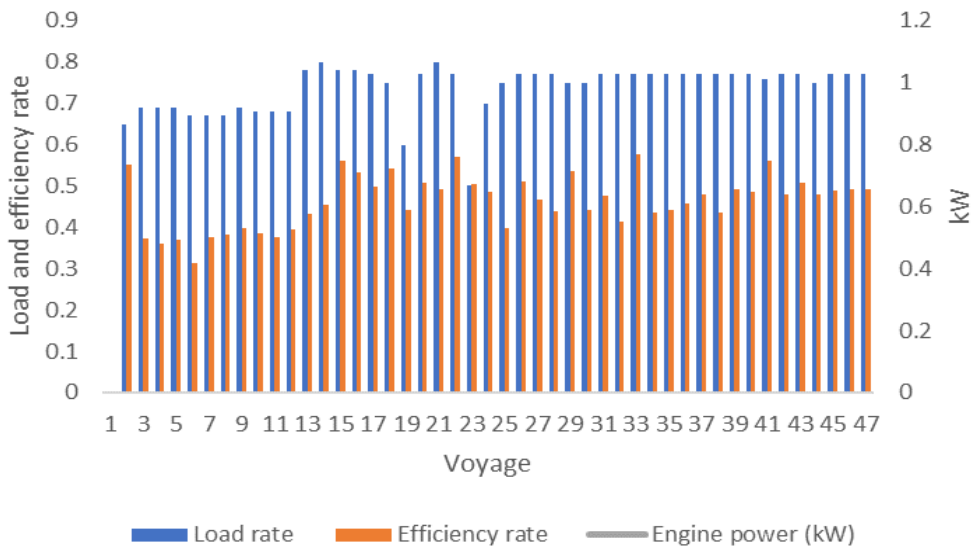
**Fig. 5.** The relationship between ship speed and distance travelled

When considering the ship's speed and distance data, the average daily speed is 11.28 knots, and the average distance traveled is 209.8 miles. The average time interval for the ship is 17.74 hours. The relationship between the ship's speed and time is directly associated with energy consumption. The relationship between speed, time, and energy consumption shows that as speed increases, the resistance applied to the water and energy consumption also rises. Specifically, the relationship between speed and energy consumption should be carefully considered. It should be noted that lower speeds positively contribute to energy efficiency, but they also result in time loss. These findings should be examined and assessed alongside energy management on ships. In Fig. 6, these values are provided for comparison for the reference ship.



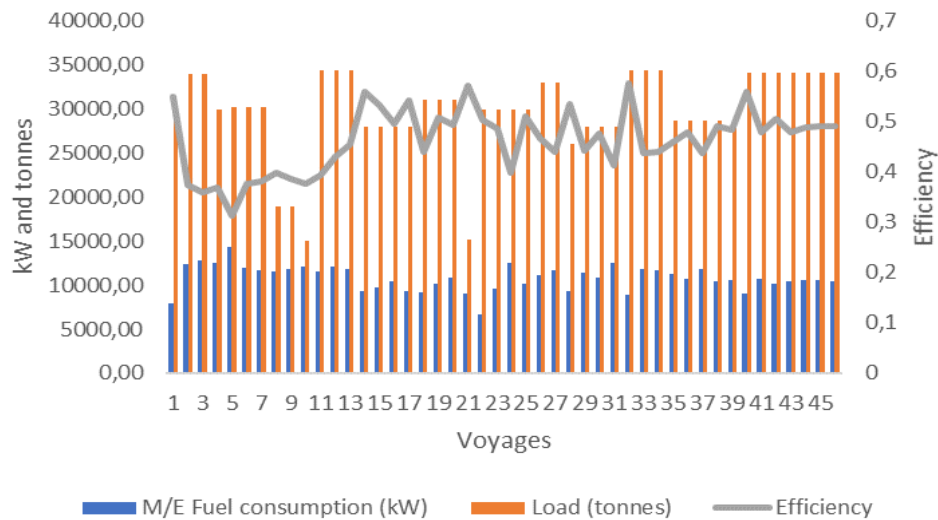
**Fig. 6.** Relationship between ship speed, distance and energy consumption

The ship's consumption behavior has been evaluated in conjunction with the distance. Specifically, the consumption values per mile under distance conditions were found to be 77 kW/mile. Based on these values, uncontrolled consumption behaviors are observed in the ship's operations. For instance, for the 40th voyage, the consumption per mile was identified as 605.41 kW. This value should not be evaluated in comparison to the ship's overall average in terms of consumption. Furthermore, six voyages with consumption levels exceeding 100 kW/mile stand out as particularly noteworthy. Developing a Key Performance Indicator (KPI) for the ship regarding its consumption should be a parameter to prioritize for evaluation. In this consumption trend, the ship's energy efficiency potential has been examined, and performance based on load rate has been analyzed, as shown in the graph in Fig. 7.



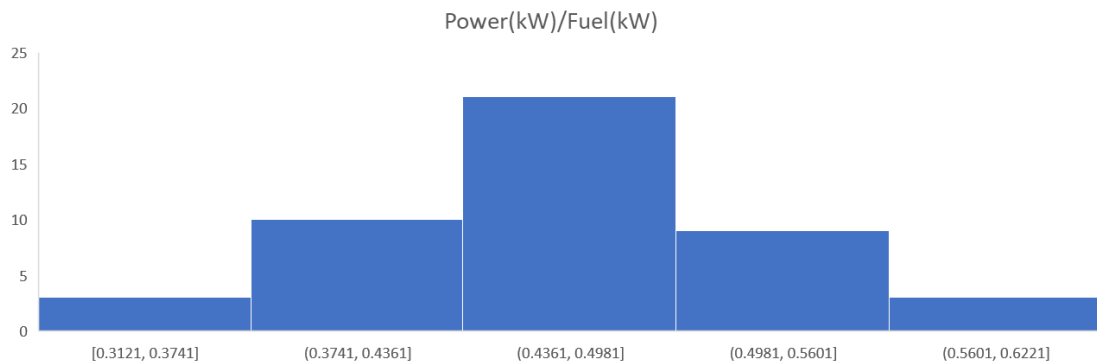
**Fig. 7.** Relationship between ship load rate and energy efficiency

The analysis shows that the ship's average load analysis is at a value of 73.65%, while its average efficiency is found to be 46.27%. This value has been evaluated alongside the engine's average power output of 4934.7 kW, and it has been observed that the ship's average load is 29,921.65 tons. When examining the ship's efficiency distributions, it is observed that it falls within the range of 31% to 55%. Within this framework, the relationship between the engine's consumption behavior and the load has also been assessed. The ship's total load range varies between 14,000 tons and 35,000 tons. The performance distribution of the engine for this load range has been analyzed and distributions given in Fig. 8.

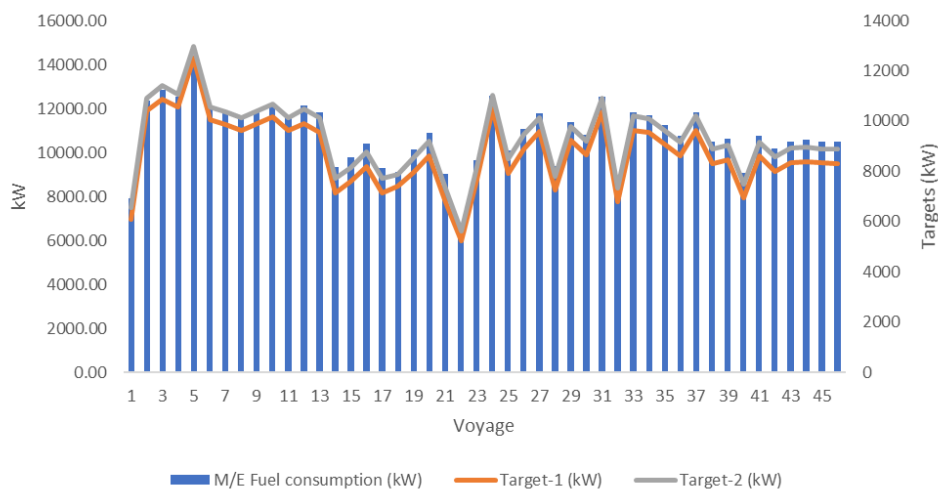


**Fig. 8.** The relationship between the ship's load rate and energy efficiency

The average consumption value based on the ship's energy efficiency rate and load distribution has been found to be 0.38 kW/ton. This value varies within the range of 0.26 kW/ton to 0.63 kW/ton. For these consumption behaviors, regression analyses were performed based on the defined criteria for the ship's energy efficiency analyses. However, the  $R^2$  value did not show any compatibility with the variables. In this context, the best consumption behavior was examined, and a histogram based on the Power/Fuel rate was created, with distributions presented in Fig. 9.



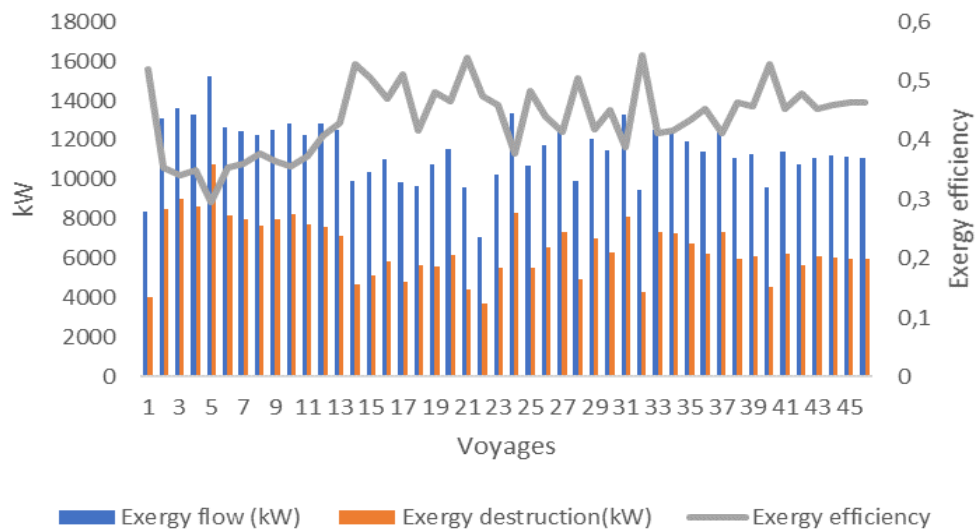
a. Power/Fuel histogram



b. Energy efficiency potential

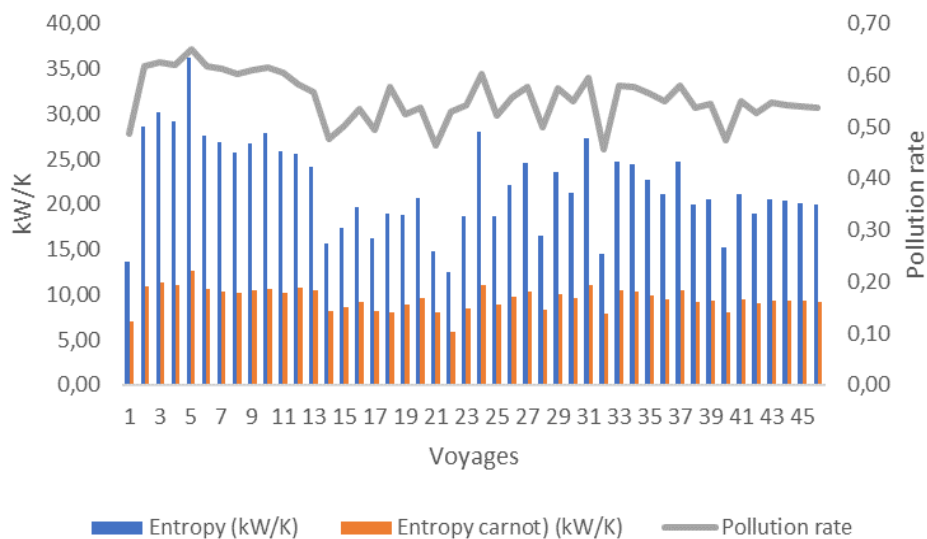
**Fig. 9.** CUSUM graph of histogram and target energy efficiency study

The CUSUM chart produces results that are directly formed by the differences between actual consumption and the target-based consumption expectations as given in Fig. 9(b), and are shaped by the least squares approach. This expectation is actually made for the cumulative total. However, it should be noted that in certain instances, the ship's consumption may fall short of initial expectations. In this study, a two-stage target was developed for the ship. The mean of the initial target unit power production was accepted as 0.422 kW according to the histogram given in Fig. 9(a), and the total fuel energy was calculated for each voyage accordingly. For the second target study, the unit consumption was taken as 0.312. In this efficiency evaluation, the average energy efficiency potential for target one was found to be 19.24%, and for target two, it was found to be 14.22%. These figures are contingent upon the operational capabilities. Based on this, the action steps for the ship's operational processes can be assessed gradually within the energy management framework. The environmental impact of the ship, according to these data, can be evaluated using exergy analysis, in equations (5–9) and a target for environmental pollution rate can be proposed. In this context, the ship's exergy efficiency has been first addressed, and the distributions are presented in Fig. 10.



