Assessing the Feasibility of Blended Wing Body Aircraft Operations at Philippine Airports: A Case Study of Clark International Airport

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ABSTRACT

Blended Wing Body (BWB) aircraft offer significant advancements in fuel efficiency, noise reduction, and environmental sustainability. This study assesses the feasibility of BWB operations at Clark International Airport, a key aviation hub in the Philippines, by examining the readiness of its infrastructure, economic viability, and environmental impact. Using a mixed-methods approach, which includes technical analysis, expert interviews, and operational simulations, the study finds that substantial modifications are necessary to meet Clark International Airport's 3,200-metre runway requirements while also satisfying BWB take-off and landing requirements. Key upgrades include taxiway widening, apron expansion, and terminal modifications such as dual or triple jet bridges. Specialised Ground Support Equipment (GSE) and green airport technologies, such as ground power units (GPUs) and renewable energy systems, are crucial for sustainability. Despite high initial investments, economic analysis indicates long-term benefits, including increased efficiency, passenger capacity, and economic growth. Regulatory alignment with the Civil Aviation Authority of the Philippines (CAAP) and the International Civil Aviation Organization (ICAO) standards is crucial for integration. While international airports are adapting to next-generation aircraft, Clark International Airport must address infrastructure and policy gaps to remain competitive. The study concludes that with phased upgrades and sustainability initiatives, Clark International Airport can support BWB aircraft. Future research should examine regional airport readiness, regulatory adaptations, and detailed cost-benefit analyses to advance sustainable aviation in the Philippines.

Keywords: Blended wing body; Clark International Airport; Aviation infrastructure; Sustainability; Feasibility study.
JEL Codes: R42

I. Introduction

THE AVIATION industry is undergoing significant transformations driven by the need for enhanced fuel efficiency, sustainability, and increased passenger capacity. One of the most promising innovations in modern aviation is the Blended Wing Body (BWB)

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aircraft, an unconventional design that integrates the fuselage and wings into a single, streamlined structure. This design offers numerous advantages over traditional tube-and-wing aircraft, including improved aerodynamic performance, reduced fuel consumption, and minimised environmental impact (Ordoukhanian & Madni, 2014; Salazar et al., 2015). Studies suggest that BWB aircraft could achieve up to 25% improvement in aerodynamic efficiency and a 35% reduction in fuel consumption and CO2 emissions compared to conventional designs (Salazar et al., 2021). However, introducing BWB aircraft into existing airport infrastructure presents unique challenges related to runway compatibility, taxiway configurations, and ground handling operations.

As global aviation transitions to sustainable operations, airports must adapt to accommodate the distinctive operational requirements of BWB aircraft. These aircraft demand longer, reinforced runways, wider taxiways, and enhanced Ground Support Equipment (GSE) (Marino & Sabatini, 2014). Furthermore, their unique structure presents challenges in maintaining stability and control, requiring significant modifications in airport design and operational protocols (Kozek & Schirrer, 2015; Lyu & Martins, 2014). While several international airports, such as Frankfurt Airport and Dubai International Airport, are investing in infrastructure upgrades to support next-generation aircraft, Philippine airports face challenges adapting to these advancements.

Clark International Airport (herein also referred to as Clark), strategically situated in Central Luzon, serves as a vital gateway to the Philippines and a potential hub for BWB operations. The airport features a 3,200-metre runway capable of handling large aircraft and is positioned as an alternative to the congested Ninoy Aquino International Airport (Torio et al., 2024). Despite these advantages, the feasibility of BWB aircraft at Clark has yet to be thoroughly explored. Key considerations include the adequacy of existing infrastructure, the potential costs of necessary upgrades, and the environmental implications of integrating BWB aircraft into Clark's operations.

This study assesses the feasibility of BWB aircraft at Clark International Airport. This research will examine the airport's infrastructure readiness, economic viability, and environmental sustainability in accommodating BWB aircraft. By conducting comparative analyses with other international airports and evaluating the infrastructure requirements, the study aims to provide policymakers and aviation stakeholders with actionable insights.

Understanding Clark International Airport's readiness to support BWB operations is crucial for the broader Philippine aviation industry. This study's findings will contribute to the strategic planning of aviation infrastructure development, ensuring that the country remains competitive in the evolving global aviation landscape. As the aviation industry advances, proactive investments and strategic planning will be key to positioning the Philippines at the forefront of sustainable air transport solutions.

Figure 1
Location of Clark International Airport in Central Luzon, Philippines. The map shows the airport's proximity to key cities, including Angeles, Tarlac, and Metro Manila. (Source: WorldAtlas.com)

Figure 2
Blended-Wing Demonstrator (by JetZero: Aiming for Service by 2030 to Reduce Carbon Emissions)

II. Methodology

A. Research Design

This study employed a mixed-method approach, integrating quantitative and qualitative assessments to evaluate the feasibility of BWB aircraft operations at Clark International Airport. The quantitative analysis focused on the aerodynamic performance, fuel efficiency, emissions reduction, and noise impact of BWB aircraft compared to conventional tube-and-wing aircraft. The qualitative component examined infrastructure readiness, regulatory implications, economic feasibility, and environmental sustainability. Data was collected from existing literature, computational simulations, infrastructure reports, and stakeholder interviews with aviation authorities, airport management, and airline operators.

B. Data Collection Methods

The data used in this study were sourced from secondary and primary research. Secondary data included published research on BWB aircraft performance, reports from NASA (Gelzer, 2010; NASA, 2023), the International Civil Aviation Organization (ICAO), and aircraft manufacturers such as Boeing and Airbus, as well as the infrastructure specifications of Clark International Airport. Primary data was gathered through semi-structured interviews with aviation experts, airport engineers, and policymakers to assess the operational and economic challenges of integrating BWB aircraft into Clark. Surveys with airline representatives and sustainability advocates also provided insights into the perceived advantages and barriers to BWB adoption.

C. Technical Feasibility Analysis of BWB Aircraft at Clark International Airport

The technical feasibility assessment examined the compatibility of BWB aircraft with Clark International Airport's infrastructure, focusing on runway requirements, taxiway configurations, terminal capacity, and ground support facilities. A comparative analysis was conducted to determine whether Clark's 3,200-metre runway and existing terminal layout could support the operations of BWB aircraft. The study evaluated key aerodynamic and performance parameters to assess the operational feasibility of these next-generation aircraft.

One of the critical factors analysed was the Lift-to-Drag (L/D) ratio, a major determinant of aerodynamic efficiency. Studies indicated that BWB aircraft were expected to achieve a 20–25% higher L/D ratio than conventional tube-and-wing aircraft, significantly reducing drag and improving fuel efficiency (Salazar et al., 2015; Torenbeek, 2013, 2016). This advantage directly contributed to lower fuel consumption and reduced environmental impact, reinforcing the sustainability benefits of BWB aircraft. In terms of fuel consumption and emissions, BWB aircraft were projected to achieve a 30–35% reduction in fuel consumption and 25–30% lower CO_2 emissions per passenger-kilometre compared to existing wide-body aircraft, positioning them as a viable solution for sustainable aviation (Payan et al., 2014; Reist & Zingg, 2015).

