A STUDY OF CLIMATE CHANGE ADAPTATION AS A TOOL TO ENSURE SUSTAINABLE AIRPORT SAFETY MANAGEMENT: A CASE STUDY AT MINANGKABAU INTERNATIONAL AIRPORT

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ABSTRACT

This study aims to examine climate change adaptation as a strategy in sustainable airport safety management, with a case study of Minangkabau International Airport (BIM), a major air transportation infrastructure on the west coast of Indonesia. Environmental protection and aviation safety are important priorities to ensure the sustainability of airport operations. This study conducted a comprehensive risk assessment of the impacts of climate change, both direct and indirect, on BIM operations. The method used was a descriptive qualitative case study approach, through analysis of historical climate documents and future climate projections, field observations, and semi-structured interviews with management and relevant agencies. The results indicate that BIM faces risks from extreme temperatures, high rainfall, and changing wind patterns that have the potential to disrupt infrastructure and operational safety. Identified vulnerable points include drainage systems, early warning systems, and infrastructure resilience. Several adaptation measures have been implemented, but their integration into the Safety Management System (SMS) is still not optimal. This study produces short- and medium-term adaptation recommendations to strengthen airport resilience, which are expected to serve as a strategic reference for managers in anticipating the challenges of climate change.

Keywords: Climate Adaptation, Climate Change, Airport Safety Management, Risk Assessment

INTRODUCTION

Minangkabau International Airport (BIM) is a major air transportation infrastructure in West Sumatra Province, playing a strategic role as a gateway for domestic and international connectivity. Since its inauguration in 2005, replacing Tabing Airport, BIM has continued to record significant growth in terms of passenger numbers, flight volume, and the diversity of routes served. In 2019, approximately 2.3 million passengers were served annually, with destinations including major Indonesian cities such as Jakarta, Batam, Medan, and Yogyakarta, as well as international routes to Kuala Lumpur, Singapore, and Jeddah. In addition to being a major air travel hub, BIM serves as the embarkation and disembarkation point for the Hajj pilgrimage for West Sumatra, Bengkulu, and parts of Jambi. Its strategic location in Batang Anai District, Padang Pariaman Regency, is not only close to the center of Padang City but also easily accessible from surrounding areas, making it vital in supporting regional mobility, tourism, and the local economy. The uniqueness of BIM is also reflected in the integration of Minangkabau cultural elements into the terminal's architectural design, so that this airport also serves as a showcase for local culture amidst infrastructure modernization.

However, this strategic advantage is accompanied by serious challenges stemming from BIM's geographical location on the west coast of Sumatra, an area prone to natural disasters. West Sumatra Province lies in the tectonically active collision zone of the Indo-Australian and Eurasian plates, making it highly vulnerable to earthquakes and potential tsunamis. Vogiatzis et al. (2021) emphasized that these geological risks are exacerbated by the region's topography and extensive coastline, heightening the potential for disaster impacts on public infrastructure, including airports. In addition to geological threats, BIM also faces hydrometeorological risks due to global climate change, such as increased extreme rainfall, flooding, and strong winds. Unpredictable changes in weather patterns can directly impact the smooth operation of flights, passenger safety, and the reliability of supporting facilities.

Global climate change is having serious consequences for the aviation industry, including airport management. Rising average temperatures, shifting seasons, and the increasing intensity of extreme weather events have become major concerns in many countries. According to Ren (2024), most modern airports are equipped with mitigation systems for daily weather fluctuations, but the scale and frequency of extreme events caused by climate change require more comprehensive strategic adjustments. International research conducted by Dimitriou & Karagkouni (2022) revealed that many airport operators still consider climate risk a low priority, assuming their systems are sufficiently resilient. However, experience from various cases shows that delays in anticipating these risks can result in significant operational, financial, and reputational losses.

Beyond threatening daily operations, the impacts of climate change also have long-term implications for investment and the sustainability of airport infrastructure. A report by the European Commission and the Airport Cooperative Research Program (ACRP) emphasized that operational disruptions caused by extreme climates can reduce airport regulatory capacity, increase maintenance and repair costs, damage physical facilities, and impact the health and safety of staff and passengers. This situation demands more adaptive risk management, where climate monitoring, vulnerability assessments, and the implementation of preventive measures are integrated. Without appropriate adaptation policies, airports risk declining competitiveness, especially amidst increasingly fierce competition in the aviation industry.

In the context of BIM, the urgency of implementing climate change adaptation strategies is increasingly important given its vital role in regional connectivity and supporting the tourism sector. Case studies such as that conducted at Athens International Airport (AIA) demonstrate that successful climate adaptation depends not only on technical capacity but also on cross-unit coordination, stakeholder engagement, and the use of scientific data for evidence-based planning (Voskaki et al., 2023). BIM offers the opportunity to adopt a similar approach by adapting to local conditions, including environmental, cultural, and national aviation policies.