**Fig. 10.** Exergetic parameters

The ship's average exergy efficiency indicates a potential of 43.65%, while the development rate based on exergy destruction has been calculated according to the generated exergy destruction. Based on the referenced voyages, the ship's improvement potential shows a potential of 31.75%. According to this value, the ship's environmental efficiency potential has been evaluated, and the distributions are presented in Fig. 11.



**Fig. 11.** Ship Entropy production and distributions

Based on the ship's consumption data, the produced entropy value is found to be an average of 1013.03 kW/K, while the thermal entropy potential (Carnot) of the ship's engine is 439.89 kW/K. According to the ship's overall consumption behavior, the pollution potential is found to be an average of 57%. Considering the improvement potential, the average efficiency potential in terms of total environmental pollution is 17.96%. Energy management, depending on the operational conditions of the ship, should consider developing an energy efficiency target based on either fuel-related consumption or environmental impact, alongside field studies. However, a stepped target has been proposed for the consumption histogram, reflecting the actual consumption values.

## 5. Conclusions

In this study, the performance and environmental efficiency of energy management for the reference chemical tanker were examined. The analysis revealed the relationship between the ship's speed, distance, and energy consumption, showing uncontrolled values and high consumption levels, particularly in terms of energy consumption per mile. This situation indicates that better management and optimization processes are required to meet the ship's energy efficiency goals. Additionally, the energy efficiency rate was defined in conjunction with the ship's load rate and consumption behavior. The environmental impact, based on entropy production, was also evaluated using an entropy-based approach. Moreover, the ship's energy efficiency rate was shaped according to its improvement rate.

The energy efficiency targets based on the histogram approach were found to be 8.80% for the first target and 32.58% for the second target. The energy efficiency analysis showed that the ship's improvement potential is 31.75%, while the average environmental pollution was found to be around 57%. Using the entropy approach, the energy efficiency rate of the ship was determined to be 17.96%.

To improve energy efficiency on ships, first of all, the operational operating data of important energy users should be reviewed together with the defined efficiency ratio. Especially in main engine consumption, air fuel ratio and air temperature are manageable tools. In addition, trainings based on the development of energy efficiency behavior culture on ships are also important. In addition, especially energy efficient technology change is also a process that needs to be planned.

The approaches set to optimize the ship's energy efficiency and environmental impact can be viewed as a new consumption-oriented approach for energy management on ships. This study suggests new areas for further research, such as making improvements in operational processes by focusing directly on the ship's targets. Evaluating the targets defined through operational processes is also proposed as a separate study. In addition, technology management and financial analyses are another suggested study for the development of investment priorities. In particular, a forecasting approach with artificial intelligence and time series for consumption management can be an effective study for energy management.

## Abbreviations

SEEMP	: Ship Energy Efficiency Management Plan
EEXI	: Energy Efficiency Existing Ship Index
IMO	: International Maritime Organization
ECAs	: Emission Control Areas
EEDI	: Energy Efficiency Design Index
CII	: Carbon Intensity Index
LNG	: Liquefied Natural Gas
MEPC 62	: 62nd session of the Marine Environment Protection Committee

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Research Article

## Modeling of a Complex Digital Air Data System for Measuring Attitude and Flight Direction of Aircraft

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### Abstract

The process of measuring attitude, yaw and drift signals of aircraft using aerometric methods becomes especially important during intercontinental flights, when GNSS is inoperative, GNSS denial during intercontinental flights limits attitude and drift measurement. To determine the values of the aircraft's pitch, roll, yaw angles, by the aerometric system the new method and modified smart probe should be used and a new method using a smart probe within a digital air data system (CDADS) is proposed. Theoretical foundations for the operation of a comprehensive complex digital air data systems are presented and a computer model for determining flight and navigation parameters is compiled, a comparison of the results of modeling the complex digital air data systems computer model and literature data was obtained, a mathematical model and computer simulations are developed obtaining information on flight and navigation signals, including additional parameters such as roll, pitch, yaw, lateral speed, wind velocity, drift angle are compiled, and a computer model simulation is performed.

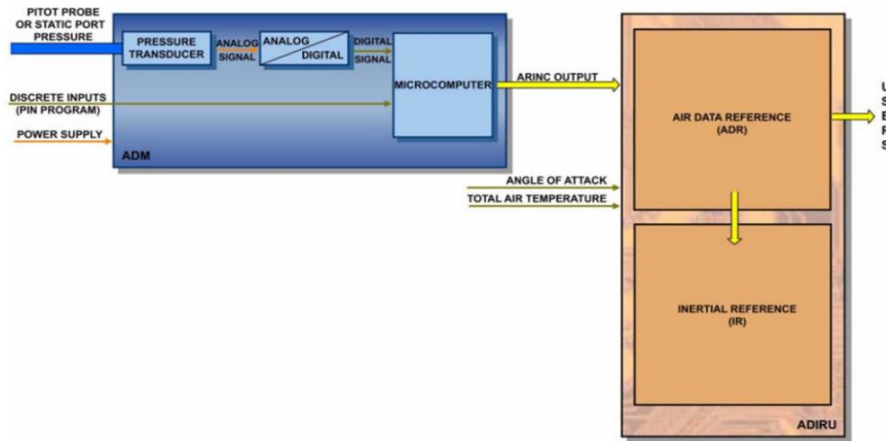


## 1. Introduction

The importance of avionics systems in aviation cannot be overstated. They are critical to the efficiency and safety of flight (Oxford Aviation, 2001).

The Air Data Inertial Reference Unit (ADIRU) is one of the most important systems in modern aircraft. Critical flight parameters such as the aircraft's attitude (roll, pitch, and yaw), airspeed, altitude, and even its orientation in space are measured by this system (Lerro & Battipede, 2021). The ADIRU helps maintain flight stability by collecting and analysing data from multiple sensors, including gyroscopes and accelerometers, especially in challenging situations such as poor visibility or turbulence. Without such reliable systems, flight safety risks would increase significantly (Airbus S.A.S., 2003).

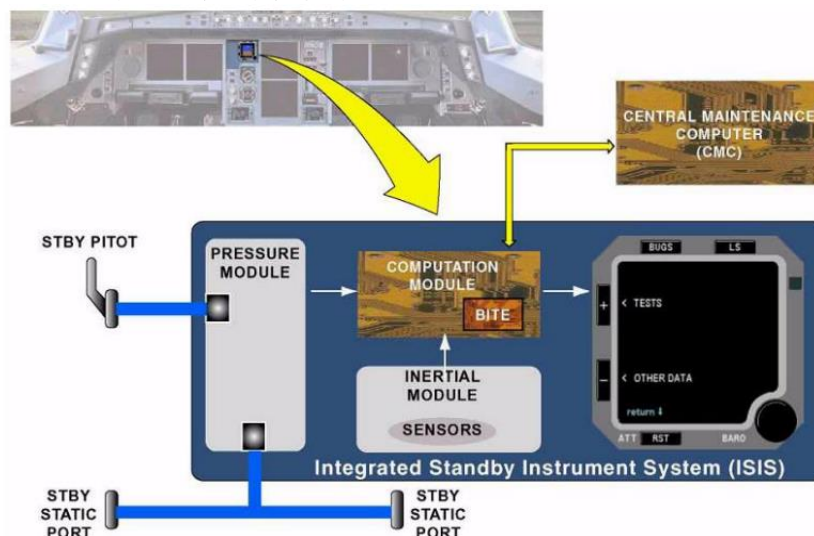
The ADIRU installed in the Airbus A-340 aircraft is part of a complex system composed of air data blocks (Air Data Reference) and inertial parameter blocks (IR) (Fig. 1).



**Fig. 1.** Airbus A-340 ADIRU

This allows for automatic adjustment of the combined parameters of the Air Data System (ADS) and inertial systems (IS). The integrated system contains three computers (ADR1, ADR2, ADR3), each connected to an Air Data Module (ADM), which measures total and static pressure. These ADM converters, which are connected to pressure transducers, essentially convert non-electrical quantities into digital signals. Computers ADR1 and ADR2 calculate the average pressure values from sensors located on the left and right sides of the Airbus A-340 fuselage (Airbus S.A.S., 2003).

Using signals from backup pressure sensors, computer ADR3 computes the altitude-speed parameters of the aircraft. The ADR1, ADR2, and ADR3 computers also receive signals from angle-of-attack sensors (AOA1, AOA2, and AOA3 sensors) and from external air temperature sensors (Capt. TAT sensor and F/O TAT sensor). Additionally, backup total and static pressure sensors (STBY pitot probe and STBY static port) are connected to the inputs of the Integrated Standby Instrument System (ISIS) (Fig. 2).

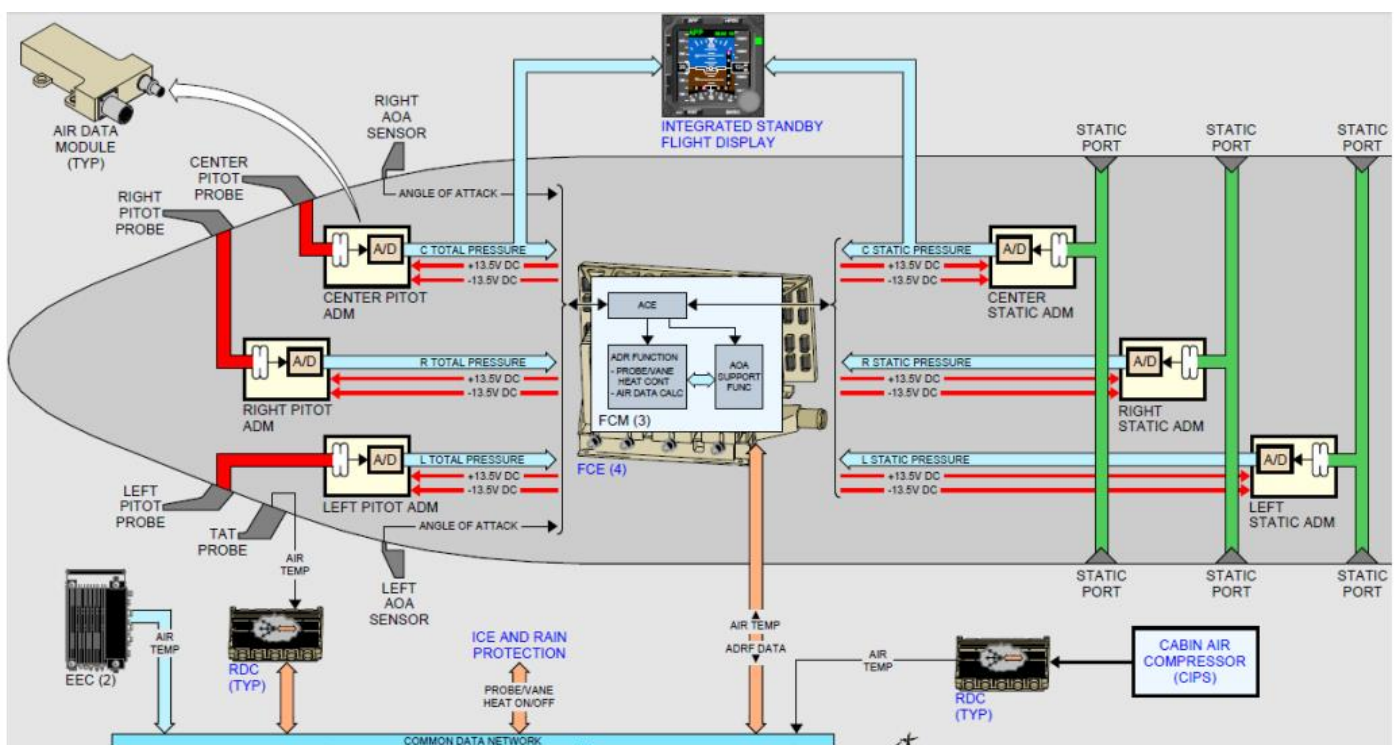


**Fig. 2.** A-340 Intergrated Standby Instrument system (A340 manual)

In the ISIS, the total and static pressures are converted into encoded digital electrical signals, which are then compared with digital signals from the inertial module.

A similar integrated system of air parameters and inertial navigation parameters is used in the Boeing 747-8 (The Boeing Company, 2015). The ADIRU system installed on these aircraft is made by the company Honeywell. However, the ADS instruments on the Boeing 747-8 differ from those of the Airbus A-340 in that the Boeing 747-8 additionally installs two static pressure ports with tubes in the tail section of the fuselage. These are intended to connect to the altitude control computer.

