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Implementation of a Category II Precision Approach Lighting System (PALS) Based on Aviation Safety and the Principles of Tri Hita Karana at I Gusti Ngurah Rai Airport, Bali

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ABSTRACT

I Gusti Ngurah Rai International Airport in Bali is an international airport with high air traffic volume and complex runway approach characteristics due to its coastal geography. This study aims to design a Category II Precision Approach Lighting System (PALS) for Runway 27 to enhance flight safety during low-visibility conditions. The research methodology employs a field observation approach, analysis of lighting configurations based on ICAO Annex 14, evaluation of obstacle limitation surfaces (OLS), and the integration of the Tri Hita Karana concept as an environmental and cultural safety approach rooted in Balinese traditions. The results indicate that a 900-meter-long PALS CAT II configuration with a sequenced flashing light system effectively enhances visual guidance for pilots during the final approach phase. The integration of the Tri Hita Karana concept supports harmony between aviation safety, coastal environmental sustainability, and local Balinese cultural values. This research offers a novel approach by combining technical aviation lighting system methodologies with culture- and environment-based safety concepts. The implementation of this system is expected to support low-visibility operations and elevate international aviation safety standards at I Gusti Ngurah Rai International Airport in Bali

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INTRODUCTION

I Gusti Ngurah Rai International Airport in Bali serves as the primary gateway for air transportation on the island of Bali, supporting the tourism and economic sectors as well as connectivity across central and eastern Indonesia. The high volume of international air traffic necessitates increasingly reliable aviation safety systems, particularly during the aircraft approach and landing phases. One critical facility supporting aviation safety is the Precision Approach Lighting System (PALS).

The approach lighting system provides visual guidance to pilots during the final approach, especially in adverse weather conditions and low visibility (Nurzaman, 2025). The geographical location of I Gusti Ngurah Rai International Airport, situated in a coastal area, creates a potential for fog, heavy rain, and "black-hole approach" phenomena that can impair pilots' visual perception. The existing system, which still operates under CAT I standards, is deemed insufficient to support optimal flight operations under low-visibility conditions (Rodríguez-Sanz et al., 2021).

In addition, smart airport-based technologies and digital monitoring systems are being implemented in the Airfield Lighting System (AFL) to improve maintenance efficiency and enable real-time monitoring of approach lights (Im et al., 2023).

This study offers a novel approach by integrating the Tri Hita Karana concept into the development of an aviation safety system rooted in Bali's environment and culture. This concept emphasizes the balance of relationships between humans and God, humans and their fellow humans, and humans and the environment (Arimbawa & Sudiarta, 2022).

THEORETICAL REVIEW

Precision Approach Lighting System (PALS) Category II

The Category II Precision Approach Lighting System (PALS) is a precision approach lighting system designed to assist pilots in landing safely and accurately under low-visibility conditions (Organization, 2022). This system is a key component of the Airfield Lighting System (AFL), providing visual guidance to pilots during the final approach phase to the runway. In modern aviation operations, the presence of PALS is crucial as it enhances pilots' ability to identify the runway threshold, the runway centerline direction, and the aircraft's approach angle during adverse weather conditions, such as heavy rain, fog, or high humidity (González-Arribas et al., 2020).

PALS Category II consists of several main components, namely a row of centerline lights, crossbars, side row barrettes, and sequence flashing lights installed symmetrically along a 900-meter stretch from the runway threshold in accordance with ICAO Annex 14 standards (Camarillo-Escobedo & ..., 2021). The sequence flashing light system operates with a sequential flashing pattern that helps pilots obtain visual orientation from a distance, while the side row barrettes serve to provide lateral visual boundaries to keep the aircraft on a safe approach path. Additionally, the use of high-intensity lighting ensures the system remains clearly visible during night operations and in extreme weather conditions (Braga et al., 2020).