Based on this background, this research focuses on identifying climate change risks that could potentially impact BIM operations, evaluating the effectiveness of existing safety systems, and formulating adaptation strategies tailored to local characteristics and needs. This step is expected to strengthen BIM's capacity to respond to extreme weather and natural disasters, thereby ensuring operational continuity while providing a sense of security to passengers and service users. This research is also expected to serve as a reference for other airports in Indonesia facing similar vulnerabilities.

Thus, the urgency of this research lies in its contribution to providing a scientific basis for developing climate change adaptation policies and strategies in the air transportation sector. Through risk identification, evaluation of existing systems, and recommendations for adaptive measures, the results of this research are expected to support the creation of airport safety management that is more resilient, sustainable, and responsive to global climate dynamics. This is not only relevant to the smooth operation of air transportation in West Sumatra but also aligns with the Sustainable Development Goals (SDGs), particularly goals related to infrastructure, climate, and public safety.

METHOD

The research method used in this study refers to a qualitative approach with a descriptive case study design, which aims to obtain a comprehensive picture of the implementation of climate change adaptation as a strategy to ensure sustainable airport safety management at Minangkabau International Airport. This approach was chosen because it is able to explore the phenomenon in depth and comprehensively, starting from the process of identifying the problem, determining the subject and object of research, to the publication of the results, with data collection through interviews, observations, documentation studies, and literature studies to obtain a factual and contextual understanding.

The research design focused on one location, namely Minangkabau International Airport, which was chosen because it faces diverse climatic conditions such as high rainfall, fog, and temperature fluctuations that can disrupt flight operations, with primary data obtained from interviews with operational managers, safety officers, and climate mitigation experts, as well as secondary data from policy documents, extreme weather reports, and scientific publications to enable comparative analysis between policies, mitigation strategies, and field practices.

Data collection was conducted through direct observation during the On The Job Training (OJT) period from January 6, 2025, to February 28, 2025, to observe the physical conditions, infrastructure, and operational procedures related to climate mitigation; semi-structured interviews to gather in-depth information regarding the impacts of climate change, adaptation strategies, policy effectiveness, and implementation challenges; literature studies to obtain theoretical foundations from literature, research reports, and official documents; and validation of research instruments by expert supervisors to ensure the suitability and feasibility of the instruments.

Data analysis was conducted using a natural qualitative descriptive approach with source and method triangulation techniques, starting from before data collection through initial context analysis, followed by further analysis after the data was collected, including data reduction to filter relevant information, data presentation in narrative and table form, discussion linking findings with theory and field conditions, to drawing conclusions that answer the problem formulation comprehensively.

This research was conducted at Minangkabau International Airport, West Sumatra, which was chosen because of its environmental characteristics that are vulnerable to the impacts of climate change as well as being a strategic flight operational center in the Sumatra region, with an implementation time of six months including the planning stage, data collection, analysis, to the preparation and refinement of the research report, which was scheduled in detail starting from the search for topics and titles, literature studies, proposal preparation, proposal seminars, data processing, writing the final report, to the final project hearing, so that all stages can be carried out effectively and on time.

RESEARCH RESULT

Observation Results

Field observations at Minangkabau International Airport (BIM) provided a comprehensive overview of the various adaptation measures implemented to address the impacts of climate change, particularly in extreme weather conditions. Direct observations focused on three main aspects: physical infrastructure, operational systems, and the adaptive behavior of field personnel. In terms of infrastructure, facilities such as drainage channels are routinely maintained through grass removal and sedimentation to prevent waterlogging. This is crucial considering that increasing rainfall intensity can increase the risk of local flooding in the airport area. An optimally functioning drainage system is vital to ensuring the safety of runways, taxiways, and aprons. Furthermore, the building design, which provides protection from heat and rain, demonstrates that adaptation has been considered since the construction planning stage, ensuring the long-term durability of the facility.

From a procedural perspective, observations indicate the clear implementation of Standard Operating Procedures (SOPs) in handling extreme weather. For example, when visibility is low, there is heavy rain, or strong winds exceeding 6 knots, Air Traffic Control (ATC) actively informs pilots to hold until conditions improve. If the bad weather persists, flights are diverted to alternative airports such as Pekanbaru (PKU) or Palembang (PLM) for flight safety. Furthermore, the airport has an Airport Emergency Plan as a disaster management guideline that involves cross-unit coordination. The implementation of these SOPs demonstrates that adaptive procedures are not only reactive but also integrated into daily operations, thereby minimizing service disruptions and the risk of accidents.