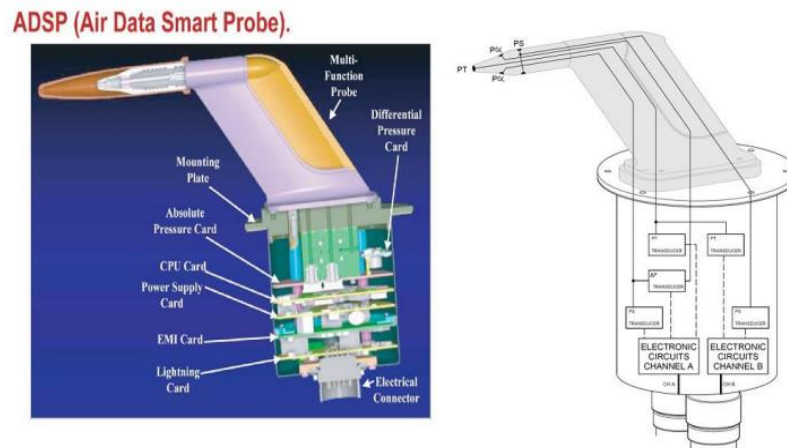
The non-integrated ADS of the Boeing 787 (Air Data Reference System - ADRS) differs in that total and static pressure information is sent through the CENTER PITOT PROBE, LEFT PITOT PROBE, and RIGHT PITOT PROBE to the Air Data Module (ADM), where it is converted into digital signals through analogue-to-digital converters (The Boeing Company, 2010). These signals, together with analogue signals from the angle-of-attack sensors installed on the left and right sides of the fuselage, are sent to the flight control module (FCM3). Digital signals from static pressure sensors connected to the STATIC PORT are also sent to the inputs of the ADM modules (Fig. 3).



**Fig. 3.** Boeing 787 Air data Reference System (ADRS)

The Air Data Smart Systems (ADSS) installed on the Embraer ERJ-170/190 aircraft consists of four Air Data Smart Probe (ADS1-ADS4) and two external air temperature sensors (TAT1, TAT2), as well as a control panel (Embraer, 2011; SmartProbe, 2017). The ADS probes are multifunctional, handling channels for total, static, and differential pressures. For vaneless angle-of-attack measurement, the differential pressure channel is used. The signals from the pressure frequency converters and ADC are connected to the Air Data Computers (ADC), forming a unified ADS system and providing additional information to the aircraft's flight control and anti-stall systems.

The ADC computer system includes a Modular Avionics Unit (MAU). Digital signals from the total, static, and differential pressures, as well as the external air temperature sensors, are sent directly to the Air Data Application (ADA) processor, which is part of this module. The system automatically adjusts current flight altitude and speed values. ADS1 serves as the primary source of information for the first pilot's flight-navigation instruments and flight control system, ADS2 for the second pilot's instruments, and ADS3 for backup instruments and the flight control system. Additionally, a fourth information source, ADS FC (Air Data Systems of Flight Control), supplies the flight control system with current air data signals. All information received from the probe, as well as data processed by the system, is displayed on the primary flight displays (PFD) and the Integrated Electronic Standby Instrument System (IES) (Miftakhov et al., 2023).



**Fig. 4.** Air Data Smart Probe of the Embraer ERJ-170/190 aircraft

Fig. 4 shows the general and structural diagrams of the Aid Data Smart Probe (ADSP) used in Embraer ERJ-170/190 (Embraer, 2011; SmartProbe, 2017).

Total pressure ( $P_t$ ) is measured by a probe in the shape of a truncated cone, with a hole at its front end along the axis of symmetry. Static pressure ( $P_s$ ) is measured by a probe in the shape of a straight tube with symmetrically placed holes at the top and bottom. Angle-of-attack data is derived from the differential pressure ( $P_\alpha$ ) measured through two holes symmetrically placed on the upper and lower surfaces of the truncated cone. The calculations performed by the ADSS computer generate an informational picture, including corrected values for static and total pressures, dynamic pressures, total and static air temperatures, barometric corrections, barometric altitude, corrected barometric altitude, current altitude changes, indicated and calibrated airspeeds, true airspeed, maximum operating speed, current Mach number, and angle of attack. The ADSS computer inputs are connected to pressure frequency converters, which are electrically connected to the corresponding pressure probe (Eski et al., 2023).

The analysis of the structural, functional, and operational characteristics of a range of ADS from different types of aircraft allows us to conclude that, despite their indisputable effectiveness, the systems also have certain drawbacks. These include the inability to generate information about roll, pitch, and yaw angles, as well as the measurement of the aircraft's lateral speed using the aerometric method.

The process of measuring attitude, yaw and drift signals of aircraft using aerometric methods becomes especially important during intercontinental flights, when GNSS is inoperative. To improve the reliability and accuracy of the obtained flight parameter information, as well as to enhance the efficiency of determining measurement method errors, it is advisable to use several redundant sources (both primary and backup) whose sensors operate on different physical measurement methods. For example, if the aircraft is flying in conditions where there is no connection with navigation satellites, ground-based radio navigation, and air traffic control systems (such situations arise during flights over oceans, the Earth's poles, or high, extensive mountain ranges), then, in these cases, the aircraft is entirely controlled by its autonomous inertial system. This places additional demands on the system's operational reliability and information precision (Derevyankin et al., 2022).

Based on this, it can be concluded that, despite the relatively high technological level of modern aircraft ADS, there remains the issue of more reliable and precise determination of flight navigation parameters such as roll, pitch, yaw, and lateral speed using aerometric measurement methods. On the other hand, the development of such a multifunctional CADS could provide the aircraft's onboard control system with an additional channel of information about current flight values and environmental conditions, which would undoubtedly improve the reliability and accuracy of flight control information, especially when there is no reliable connection with ground and space-based navigation systems.

## 2. Method

To achieve a stable level of providing flight navigation information, especially in areas with uncertain satellite navigation signal reception or even in cases where such signals are completely absent, it is necessary to use alternative techniques and tools for flight navigation measurements that allow for autonomous resolution of

relevant tasks. Among them are the so-called aerometric methods, which provide highly reliable and precise information about flight parameters, such as, attitude, angles of attack and side slip, which determine the corresponding flight navigation characteristics of the aircraft.

In other words, aerometric methods of measuring air signals form an effective scientific and technical base for developing high-tech tools for measuring fundamental flight navigation signals, such as devices for measuring roll, pitch, yaw angles and drift of the aircraft, as well as systems for controlling and monitoring vertical and horizontal flight speeds.

One such device, operating since aerometric measurement methods, consists of a movable vane, a heater, and a housing, inside which the measuring circuit is placed. The device generates an electrical signal corresponding to the value of the angle of attack, which is formed by converting the mechanical rotation of the vane, depending on the aircraft's angle of attack, into the corresponding electrical quantity.

The vane is a streamlined symmetrical body of wing-like shape that rotates around its axis in accordance with the direction of the airflow, resulting in an aerodynamically balanced state. However, besides its ability to determine only the values of the angle of attack and slip, this device has drawbacks such as reduced sensitivity and increased instrument errors caused by friction during its rotation.

It is known that on aircraft models such as Airbus A318/319/320/321, A340-500/600, Boeing 747-8, Boeing 767, Boeing 787, which are equipped with aerometric measurement systems, four (three on the Boeing 787) total pressure tubes and six static pressure ports are installed, along with two air temperature sensors and angle-of-attack sensors with two vanes and heaters. In the corresponding blocks and computers, operations such as calculation, heating of pressure sensors, temperature and angle of attack measurement, as well as monitoring malfunctions in the air signals determination system, are performed.

The air data determination systems generate information that contains data on static, dynamic, total and effective pressures, as well as static and total air temperatures, barometric altitude and its rate of change, indicated speed, calibrated and true airspeed, maximum operating speed, Mach number, and angle of attack.

However, such systems are unable to measure pitch, roll, yaw angles, drift which is a significant disadvantage of the aerometric method, since there are strict limits for these angles on aircraft. It should be noted that in the most modern and advanced air signals measurement systems based on the application of the aerometric method, it is possible to obtain information on the following signals: barometric and relative altitude, vertical speed (by measuring static pressure, which changes depending on flight altitude); indicated speed and Mach number (by measuring dynamic pressure, which changes depending on the change in flight speed); air temperature; true airspeed (by measuring static and total air pressures); and the aircraft's angle of attack (by measuring differential pressure).

In the newest civil and military fifth-generation aircraft models, such as the Airbus A380, A350, A400M, Embraer 170/190, Bombardier Learjet 85, Boeing C-130 AMP, Boeing X-45C, Lockheed Martin F-22, F-35, Northrop Grumman X-47B, Sikorsky X2, the products of GOODRICH, UTC Aerospace Systems are successfully used—systems for measuring air data signals based on the aerometric method – Air Data Smart Probe, where several smart probe (from two to four) are used as primary sources of information to measure air signals, as well as two sensors to measure the total air temperature (SmartProbe, 2017).

In the aerometric system under analysis, there is no capability to measure static pressure at the tips of the aircraft wings or at the tail section of the fuselage, which is determined by the structural layout of its components. This leads to the inability to obtain information about pitch, roll, yaw angles, and lateral speed, which is undoubtedly a significant disadvantage of the considered air data signals measurement system.

In this regard, conducting relevant scientific research aimed at further improving the functional and operational characteristics of the pressure receivers and air signal measurement systems currently used on aircraft seems to be a very relevant and therefore in-demand task. At the same time, of particular interest is the development of such an air signal system in which it would be possible to generate operational information on such important flight and navigation parameters as bank, pitch, yaw and attack angles, as well as lateral speed using pressure sensors appropriately placed along the aircraft profile.

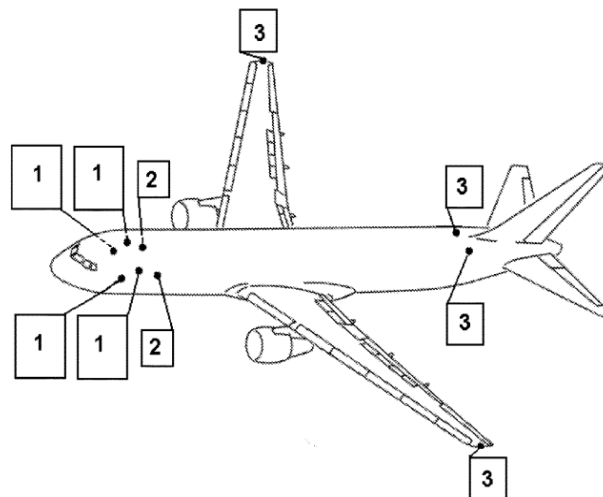
For this purpose, along with their traditional arrangement in the front part of the aircraft fuselage, pressure ports should also be placed on other elements of its design that are promising from the point of view of solving the task at hand. Thus, with the help of pressure probe placed on the tail section of the aircraft fuselage on both sides, it is possible to obtain with sufficient accuracy the necessary information related to determining the values of the pitch, yaw and lateral speed angles, and with the help of pressure receivers that are supposed to be installed on the wingtips - about the bank angle.

The development of such a multifunctional Complex Digital Air Data Systems (CDADS) could provide the aircraft on-board control system with an additional information channel on current flight values and air conditions, which would improve the reliability and authenticity of the relevant information to manage aircraft in an environment where there is no reliable connection to ground and space navigation systems.

Fig. 5 shows a schematic diagram showing the placement of air pressure probes, which allows performing aerometric measurements of such parameters, as pitch, roll, yaw and lateral speed. Located in the front section of the fuselage four smart probes (1) (total, static, differential and lateral static pressure probes), two air temperature sensors (2) (total air temperature), four smart probes (3) (static and lateral static pressure probes), and four air data computers (not shown in the diagram) constitute the basis of the aerometric system.

The roll angle is generated based on the difference in signals received from the static pressure probes (3) installed at the wingtips of the aircraft; the pitch angle is generated based on the difference in signals received from the static pressure probes installed in the nose (1) and tail (3) sections of the fuselage; the yaw angle is generated based on the difference in signals received from the lateral static pressure probes installed in the nose (1) and tail (3) sections of the fuselage; and the lateral speed of the aircraft is generated based on the variation of the difference in signals received from the lateral static pressure probes installed in the nose (1) and tail (3) sections of the fuselage.

To determine the value of the aircraft yaw angle, the output signals of the static pressure probe 1, 3 located in the modified smart sensors of the front and rear fuselage should be used. If, during a flight affected by a crosswind, a yaw effect occurs, this leads to the fact that the lateral pressure acting on the pressure receiver located on the leeward side of the aircraft fuselage will increase, and this increment should be the same for both the receivers of the front and rear parts of the aircraft. As for the corresponding devices installed on the opposite side of the fuselage, the pressure here will decrease accordingly to the same extent.