In practice, PALS Category II serves not only as a visual aid but also as a critical component of a technology-integrated aviation safety system. This system is typically linked to the Instrument Landing System (ILS), Precision Approach Path Indicator (PAPI), and Runway Lighting System, thereby ensuring synchronization between visual guidance and instrument navigation. This integration is crucial for supporting Low Visibility Operations (LVO) at international airports with high traffic volumes.

At I Gusti Ngurah Rai International Airport in Bali, the implementation of PALS Category II is particularly relevant due to the characteristics of Runway 27's approach, which faces directly toward the coastal sea area. These conditions have the potential to cause a "black-hole approach" phenomenon, a situation where pilots experience limited visual references due to the dominance of dark areas around the approach path. Therefore, the PALS Category II system is necessary to improve the accuracy of visual guidance, maintain the stability of the aircraft's glide path, and minimize the risk of undershoot or go-arounds during the landing process.

In addition to technical considerations, the implementation of PALS Category II can also be linked to the concept of sustainable aviation safety. The use of energy-efficient, high-intensity LED lighting technology can enhance airport operational efficiency while reducing electricity consumption. Thus, the development of modern aviation lighting systems is not only focused on operational safety but also supports the concept of sustainable airport infrastructure, which is currently a key priority in the development of international airports (Braga et al., 2020).

ICAO Annex 14

ICAO Annex 14 is an international regulation published by the International Civil Aviation Organization (ICAO) that serves as the primary guideline for the planning, design, and operation of airports worldwide. This standard governs various technical aspects of aviation, ranging from runway dimensions, airport lighting systems, and obstacle limitation surfaces (OLS) to aviation safety facilities that every international airport must meet. The existence of ICAO Annex 14 is crucial for establishing uniform global aviation safety standards so that aircraft operations can proceed safely, efficiently, and in an integrated manner (Organization, 2022).

In the context of visual aid systems, ICAO Annex 14 regulates the configuration of Precision Approach Lighting Systems (PALS) for various categories of flight operations, including Category I, Category II, and Category III. For precision categories such as CAT II, ICAO sets a standard approach lighting length of 900 meters with a specific configuration consisting of centerline lighting, crossbars, side row barrettes, and sequence flashing lights. These specifications aim to provide optimal visual guidance for pilots during landings in low-visibility conditions (Organization, 2021).

In addition to regulating lighting system configurations, ICAO Annex 14 also emphasizes the importance of obstacle control around airport areas through the concept of Obstacle Limitation Surfaces (OLS). This regulation aims to keep the approach and takeoff areas free of obstacles such as tall buildings, vegetation, towers, or other objects that could compromise flight safety. In practice, obstacle monitoring is a critical component in maintaining the effectiveness of the visual approach system, particularly on runways with complex geographical conditions (Tan & Masood, 2021).

At I Gusti Ngurah Rai International Airport in Bali, the implementation of ICAO Annex 14 standards presents unique challenges due to the runway's geographical location in a coastal area directly facing the sea. Maritime weather conditions such as light fog, high humidity, and seasonal rain require visual aid systems to be designed with a high degree of precision and light intensity. Therefore, the implementation of ICAO Annex 14 standards on this runway not only serves to meet international regulations but also constitutes a critical strategy for enhancing aviation operational safety (Organization, 2020).

Beyond technical safety aspects, the implementation of ICAO Annex 14 also supports the concept of a sustainable airport. The use of energy-efficient lighting technology, environmentally friendly obstacle zone management, and the integration of digital monitoring systems are integral to the development of modern, efficient, and sustainability-oriented airports. In the context of Bali as a culture-based international tourist destination, the application of aviation safety standards that align with environmental conservation and local values is crucial for maintaining a balance between infrastructure development and the sustainability of the tourist region (Organization, 2021).

The Tri Hita Karana Concept

Tri Hita Karana is a Balinese philosophy of life that emphasizes the balance of relationships between humans and God, humans and their fellow humans, and humans and the environment. In the context of airport development, this concept can be applied through infrastructure development that prioritizes human safety, environmental sustainability, and harmony with the surrounding area (Arimbawa & Sudiarta, 2022).