Observations also noted that technology plays a crucial role in supporting the climate adaptation system at BIM. The existence of a Warning Receiver System connected to information from the BMKG (Meteorology, Climatology, and Geophysics Agency) allows the airport to receive early warnings regarding potential earthquakes, tsunamis, and other high-risk weather phenomena. The use of this technology not only facilitates rapid decision-making but also enables effective coordination between internal and external stakeholders, such as airlines, aviation authorities, and relevant agencies. With a reliable monitoring system, the airport can anticipate the impacts of climate change more precisely, reduce potential material losses, and protect the safety of passengers and crew.

Furthermore, observations indicate a robust communication and coordination system through clear cooperation protocols. In disaster situations, communication between units is carried out quickly using walkie-talkies (HT) or telephones, while strategic coordination is carried out by the disaster management committee. This process ensures that every response step can be carried out synchronously and in a timely manner, reducing the risk of miscommunication that could exacerbate the emergency situation. This structured coordination demonstrates that climate change adaptation in BIM relies not only on infrastructure and procedures but also emphasizes synergy between actors in the air transportation system.

Finally, human resources (HR) are also a crucial part of the adaptation observed in the field. Staff training programs through disaster preparedness scenario simulations at the terminal equip personnel with the skills and knowledge necessary to deal with emergency situations. Passenger education is also conducted as part of efforts to build collective awareness of potential disasters. The combination of infrastructure readiness, completeness of SOPs, utilization of technology, strong coordination, and HR competency demonstrates that Minangkabau International Airport has comprehensively implemented risk-based adaptation principles, in accordance with the theoretical framework of climate adaptation in the air transportation sector. Therefore, these observations can serve as a basis for evaluation and a learning model for other airports in anticipating the impacts of climate change.

Interview Results

Based on the results of interviews conducted with the BMKG (07/08/2024), Airport Safety & Risk Department Head (14/08/2024), and Airport Operation Airside Department Head (15/08/2024), a comprehensive picture was obtained regarding the impact of climate change, adaptation strategies that have been implemented, as well as challenges and recommendations for increasing the effectiveness of adaptation at Minangkabau International Airport (BIM).

Climate change in West Sumatra is characterized by an average temperature increase of approximately 0.1°C per decade and an increase in the frequency of hydrometeorological disasters of approximately 10% (BMKG, interview, August 7, 2024). Extreme weather phenomena such as heavy rain, strong winds, and the formation of cumulonimbus (CB) clouds are the main factors affecting BIM operations. The BMKG explained that CB clouds have the potential to reduce visibility to below the minimum standard of 800 meters, resulting in disruptions such as holding patterns, delays, and flight diverts. Although there have been no serious safety incidents such as runway excursions or weather-related facility damage, operational personnel confirmed that during the rainy season the risk of flight disruptions increases significantly. Strong winds, especially crosswinds with speeds above 10 knots, are also a concern because they can disrupt aircraft landing stability (Airport Safety & Risk Department Head, interview, August 14, 2024).

In response to these risks, the airport implemented a number of technical and coordinative adaptation strategies. Based on an interview with the Airport Operation Airside Department Head (August 15, 2024), the technical steps taken included increasing the frequency of inspections of visual aid facilities such as markings and airfield lighting systems, normalizing drainage to prevent waterlogging on runways, and conducting regular maintenance on operational support infrastructure. In terms of coordination, close cooperation is carried out between internal airport parties (safety, operational, and facilities divisions) and external parties, including the Meteorology, Climatology, and Geophysics Agency (BMKG) as a weather data provider, Air Traffic Controllers (ATC) as air traffic controllers, airlines, and ground handling service providers. The BMKG provides early warnings (aerodrome warnings) and real-time weather information, which serve as the basis for ATC and airport authorities in making take-off or landing decisions. The BIM General Manager regularly issues circulars and safety advisories to ensure all parties follow applicable procedures when potential extreme weather is detected.

In general, the implemented adaptation strategies are considered quite effective. The BMKG's early warning system, routine inspections, and cross-agency coordination have helped minimize the impact of extreme weather on aviation safety. However, interviews also revealed a number of challenges. These include limited budgets for developing climate-friendly infrastructure, existing infrastructure that has not been designed with climate adaptation in mind, and low levels of risk literacy among operational and ground handling personnel. To address these challenges, the interviewees recommended increasing education on climate change for all stakeholders, strengthening cross-sector communication, and optimizing automated weather monitoring technology to accelerate the detection of changes in weather parameters. Furthermore, investing in energy-efficient airport building designs that are resilient to extreme weather is considered crucial as part of long-term adaptation, in line with Presidential Regulation No. 98 of 2021 concerning the Economic Value of Carbon.