**Fig. 5.** Layout of pressure receivers of the integrated central pressure system on aircraft

### 3. Results

Fig. 6(a) show a schematic diagram of acquiring air data by the information sources, which reflects the generation by the air data computer of the algorithm for calculating the proposed additional parameters, such as roll, pitch and yaw angles as well as lateral speed in the following form (Pashayev et al., 2019):

1. Roll angle: determined as  $\gamma \sim P_{stat4} - P_{stat3}$ , where  $\gamma < 0$  corresponds to a left roll (left wing down), and  $\gamma > 0$  corresponds to a right roll (right wing down). When  $P_{stat4} - P_{stat3} = 0$ ,  $\gamma = 0$ ;

2. Pitch angle: determined as  $\vartheta \sim P_{stat5} - P_{stat1}$  or  $\vartheta \sim P_{stat6} - P_{stat2}$ , where  $\vartheta < 0$  corresponds to a dive (nose down), and  $\vartheta > 0$  corresponds to a pullup (nose up). When  $P_{stat5} - P_{stat1} = 0$  or  $P_{stat6} - P_{stat2} = 0$ ,  $\vartheta = 0$ ;
3. Yaw angle: determined as  $\psi \sim (P_{lateral\ stat5} - P_{lateral\ stat1}) = (P_{lateral\ stat2} - P_{lateral\ stat6})$ , where  $\psi < 0$  corresponds to a left yaw, and  $\psi > 0$  corresponds to a right yaw. When  $(P_{lateral\ stat5} - P_{lateral\ stat1}) = (P_{lateral\ stat2} - P_{lateral\ stat6}) = 0$ ,  $\psi = 0$ ;
4. Lateral speed:

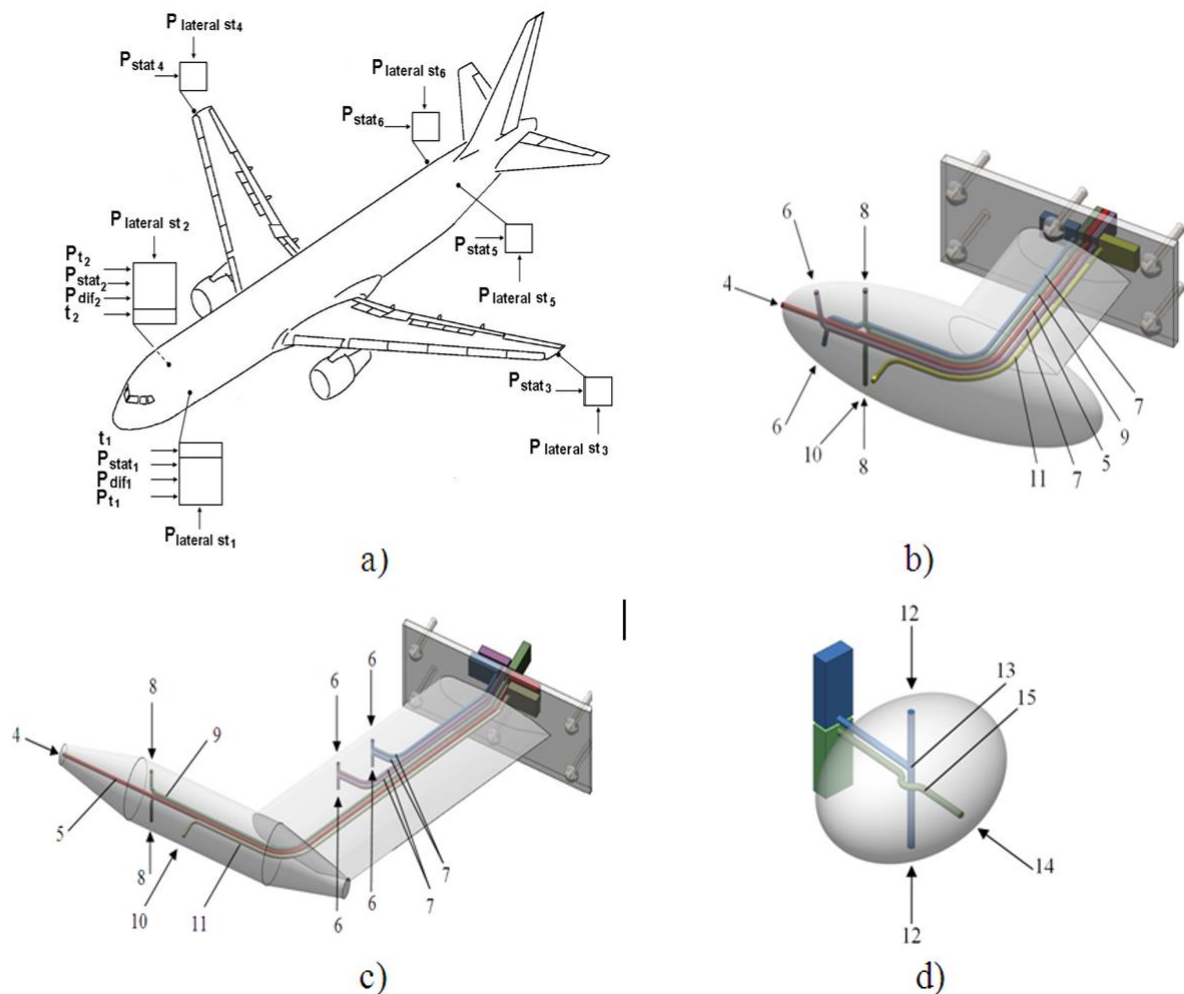
$$\begin{cases} v_{lateral} \sim (P_{lateral\ stat1} - P_{lateral\ stat2}) = (P_{lateral\ stat5} - P_{lateral\ stat6}) \\ P_{lateral\ stat1} = P_{lateral\ stat3} = P_{lateral\ stat5} \\ P_{lateral\ stat2} = P_{lateral\ stat4} = P_{lateral\ stat6} \end{cases}$$

where  $v_{lateral} < 0$  corresponds to a leftward movement, and  $v_{lateral} > 0$  corresponds to a rightward movement.

5. In case of concurrent yawing and lateral speed of the aircraft:

$$\begin{cases} \varphi \sim (P_{lateral\ stat5} - P_{lateral\ stat1}) = (P_{lateral\ stat2} - P_{lateral\ stat6}) \\ v_{lateral} \sim (P_{lateral\ stat1} - P_{lateral\ stat2}) = (P_{lateral\ stat5} - P_{lateral\ stat6}) \end{cases}$$

Fig. 6(b)-(d) presents the developed schemes of CDADS. Located at the front of the fuselage are four smart probes (total, static, differential and lateral static air pressures), two air temperature sensors 2 (total air temperature), four smart probes 3 (static and lateral static air pressure probes), as well as four air data computers form the basis of the comprehensive (fig. 6(a)).



**Fig. 6.** Complex CDADS: (a) the scheme for the placement of CDADS and pressure probes; (b), (c) design schemes of total, static, differential, lateral static pressures; (d) the scheme of static and lateral static pressure probe

Fig. 6(b) presents a scheme of pressure probes, which are designed for non-maneuvrable aircraft (for civilian), in fig. 6(c) - for manoeuvrable aircraft (for aircrafts flying at large angles of attack). Pressure receivers consist of a total air pressure probes 4, its pipeline 5 and de-icing system.

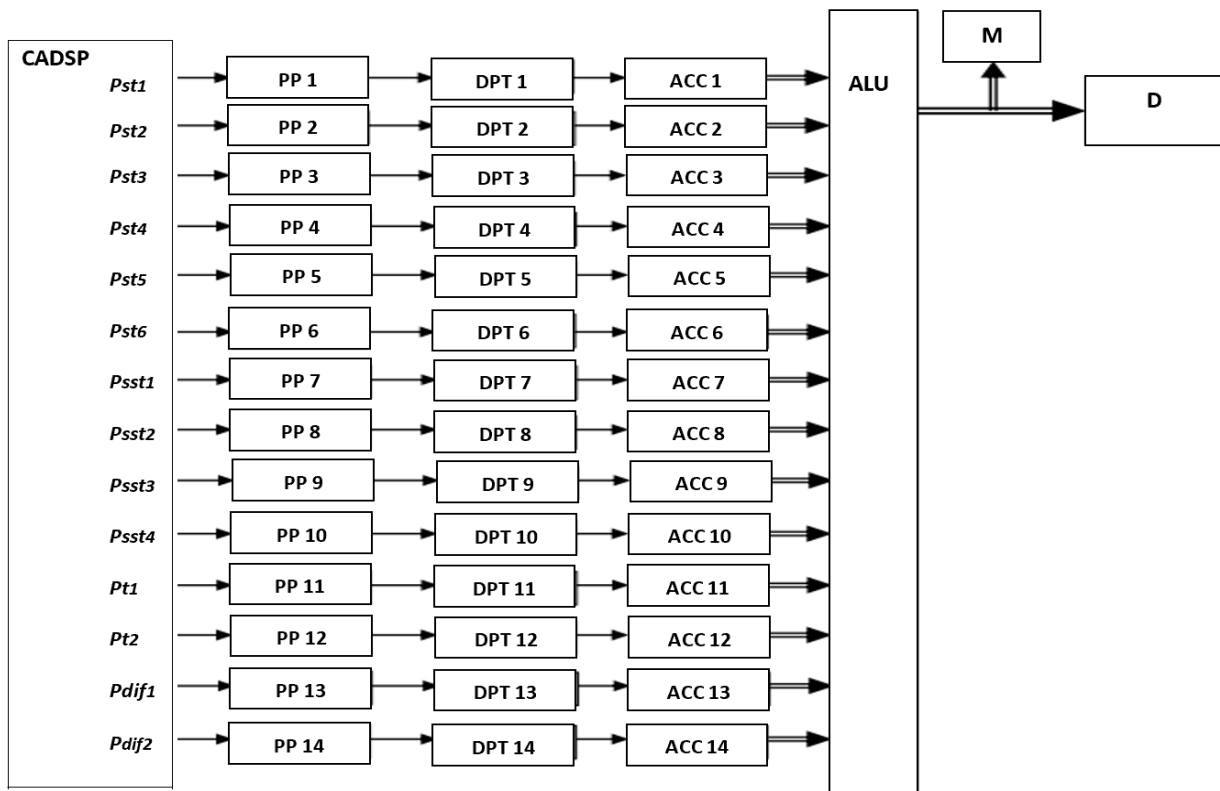
Figure 6(d) presents a scheme of pressure probes installed on the wing tips and tail of the aircraft consist of static pressure probes 12, its pipeline 13 and de-icing system, the probe of the lateral static pressure 14, its pipeline 15 and de-icing system, The air data probe includes static pressure ports 6 for ambient pressure measurement, pressure transmission tubes 7 for conveying pressure to onboard sensors, a total pressure port 8 for stagnation pressure measurement, drain holes 9 to remove moisture, a temperature sensor 10 for air temperature measurement, and heating elements 11 to prevent ice formation. (Pashayev et al., 2019; Karimli, 2023).

Logical algorithms for obtaining information about flight and navigation parameters have been designed and a simulation of the computer model has been performed.

In the process of spatial evolutions of aircraft associated with its roll, you should use the output signals of static pressure probes installed at the wing tips - (Pst3, Pst4). In this case, the value of the angle of the bank will be determined by the difference of these signals. In determining the value of the pitch angle, you should use the difference in output signals of static pressure probes installed on the nose and tail parts of the fuselage surface - (Pst5, Pst1) and (Pst6, Pst2). In the process of yawing and determining the lateral speed of aircraft the difference in output signals of lateral static pressure probes (Plateralst3, Plateralst1) and (Plateralst2, Plateralst4) should be used.

On the basis of these algorithms, a generalized functional scheme of the comprehensive CDADS is drawn up, as well as a computer model of the subsystem for determining the direction of the angle.

The theoretical basis for the operation of the comprehensive CDADS has been presented and a computer model has been drawn up to determine qualitative parameters (Karimli, 2023).