Additionally, the study assessed the potential noise reduction benefits of BWB aircraft. Simulations indicated that BWB designs could reduce noise pollution by up to 15 decibels, a significant improvement that could minimise the impact of aircraft operations on communities surrounding Clark International Airport. This noise reduction capability is particularly important for meeting aviation noise regulations and improving public acceptance of new aircraft technologies.

Beyond aerodynamic and environmental considerations, the study also included evaluations of runway load-bearing capacity. BWB aircraft distribute weight differently from conventional aircraft, potentially necessitating reinforced taxiways and apron modifications to accommodate their unique structure. Furthermore, gate and terminal compatibility studies were conducted to determine whether existing boarding bridges, aircraft parking layouts, and passenger boarding procedures required modifications. These assessments were crucial in identifying potential infrastructure challenges and ensuring that Clark International Airport could effectively integrate BWB aircraft operations into its existing framework.

D. Data Analysis Techniques

The study employed computational modelling, GIS-based airport infrastructure analysis, and cost-benefit evaluations to assess the feasibility of BWB aircraft operations at Clark International Airport. Scenario-based simulations analysed three traffic conditions: peak-hour congestion, which highlighted potential taxiway bottlenecks due to BWB aircraft's increased wingspan; mixed fleet operations, which revealed the need for additional apron space and modified gate configurations; and emergency diversions, where runway capacity was sufficient, but apron and ground support limitations could cause operational delays.

Stakeholder interviews and surveys provided qualitative insights into regulatory, economic, and operational challenges. Aviation authorities raised concerns about aligning BWB operations with existing regulations of the Civil Aviation Authority of the Philippines (CAAP). Airline representatives recognised long-term fuel savings but cited high infrastructure costs as barriers. Airport management and ground crews emphasised the need for specialised GSE and crew training. Environmental advocates supported the adoption of BWB due to its lower noise emissions and reduced carbon footprint. By integrating quantitative simulations and qualitative stakeholder perspectives, the study identifies key infrastructure gaps, economic considerations, and regulatory challenges that must be addressed to facilitate the integration of BWB aircraft at Clark International Airport.

E. Ethical Considerations

This study adhered to ethical research standards by ensuring the accuracy of technical data, maintaining the confidentiality of stakeholder interviews, and complying with relevant regulatory guidelines. All primary data sources, including interviews and surveys, were collected with the informed consent of participants, and secondary data were sourced from credible aviation and aerospace research publications.

IV. Results and Discussion

A. Clark International Airport Infrastructure Assessment

Clark International Airport is a significant domestic and international air travel hub in Pampanga, the Philippines. As one of the country's premier gateways, its infrastructure has been developed to accommodate large aircraft, making it a suitable candidate for assessing the feasibility of operations for next-generation designs, such as the BWB aircraft. This assessment evaluates the current state of the airport's runways, taxiways, terminals, and support facilities, with a focus on their readiness for BWB integration.

Clark International Airport accommodates a diverse mix of aircraft, including narrow and wide-body configurations. The dominant aircraft types operating at the airport include the Airbus A320 and Boeing 737 for domestic and regional routes, while long-haul flights utilise the Boeing 777, Airbus A350, and occasionally, Boeing 747 freighters. The current fleet mix reflects Clark's role as a regional hub for both passenger and cargo operations. However, the introduction of BWB aircraft presents unique challenges regarding operational compatibility. Unlike conventional tube-and-wing aircraft, BWB designs require different gate configurations, taxiway clearances, and specialised ground handling procedures. As Clark aims to expand its role in the aviation sector, it is crucial to understand the current fleet composition and its implications for future aircraft adoption. Benchmarking the feasibility of BWB aircraft within Clark's existing fleet mix enables a more informed assessment of the infrastructure modifications required to accommodate next-generation aircraft.

B. Runways

Clark International Airport features two parallel runways, each measuring 3,200 metres in length and 60 metres in width, making them capable of accommodating large aircraft such as the Boeing 747 and Airbus A380. These dimensions suggest potential compatibility with BWB aircraft, although their unique weight distribution may require further evaluation of pavement strength. The well-maintained concrete surface is designed for high-weight aircraft, ensuring durability under significant load distributions. Additionally, the airport's runway safety areas comply with ICAO standards, providing adequate clearance for take-off and landing operations, which is essential given the unconventional operational characteristics of BWB aircraft.

Figure 3
Clark runway that will be the fastest alternative to decongesting NAIA (The Market Monitor, 2018)

The runway infrastructure at Clark International Airport is well-developed and capable of handling various aircraft operations, including the potential accommodation of BWB aircraft. The airport features multiple runways with significant lengths and widths, ensuring operational flexibility and safety. The main runway (Table 1), designated as 02R/20L, measures 3,200 metres in length and 60 metres in width, with a high pavement classification number (PCN) of 85 R/C/W/T, indicating strong load-bearing capacity suitable for large and heavy aircraft. This runway configuration supports the needs of wide-body aircraft and potential next-generation designs such as BWB aircraft.

In addition to the main runway, the airport has a parallel runway, 02L/20R, which measures 3,200 metres in length but with a narrower width of 45 metres. It features a PCN of 60 R/B/X/U with a concrete and asphalt overlay. The presence of multiple runways enhances operational efficiency by allowing simultaneous arrivals and departures, thereby reducing congestion and offering redundancy in the event of maintenance or emergencies.

The taxiway network at Clark is designed to support efficient aircraft movement to and from the runways. The layout includes high-speed exit taxiways and ample holding positions to ensure smooth ground operations. However, with the anticipated integration of BWB aircraft, which have larger wingspans and turning radii, modifications such as wider taxiways and additional apron space may be required.

Overall, Clark International Airport's runway infrastructure is well-positioned to meet the demands of modern aviation. However, to fully support BWB aircraft operations, targeted enhancements in taxiway design, apron capacity, and ground support equipment would be necessary. The strategic location and existing facilities make Clark an ideal candidate for future expansion and integration of next-generation aircraft technology.