Literature Study Results

1. Identify the Impacts of Climate Change

Based on interviews and secondary data, the most significant impacts of climate change in the Minangkabau International Airport (BIM) environment include an increase in maximum air temperature and the frequency of hydrometeorological disasters. According to Yudha (2025), the BIM area has shown a consistent trend of increasing maximum temperatures in recent years, which is supported by data from the Central Statistics Agency (BPS) of Padang City for the period 2003–2024. The data indicates an increase in the average annual temperature with the highest anomaly in the mid-2010s, reaching 28.5°C in 2024. This increase has direct implications for airport operations, considering that extreme weather phenomena such as strong winds, wind shear, microbursts, and the formation of cumulonimbus (CB) clouds can disrupt flights. These conditions affect the minimum visibility recorded, which can drop to 800 meters, which is one of the main factors forcing special operational procedures, such as delays in landings (holding) or flight diversions (diverts). This fact is reinforced by reports from the National Disaster Management Agency (BNPB) and BMKG, which show an increase in the number of extreme weather events in the West Sumatra region, especially Padang, over the past two decades.

BIM's geographical location close to the coastline makes the airport more vulnerable to the formation of thick fog and high-intensity rain, as stated by Arafat (2025). Reduced visibility due to these phenomena is one of the biggest operational challenges, given that flight safety is highly dependent on adequate visibility. Common responses include adjusting landing patterns, delaying flights, or diverting flights to alternative airports specified in flight plans. Another source, Hari (2025), added that the extreme weather that most impacts operations is high-intensity rain and strong winds exceeding 10 knots, which can trigger operational mitigation measures. Although there have been no major incidents such as runway excursions or incursions caused directly by weather in the past five years, the risk remains and requires anticipation based on the latest weather data. This shows that even minor disruptions can develop into significant safety risks if not anticipated in a timely manner.

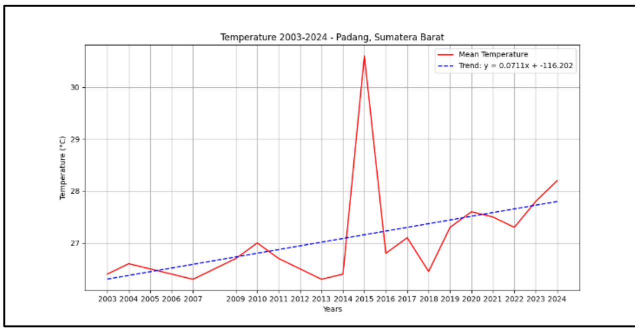

Figure 1. Daily Temperature Trend Graph for Padang Region 2003-2024

Beyond the direct impacts on aviation, climate projections also indicate potential health and productivity risks. Secondary data indicates that the number of days with a Heat Index (HI) above 35°C during the 1991–2020 period remains within the safe range, at less than three months per year. However, the Ensemble model predicts a significant increase for the 2040–2059 period, where Padang and the West Sumatra coast could experience 6–9 months per year with extreme heat indices. The orange to dark red projection map indicates the risk of prolonged heat exposure, which could impact the health of airport workers, increase the risk of heat stress, and reduce work productivity. Temperature anomaly data from Meteoblue for the 1980–2024 period also shows a predominance of positive anomalies since 2010, meaning temperatures are more frequently above average. This phenomenon emphasizes that climate change in BIM is not just a potential threat but has become an operational reality that must be addressed with measured adaptation strategies.

2 Wind Vectors in Climate Change Adaptation

Analysis of BMKG data for the Minangkabau International Airport (BIM) area shows that wind direction and speed have a fairly consistent pattern seasonally, but still show significant variations due to extreme weather phenomena. During the rainy season, the dominant wind direction is from the southwest to northwest sector, influenced by the west monsoon system and convective activity in the Indian Ocean. During the dry season, the wind direction shifts to the northeast to the east, in line with the influence of the east monsoon and the strengthening of the cross-equatorial wind flow. This variation in wind direction has direct implications for runway design and operations, as runway orientation must minimize the risk of crosswinds that can interfere with landings and takeoffs. Field data indicates that the average wind speed at BIM is within the safe range for flight operations, but strong winds above 10 knots still occur sporadically, especially during mesoscale weather disturbances such as squall lines or local storms. This phenomenon requires air traffic control (ATC) personnel to be prepared to adjust operating procedures in real time to maintain safety.

An interview with Arafat (2025) revealed that significant strong wind events are often associated with the formation of cumulonimbus (CB) clouds around airports. These clouds not only trigger sudden turbulence and wind shear, but also affect visibility due to accompanying heavy rainfall. Under certain conditions, winds can change direction abruptly within seconds, forcing pilots to perform a go-around or even divert flights. Adaptations that have been implemented include improvements to surface wind monitoring and wind shear detection systems, which enable early detection of changes in wind direction and speed. Furthermore, regular training for ATC and cabin crew on how to respond to extreme wind changes is a key part of the adaptation strategy. This approach ensures that any disruptions can be anticipated with safe maneuvers, whether through modified flight routes, adjusted takeoff/landing times, or diverting to alternative airports.