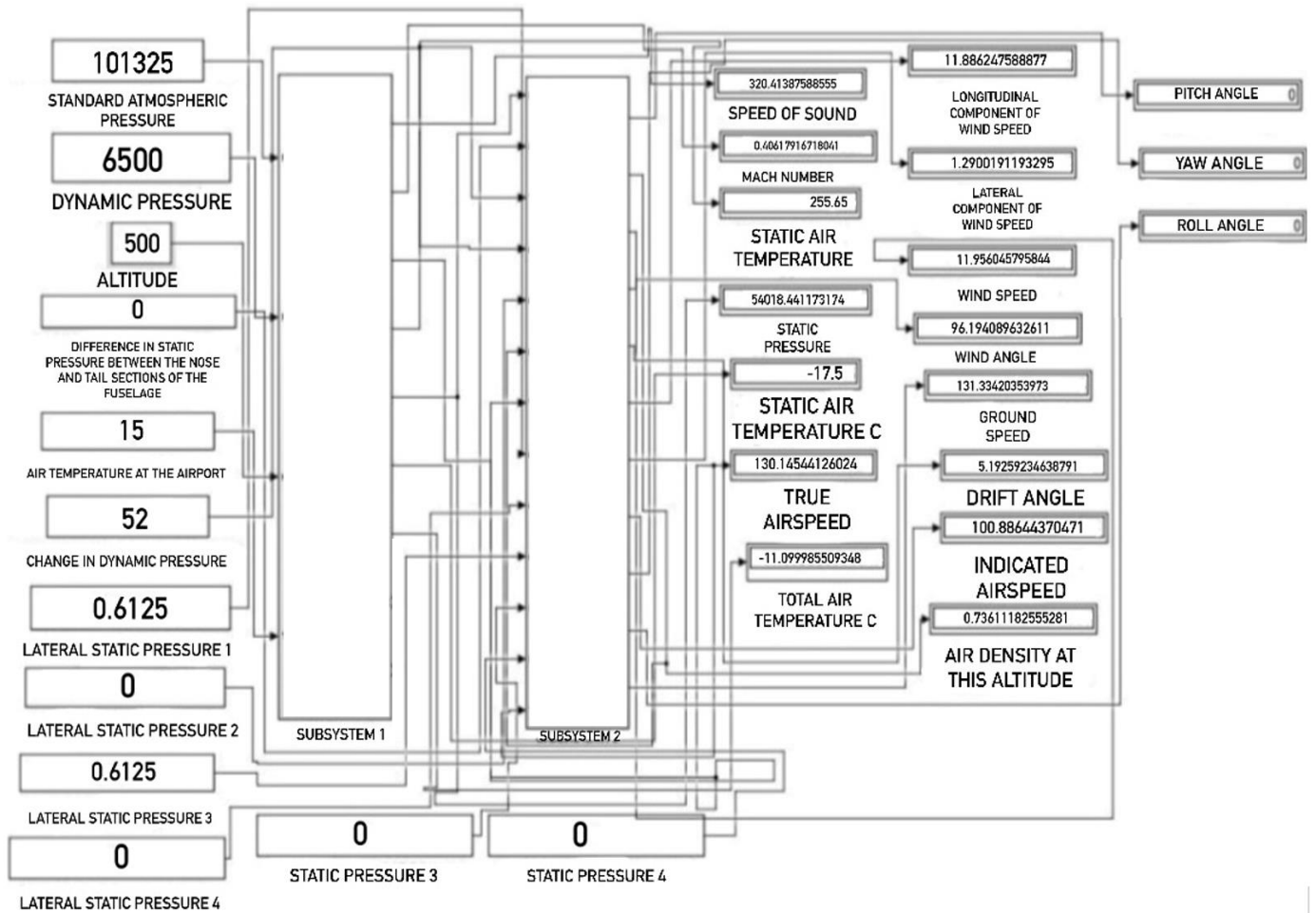


**Fig. 7.** Generalized functional diagram of the Complex Digital Air Data System

Fig. 7 illustrates the CADSP - comprehensive Complex Aid Data Smart Probe; PP - pressure probe; DPT - Digital Pressure Transducer; ACC - Analog-Code Converter; ALU- Arithmetic and Logical Operations Unit; D - Display or Monitor; M - Memory

To model the system for measuring air temperature, static atmospheric pressure, air speed and determining the Mach number using the aerometric method, we will use formulas (Karimli, 2023).

Fig. 8 shows the developed complex model of CDADS:



**Fig. 8.** Computer model of the CDADS (MATLAB Simulink)

"Subsystem 1" is based on the aerometric formulas. The "Subsystem 2" block contains algorithms for determining the angles of roll, pitch, yaw, lateral speed of the aircraft and well-known formulas of the sine and cosine laws for solving the navigation triangle, determining the ground speed, wind angles and drift (Karimli, 2023).

The "Subsystem 2" block also contains a formula for determining air density depending on the altitude, which is characterized by static pressure at a given altitude.

To determine the difference in altitude relative to the horizontal position, the difference in barometric air pressure between the nose and tail of the aircraft is used, that is, between the places where the pressure sensors Pst1 and Pst5 or Pst2 and Pst6 are located.

To determine the pitch, roll and yaw angles in degrees, known trigonometric formulas are used. According to the standardized data, the distance R between the aircraft neutral centring point and the pressure receiver installation point is taken to be 28.65 m. Since with the values of the pitch, roll and yaw deviation angles from the initial position at an angle of  $\varphi = 1^\circ$  with a displacement of  $L = 0.5$  m from the geometry formula  $L = \frac{2\pi r}{360} \varphi$ , we see that  $R = 28.65$  m.

#### 4. Discussion

Table 1 presents the simulation results for determining parameters such as static temperature and pressure, air density, and the speed of sound at flight altitudes of H=5000 m, 9000 m, 10000 m and 12000 m, with dynamic

pressure  $P_d=6650$  Pa and with a difference of static pressures taken from sensors Pst1 and Pst5 or Pst2 and Pst6 of 4.579 Pa.

**Table 1.** Comparison of simulation results of the CDADS computer model

Flight Altitude (m)		Static Temperature (K, C°)		Static Pressure (Pa)	Air Density (kg/m³)	Speed of Sound (m/s)
5000	Results of Simulations;	255.65	-17.5	54018.4	0.737	320.4
	Literature data	255.68	-17.47	54048.3	0.736	320.5
9000	Results of Simulations;	229.65	-43.45	30740.8	0.467	303.68
	Literature data	255.73	-43.42	30800.7	0.467	320.8
10000	Results of Simulations;	223.15	-50	26434.7	0.413	299.35
	Literature data	223.25	-49.40	26499.9	0.413	299.6
12000	Results of Simulations;	216.65	-56.5	19330.2	0.310	294.9
	Literature data	216.68	-56.5	19399.4	0.312	295.1

As can be seen from the table, the reliability of the simulation results, with sufficiently high accuracy (for visual devices, and automatic control system, when GNSS is inoperative), is confirmed by the data given in the literature.

Table 2 presents the simulation to determine the crosswind, drift, pitch, yaw, roll, and some aerometric signals of the aircraft by CDADS at altitude  $H=10000$  m (Karimli, 2023).

**Table 2.** Results of computer simulation of the improved CDADS

№	Input signals			Output signals		
	Signals	Symbol	Value of measurement	Signals	Symbol	Value of measurement
1	2	3	4	5	6	7
1	Standard Atmospheric Pressure	Pa	101325	Static pressure at a given altitude	Pa	26434
2	Dynamic Pressure	Pa	12500	Static air temperature at a given altitude	K (°C)	223.5 (-50)
3	Altitude	feet meter	30480 10000	Total air temperature at a given altitude	°C	-30.19
4	Difference of static pressure in the nose and tail sections of the fuselage	Pa	12.5	Speed of sound	m/sec	299.3
5	Standard air temperature	K (°C)	288.15 (15)	Mach number		0.76
6	Dynamic pressure difference	Pa	0	True airspeed	knot km/hour	445 824.2

7	Lateral static pressure 1	Pa	0,6125	Longitudinal component of wind velocity	m/sec	0
8	Lateral static pressure 2	Pa	0	Crosswind velocity	m/sec	6.22
9	Lateral static pressure 3	Pa	0,6125	Wind velocity	m/cek	15.95
10	Lateral static pressure 4	Pa	1,2	Wind angle relative to true airspeed vector	<sup>o</sup> deg.	90
11	Static pressure 3	Pa	2,03	Ground speed	knot km/hour	445.2 824.5
12	Static pressure 4	Pa	-2,03	Drift angle	<sup>o</sup> deg.	1.55

The aerometric systems existing on modern aircraft are not capable of measuring the parameters of roll, pitch, yaw angles, as well as crosswind and drift of the aircraft.

## 5. Conclusions

This work presents the development and analysis of a complex Computational-Digital Air Data System (CDADS) designed to determine flight and navigation parameters using data obtained from the Aid Data Smart Probe air pressure sensor, supported by computer-based modeling and simulation. The following key outcomes have been achieved:

- It is proposed to create a complex CDADS for determining flight and navigation parameters based on processing signals taken from Aid Data Smart Probe air pressure probe, and a computer model simulation is performed;
- Theoretical foundations for the operation of a complex CDADS are presented and a computer model for determining flight and navigation parameters is compiled;
- A mathematical model for obtaining information on flight and navigation signals, including additional parameters such as roll, pitch, yaw, lateral speed, is compiled, and a computer model simulation is performed;
- As the simulation of the resulting model shows, it is clear that it is possible to use the measured parameters of roll, pitch, yaw, lateral velocity of the aircraft, as well as wind direction and speed based on the aerometric method with sufficient accuracy for visual displays, as well as in automatic control systems, in the absence of GNSS satellite navigation

After digging into all the technical stuff in this study, the big takeaway is actually pretty simple: aircraft need better backup systems for when GPS or external signals aren't there to help. That's where this new system, CDADS, really shines.

What makes this setup clever is how it uses pressure sensors placed all around the aircraft—not just in the usual places at the front, but also at the wingtips and the tail. That way, it can pick up on small changes in pressure that actually tell you a lot about how the aircraft is moving and we can receive a lot of data, which is very beneficial. And with those sensors feeding data into some solid math and logic in a computer model, it turns out the results are pretty accurate. They tested the system under different flight conditions, and the numbers matched up well with real-world data. That's a good sign.

By using simulation model, it is clear that different types in size of aircraft can be studied for next research programs.

This method can also be applied to submarines.

## Abbreviations

ACC : Analog Code Converter

ADIRU : Air Data Inertial Reference Unit

ADS : Air Data Smart Systems  
ADSP : Air Data Smart Probe  
ALU : Arithmetic and Logical Operations Unit  
CDADS : Complex Digital Air Data Systems  
GNSS : Global Navigation Satellite Systems

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**Research Article**

## **Comparative Analysis of Ukrainian Legislation and International Norms Regulating the Formation and Management of the Logistics System**

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### **Abstract**

Logistics is an important component of any business, which covers the processes of planning, organizing, managing and controlling the movement of resources, products and information. Its main goal is to ensure the optimal and efficient use of resources, satisfy the needs of consumers and achieve competitive advantages in the market. Logistics covers various activities related to material flows - from the purchase of raw materials to the delivery of the final product to consumers. In traditional logistics systems, the use of information technology was limited, and the main focus mechanical inventory management and transportation. In modern approaches, automation, information technologies, and artificial intelligence play a significant role, which allow predicting changes in demand, optimizing routes, and improving inventory management. These technologies make it possible to reduce costs, increase the accuracy and efficiency of decision-making.



## 1. Introduction

Logistics, as a management function, has deep historical roots dating back to antiquity. Its original purpose was to ensure the efficient delivery of goods and resources across different territories, which facilitated the development of trade and economic ties between different cultures. Already in Ancient Egypt, Mesopotamia and the Roman Empire, logistics played an important role in ensuring the supply of materials for construction, military campaigns and expansion of territories. Transportation of goods, construction of roads and development of navigation were important elements of the logistics processes of that time.

The main aim of the article is to provide the research of the main challenges and problems of activity of logistics development tendencies. This article provides accurate information on the history and contemporary tendencies and comparison of Ukrainian and International law regulatory base. The comparison between traditional and contemporary logistics was also researched.

This study employs a comparative legal analysis methodology, examining and contrasting the Ukrainian legal framework regulating logistics with relevant international standards, including EU directives, ISO standards, and global conventions. The analysis is complemented by a qualitative assessment of secondary sources such as policy documents, regulatory acts, and analytical reports. In addition, desk research was used to identify implementation gaps and policy mismatches, while a contextual institutional approach helped interpret the observed discrepancies. This methodological triangulation allows for a structured understanding of both legal convergence and divergence across multiple regulatory dimensions.

## 2. Literature Review

Today's logistics is a global system where companies interact with suppliers and consumers on different continents. Modern technologies such as the Internet of Things (IoT), unmanned vehicles, warehouse robotics and 3D printing open up new opportunities to improve logistics efficiency. All this allows companies to reduce costs, increase the accuracy and speed of delivery of goods, as well as reduce environmental impact by optimizing routes and reducing energy consumption (Steinbach et al., 2017).

Logistics is a multifaceted discipline that encompasses the management of material, information and financial flows to ensure their efficient movement between points of supply and consumption. The classic definition of logistics, proposed by Klaus Peter in 2009, emphasizes its function of managing flows in order to optimize the movement of resources. According to this approach, logistics aims to minimize costs and time in delivering goods to the end consumer. Another view of logistics is presented through a systems approach that emphasizes the integration of processes. V. Yadav, R. Jain and P. Gaur (2021) describe logistics as a system that covers all stages from sourcing to delivery of goods, emphasizing its comprehensive nature. Mishrif et al. (2024) refers to a process approach in which logistics is viewed as a set of supply chain management processes. This approach covers the planning, execution and control of the movement of goods, ensuring the effective functioning of the logistics system. The information aspect of logistics is also an important component, as noted by Jodlbauer et al. (2023). The author emphasizes that logistics includes not only the physical movement of goods, but also the processing of information that is necessary for decision-making. This aspect is key to ensuring the efficiency and timeliness of logistics operations.

Supply chain management has become a central focus in logistics, and this conceptual framework was developed back in the 1990s by researchers such as S. Pan, D. Trentesaux, D. McFarlane, B. Montreuil, E. Ballot, G.Q. Huang (2021). They drew attention to the fact that effective logistics is impossible without coordination between different supply chains: manufacturers, suppliers, transport companies and end consumers. The main focus of their work is on how information flows, financial transactions and material resources can be combined and integrated. Thanks to their approach, SCM ceases to be only an internal matter of one company and begins to be considered as an inter-organizational system, where close interaction between participants ensures cost reduction and efficiency improvement.