Environment-Based Aviation Safety

Modern aviation safety does not focus solely on technology but also considers the environmental conditions surrounding airports. Factors such as obstacle limitation surfaces, vegetation, coastal weather, and geographical conditions influence the effectiveness of visual approach systems.

METHODOLOGY

This study employs a technical descriptive method using a field observation approach, document review, technical interviews, and analysis of ICAO Annex 14 standards. The technical descriptive method was chosen because the study focuses on analyzing the existing conditions of the visual approach system and planning the configuration of a Category II Precision Approach Lighting System (PALS) in the approach area of Runway 27 at I Gusti Ngurah Rai Airport in Bali. This approach was used to obtain a comprehensive overview of aviation lighting system requirements based on geographical conditions, airport operational characteristics, and international aviation safety standards (Deviatkina et al., 2024).

Field observations were conducted to identify the physical conditions of the runway approach area, the presence of obstacles, the configuration of the existing lighting system, and the environmental conditions surrounding the airport area. A document review was conducted by collecting technical data, including runway layouts, obstacle limitation surfaces (OLS) data, ICAO Annex 14 standards, and supporting documents related to the Airfield Lighting System (AFL). Technical interviews were conducted with airport operational personnel and technicians to gather information regarding the operational status of the currently used approach lighting system and the requirements for upgrading to Category CAT II.

The research focuses on the approach area of Runway 27 at I Gusti Ngurah Rai International Airport in Bali, as this runway has complex geographical characteristics due to its direct exposure to the coastal waters of Bali. These conditions necessitate a more precise visual approach system to support flight operations in low-visibility conditions. Additionally, the high volume of international air traffic at I Gusti Ngurah Rai International Airport makes the enhancement of aviation safety systems a critical need to support safe and sustainable airport operations (Tchivwila et al., 2025).

This study also integrates an environment-based aviation safety approach through the Tri Hita Karana concept as an effort to harmonize modern aviation technology, operational safety, and the preservation of the environment surrounding the airport area. This approach is implemented by considering aspects of obstacle control, energy efficiency in lighting systems, and the sustainability of the coastal environment around the runway (Arimbawa & Sudiarta, 2022).

The research phases include:

Identification of obstacles in the runway approach area

This phase is conducted to identify obstacles in the vicinity of the approach area that could potentially compromise flight safety. The obstacle analysis is performed in accordance with the Obstacle Limitation Surfaces (OLS) requirements as specified in ICAO Annex 14(Zhang et al., 2025).

Analysis of PALS CAT II system requirements

The analysis is conducted to determine the technical specifications of the approach lighting system suitable for CAT II operations, including visual guidance requirements during low-visibility operations (Putra et al., 2021).

Design of the approach lighting configuration

This phase involves designing the configuration of the centerline light, crossbar, side row barrettes, and sequence flashing lights based on the ALSF-II standard, with an approach lighting system length of 900 meters (Huo et al., 2021).

Electrical Power Requirements Analysis

The analysis was conducted to calculate the total power requirements of the approach lighting system, the electrical supply capacity, and the need for backup systems such as UPS and generators to ensure the continuity of the lighting system's operation.

Evaluation of Compliance with ICAO Standards

The final stage involves evaluating the design results against ICAO Annex 14, CASR Part 139, and relevant aviation safety regulations to ensure the designed system meets international operational standards (Organization, 2022).

RESULTS

Characteristics of the Runway 27 Approach Area

Runway 27 at I Gusti Ngurah Rai Airport in Bali has distinct geographical characteristics compared to most other airports in Indonesia, as its approach area faces directly toward the coastal waters off the southern coast of Bali. This situation often results in pilots on approach to the runway facing limited visual references, particularly at night or during weather conditions that reduce visibility. This phenomenon is known as a "black-hole approach," a condition where pilots see only minimal light references along the approach path, making it more difficult to visually maintain perception of distance, glide path angle, and aircraft altitude. This situation has the potential to increase the risk of an undershoot or instability during the final approach if not supported by adequate visual aids (Organization, 2022).