From a long-term planning perspective, changing wind patterns due to climate change can impact energy efficiency and carbon emissions in aviation operations. Tailwinds and headwinds directly affect fuel consumption, so fluctuations in wind direction and speed can increase the need for more conservative fuel planning. Climate projections indicate that the intensity of extreme wind events is likely to increase in the future, particularly in light of the increasingly unpredictable El Niño and La Niña phenomena. Therefore, integrating climate projection data into airport infrastructure design, such as determining new runway orientations or adding lateral wind protection systems, is crucial. Adaptation should also include modernizing early warning technology and integrating with real-time data-driven air traffic management systems, so that any sudden changes in wind vectors can be responded to quickly and effectively.

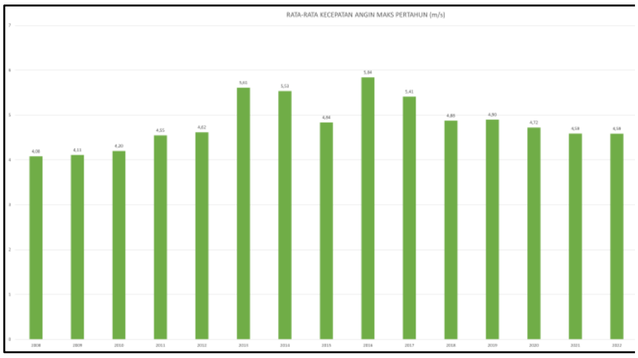

Figure 2. Average Wind Speed per Year

.3 Adaptation Strategies That Have Been Implemented by BIM

The initial phase of climate change adaptation at Minangkabau International Airport (BIM) demonstrates that efforts are still focused on increasing stakeholder awareness and understanding of climate risks. According to Yudha (2025), the strategy adopted in this phase is fundamental, namely building collective awareness before entering the more complex technical implementation phase. This approach is realized through outreach activities, education, and provision of materials on the potential impacts of climate change on airport operations, such as increasing temperatures, extreme rainfall, and changing wind patterns. This awareness is crucial because all operational lines, from management to field technical staff, need to understand that climate change not only impacts passenger comfort but also directly affects aspects of flight safety and smoothness. In this context, BIM strives to foster an adaptive mindset among personnel through regular briefings, cross-unit coordination, and the integration of climate issues into daily operational planning agendas.

In addition to awareness-raising efforts, BIM has also implemented concrete steps through the modernization of its weather observation system. The transition from a manual to an automated observation system was carried out to improve the accuracy and availability of real-time meteorological data, which is crucial for decision-making in extreme weather conditions. According to Yudha (2025), this modernization allows airport managers, Air Traffic Controllers (ATC), and airlines to obtain more precise data on weather parameters such as wind speed, wind direction, visibility, rainfall, and heat index. This data is then used to determine operational procedures such as departure delays, flight rerouting, or adjusting runway usage. Furthermore, cross-agency coordination with the BMKG, the Ministry of Transportation, and other airport authorities has been strengthened to ensure a common understanding of information and a faster response to potential hydrometeorological disasters. This collaborative approach is expected to reduce the risk of miscommunication, which often hinders handling emergency situations caused by extreme weather.

Another strategic step that has begun is planning to strengthen building structures to make them more resilient to climate change. While BIM's initial design focused on earthquake resistance, there is now talk of developing infrastructure that is more resilient to high temperatures, heavy rainfall, and strong winds. Several airlines operating at BIM have also begun adopting environmentally friendly aircraft technology with more efficient fuel consumption, as part of efforts to reduce carbon dioxide emissions. Operationally, BIM has begun implementing Airport Collaborative Decision Making (ACDM) principles, which facilitate real-time information exchange between stakeholders, although implementation is not yet fully automated. This principle has proven to aid coordination in handling extreme weather events, such as diverting landings, managing holding patterns, and rescheduling flights. Furthermore, BIM also responds quickly to extreme weather warnings from the Meteorology, Climatology, and Geophysics Agency (BMKG) by implementing adaptive protocols such as drainage inspections, grass trimming to prevent waterlogging, and strengthening building roofs and ground support equipment. These strategies have been integrated into the Safety Management System (SMS) to ensure climate change adaptation becomes part of standard operating procedures and can be implemented consistently.

4 Challenges and Obstacles

Although Minangkabau International Airport (BIM) has initiated climate change adaptation measures, its implementation faces various complex obstacles. One major challenge is the limited integration of climate change issues into the airport's long-term strategic planning. According to Yudha (2025), although awareness of climate risks has begun to build, the implementation of policies based on long-term climate projections remains minimal. This is due to limited historical climate data integrated with the airport's infrastructure planning system, making it difficult to simulate risks and formulate designs that are truly resilient to climate change.