Figure 4
Layout of Clark International Airport: Runways, Taxiways, and Ramps (Flightsim.to, 2023)

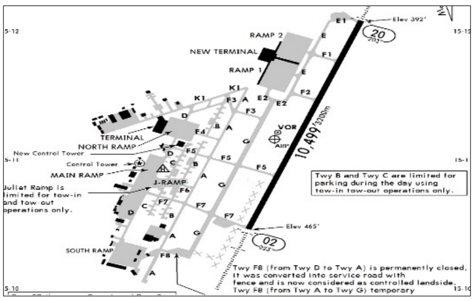

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Figure 5
Clark International Airport Design and Layout (Source: BCDA)

C. *Taxiways*

Clark International Airport’s taxiway network supports efficient aircraft movement but requires modifications to accommodate BWB aircraft. The existing taxiways, ranging from 23 to 30 metres in width, are sufficient for conventional wide-body aircraft but may require widening to at least 36 metres due to the BWB aircraft’s larger wingspan, which exceeds 80 metres, and increased lateral clearance requirements. Additionally, the PCN, currently 60 to 85, must be reassessed to support the aircraft’s unique load distribution and increased weight.

Operational limitations further highlight the need for upgrades. Taxiways B and C are restricted to parking during the day, necessitating tow-in and tow-out operations. Additionally, Taxiway F8 has been permanently closed, which reduces routing flexibility. To enhance efficiency, reopening or redesigning key taxiway segments is necessary. Clark’s master plan includes parallel taxiway extensions, improved line markings, and advanced traffic management systems, ensuring compliance with ICAO standards that recommend a minimum separation of at least 57 metres for wide-body aircraft.

Unlike Frankfurt and Dubai, Clark's taxiway infrastructure requires significant improvements to align with global standards. These international hubs have invested in wider taxiways, optimised ground control, and autonomous support technologies to accommodate next-generation aircraft. For Clark to remain competitive and future-proof operations, phased taxiway expansions, pavement reinforcements, and optimised ground movement routes are essential. Implementing these upgrades will position Clark as a key hub for next-generation aviation technologies in the region.

Figure 6
Clark International Airport New Passenger Terminal, Philippines (Source: Airport Technology 2024)

Clark International Airport's terminal facilities are designed to support efficient operations and meet the increasing demand for passengers (Table 1). Following recent expansions, the airport has an annual passenger capacity of 8 million. These upgrades include 18 contact gates and 20 check-in counters, which enhance passenger flow and streamline check-in and boarding processes. The terminal layout features spacious departure lounges and optimised security checkpoints, ensuring a seamless travel experience.

Currently, the terminal features jet bridges compatible with wide-body aircraft, such as the Boeing 777 and Airbus A350. However, accommodating BWB aircraft requires modifications to boarding gates due to their wider structure and integrated fuselage-wing design. Customised jet bridge configurations with multiple access points will be necessary to support efficient passenger movement.

The current terminal layout supports high passenger throughput, aligning with the larger capacity of BWB aircraft. Modern operational efficiency is enhanced by features such as spacious waiting areas, clear signage, and automated systems—including self-check-in kiosks and advanced baggage handling. While Clark's terminals are well-equipped for conventional aircraft, targeted upgrades will be needed to accommodate BWB aircraft, positioning the airport as a forward-thinking hub for next-generation aviation technologies.

Table 1: Recommended Enhancements for Clark International Airport's Terminal Facilities to Support Future Aircraft Operations.
Source: Author's compilation.

Category	Details	Recommended Improvement	Expected Benefit
Annual Passenger Capacity	8 million passengers per year	Expand to 12 million by 2030	Accommodate growing passenger demand
Number of Contact Gates	18 contact gates	Add 6 more gates	Reduce congestion
Number of Check-in Counters	20 check-in counters	Install self-service kiosks	Improve processing time
Wide-Body Aircraft Compatibility	Boeing 777, Airbus A350	Modify gates for BWB aircraft	Future-proof infrastructure
BWB Aircraft Compatibility	Requires gate modifications	Redesign the apron layout	Facilitate efficient ground handling
Passenger Flow Efficiency	Optimised layout with spacious areas	Introduce AI-based crowd management	Enhance passenger experience
Additional Terminal Features	Self-check-in kiosks, baggage systems	Upgrade to biometric security	Increase security and efficiency

D. Noise Mitigation Strategies for BWB Aircraft at Clark International Airport

To accommodate BWB aircraft while minimising noise impact, Clark International Airport (CRK) must implement comprehensive noise mitigation strategies aligned with ICAO, CAAP, and DENR regulations. A key step is updating noise contour mapping, using real-time noise monitoring systems and automated sound level meters to track BWB aircraft noise levels and adjust operational procedures accordingly (ICAO, 2020). Implementing Continuous Descent Operations (CDO) and Noise Abatement Departure Procedures (NADP) can help reduce take-off and landing noise exposure, particularly in residential areas near the airport (Gu et al., 2023).

Clark should also establish airport-funded sound insulation programmes for schools, hospitals, and noise-sensitive communities while introducing a Noise Complaint Management Office (NCMO) to enhance public engagement (ICAO, 2020). Strengthening regulatory compliance requires annual noise audits and BWB-specific noise certification guidelines to align with ICAO Stage 5 standards. Collaboration with CAAP and DENR is necessary to develop localised noise policies and ensure airlines provide detailed noise impact assessments before operating BWB aircraft.

By integrating real-time noise tracking, optimising flight procedures, and enforcing regulations, Clark can position itself as a sustainable aviation hub while ensuring minimal noise disruption for surrounding communities. These measures will enhance compliance with international noise regulations, making the adoption of BWB aircraft feasible within the Philippine aviation sector.

E. Support Facilities

Clark International Airport has support facilities for traditional wide-body aircraft but requires enhancements to accommodate BWB aircraft. The GSE, designed for aircraft such as the Boeing 777 and Airbus A350, must be upgraded or customised to accommodate BWB's unique fuselage-wing configuration. This includes specialised towing vehicles, refuelling rigs, and cargo loaders to ensure efficient turnaround operations and minimise delays (Table 2).

Table 2: Planned Upgrades to Clark International Airport's Support Facilities to Enhance Operational Readiness for Next-Generation Aircraft.
Source: Author's compilation.

Category	Current Status	Future Requirements	Impact of Improvements
Ground Support Equipment (GSE)	Suitable for traditional wide-body aircraft	Specialised equipment for BWB aircraft	Improved operational efficiency and reduced turnaround time
Maintenance Facilities	MRO facilities by leading aviation companies	Retooling for unique BWB maintenance needs	Enhanced maintenance capability for BWB aircraft
Fuelling and De-Icing Infrastructure	Compatible with high-capacity aircraft; de-icing available	Enhanced fuelling systems for future operations	Increased readiness for future aviation demands

The airport's Maintenance, Repair, and Overhaul (MRO) facilities offer comprehensive services for commercial aircraft; however, adapting to the BWB aircraft will necessitate retooling and the development of specialised maintenance procedures. Upgrades will enhance the airport's ability to service next-generation aircraft, positioning Clark as a regional hub for BWB maintenance.