In addition to geographical factors, the meteorological conditions along Bali's coastline present unique challenges for flight operations. High humidity levels, the presence of light fog in the morning and at night, and seasonal rainfall can cause runway visibility to decrease significantly (Liu et al., 2022). Under certain conditions, pilots require clearer visual assistance to maintain the centerline and glide path angle during the landing process. Therefore, a high-intensity approach lighting system with a precise configuration is a necessity (Braga et al., 2020).

Analysis of Requirements for a Category II PALS

Based on the results of the aviation operational requirements analysis, the existing approach lighting system on Runway 27 is deemed not yet fully optimal for supporting flight operations under low-visibility conditions. The visual approach system, which remains at the basic category, has limitations in providing visual guidance to pilots when visibility decreases due to heavy rain, fog, or coastal atmospheric conditions. Therefore, an upgrade to a Precision Approach Lighting System (PALS) Category II is required, which offers better visual guidance capabilities and complies with ICAO Annex 14 standards.

The PALS CAT II configuration is designed using the ALSF-II system with a total length of 900 meters from the runway threshold. This system consists of centerline lighting, crossbars, side row barrettes, and sequence flashing lights installed symmetrically in the approach area. The centerline lights serve to guide aircraft toward the runway threshold, while the crossbars help pilots identify the aircraft's lateral position relative to the approach centerline. Additionally, the sequence flashing lights provide a dynamic visual effect in the form of sequential light flashes that help pilots orient themselves to the runway from a distance, particularly at night or in poor weather conditions.

The analysis results show that the implementation of PALS CAT II improves pilots' ability to maintain approach angle stability and aircraft position accuracy during the final approach. This system also helps reduce the likelihood of go-arounds caused by loss of visual reference during the final landing phase. With the increasing volume of international air traffic at I Gusti Ngurah Rai International Airport in Bali, the presence of a precision visual approach system has become crucial for maintaining operational safety and supporting international airport service standards.

Lighting Configuration Analysis

The lighting configuration design in this study adheres to ICAO Annex 14 standards for the ALSF-II (Approach Lighting System with Sequence Flashing Category II) system. The system configuration spans 900 meters with a bar spacing of 30 meters and includes two main crossbars located 150 meters and 300 meters from the runway threshold. This installation pattern aims to provide clear and directed visual guidance to pilots during the approach to the runway, especially under low-visibility conditions.

The lighting system utilizes high-intensity LED-based lighting, which offers better energy efficiency compared to conventional halogen lamps. The use of LED technology provides several advantages, such as a longer operational lifespan, more stable light intensity, and reduced maintenance requirements. Additionally, the sequence flashing light system is designed with a pattern of two flashes per second, enabling a visual effect that is easily recognizable by pilots at specific approach distances. The integration of the lighting configuration with the ILS and PAPI systems also helps create synchronization between instrument guidance and visual guidance during the landing process.

The results of the configuration analysis indicate that the ALSF-II pattern is highly suitable for implementation on Runway 27 at I Gusti Ngurah Rai Airport in Bali, as it effectively addresses the limitations of visual references caused by open-water conditions in the approach area. The presence of crossbars and side row barrettes provides lateral visual aids that help pilots keep the aircraft on the runway centerline. In addition to enhancing flight safety, the use of an LED-based lighting system also supports the concept of a sustainable airport by reducing electricity consumption and improving the operational efficiency of the airport’s lighting system.

Integration of Tri Hita Karana into the PALS System

In this study, the concept of Tri Hita Karana is applied as an integrative approach between aviation safety technology and the local cultural values of Bali. The Tri Hita Karana philosophy emphasizes the balance of relationships between humans and God (Parahyangan), humans and their fellow humans (Pawongan), and humans and the environment (Palemahan). In the context of the PALS CAT II system, this concept is implemented through lighting system planning that is not only focused on technical safety aspects but also considers environmental sustainability and the harmonization of the airport area with local Balinese culture.