Other challenges arise from human resources and supporting technology. While the shift from a manual observation system to an automated one improves data accuracy, it also demands higher technical competency from operators and support staff. Not all personnel possess the necessary skills to operate, analyze, and optimally utilize real-time weather data for decision-making. This poses the risk of delayed responses when sudden weather anomalies occur, such as wind shear, local storms, or dense fog. Furthermore, the automated system faces the risk of technical disruptions, requiring specialized technician support and spare parts that are sometimes not readily available in West Sumatra. Furthermore, inter-agency coordination, while well-established, still faces challenges in standardizing data formats, speeding up information distribution, and synchronizing response times, particularly when multiple airlines and government agencies are involved.

From a funding perspective, the implementation of climate adaptation strategies is often hampered by budget constraints, both from airport management and government support. Investments in climate-resilient infrastructure, such as increasing drainage capacity, strengthening roof structures, and modernizing supporting facilities, are costly and long-term, while budget priorities are often focused on increasing passenger capacity or expanding flight routes. Furthermore, incentives for the use of low-emission technology or fuel-efficient aircraft have not been fully attractive to airlines operating in BIM, resulting in slow progress in carbon emission mitigation efforts. External factors such as uncertainty over national regulations regarding climate adaptation standards for air transportation infrastructure also slow the planning process. All of these obstacles indicate that even though BIM has initiated adaptation measures, the sustainability and effectiveness of the strategies implemented will depend heavily on strengthened coordination, policy support, and adequate budget allocation in the future.

5. Evaluation Steps That Have Been Carried Out by BIM

An evaluation of the adaptation strategies implemented by Minangkabau International Airport shows that management has initiated several important steps, although they are still in the early stages and have not yet been fully integrated into long-term planning. The adaptation approach in BIM can be divided into three main categories: structural adaptation, non-structural adaptation, and institutional evaluation. Structural adaptation focuses on infrastructure maintenance and strengthening, such as routine inspections of runway markings, navigation lights, and drainage systems, which are crucial for maintaining smooth operations during extreme weather. Preventive measures such as cleaning drainage channels when the BMKG issues an extreme weather warning and maintaining heat and moisture-protecting structures in outdoor work areas demonstrate awareness of climate risks. However, these efforts tend to be reactive and do not utilize long-term climate projections as a planning reference. In other words, BIM only optimizes basic preventative measures but does not yet address adaptive reconstruction or infrastructure redesign to address predicted future increases in temperature and rainfall intensity.

Meanwhile, non-structural adaptations in BIM demonstrate flexibility and speed in responding to extreme weather dynamics. Intensive coordination with the BMKG and ATC is a fairly effective step in adjusting landing procedures, delaying, or diverting flights when there is reduced visibility or potential thunderstorms. The implementation of standard operating procedures (SOPs) in aerodrome warning conditions, such as temporarily suspending ground support activities, moving vehicles, and closing parts of risky aprons, has been carried out, although its implementation still relies heavily on verbal and manual communication. Inter-divisional coordination forums during extreme weather crises demonstrate the application of basic ACDM principles, although they are not yet based on an integrated information system or digital dashboard. This lack of technology utilization means that the flow of real-time information is suboptimal, potentially delaying decision-making, especially in situations that require a response within minutes.

From an institutional perspective, the evaluation found that the integration of adaptation strategies into long-term operational policies remains weak. BIM does not yet have a climate adaptation action plan, as mandated by Presidential Regulation No. 98 of 2021, which should serve as the official reference document for addressing climate risks. Furthermore, there is no specific budget allocation for adaptation, so all funding is still drawn from routine budget items, which are vulnerable to being absorbed by daily operational needs. The level of understanding of climate issues also varies among work units, with outreach from the Meteorology, Climatology, and Geophysics Agency (BMKG) not yet evenly reaching technical staff in the field. This creates a gap between risk awareness and technical readiness to respond. Overall, although BIM has initiated relevant adaptation measures, the evaluation indicates that the sustainability and effectiveness of these strategies will depend heavily on improved institutional integration, digitalization of coordination, and planning based on long-term climate projections.