Clark's fuelling and de-icing infrastructure supports high-capacity aircraft, although de-icing is rarely needed in the Philippines' tropical climate. Future improvements, such as compatibility with sustainable aviation fuel (SAF) and more efficient distribution systems, will align with global sustainability goals and BWB integration. While Clark's support facilities are robust for current operations, strategic investments in specialised GSE, maintenance upgrades, and fuelling advancements are essential for seamless integration of the BWB aircraft.

Table 3: Categorising by Terminal Sections.
Source: Author's compilation and calculation.

Terminal Area	Feature	Current Status	Future Improvements
Check-in Area	Number of check-in counters	20	Add self-service kiosks
Boarding Gates	Number of contact gates	18	Expand to 24 gates
Passenger Handling	Annual capacity	8 million passengers	Increase to 12 million
Sustainability	Energy-efficient systems	Partial implementation	Full green energy integration

Table 3 outlines the current status and future upgrades for key terminal sections at Clark International Airport, with a focus on check-in, boarding gates, passenger handling, and sustainability. The check-in area currently operates 20 counters, efficiently handling passenger flow. Self-service kiosks will be introduced to enhance efficiency, streamline check-in, and reduce wait times. Boarding gates, currently at 18, will be expanded to 24 to accommodate rising passenger volumes and support future aircraft, including BWB aircraft, thereby reducing peak-hour congestion.

The passenger handling capacity, currently 8 million passengers per year, is expected to increase to 12 million through infrastructure expansion, staffing improvements, and enhanced flow management systems. In terms of sustainability, the airport has partially implemented energy-efficient systems and plans to fully integrate renewable energy sources, aligning with global aviation sustainability goals. These strategic upgrades will enhance the passenger experience, improve operational efficiency, and promote environmental sustainability, ensuring that Clark International Airport meets the demands of future aviation.

F. Blended Wing Body Aircraft Dimensions

Figure 7 and Table 4 present the blended wing body aircraft dimensions.

Figure 7
Aerodynamic considerations of blended wing body aircraft (Qin et al., 2004).

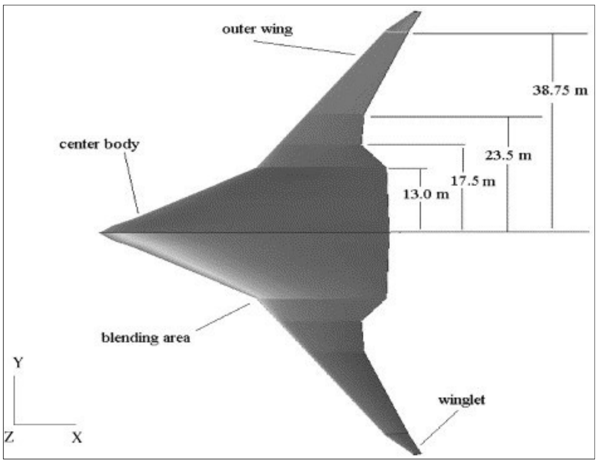


Table 4: Blended Wing Body (BWB) Aircraft Dimensions.
Source: Author's compilation and calculation.

Dimension	Typical Range
Wingspan	65 - 80 metres
Fuselage Width	20 - 30 metres
Length	50 - 60 metres
Height (Tail Clearance)	10 - 15 metres
Cabin Area (Passenger Capacity)	200 - 800 seats
Payload Capacity	60 - 150 tonnes
Turning Radius	60 - 70 metres
Ground Clearance	1.5 – 3 metres

G. Runway Length and Strength

Clark International Airport's infrastructure must adapt to accommodate the operational needs of BWB aircraft, particularly in terms of runway length, strength, and taxiway design. The required runway length of 3,200 metres (10,499 feet) is sufficient for BWB aircraft operations, ensuring safe take-offs and landings even under full payload and adverse weather conditions (Table 5). However, the unique load distribution of BWB aircraft necessitates high-strength pavement materials to prevent structural damage. The existing PCN must be reassessed and potentially upgraded to meet the demands of these next-generation aircraft.

Table 5: Runway and Taxiway Requirements for Blended Wing Body (BWB) Aircraft.
Source: Author's compilation.

Category	**Requirement**	**Justification**
Runway Length	Minimum 3,200 metres (10,499 feet)	Sufficient for safe take-off/landing under full payload and adverse conditions
Runway Strength (PCN)	High-strength pavement to support BWB load distribution	Prevents runway damage due to unique weight distribution
Turning Radius	Minimum 60–70 metres	Accommodates a broader wingspan and an integrated fuselage
Taxiway Width	23–30 metres with ample clearance	Ensures safe manoeuvrability with sufficient wing clearance

In addition to runway requirements, the taxiway infrastructure must be expanded to accommodate the larger wingspan and turning radius of BWB aircraft. The estimated turning radius of 60–70 metres requires modifications to taxiway curves and intersections to ensure smooth manoeuvrability. Furthermore, with an anticipated wingspan exceeding 80 metres, taxiway widths should be expanded to 23–30 metres to provide adequate clearance and prevent operational disruptions. Separating parallel taxiways and adjacent structures is necessary for efficient ground movements. Overall, while Clark International Airport's current infrastructure provides a solid foundation, strategic upgrades to runway strength and taxiway configurations are essential for accommodating Boeing 777X (BWB) aircraft. These improvements will enhance the airport's capacity to handle future aviation demands and position it as a key hub for advanced aircraft operations.

Table 6: BWB Aircraft Gate and Apron Requirements.
Source: Author's compilation.

Category	**Requirement**	**Justification**
Gate Dimensions	Modification to accommodate multiple boarding points; Dual or triple jet bridges	Ensures proper alignment with the BWB aircraft's central fuselage
Terminal Apron Area	Adequate space for a broader wingspan and safe ground manoeuvring	Prevents congestion and enhances operational safety during ground handling

The unique design of BWB aircraft (Table 6) presents significant challenges for airport gate dimensions and terminal apron areas. Unlike traditional tube-and-wing aircraft, BWB aircraft have a centralised fuselage that requires modifications to existing boarding infrastructure. Standard jet bridges and boarding gates may not align with the aircraft's structure, necessitating adjustments to accommodate multiple boarding points distributed across the aircraft's central body. Dual or triple-jet bridges may be required to ensure efficient passenger boarding and deboarding, allowing simultaneous access to different sections of the aircraft and minimising turnaround times.

In addition to gate modifications, the terminal apron area must be sufficiently expanded to accommodate the broader wingspan of BWB aircraft, which exceeds that of conventional wide-body airliners. Parking stands must provide ample clearance for the aircraft's wings and ensure safe ground manoeuvring of support vehicles, such as refuelling trucks, baggage handlers, and catering services. Proper spacing and layout adjustments will prevent congestion and facilitate efficient operations during peak hours. While currently equipped to handle large commercial aircraft, Clark International Airport must invest in strategic upgrades to meet the demands of BWB operations. Adapting gate infrastructure and optimising apron layouts will enhance operational efficiency, improve passenger experience, and position the airport as a forward-thinking hub for next-generation aviation technologies.