G.F. Frederico (2023) defined supply chain management as the coordination of not only material flows but also information flows, which play a key role in ensuring the continuity and accuracy of supplies. Their work changed the view of logistics, transforming it from a local discipline to a global approach to management.

### 3. Results

Logistics in Ukraine and internationally is regulated by a set of legislative and regulatory acts that ensure the effective functioning of supply chains, transportation, storage and distribution of goods. A comparative analysis of the national legislation of Ukraine and international norms in the field of logistics allows us to assess the compliance of domestic regulation with world standards and identify possible areas for improving the legal framework.

The logistics system of Ukraine is a complex mechanism that is regulated by various legislative acts that cover numerous aspects of logistics activities. The main document that defines the principles of the functioning of the transport infrastructure is the Law of Ukraine "On Transport". This law establishes general requirements for all types of transport, including road, rail, water and aviation. It is aimed at ensuring the safety of transportation, the efficiency of the use of vehicles and infrastructure, as well as the protection of the rights of consumers of transport services (Myers et al., 2012).

The Customs Code of Ukraine is also of key importance for logistics activities, as it regulates the processes of moving goods across the customs border. This code defines customs clearance procedures, including the rules for declaring goods, paying customs duties and taxes. It also establishes requirements for documents that must be submitted for customs control, which is an important aspect for ensuring transparency and efficiency of foreign economic activity (Timane, 2012; Hammer & Champy, 2006).

In addition, the logistics activities in Ukraine are significantly influenced by regulatory acts that regulate environmental standards and safety during the transportation of dangerous goods. In particular, the legislation provides for requirements for packaging, labeling and transportation of hazardous materials, which is critical for protecting the environment and public health. There are also regulations that regulate the standards for storing goods in warehouses, which ensures their proper protection and preservation.

Legislation on e-commerce and information technologies plays an important role in modern logistics processes. This legislation regulates the use of digital solutions, such as electronic documents, supply chain management systems, as well as other technologies that contribute to the automation and optimization of logistics operations. The use of electronic platforms for order management, cargo tracking, and payment processing is becoming increasingly common, increasing the efficiency and speed of logistics processes (Kostina, 2018; Repin & Yeliferov, 2013).

To support the discussion with practical examples, this study highlights the implementation of the "Single Window" customs clearance system, which has decreased average cargo processing time by 30%, according to the State Customs Service of Ukraine. In the private sector, the logistics company Nova Poshta has introduced automated sorting terminals and predictive routing based on artificial intelligence, which has improved delivery accuracy and customer satisfaction. Moreover, according to data from the Ukrainian Logistics Alliance (2023), there is an observed annual 12% increase in the adoption of warehouse and transport management systems (WMS/TMS) among SMEs. These cases illustrate successful local applications of digital logistics technologies and support the transition towards modern logistics practices (Table 1) (State Customs Service of Ukraine, 2023; Nova Poshta, 2023; Ukrainian Logistics Alliance, 2023; Ministry for Digital Transformation of Ukraine, 2023).

**Table 1.** Elements of Ukrainian legislation affecting logistics

Category	Main legislative acts	Key provisions
Transport	Law on transportation of Ukraine	Establishes principles for managing transport infrastructure and road safety
Customs Clearance	Customs laws of Ukraine	Regulates import/export procedures, customs clearance and taxation of cargo
E-commerce	Law of Ukraine on Electronic Commerce	Regulates the use of electronic documents and digital tools in logistics
Labour security	Resolutions of the Cabinet of Ministers of Ukraine on the safety of transportation of dangerous goods	Establish requirements for the transportation of dangerous goods

In the context of standardization of logistics management processes, international ISO standards are important, such as ISO 9001, which concerns the quality management system, and ISO 28000, which regulates the security management system in supply chains. These standards ensure international harmonization of logistics processes, increasing their efficiency and security. The implementation of ISO standards allows companies to improve the quality of customer service, reduce security risks, and increase trust in their services in the international market (Yu et al., 2022; Nickols, 2016; Becker et al., 2018).

A comparison of the national legislation of Ukraine with international norms shows that the domestic legal framework in the field of logistics has some compliance with international standards, but there are also a number of aspects that need improvement. For example, Ukraine is actively integrating into international transport systems through participation in such initiatives as the European Network of Trans-European Transport Corridors (TEN-T). However, some international conventions have not yet been fully implemented in Ukraine, in particular those relating to environmental standards and automation of logistics processes (Powell, 2017; Sinnaiah et al., 2023).

Regarding the transportation of dangerous goods, Ukrainian legislation (Resolutions of the Cabinet of Ministers of Ukraine) regulates the safety of transportation of these goods, but the regulations are often based on domestic requirements and may not take into account all international standards and practices. These regulations indicate the importance of safety during the transportation of dangerous materials, but do not always sufficiently cover modern technological advances and risk management methods adopted in the world (Steinbach et al., 2017).

It is worth noting that Ukraine plays an important role in the international transport system due to its strategic location at the intersection of key transport corridors between Europe and Asia. The country's integration into international transport networks contributes to strengthening economic ties with other regions, increasing the efficiency of logistics and developing infrastructure. Ukraine's participation in such global projects as transport corridor No. 5, TRACECA and the Trans-European Transport Network (TEN-T) opens up new opportunities for trade, attracting investment and technological progress (Stukalo et al., 2018).

One of the important initiatives is Ukraine's cooperation with the European Union. This cooperation envisages the implementation of numerous projects aimed at modernizing Ukraine's transport infrastructure, including roads, ports and railway lines. One of the main aspects of this cooperation is the introduction of "green corridors". These corridors simplify customs clearance of goods, significantly reduce the time for crossing the border and reduce the number of administrative procedures. This step is of great importance for business, as it ensures faster and more efficient transportation of goods through Ukraine, which, in turn, increases the country's attractiveness as a transit hub for international trade (Thompson et al., 2013).

Ukraine also actively participates in international agreements and conventions that regulate cargo transportation and promote the harmonization of transportation processes. This is important not only for improving the efficiency of logistics operations, but also for the country's integration into global transport networks, which in turn increases its competitiveness as a transit hub (Wiedemann et al., 2019).

This project involves significant investments in the modernization of important transport facilities, such as the Port of Odessa, which is of strategic importance for the development of international maritime transport. In addition, the project includes the reconstruction of railway lines and the expansion of opportunities for international freight transport. Thanks to such initiatives, the throughput capacity of transport corridors is improved, the time for cargo transportation is reduced, and the efficiency of logistics operations is increased (Xia & Huang, 2021).

Of particular importance is the project "Europe-Asia Railway", which involves the modernization and optimization of railway connections between Europe and Asia through the territory of Ukraine. This is an important project for the transit of Chinese goods through Ukrainian territory to Europe and back. Thanks to this project, the time for cargo delivery times are shortened and transportation costs are significantly reduced, which increases the attractiveness of Ukraine as a key transit route for international trade. Modernization of railway infrastructure allows ensuring the stability and efficiency of freight transportation, which has a positive impact on the country's economy and its position in international logistics chains (Yilmaz & Flouris, 2017).

The results reveal a partial alignment between Ukrainian logistics legislation and international standards, particularly in areas such as customs regulation and transport safety. However, significant discrepancies persist in digitalization, environmental regulation, and infrastructure modernization. The discussion section highlights

key challenges, including outdated regulatory instruments, insufficient state investment, and institutional inertia. Notably, Ukraine's partial integration into the TEN-T network and selective compliance with ADR and ISO standards indicate fragmented harmonization. Moreover, the country's legal framework fails to adequately support automation, digital logistics solutions, and emission reduction targets, hindering its international competitiveness. These findings underscore the need for targeted reforms grounded in EU-compatible standards and supported by strategic financial and institutional initiatives.

To move beyond a purely descriptive narrative, this study integrates a critical analysis of the institutional and political-economic context influencing Ukraine's regulatory gaps. One key finding is that the persistence of bureaucratic barriers and a legacy of post-Soviet administrative structures have hindered the uptake of international logistics standards. Furthermore, constrained fiscal capacity and political volatility have limited the implementation of green logistics policies and advanced digital technologies. Ukraine's hybrid legal architecture, shaped by fragmented reforms and overlapping competencies, contributes to legal inconsistency and policy inefficiency. These factors collectively explain why, despite formal commitments, the adoption of global best practices remains inconsistent and incomplete.

#### *Ways to overcome implementation challenges*

##### *1. Development of new legislative initiatives*

- Harmonization of environmental legislation. Ukraine should develop new environmental standards that meet European requirements, including strict limits on carbon emissions and requirements for energy efficiency of transport. This requires the introduction of mechanisms to encourage enterprises to reduce emissions through financial instruments such as "green bonds".
- Digitalization. It is necessary to develop a legislative framework for the implementation of electronic document management in the logistics sector and ensure transparency of regulatory procedures for the implementation of automated cargo tracking and warehouse management systems.

##### *2. Implementation of modern technologies*

- Digital solutions. Investments in digital infrastructure for logistics should be a priority. New technologies such as blockchain for cargo tracking and electronic transport documents (e-TIR) should be introduced, which will help reduce transportation time and costs.
- Automation. Supporting small and medium-sized enterprises (SMEs) in implementing automated warehouse management systems through soft loans and government grants can accelerate adoption to international standards.

##### *3. International cooperation and financing*

- Ukraine should make more active use of international financial instruments, such as grants from the European Investment Bank or loans from the World Bank for infrastructure modernization. Participation in European programs for the development of transport corridors, such as TEN-T, will allow access to new sources of financing.

##### *4. Educational programs and training*

- The integration of international standards requires advanced training of personnel responsible for logistics processes. Advanced training programs should include training in modern digital solutions, environmental standards and management technologies.

Thus, a comparative analysis of Ukrainian legislation and international norms in the field of logistics shows both achievements and significant challenges for the Ukrainian legal system. Ukrainian legislation in some aspects, such as transport, customs procedures, environmental standards and transportation safety, meets international standards. However, there are serious gaps in harmonization with international standards, especially in areas such as ecology and digitalization of logistics processes. This creates barriers to Ukraine's full integration into global logistics networks and improvement of its competitiveness in the international market. Therefore, for the further development of Ukraine's logistics system, it is necessary to focus on harmonizing environmental standards, introducing digital technologies, modernizing infrastructure and training qualified personnel, which will allow Ukraine to become competitive in the international market.

Ukraine's logistics infrastructure is developing slowly, especially compared to the European TEN-T network. The problem lies in the lack of funding and outdated transport corridors. Although Ukraine has access to international funding through grants and loans from the European Investment Bank and the World Bank, restrictions due to bureaucracy, corruption and the lack of effective financial mechanisms make it difficult to use these resources.

The state of education and training in the logistics sector is also problematic. The low level of qualifications and the lack of state training support programs hinder the implementation of international standards and the training of competitive specialists.

Differences between Ukrainian legislation and international standards on environmental safety and transportation of dangerous goods.

Criteria Ukrainian legislation International standards

Greenhouse gas emissions Law of Ukraine "On Environmental Protection" Standard ISO 14064 (accounting and reporting on greenhouse gas emissions)

Transportation of dangerous goods CMU Resolutions on the safety of transportation of dangerous goods European ADR agreement.

Regarding the digitalization of logistics processes, the implementation of modern warehouse management systems (WMS) and cargo tracking (TMS) is partial, as there is a lack of access to digital infrastructure, as well as qualified specialists. Paper-based documentation continue to be used instead of electronic transport invoices, as there is no legislation regulating the implementation of electronic solutions (Atadoga et al., 2024; Baldwin, 2012).

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Logistics plays a key role in the economy of Ukraine, providing a link between producers and consumers both in the domestic and foreign markets. The efficiency of logistics companies directly affects the competitiveness of the economy, because high costs of transportation, storage and other logistics services can increase the final cost of goods and services, which in turn reduces their competitiveness in global markets. To increase the efficiency of logistics companies, it is important to take into account various economic aspects and factors that directly affect their activities.

In addition, customs procedures play an important role in ensuring the efficiency of logistics. Simplification of customs formalities, the introduction of modern customs clearance technologies and ensuring compliance with international standards significantly reduce the time and costs of transporting goods. In Ukraine, they are actively working on improving customs procedures, including integration with international customs systems, which allows for improved transparency and reduced transaction costs for companies (Atadoga et al., 2024; Baldwin, 2012).

Another serious challenge is customs clearance. Although Ukraine is actively working to simplify customs procedures, bureaucratic barriers and delays at customs can significantly increase the cost and duration of transportation. In addition, political and economic instability are also important factors that can affect the development of logistics. Geopolitical risks, economic difficulties and unpredictability of changes in legislation can create difficulties for international transportation and planning of logistics operations (Atadoga et al., 2024; Baldwin, 2012).