6. Strategic Implications and Recommendations for Sustainable Adaptation

Research findings indicate that Minangkabau International Airport (BIM) has begun to face the real impacts of climate change, affecting safety, operational smoothness, and user comfort. These impacts include not only increased temperatures and extreme weather events, but also direct disruptions to flight schedules, navigation equipment performance, and the resilience of supporting infrastructure. Therefore, the strategic implications resulting from these findings require BIM to transition from a reactive approach to an adaptive and prospective approach oriented towards mitigating future risks. Integrating adaptation strategies into the Safety Management System (SMS) in accordance with ICAO recommendations and the integration theory in Chapter 2.4 is a crucial foundation, given that the SMS is a formal framework capable of combining climate risk management with aviation safety management. Thus, BIM can broaden the definition of safety to encompass not only technical and human factors, but also environmental factors, which are now a significant threat.

These strategic implications encompass five key pillars that BIM management must address. First, the need for a real-time, data-driven weather prediction and monitoring system integrated across all operational units, so that any changes in climate indicators such as visibility, heat index, rainfall, and wind speed can immediately trigger an appropriate response. Second, adjustments to standard operating procedures (SOPs) based on quantitative climatological indicators, such as visibility <800 meters or winds >20 km/h, can serve as objective parameters for deciding on delays, diversions, or rescheduling of field personnel. Third, increasing infrastructure and logistics capacity to cope with long-term climate pressures, including evaluating drainage capacity, runway pavement, and terminal cooling systems. Fourth, the establishment of a dedicated climate adaptation unit to serve as a cross-functional coordination center and liaison between operations, planning, the Meteorology, Climatology, and Geophysics Agency (BMKG), and regulators. Fifth, the development of a climate adaptation action plan, as mandated by Presidential Decree No. 98 of 2021, containing risk assessments, mitigation strategies, funding sources, and success indicators that can be monitored regularly.

Based on these implications, a number of strategic recommendations have been developed to ensure BIM can develop into a climate-resilient airport. These recommendations include the development of a Climate Adaptation Action Plan (RAAI) document based on local risks and long-term projections, the implementation of operational SOPs based on climate indicators, optimization of the drainage system, the development of a real-time weather monitoring dashboard, and strengthening the implementation of ACDM with specific protocols for extreme weather. Furthermore, ongoing training and outreach to all operational personnel, the reorganization of facilities and vehicles on the apron, the redesign of facilities to be heat-resistant and energy-efficient, and the allocation of a dedicated adaptation budget are also priorities. If all these recommendations are implemented in a gradual and measured manner, BIM will have an adaptation system that is not only responsive but also sustainable, thus capable of maintaining flight safety and smooth operations amidst increasing climate uncertainty.

DISCUSSION

Based on field observations, one clear indication of the impact of climate change at BIM is the occurrence of water puddles at several points on the apron and airside vehicle paths after short-duration heavy rain. This phenomenon indicates that the existing drainage system is not fully capable of accommodating the surge in water volume caused by extreme rainfall intensity, even if the duration is short. This condition creates potential disruptions to aircraft and operational vehicle movements, and can trigger the risk of Foreign Object Debris (FOD) if the puddles carry loose material into the operational area. Furthermore, the significant increase in apron surface temperature during the day poses a risk of heat stress for field personnel, especially ground handling and apron movement control personnel. Excessive heat exposure can reduce work concentration, increase the risk of human error, and ultimately impact operational safety. Observations also noted cracks in the apron and taxiway pavement suspected to be due to thermal expansion, which, if not promptly repaired, could develop into dangerous structural damage.

Interviews with various stakeholders strengthened the observation findings and provided a richer perspective on the challenges and adaptation strategies implemented. Airport Safety & Risk Management identified weather fluctuations, particularly unpredictable wind changes, as a key challenge requiring a rapid response from pilots and air traffic controllers. Sudden changes in wind direction can disrupt critical flight phases such as takeoff and landing, necessitating a more sophisticated weather monitoring system to provide early warning. The Minangkabau Meteorology, Climatology, and Geophysics Agency (BMKG) confirmed a trend of increasing daily temperatures and a shortening of the rainy season, accompanied by higher rainfall intensity. These conditions have implications for the increased risk of airport flooding and operational disruptions due to extreme weather. BMKG recommends integrating real-time weather data into airport decision-making systems to expedite operational responses.

From an operational perspective, an interview with the Airport Operations Air Side Dept Head revealed that operational disruptions due to waterlogging and heat stress have occurred several times in recent years. As an initial mitigation measure, operations accelerated coordination with the engineering unit to address waterlogging and adjusted work schedules to minimize heat exposure during peak daytime hours. However, the interview also indicated technological and budgetary limitations for implementing a more comprehensive adaptation strategy. Awareness of climate change issues is growing, but it is not yet evenly distributed across all work units, so ongoing outreach is needed to ensure all personnel have an equal understanding and involvement in adaptation efforts.