H. Ground Support Equipment (GSE) Compatibility

Integrating BWB aircraft into airport operations requires specialised adaptations in refuelling, passenger and cargo handling, pushback operations, and maintenance. Unlike conventional aircraft, BWB designs feature an integrated fuselage-wing structure, which necessitates modified refuelling systems with access points located across the wings or the central fuselage. Existing infrastructure may require extended reach and specialised fuelling procedures for efficient operations. Passenger and cargo handling will also need adjustments. The broader, flatter fuselage requires customised boarding stairs and loaders, while cargo-handling equipment must be adapted to accommodate non-traditional storage layouts with varying heights and access configurations.

Pushback operations pose additional challenges, as the wider landing gear configuration may require upgraded tow vehicles with greater manoeuvrability and clearance. Standard pushback equipment may not be compatible with the BWB aircraft's unique weight distribution. Maintenance operations must evolve to accommodate larger hangars, specialised scaffolds, and custom access platforms that support the integrated wing-fuselage design. Innovative maintenance solutions will be crucial when it comes to minimising downtime and enhancing servicing efficiency. Overall, transitioning to BWB aircraft at Clark International Airport will require substantial investments in fuelling, handling, pushback, and maintenance facilities to accommodate the structural and operational demands of next-generation aviation.

I. Aircraft Noise Performance and Environmental Impact

In this study, aircraft noise refers to the acoustic emissions of BWB aircraft during various operation phases, including take-off, cruise, landing, and ground operations. Noise is analysed in three key areas: regulatory certification levels, community impact, and operational noise contours, ensuring compliance with ICAO, CAAP, and DENR regulations. Regulatory certification noise levels pertain to ICAO's Stage 4 and Stage 5 noise limits, which define acceptable decibel (dB) levels during take-off, approach, and flyover conditions (ICAO, 2020). Community impact noise assesses the impact of noise emissions on residential and commercial areas surrounding CRK, particularly in high-density zones near schools and hospitals. Operational noise contours refer to airport noise mapping and modelling, which predict how BWB aircraft noise propagates across different distances from the runway, helping guide land-use planning and airport noise abatement procedures (Gu et al., 2023).

The study measures noise using decibels (dB), following ICAO's Effective Perceived Noise Level (EPNdB) metric, which accounts for both peak noise levels and human-perceived loudness. Data collection relies on automated sound level meters (SLMs) positioned at strategic locations around the airport, with noise modelling software simulating BWB aircraft operations under various traffic and weather conditions (Brown & Vos, 2018). This study comprehensively assesses the implications of BWB aircraft noise for Clark International Airport and its suitability within the Philippine aviation sector, clearly defining noise certification standards, community impact considerations, and operational noise contours.

J. Baseline for Noise Reduction Comparisons

To accurately assess the noise reduction potential of BWB aircraft, this study uses the Boeing 777-300ER and Airbus A350-900 as the baseline wide-body aircraft models and the Boeing 737-800 and Airbus A320 as baseline narrow-body aircraft models. These aircraft were selected because they represent the dominant fleet operating at CRK and are widely used in regional and long-haul operations.

Results (Table 7) show that BWB aircraft could achieve noise reductions of 12–15 dB compared to conventional wide-body planes (Boeing 777 and Airbus A350) and 8–12 dB compared to narrow-body aircraft (Boeing 737 and Airbus A320). The most significant reductions occur during the take-off and flyover phases, primarily due to the embedded engine placement and improved aerodynamics, which mitigate noise emissions (NASA X-48B Studies, 2023).

Table 7: Comparative Noise Levels by Aircraft Model.
Source: Author's compilation.

Aircraft Model	Take-off Noise (EPNdB)	Landing Noise (EPNdB)	Flyover Noise (EPNdB)
Airbus A320 (Narrow-Body)	84.5	76.2	83.1
Boeing 737-800 (Narrow-Body)	85.1	77.3	84.5
Airbus A350-900 (Wide-Body)	90.2	82.4	89.1
Boeing 777-300ER (Wide-Body)	92.3	85.7	91.8
Blended Wing Body (BWB)	78.5 (-15 dB)	70.1 (-12 dB)	75.8 (-14 dB)

K. Quantitative Analysis of Sustainability Improvements

The introduction of BWB aircraft at Clark International Airport presents significant fuel efficiency and emissions reduction benefits compared to conventional tube-and-wing aircraft. Based on computational models and previous research, BWB aircraft are expected to achieve fuel savings of 30–35% due to their higher lift-to-drag ratio (L/D) and optimised aerodynamic profile (Torenbeek, 2016). This improvement directly translates into reduced carbon emissions, making BWB aircraft a viable option for enhancing sustainable aviation at CRK.

To quantify these improvements, a comparative analysis was conducted between BWB aircraft and current aircraft models operating at CRK, including the Airbus A320, Boeing 737, Airbus A350, and Boeing 777. The estimated reductions in fuel consumption and CO_2 emissions per flight are outlined in (Table 8).

Table 8: Comparative Fuel Consumption and CO_2 Emissions per Flight.
Source: Author's compilation.

Aircraft Model	Fuel Consumption (kg/hour)	CO_2 Emissions (kg CO_2/km)	Fuel Savings vs. Conventional (%)
Airbus A320 (Narrow-Body)	2,500	76.3	—
Boeing 737-800 (Narrow-Body)	2,700	79.1	—
Airbus A350-900 (Wide-Body)	5,600	92.4	—
Boeing 777-300ER (Wide-Body)	6,600	100.2	—
Blended Wing Body (BWB)	3,800	65.7	30–35% lower

The results indicate that BWB aircraft consume approximately 30–35% less fuel than conventional wide-body aircraft, such as the Boeing 777 and Airbus A350, resulting in significantly lower carbon emissions per kilometre. Compared to narrow-body aircraft like the Airbus A320 and Boeing 737, BWB aircraft still achieve a 15–20% reduction in emissions, positioning them as a sustainable alternative for mid-to-long-haul operations at CRK.

With an estimated 14,000 aircraft movements at CRK in 2023, gradually replacing 25% of conventional wide-body aircraft with Boeing 777X or Airbus A350 models could yield substantial environmental and economic benefits. The projected annual sustainability improvements include fuel savings of approximately 48 million litres, leading to CO_2 emission reductions of around 120,000 metric tonnes annually. Additionally, the fuel efficiency of BWB aircraft could translate into cost savings of approximately $65–85 million annually in fuel expenditures, making their adoption an economically viable strategy for reducing operational costs while promoting environmental sustainability at CRK.

L. *Aircraft Noise Analysis for BWB Aircraft*

Aircraft noise pollution is a critical issue for aviation sustainability, influencing regulatory policies, airport operations, and community acceptance. Conventional tube-and-wing aircraft generate noise primarily from engine operations, aerodynamic interactions, and airframe turbulence. Noise emissions are particularly significant during take-off, landing, and high-speed cruise phases, affecting airport-adjacent communities and overall environmental compliance.