To provide a more evidence-based assessment, this study incorporates key empirical indicators. According to the World Bank's Logistics Performance Index (LPI) 2023, Ukraine scores 2.8 out of 5, lagging behind the EU average of 3.4, particularly in infrastructure and customs efficiency. Transport-related costs account for approximately 13% of Ukraine's GDP, compared to 7% across the EU. Furthermore, a 2023 survey by the European Business Association reveals that 64% of Ukrainian logistics firms consider the lack of digital infrastructure a critical obstacle to modernization. These figures demonstrate the measurable performance gaps and justify the need for urgent institutional and technological upgrades in Ukraine's logistics sector (Table 2) (World Bank, 2023; OECD,

2022; European Business Association, 2023; Ministry for Communities, Territories and Infrastructure Development of Ukraine, 2023).

**Table 2.** Problems of implementing international norms in Ukraine

Category	International standard	The situation in Ukraine	Main barriers
Environmental regulations	CO <sub>2</sub> emission requirements (EU: up to 95 g/km)	High emissions (135-150 g/km)	Old transport, lack of incentives for modernization
Energy efficiency of transport	Energy efficiency class (A)	Lack of clear standards	Low investment in new technologies
Waste Management	ISO 14000	Lack of a national strategy	Insufficient legal framework and control
Digitalization of logistics	Warehouse Management Systems (WMS) and TMS	Partial automation	Lack of access to digital infrastructure and qualified personnel
Electronic document management	Electronic consignment notes (EU)	Use of paper documents	Lack of legislation for the implementation of electronic solutions
Cargo tracking	eFTI (Electronic Transport Information)	Limited implementation	Low investment and lack of digital systems
Logistics infrastructure	European TEN-T Network	Partially developed transport corridors	Lack of funding and aging infrastructure
Project financing	Grants from the European Investment Bank, loans from the World Bank	Limited access to financial resources	Bureaucracy, corruption, lack of financial mechanisms
Education and training	Training according to international standards	Low level of qualification in logistics	Lack of state programs to support training and development

#### International cooperation and financing

- Ukraine should make more active use of international financial instruments, such as grants from the European Investment Bank or loans from the World Bank for infrastructure modernization. Participation in European programs for the development of transport corridors, such as TEN-T, will allow access to new sources of financing.

#### Educational programs and training

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## 4. Conclusions

Logistics, as an important component of business, covers a wide range of processes that include planning, organizing, managing and controlling the movement of resources, products and information. Today, logistics not only includes transportation, but also inventory management, warehousing operations, purchasing and distribution of goods. Current trends in logistics emphasize the integration of new technologies, such as automation, information systems, and the use of data to improve supply chain management processes. The analysis of Ukrainian legislation revealed that, although there is some compliance with international standards, there are significant gaps that need to be improved. This includes insufficient harmonization of environmental standards, a low level of digitalization of logistics processes and limited funding for infrastructure projects. Thus, some international conventions related to environmental standards and automation of logistics processes have not yet been fully implemented in Ukraine, which complicates integration into global supply chains. Important aspects are also problems with risk management and insufficient qualification of personnel in the field of logistics.

The economic aspects of increasing the efficiency of logistics companies in Ukraine require a comprehensive approach. Among the key areas that can increase efficiency, one can single out the modernization of transport infrastructure, the introduction of new technologies, cost optimization and active cooperation with international partners. For example, the modernization of ports, railway lines and highways can significantly reduce cargo processing time and increase the speed of delivery. The introduction of the latest information systems for supply chain management will reduce costs and increase the accuracy of management decisions.

In addition, personnel training is an important component, since qualified specialists can significantly affect the quality of service and the efficiency of logistics processes. In the context of globalization and growing demands for sustainable development, Ukraine needs to focus on harmonizing its legislation with international standards, introducing modern technologies and strategic management of logistics processes. This will ensure the efficiency and stable development of the country's logistics system, which, in turn, will increase competitiveness in the international market.

Thus, to achieve success in the logistics sector, Ukraine needs to actively implement reforms aimed at improving the legislative framework, increasing the level of digitalization, investing in infrastructure and developing human resources. These steps will ensure not only Ukraine's integration into international logistics networks, but also create conditions for sustainable economic growth in the context of globalization.

In conclusion, while Ukraine has made progress in aligning its logistics legislation with international norms, critical regulatory gaps remain – particularly in the domains of digital transformation, environmental protection, and infrastructure development. The study emphasizes the urgency of legislative harmonization with EU practices, investment in digital infrastructure, and the enhancement of institutional capacity. To achieve deeper integration into global logistics systems, Ukraine must adopt a strategic approach to reform that includes both regulatory modernization and the empowerment of public-private partnerships. The article calls for further empirical research to monitor the impact of ongoing reforms and to identify scalable best practices for logistics development in transition economies.

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Research Article

## A Study on the Relationship between ANSP Financial Profitability and Emission Gas Values

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### Abstract

During the initial quarter of the 21st century, the planet experienced a substantial shift in its climate, with the onset of a process of global heating that began to disrupt the environmental equilibrium. While a multitude of factors have contributed to this phenomenon, a significant contributing element is the substantial increase in the emission of pollutants on a national, regional and international scale. This phenomenon poses a significant challenge for nations worldwide. This paper proposes a novel econometric approach to describe European airspace with regard to emission production. To this end, the model utilises a panel regression approach incorporating variables (as GRA methodology based profitability ratios, emission values, GDP, population, labour, cargo volume, number of passengers and emission values) of Air Navigation Service Providers in continental Europe. The findings indicate a positive relationship between the formed-profitability index values and carbon dioxide and nitrogen oxide values. Specifically, a one percent increase in carbon dioxide (CO<sub>2</sub>) emissions is associated with a 0.442 percent increase in profitability (index), while a one percent increase in nitrogen oxide (NO) is linked to a 0.174 percent increase in profitability (index) for the 2017-2020 (pre-Covid 19) period. The analysis indicates that the busiest routes or countries are those where the production of carbon dioxide and nitrogen oxide is highest. In addition to this, a conceptual map is formulated, drawing upon extant literature.



## 1. Introduction

The "Paris Agreement", the key outcome of the 21st meeting of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), sets out an ambitious emissions reduction path. The long-term objective of maintaining average warming well below the 20°C threshold necessitates considerable reductions in anthropogenic greenhouse gases (GHG) by mid-century (Becken & Mackey, 2017). As Larsson et al. (2018) and Şöhret (2019) note, global civil aviation accounts for 3-5% of total greenhouse gas emissions, which are increasing. According to Macintosh and Wallace (2009), international aviation carbon dioxide (CO<sub>2</sub>) emissions are projected to rise by more than 110 per cent between 2005 and 2025. It is implausible that these emissions could be stabilised at levels consistent with risk-averse climate targets without restrictions on demand. Prussi et al. (2021) attribute this negativity to fuel or petroleum-derived jet fuel, as is the case in every industrial structure of the producing world, such as marine transportation (McCollum et al., 2010) and tourism (Scott et al., 2010). Consequently, the decarbonisation of civil aviation and the transition to petroleum-derived fuel have garnered significant attention, as corroborated by Tian et al. (2020). In addition to the aforementioned elements, Cai et al. (2019) contribute to this body of research by examining the impact of carbon dioxide, methane, nitrous oxide and fluorinated Greenhouse Gases on air pollution in China. However, the impact of these gases is not limited to the atmosphere; they also contribute to soil and water contamination. Consequently, they exert a detrimental effect on the environment and its habitats. Furthermore, according to Harrison et al. (2015), human health is adversely impacted by airport-related emissions, including those emanating from ground service equipment and road traffic. In this context, Khalili et al. (2019) propose the concept of a "climate-constrained world," a term that aligns with the work of Işık et al. (2024a). These researchers categorise environmental dimension measures as follows: renewable energy consumption, combustible renewable energy, renewable electricity output, forest area, control of air pollution, natural resources depletion, access to clean fuels and technologies for cooking and wastewater treatment. In this context, the present research can be positioned to control air pollution. Conversely, the undertaking of sustainability and air pollution research by countries and regions has been well-documented in the extant literature (Işık et al., 2024b; Mannucci & Franchini, 2017; Emberson et al., 2001). This study undertakes such analyses for European countries. The relationship between energy transformations and the economy is a subject that has been explored in various studies. For instance, Taghavi and Lee (2025) examined the relationship between exergy and economics in novel hydrogen liquefaction structures.

In an effort to address the issue of greenhouse gas emissions, national, regional and international organizations have embarked on the development of various scenarios and regulations, with the aim of establishing more stringent emission targets. For instance, Lyle (2018) has voiced criticism of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), while Ahmad (2015) has highlighted the European Union Emissions Trading System (EU ETS) and its implications for both European and aviation governance structures. Additionally, Lindenthal (2014) has underscored the European Union's leadership role in the International Civil Aviation Organization (ICAO) managerial structure with regard to environmental matters. Guo et al. (2023) categorise the Greenhouse Gas Emissions (GHGE) under various titles (e.g. CO<sub>2</sub> and other air pollutants) and according to their detrimental impacts on the environment in China. Tsai and Petsonk (1999) also emphasise the efforts made by international authorities to eliminate GHGE or at least their impacts on the civil aviation industry. Furthermore, Barrett (1996) asserts that the incorporation of aviation environmental charges within the context of a development process serves as a sustainability metric for GHGE. Miller (1997) emphasises the importance of technical and technological expertise in the design of aircraft and engine systems and in the conduct of civil aviation activities. The use and utilisation of new sustainable fuels are also important in the solution scheme (Stratton et al., 2010). The literature also includes regional studies. For instance, Harris et al. (2012) developed a framework for Hong Kong, which has one of the densest GHGE rates in the world. The authors argue that diminishing the negatives sourced from the aviation and shipping industries should be an aim for Hong Kong state management and governance structure. Another regional study was conducted by Ryerson et al. (2015), who asserted that effective and efficient policies from ANSPs could serve as a solution to reduce GHGE emissions in the United States' airspace. Grabar et al. (2011) and Dmitrieva (2014) designed an analysis for Russia to show the negatives sourced from GHGE as externalities of aviation activities by stating the strategic implications of emission allowance in trade credits. De Azevedo et al. (2018) conducted research in Brazil, proposing a redesign of industrial activities to achieve optimal solutions to the GHGE problem.

The present paper aims to map European airspace concerning emission values in an area where there is a paucity of research and papers on ANSPs. It will address this lacuna by investigating the relationship between gas emission and ANSP profitability. Moreover, the research develops an econometric model to explain the relationship

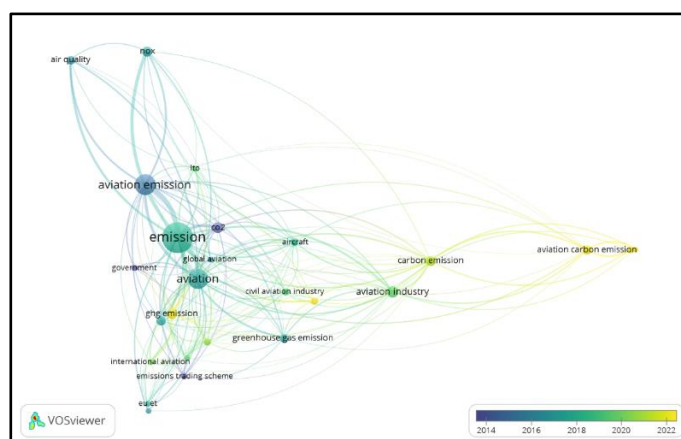
between the profitability values of Air Navigation Service Providers (ANSPs) in European countries and emission gases. The analysis will address the question of whether the densest airspace has the highest emission values in European airspace. This will be answered by considering the profitability to be an indicator of air space density. The initial section of the analysis will entail a comprehensive review of the extant literature. The subsequent section will encompass the data and methodology, while the conclusions, policy implications and recommendations will be outlined in the final section.

The study is subject to two limitations. The primary data resource for this analysis, EUROCONTROL, commenced the issuance of the dataset in 2017. The second restriction pertains to the acceptance of ANSP profitability as a direct measure of airspace utilisation. The second assumption is that the most financially profitable country has the densest airspace. The dataset utilised in the research is notable for its high validity and reliability. The paucity of literature on the subject of ANSP on a regional basis lends further support to the paper's value.