Literature studies support these empirical findings with data showing an increasing trend in the average annual temperature at BIM of ±0.07°C over the past two decades, which aligns with the global warming phenomenon. This temperature increase triggers an increase in the number of days with a heat index above 35°C, which impacts passenger comfort, staff health, and the efficiency of the terminal's cooling system. Structurally, extreme temperatures can reduce the strength of pavement materials such as asphalt and concrete, thus requiring design improvements and the selection of more heat-resistant materials. Furthermore, changes in dominant wind patterns also have implications for aircraft maneuvers, especially when significant crosswinds occur. Adjustments to runway usage, pilot briefings, and real-time coordination between ATC and BMKG are crucial steps to maintain operational safety.

Further analysis of the adaptation measures taken shows that BIM has implemented several strategies, such as increasing drainage capacity, strengthening the terminal roof structure, installing an early warning system, and technology-based weather monitoring. However, these adaptations are still sector-specific and have not been fully integrated into the overall safety management system (SMS). Disparities in readiness between units are also evident, with engineering and maintenance units tending to be more prepared than passenger service units. This has the potential to reduce the effectiveness of collective adaptation, as weaknesses in one sector can impact the entire safety chain.

Within the SMS framework, BIM already has a safety policy that includes climate disaster scenarios in its Airport Emergency Plan (AEP), updated in 2023. Risk assessments of climate threats have also been conducted, including identification of flood-prone areas and impacts on runways. However, this risk mapping process still relies on manual reports and has not been fully integrated with real-time digital systems, resulting in delays in decision-making. Furthermore, while routine safety training is conducted, topics focused on climate risks such as extreme temperatures and heatwaves have not been prioritized in mandatory simulations. This indicates a gap that needs to be addressed to ensure personnel are prepared to face future climate risks.

The integration of climate change adaptation with safety management in BIM is currently suboptimal. Although sectoral awareness and initiatives exist in engineering, operations, and safety units, these adaptation measures are not yet integrated within a unified coordination framework based on long-term climate data. In fact, ICAO, through its Climate Adaptation Planning for Aviation (2020), emphasizes that all adaptation efforts must be directly linked to safety objectives and have formal status within the SMS system. Without a formal integration mechanism, adaptation efforts risk becoming reactive and short-term, rather than anticipatory and sustainable. Therefore, BIM needs to develop an integrated risk management platform that combines meteorological data, critical infrastructure, and operational procedures to ensure that climate adaptation is truly an integral part of the airport safety strategy.

CONCLUSION

Based on research results obtained through direct observation, semi-structured interviews, and documentation studies, it can be concluded that climate change has had a significant impact on the safety and operational sustainability of Minangkabau International Airport (BIM). The main risks identified include extreme temperatures that trigger thermal expansion and damage to runway surfaces, high-intensity rainfall that causes inundation and potential flooding in the operational area, and changes in wind patterns that disrupt aircraft takeoffs and landings. Long-term threats such as sea level rise also increase potential vulnerabilities given BIM's location in a coastal area. Although airport management has implemented mitigation measures such as manual weather monitoring, drainage maintenance, and staff training, these measures are not fully adequate to address the increasing complexity of climate risks, primarily due to the lack of an integrated weather information system with automatic early warnings, comprehensive SOPs for extreme weather, and adaptive training based on climate disaster scenarios. Institutionally, the integration of climate change adaptation strategies into the Safety Management System (SMS) remains suboptimal, particularly in terms of utilizing accurate climate data, strengthening the early warning system, and developing responsive operational policies. Funding limitations, suboptimal coordination between units, and the absence of structured adaptation policies are key challenges that must be addressed. Therefore, strengthening infrastructure, updating operational procedures to consider future climate scenarios, and increasing awareness and engagement of all stakeholders are key to ensuring flight safety and the sustainability of air transportation services in BIM.

Based on the research results and conclusions obtained, it is recommended that Minangkabau International Airport management and other relevant parties strengthen integrated climate change adaptation strategies within the Safety Management System (SMS) to make airport operations more adaptive and sustainable. Priority should be given to increasing infrastructure capacity to withstand extreme weather events by optimizing drainage systems, using heat-resistant materials on runways, and strengthening building structures against strong winds. Integrating climate change adaptation into safety policies should include climate data-based risk assessments, developing adaptive safety indicators, and integrated monitoring and reporting with applicable safety procedures. Cross-sectoral coordination between airport management, the Meteorology, Climatology, and Geophysics Agency (BMKG), aviation authorities, local governments, and disaster agencies needs to be improved to develop long-term adaptation policies supported by dedicated funding, either through green infrastructure investment or sustainable financing. Further research is recommended to include quantitative studies of the economic impacts of climate change, including estimates of operational losses and adaptation budget requirements, to strengthen the basis for strategic planning. Furthermore, developing long-term climate scenario simulation models based on weather projection software will enhance risk analysis, enabling BIM to anticipate various possible extreme climate conditions with more precise and comprehensive planning.

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