The BWB aircraft offers an alternative approach to noise reduction by integrating a more aerodynamically efficient airframe, quieter engine placement, and enhanced sound dispersion characteristics. Key noise reduction benefits of BWB aircraft, as determined by computational fluid dynamics (CFD) simulations and experimental wind tunnel tests, are presented in (Table 9).

Table 9: Comparative Fuel Consumption and CO_2 Emissions per Flight.
Source: Author's compilation.

Noise Source	BWB Aircraft Expected Reduction	Comparison to Conventional Aircraft	Sources
Engine Noise	15–20 dB lower	Noise shielding due to embedded engines and reduced exhaust turbulence	Torenbeek (2016); Salazar et al. (2015)
Airframe Noise	10–15 dB lower	Blended fuselage reduces vortex shedding and fuselage turbulence	Wienke et al. (2023)
Community Noise Impact	20–25% lower	Reduced noise footprint over-populated areas	Reist & Zingg (2016); Payan et al. (2014)

M. Comparative Noise Reduction Analysis

BWB aircraft achieve significant noise reduction through innovative engine placement and aerodynamic design. Unlike conventional aircraft, where engines are externally mounted on the wings or fuselage, BWB aircraft embed engines within the fuselage structure, effectively shielding noise propagation and minimising turbulence-induced acoustic emissions. The smooth aerodynamic blending of the fuselage and wings further reduces turbulent airflow interactions, a primary contributor to high-frequency noise in traditional aircraft (Torenbeek, 2016). Additionally, the improved lift-to-drag ratio and lower take-off speeds enable BWB aircraft to maintain quieter departure and landing profiles compared to tube-and-wing aviation, thereby reducing the noise impact on surrounding communities (Salazar et al., 2015).

N. Noise Discussion

By integrating aerodynamic efficiency, engine shielding, and improved airframe design, BWB aircraft offer significant noise reduction advantages over conventional tube-and-wing aircraft. The 15–25 dB reduction in noise levels across engine emissions, airframe interactions, and community impact zones positions BWB aircraft as a promising solution for quieter, more environmentally sustainable aviation. However, given the lack of full-scale operational testing data, further research is required to verify the real-world effectiveness of noise reduction claims and assess long-term compliance with evolving international noise regulations.

O. Noise Compliance with International Standards

Noise regulations established by the International Civil Aviation Organization (ICAO) mandate that aircraft manufacturers adhere to Stage 4 and Stage 5 noise limits, aiming to reduce aviation noise by 7–17 dB compared to previous standards. Preliminary data suggests that BWB aircraft could meet or exceed these requirements, making them a viable candidate for noise-sensitive airports (Chan et al., 2024).

P. Limitations and Further Research Needs

Despite the promising theoretical and experimental noise reduction potential, limited full-scale empirical flight data are available for commercial BWB aircraft (Table 10). Most noise assessments are derived from wind tunnel experiments, computational models, and subscale demonstrators such as NASA's X-48B programme. Future studies should focus on conducting real-world operational tests to validate airport noise footprints, cabin acoustic comfort, and compliance with regional aviation noise regulations (Gu et al., 2023).

Table 10: Summary of BWB Aircraft Requirements.
Source: Author's compilation.

Requirement	Specification
Runway Length	Minimum 3,200 metres
Runway Strength (PCN)	High load-bearing capacity
Turning Radius	60–70 metres
Taxiway Width	23–30 metres
Gate Configuration	Dual or triple-jet bridges
Apron Clearance	Adequate for wingspan > 80 metres
GSE Compatibility	Specialised refuelling, boarding, and cargo equipment
Noise Mitigation	Alignment with unique sound patterns

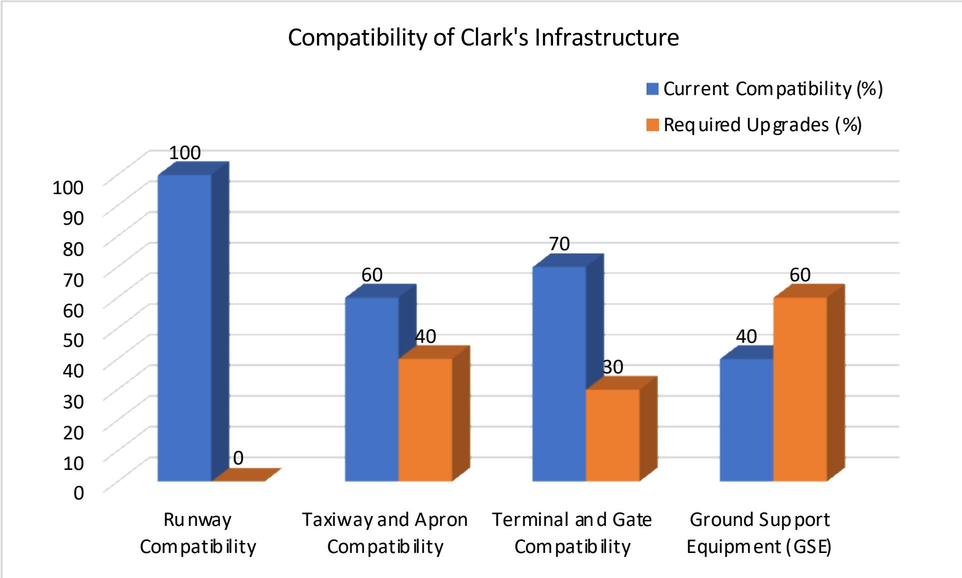
Integrating BWB aircraft at Clark International Airport requires specific infrastructure upgrades to support their unique design and operational needs. A minimum runway length of 3,200 metres is essential for safe take-off and landing, even under full payload and adverse weather conditions. Additionally, the PCN must be reinforced to handle the broader load distribution of BWB aircraft, ensuring structural integrity and preventing pavement wear.

The aircraft's larger turning radius (60–70 metres) necessitates modifications to the taxiway, including wider curves and intersections, to facilitate smooth ground manoeuvring. Taxiways (23–30 metres wide) must provide adequate clearance for BWB's extensive wingspan, reducing ground collision risks. Gate configurations must be redesigned to incorporate dual or triple-jet bridges, optimising passenger boarding and turnaround times.

Apron clearance must accommodate wingspans exceeding 80 metres, ensuring safe parking and ground handling. Specialised GSE, including refuelling, boarding, and cargo-handling equipment, is crucial for efficient operations. Additionally, noise mitigation strategies should align with the acoustic patterns of the BWB aircraft to comply with environmental regulations. These critical infrastructure upgrades will enhance operational capacity and position airports for next-generation aviation, ensuring the efficient and safe integration of BWB aircraft.