## 2. Literature review

Air Navigation Systems (ANS) are considered to be fundamental elements of modern aviation. These systems have been developed for the purpose of ensuring that aircraft are able to navigate both safely and efficiently (Bourgois et al., 2018). Air Navigation Service Providers (ANSPs) have been identified as key contributors to enhancing aviation safety and efficiency through the provision of airspace management, flight guidance and control services (Efthymiou, 2023; Adler et al., 2020). However, as air travel, with its convenient and rapid transportation, has become increasingly popular, it has led to a rise in emissions. This increase in emissions has raised environmental concerns (Bergero et al., 2023). This situation has drawn the attention of both airlines and institutions that carry out ANSP activities. Moreover, the impact of air travel on global warming, climate change and human health (Klenner et al., 2022) has led to it becoming a matter of public concern, as evidenced by the activities of environmental activists (Elessawy et al., 2013). ANSPs are vital for aviation safety and efficiency. A balance must be struck between air traffic management and environmental sustainability goals. ANSPs should develop methods that enhance operational efficiency to reduce carbon emissions (Castelli et al., 2013; Buyle et al., 2021). For instance, the National Air Traffic Services (NATS) of the United Kingdom, as the ANSP, is set to have a positive impact on the reduction of CO<sub>2</sub> consumption and the deceleration of climate change through its 3Di (3-Dimensional Inefficiency Score) method (Elessawy et al., 2013). However, it should be noted that flight operations can be adversely affected by meteorological conditions. While a shorter route is typically required, various adverse conditions can change this situation. This has been shown to result in increased fuel consumption and CO<sub>2</sub> emissions (Klenner et al., 2022; Efthymiou, 2023). Furthermore, an increase in the number of seats and passengers on board results in a greater demand for fuel during take-off, thereby reducing the aircraft's efficiency and increasing its emission rates (Drews, 2011; Dempsey-Brench & Volta, 2018).

The following Air Navigation Service Providers (ANSP) can be listed: National Air Traffic Services (NATS), The Federal Aviation Administration (FAA), Deutsche Flugsicherung GmbH (DFS), Direction des Services de la Navigation Aérienne (DSNA), Ente Nazionale per l'Aviazione Civile (ENAV), State Airports Authority (DHMI), NAV CANADA, Departamento de Controle do Espaço Aéreo (DECEA), Japan Civil Aviation Bureau (JCAB), Civil Aviation Administration of China (CAAC), ENAIRE, AIRSERVICES AUSTRALIA et al. The optimisation of flight processes by ANSPs in countries situated along significant flight routes is projected to result in a reduction in CO<sub>2</sub> emissions in the future. The transportation sector is responsible for approximately 14% of global CO<sub>2</sub> emissions (IPCC, n.d.). In addition, the aviation sector has been responsible for approximately 2% of these emissions (Terrenoire et al., 2019; Klenner et al., 2022).



**Fig. 1.** Studies on Aviation and Emissions

A study was conducted using the keywords "Aviation" and "Emissions" in the Web of Science (WOS) database. Thereafter, the analysis software VOSviewer was utilised to obtain the output. The results of this study are presented in Fig. 1. The analysis revealed a notable increase in the frequency of research publications concerning aviation, carbon emissions and other emissions in recent years.

However, in the context of contemporary global conflicts, it is plausible that airlines have been compelled to select available routes rather than optimal ones, resulting in an escalation in CO<sub>2</sub> emissions. For instance, the Ukrainian airspace is not usable for east-west transitions. This predicament, akin to the broader context of transportation corridor routes, necessitates the identification of alternative routes, which in turn engenders augmented fuel consumption, elevated CO<sub>2</sub> emissions and escalating costs, factors that are of particular concern to business enterprises (Ranasinghe et al., 2019; Toraman, 2023).

### 3. Data and methodology

The research data were collected from the Eurocontrol website and worldbank.com between the years 2017 and 2020 for 36 European Air Navigation Service Providers (see Appendix 1). The GRA-based index values employed in the econometric analysis are drawn from Ölçen and Alnıpak (2023).

Following a comprehensive review of the extant literature, the research model is formed by the following variables. The utilisation of panel data is predicated on its superiority over time series or cross-sectional data concerning the quantity of information, variability and efficiency it contains (Baltagi, 2008; Wooldridge, 2002). The selection of variables was informed by extant literature, encompassing the population (Bartlett, 1994; Daily & Ehrlich, 1992), Gross Domestic Product (Fleurbaey & Blanchet, 2013; Liu et al., 2024) and passenger and cargo numbers (Aparicio, 2016; Song & Choi, 2020).

$$Indexvalue_{ij} = \beta_0 + \beta_1 \log\_Population_{ij} + \beta_2 \log\_GDP_{ij} + \beta_3 \log\_Labor_{ij} + \beta_4 \log\_Passenger_{ij} + \beta_4 \log\_Cargo_{ij} + \beta_5 \log CO_{2ij} + \beta_4 \log NO_{ij} + \beta_4 \log METH_{ij} + \varepsilon_{ij} \quad (1)$$

Where,

Index value - the GRA results of the air navigation service providers.

Log\_population - population of the country with logarithmic transformation.

Log\_GDP - gross domestic production of the country with logarithmic transformation.

Log\_LABOR - the active labour force of the country with logarithmic transformation.

Log\_passenger - the yearly passenger number of the country with logarithmic transformation.

Log\_cargo - the yearly cargo amounts with logarithmic transformation.

Log\_CO<sub>2</sub> - carbon dioxide emissions (metric tons) with logarithmic transformation.

Log\_N<sub>2</sub>O - nitrous oxide emissions (metric tons) with logarithmic transformation.

Log\_METH - methane emissions (metric tons) with logarithmic transformation.

### 4. Findings

Subsequent to the establishment of the research model, data pertaining to Gross Domestic Product (GDP), population, labour, cargo (in terms of volume in kilometres), passenger (in terms of head number in kilometres) and emission values (carbon dioxide, nitrous oxide and methane) are retrieved from the World Bank database. The presence of individual effects or time effects on the data is determined by conducting F-tests on the data set. The detection of these two important effects results in the selection of the two-way fixed effect regression model. However, it is acknowledged that the data may be subject to temporal constraints. The research model is subject to data limitations. Consequently, the time effect was disregarded. To this end, a range of statistical estimations have been employed, including fixed effect (FE) estimation, random effect (RE) estimation and maximum likelihood (MLE) estimation, utilising the Stata program (Yerdelen Tatoğlu, 2020). The selection between RE and FE is made using a Hausman test. The results can be found in Table 1.

**Table 1.** Model selection results

	Fixed effect estimation	Random effect estimation	Maximum likelihood effect estimation
F test value	5.307		
Score test			125.636
LR test (chi2_c)			14.934
Breusch Pagan LM test		20.621	
Hausman test score		40.213	
p values	0.000***	0.001***	0.000***

Pursuant to the outcomes of the model selection process, it is postulated that the fixed effect estimation results are commensurate with the continuation of the analytical process. The fixed estimation results are presented in Table 2.

**Table 2.** Fixed estimation results of the model

INDEX VALUE GRA	Coefficient	Std. err	T	P value
<i>Log Population</i>	-2.653	0.790	-3.36	0.001
<i>Log GDP</i>	-0.176	0.090	4.03	0.000
<i>Log Labor</i>	1.499	0.372	3.29	0.001
<i>Log Cargo</i>	-0.004	0.005	-0.87	0.387
<i>Log Passenger</i>	0.023	0.089	2.66	0.009
<i>Log CO<sub>2</sub> emission</i>	0.238	0.738	3.23	0.002
<i>Log NO emission</i>	0.104	0.053	1.97	0.052
<i>Log MET</i>	-0.066	0.062	-1.08	0.284
<i>cons</i>	10.590	4.498	2.35	0.021
<b>R Squared values</b>		<b>F test Results</b>		
<i>Within</i>	0.410	F (8,81)=7.05		prob=0.0000***
<i>Between</i>	0.028			
<i>Overall</i>	0.016			

The research model can be described and formed using the following equation:

$$\begin{aligned}
 \text{Indexvalue}_{ij} = & 10.590 + -2.653 \log\_Population_{ij} - 0.293 \log\_GDP_{ij} + 2.002 \log\_Labor_{ij} \\
 & + 0.023 \log\_Passenger_{ij} + 0.442 \log CO_{2ij} + 0.174 \log NO_{ij} + \beta_4 \log METH_{ij} + \varepsilon_{ij}
 \end{aligned}
 \tag{2}$$

According to the findings of the FRE analysis, in the absence of fluctuations in other variables, a one-percent increase in population results in a three-fourth of a percent decrease in profitability (index) values. Similarly, a one-percent rise in GDP leads to a zero-tenths of a percent decrease in profitability (index). Furthermore, a one-percent rise in labour results in a one-percent increase. The data also reveals a 499% increase in profitability (index) for every 1% increase in passenger numbers, a 0.023% increase in profitability (index) for every 1% increase in carbon dioxide (CO<sub>2</sub>) emissions and a 0.104% increase in profitability (index) for every 1% increase in nitrogen oxide (NO) emissions, for the 2017-2020 (pre-Covid 19) period. The R-squared value was found to be 0.440 and the F-test value was found to be statistically significant. The statistical analysis indicates an absence of a significant relationship between cargo volume and methane values and GRA-based index values.

## 5. Discussion, conclusions and suggestions

The findings indicate that the results are consistent with the European continent's norms with respect to industrial development and development level. It can be concluded that the most profitable routes (countries) have relatively low population density, low GDP values, high labour force values, relatively high passenger values and high CO<sub>2</sub> and NO<sub>x</sub> values for the research period. Consequently, if we consider the positive relationship between ANSPs (Air Navigation Service Providers) profitabilities and utilization of airspace, it can be inferred that the densest airspaces have these values. It is important to note that the research findings may be influenced by the impact of the pandemic on air traffic indicators, such as passenger and cargo numbers and emission values.

The present findings are consistent with those reported in the extant literature. Li et al. (2024) emphasise the significance of energy production and clean energy markets in this context for countries with elevated CO<sub>2</sub> and NO<sub>x</sub> emissions. In a similar vein Andrejiová et al. (2020) assert that the transportation sector, encompassing air transport, constitutes a primary contributor to air pollution. This emphasis is also realised by Moffat (2010) for the shipping industry. In a detailed analysis of China, Wang et al. (2022) states that nations should have a national emissions inventory that includes information on transportation-related activities and emissions. A similar analysis of Seymore et al. (2014) for South Africa corroborates the effective and efficient use and utilisation of national emissions inventory. The utilisation of sustainable fuels and measures to decarbonise can be regarded as other significant measures (Jing et al., 2022). Another significant step in the Clean Development Mechanisms (CDM) in transportation, particularly in civil air transportation, is on the research and development agenda of the International Civil Aviation Organization (ICAO) and international authorities (Warnecke et al., 2019). Concurrent with these developments, Wang et al. (2014) posit that new generations of aircraft and engine designs incorporating sustainable components are emerging. The industry's efforts to harmonise profit and sustainability across nations, as exemplified by the SESAR (Single European Sky ATM Research) initiative, underscore the need for comprehensive air traffic optimization. The EU ETS (The European Union Emissions Trading System) has also brought the European continent to the verge of more strict and comprehensive amendments regarding the sustainability of air. Concurrently, the provisions of Annex 16 and its overarching vision, embodied by CORSIA (the Carbon Offsetting and Reduction Scheme for International Aviation), are poised to exert a profound influence on the evolution of aviation in the post-pandemic era. It is premature to draw any conclusions about the impact of this development on air quality.

It is reasonable to hypothesise that the government will be unable to reduce its transportation activities. Nevertheless, it is recommended that the government focus on enhancing its technological, technical and legal foundations to achieve sustainable objectives. The economic development of the country will be another challenge to be faced. Future research endeavours should take into account these significant factors, incorporating the impact of civil aviation at the national, regional and international levels, utilising a specialised econometric model and techniques.

### Nomenclature

ANSP	: Air Navigation Service Providers
CO <sub>2</sub>	: Carbon dioxide
NO	: Nitrogen Oxide
MET	: Methane
EBITDA	: Earnings before Interests, Taxes, Depreciation and Amortization

OPEX	: Operational Expenditures
CAPEX	: Capital Expenditures
POPEX	: Profit per operational expenditure
PAPEX	: Profit per capital expenditure
ROA	: Return on Assets
ROD	: Return on Debts,
ROE	: Return on Equity
FCF	: Free Cash Flow
SE	: Shareholder Equity
RONOA	: Return on Operational Activity
RONIA	: Return on Investment Activity
EU ETS	: The European Union Emissions Trading System
CORSIA	: Carbon Offsetting and Reducing Scheme for International Aviation

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## APPENDIX 1.

ANSP COMPANY	COUNTRY
Albcontrol	Albania
ANS CR	Czech
Fintraffic	Finland
ARMATS	Armenia
Austro Control	Austria
Avinor Flysikring	Norway
BULATSA	Bulgaria
Croatia Control	Croatia
DFS	Germany
DHMI	Türkiye
DSNA	France
EANS	Estonia
ENAIRE	Spain
ENAV	Italy
Hungaro Control	Hungary
IAA	Ireland
LFV	Sweden
LGS	Latvia
LPS	Slovak republic
LVNL	Netherlands
MATS	Malta
M-NAV	North Macedonia
MOLDATSA	Moldova
NATS	United Kingdom
NAV Portugal	Portugal
NAVIAIR	Denmark
Oro Navigacija	Lithuania
PANSA	Poland
ROMATSA	Romania
Skyguide	Switzerland
Slovenia Control	Slovenia
SMATSA	Serbia and Montenegro



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