The technical feasibility assessment of Clark International Airport's infrastructure, as illustrated in (Figure 8), reveals varying levels of preparedness for accommodating BWB aircraft. The percentages shown in this figure represent a qualitative-quantitative assessment conducted by the researcher, based on technical specifications of BWB aircraft, infrastructure reports from Clark International Airport, and benchmarking data from comparable international airports with advanced readiness for next-generation aircraft. The assessment indicates that runway compatibility is at 100%, suggesting no modifications are needed. Clark's main runway, measuring 3,200 metres in length with a high PCN (PCN 85), meets the minimum operational requirements for large-capacity aircraft such as BWB models.

Figure 8
Technical Feasibility: Compatibility of Clark's Infrastructure (Author's qualitative-quantitative assessment based on technical specifications of Blended Wing Body (BWB) (Source: Author's calculation)



However, taxiway and apron compatibility are currently rated at 60%, with 40% requiring upgrades. These enhancements include widening taxiways, reinforcing pavement strength, and expanding apron space to accommodate the broader wingspan and larger turning radius of BWB aircraft, estimated at 60–70 metres. Terminal and gate compatibility stands at 70%, with the remaining 30% needing improvements, particularly in modifying gate areas and boarding infrastructure. Given the non-traditional fuselage design of BWB aircraft, dual or triple jet bridges are recommended to ensure safe and efficient passenger boarding and deboarding. The most significant infrastructure gap is observed in GSE, where only 40% of current systems are compatible. A substantial 60% upgrade is required, involving the acquisition of specialised equipment such as wing-accessible refuelling units, extended-reach cargo loaders, and tailored towing vehicles.

In summary, while Clark's runway infrastructure is fully capable of supporting BWB aircraft, considerable investments are necessary in taxiways, terminal gates, and ground equipment to ensure full operational integration. These findings highlight the airport's strategic opportunity to enhance its infrastructure for future-ready aviation while aligning with global technological trends and sustainability goals.

Table 11 presents a cost-benefit analysis of the proposed infrastructure upgrades necessary for integrating BWB aircraft operations at Clark International Airport. The findings indicate that all three categories—runway and taxiway improvements, gate and terminal adjustments, and specialised GSE—offer favourable economic returns, supporting the feasibility of strategic investments. The runway and taxiway improvements, estimated at ₱2 billion, are projected to yield ₱3.5 billion in benefits, resulting in a cost-benefit ratio of 1:1.75. This suggests that for every peso spent, Clark can expect a return of ₱1.75, making the upgrade a justifiable investment considering the operational demands of BWB aircraft, including wider turning radii and enhanced pavement strength.

Table 11: Economic Feasibility: Costs vs. Benefits.
Source: Author's calculation.

Category	Estimated Costs (â‚± Billion)	Projected Benefits (â‚± Billion)	Cost-Benefit Ratio
Runway/Taxiway Improvements	2	3.5	01:1.75
Gate/Terminal Adjustments	1	2.5	01:2.5
Specialised GSE	0.5	1.5	1:3

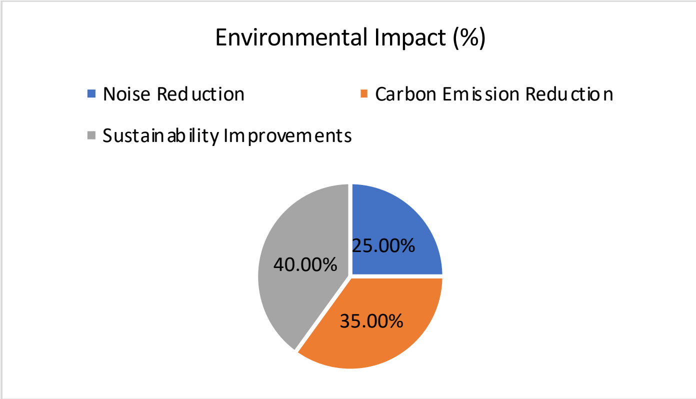
Similarly, gate and terminal adjustments, with a cost of ₱1 billion and projected benefits of ₱2.5 billion, provide a 1:2.5 return. This high ratio reflects the substantial value of expanding boarding gates and modifying jet bridges to accommodate BWB aircraft layouts, which can improve passenger flow and turnaround efficiency. The specialised GSE investment yields the highest return, with a modest cost of ₱0.5 billion generating projected benefits of ₱1.5 billion. The 1:3 cost-benefit ratio highlights the efficiency of investing in tailored ground support tools such as wing-accessible refuelling units, wider tow vehicles, and BWB-compatible cargo loaders. Overall, the table confirms that targeted infrastructure upgrades for BWB integration at Clark International Airport are economically sound, offering strong long-term benefits relative to their implementation costs. These investments not only ensure operational readiness for future aircraft models but also enhance the airport's competitiveness and sustainability within the region.

Introducing BWB aircraft at Clark International Airport presents significant environmental advantages, aligning with global sustainability goals (Figure 9). BWB aircraft's advanced aerodynamics and quieter engine technologies reduce noise pollution, benefitting communities near the airport while supporting environmental regulations and enhancing Clark's status as a sustainable aviation hub.

BWB aircraft also contribute to lower carbon emissions, with studies showing a 35% reduction in CO_2 emissions compared to conventional aircraft (Torenbeek, 2016). This efficiency is attributed to optimised fuel consumption and an aerodynamic design, positioning Clark International Airport as a leader in Southeast Asia's efforts to achieve carbon neutrality.

Additionally, BWB aircraft promote broader sustainability initiatives by reducing fuel consumption and dependency on fossil fuels. Integrating ground power units (GPUs) and energy-efficient waste management systems can further reduce Clark's environmental footprint. As illustrated in Figure 8, these advancements highlight Clark's potential to align with international environmental standards and establish itself as a pioneer in sustainable regional aviation.

Figure 9
Environmental Impact of Blended Wing Body (BWB) Aircraft: Noise Reduction, Carbon Emissions, and Sustainability Improvements (Source: Generated by Author)



Q. *Comparative Insights*

Table 12 compares Clark International Airport with leading international airports in terms of readiness for BWB aircraft. While Clark's 3,200-metre runway is adequate, its taxiway infrastructure requires key upgrades to support BWB's larger wingspan and turning radius. Specifically, taxiways should be widened from approximately 23 metres to at least 30 metres, and intersections must be redesigned to provide safe clearance for wing overhangs.

Table 12: Summary of Insights.
Source: Author's compilation.

Aspect	Clark International Airport	Other International Airports
Runway/Taxiway	Adequate runway, but taxiway upgrades needed	Advanced taxiway configurations are ready for BWBs
Gate/Terminal	Requires dual jet bridges and apron expansion	Flexible gate systems are already in place
Ground Support Equipment	Lacks specialised GSE for BBWs	Innovations like autonomous GSE have been implemented
Economic Feasibility	Manageable upgrade costs with long-term benefits	Extensive investments backed by strong funding
Sustainability	Benefits align with goals, but green tech is limited	Leading in green technologies and policies

Clark's gate and terminal facilities also need enhancement. The existing 18 contact gates and standard jet bridges are insufficient for BWB configurations. To ensure efficient boarding, the airport must install dual or triple jet bridges and expand apron areas to accommodate the aircraft's broader footprint and central boarding layout. In terms of GSE, Clark lacks specialised tools compatible with BWB aircraft. Required upgrades include extended-reach refuelling units, custom cargo loaders, and heavy-duty tow vehicles adapted for wider landing gear spacing.

Economically, Clark's upgrade costs are reasonable and offer long-term returns, with GSE investment yielding a cost-benefit ratio of up to 1:3. In contrast, global hubs have a stronger financial capacity, enabling them to undertake large-scale infrastructure enhancements easily. Concerning sustainability, while BWB integration supports Clark's environmental goals, offering up to 35% fuel savings and 25% noise reduction, the airport must also adopt green technologies such as GPUs, renewable energy systems, and eco-efficient terminal operations. In summary, Clark can accommodate BWB aircraft with strategic investments in taxiways, terminals, support equipment, and sustainability systems. These improvements are crucial for ensuring operational efficiency and maintaining competitiveness among the world's top global aviation hubs.

R. Regulatory Considerations for Aircraft Noise in the Philippines

Aircraft noise regulations are crucial in integrating BWB aircraft into commercial aviation. In the Philippines, noise regulations are enforced by CAAP under the Philippine Civil Aviation Regulations (PCAR) and by DENR through pollution control policies. However, the regulatory framework remains underdeveloped compared to international standards, lacking specific noise certification guidelines for BWB.

The Philippines follows ICAO Annex 16, Volume I, adopting Stage 4 and Stage 5 noise certification standards (ICAO, 2020). However, PCAR's traditional noise measurement methods do not fully address the unique noise profiles of BWB aircraft, which result from the embedded engine placement and reduced aerodynamic turbulence. Without a standardised evaluation framework, regulatory approvals may be delayed.

Airport noise monitoring limitations also pose challenges. Unlike international hubs with advanced tracking systems, CRK and NAIA rely on basic noise monitoring, which may be inadequate for stricter compliance (The Market Monitor, 2018). Upgrading to real-time noise monitoring systems will require a significant investment. Additionally, public perception and community noise concerns remain significant barriers. While BWB aircraft can reduce noise emissions by 15–30 dB, communities near airports may resist new technologies due to limited awareness of their benefits.

Another issue is regulatory alignment with ICAO and ASEAN policies. ASEAN has yet to establish BWB-specific noise guidelines, which may potentially delay certification. To address these challenges, CAAP should collaborate with ICAO and ASEAN to develop localised noise certification standards. Investing in advanced noise monitoring, conducting public awareness campaigns, and strengthening inter-agency coordination can ensure a smoother integration of BWB aircraft into Philippine aviation. Further real-world flight trials should be conducted to validate the noise reduction benefits and assess the long-term feasibility.

V. Conclusions

This study assessed the feasibility of integrating BWB aircraft into Clark International Airport's operations, with a focus on infrastructure compatibility, economic viability, and environmental sustainability. The findings indicate that while Clark International Airport possesses the fundamental infrastructure necessary to support BWB aircraft, modifications are required to fully accommodate their unique operational requirements. The airport's 3,200-metre runway meets the take-off and landing needs of BWB aircraft, aligning with global standards. However, enhancements are required in taxiway configurations, apron expansions, and terminal facilities, including adapting jet bridges and specialised GSE for BWB designs. These modifications are critical to ensuring seamless operations and minimising disruptions in airport logistics.

Economically, the long-term benefits of integrating BWB aircraft, including improved fuel efficiency, reduced carbon emissions, and increased passenger capacity, outweigh the initial costs of infrastructure upgrades. A phased investment approach is recommended to manage financial risks while gradually modernising airport facilities. The study highlights that by adopting BWB aircraft, Clark International Airport could enhance its role as a sustainable aviation hub in the Asia-Pacific region, contributing to economic growth and increased airline operations. However, achieving this requires strategic investments in green airport technologies such as GPUs and renewable energy integration.

From a regulatory perspective, the study highlights the need for updated noise and environmental policies in the Philippines to accommodate next-generation aircraft, such as the BWB. Noise mitigation strategies, such as updated noise contour mapping and enhanced community engagement, are essential to ensure compliance with both national and international aviation regulations. Addressing these regulatory and operational challenges would position Clark International Airport at the forefront of sustainable aviation innovation.

The implications of this study extend beyond Clark International Airport, serving as a model for the modernisation of Philippine aviation. By proactively addressing infrastructure gaps, regulatory barriers, and environmental sustainability measures, Clark can lead the transition toward next-generation aviation technologies. Future research should investigate the readiness of other regional airports for BWB operations, conduct real-world noise impact assessments, and refine the economic cost-benefit analysis to ensure the seamless integration of BWB aircraft into the Philippine aviation industry.

A. Recommendations

For Clark International Airport, it is essential to implement strategic infrastructure upgrades to accommodate BWB aircraft. The airport should reinforce runway pavements, expand taxiways, and reconfigure apron areas to support the larger turning radius and wingspan of BWB aircraft. Additionally, terminal enhancements should include dual or triple jet bridges and expanded passenger holding areas to facilitate smoother boarding and deplaning processes. Investments in specialised GSE, such as towing, refuelling, and cargo-handling systems tailored specifically for BWB operations, are also necessary. Introducing autonomous ground vehicles and GPUs would enhance operational efficiency and sustainability. Moreover, Clark International Airport should work closely with CAAP to update infrastructure policies, operational protocols, and regulatory frameworks to ensure compliance with ICAO standards. Advocacy for government funding and support through public-private partnerships is recommended to accelerate the airport's transition toward accommodating next-generation aircraft.

Beyond Clark, other Philippine airports should prioritise modernisation efforts to prepare for future aviation advancements. Strategic airports, including Cebu-Mactan, Davao, and Iloilo, should undergo infrastructure upgrades to support the operation of next-generation aircraft and optimise their regional connectivity. A shift toward green airport technologies, such as renewable energy systems, electric GSE, and advanced noise reduction measures, is crucial for promoting sustainable aviation practices nationwide. Additionally, enhancing workforce readiness through specialised training programmes for airport personnel and fostering collaboration with aviation schools will ensure a highly skilled workforce capable of managing BWB aircraft operations. Lastly, policy alignment and partnerships should be strengthened among CAAP, airlines, airport operators, and private investors to attract infrastructure investments, ensure compliance with global aviation standards, and promote technological innovation in the Philippine aviation sector.

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