The Parahyangan aspect is realized by interpreting aviation safety as a form of respect for the value of human life. The PALS CAT II system is designed to minimize the risk of aviation accidents and provide a sense of security for all users of air transportation services. Meanwhile, the Pawongan aspect is realized through improved operational safety for pilots, passengers, technicians, and all airport personnel involved in aviation activities. With a more precise visual approach system, the landing process can proceed more safely and efficiently under various weather conditions.

The Palemahan aspect is implemented through efforts to maintain environmental balance in the area surrounding the runway approach. The use of energy-efficient LED lights is part of the strategy to reduce electricity consumption in the Airfield Lighting System (AFL). Additionally, obstacle control is conducted while taking into account the presence of coastal vegetation and the surrounding airport ecosystem. This approach represents a novelty in research as it integrates Balinese cultural philosophy into the development of a modern aviation safety system based on environmental sustainability.

Aviation Safety Analysis

The research findings indicate that the implementation of PALS CAT II significantly improves flight operational safety on Runway 27 at I Gusti Ngurah Rai International Airport in Bali. This system provides pilots with clearer visual guidance during the final approach phase, thereby helping to maintain a stable approach angle and keep the aircraft aligned with the centerline. In adverse weather conditions or during night operations, the presence of sequence flashing lights and high-intensity approach lights greatly assists pilots in identifying the runway threshold position more quickly and accurately.

Based on technical analysis, the integration of PALS CAT II with the Instrument Landing System (ILS) and Precision Approach Path Indicator (PAPI) creates synchronization between instrument and visual approach guidance. This integration provides system safety redundancy so that if one system experiences limitations, the pilot still receives navigation assistance from the other systems. Additionally, the standardized lighting configuration also reduces the risk of visual disorientation caused by the "black-hole approach" phenomenon, which frequently occurs on runways with approach areas facing open water.

The implementation of the PALS CAT II system also contributes to improved operational efficiency at the airport. With enhanced operational capabilities in low-visibility conditions, the potential for flight delays and go-arounds can be minimized. This is particularly important given that I Gusti Ngurah Rai International Airport in Bali is one of Indonesia's busiest international airports. Therefore, the development of a safety system based on precision visual approaches is a strategic step in supporting the safety, efficiency, and sustainability of international airport operations.

DISCUSSION

I Gusti Ngurah Rai International Airport in Bali plays a vital role as the main gateway for international tourism on the island of Bali. The high number of international tourists arriving by air makes the need for a reliable aviation safety system increasingly critical. The implementation of PALS CAT II not only enhances flight operational safety but also supports the improvement of airport service quality as an international tourism-based airport.

Upgrading the visual approach system to the precision category reflects positively on I Gusti Ngurah Rai International Airport's readiness to meet international aviation safety standards. A modern, integrated approach lighting system demonstrates the airport's ability to adapt to global aviation technology advancements. Additionally, the capability to operate under low-visibility conditions ensures the smooth flow of air traffic, allowing Bali's tourism and economic activities to continue optimally even during adverse weather conditions.

The integration of the Tri Hita Karana concept into the development of aviation safety systems provides unique added value for I Gusti Ngurah Rai International Airport in Bali. This approach demonstrates that the development of modern infrastructure can be achieved without neglecting cultural values and local environmental sustainability. Thus, the implementation of PALS CAT II serves not only as a technical solution for aviation safety but also as part of sustainable airport development that aligns with Bali's cultural identity as an international tourist destination.

CONCLUSION AND RECOMMENDATION

Based on the results of a study on the design of a Category II Precision Approach Lighting System (PALS) for Runway 27 at I Gusti Ngurah Rai Airport in Bali, the following conclusions were reached:

The geographical characteristics of Runway 27, which faces directly toward the coastal sea area, result in pilots facing limited visual references, particularly during adverse weather conditions, at night, and during operations with low visibility. These conditions increase the need for a more precise visual approach system that complies with international aviation safety standards.

Analysis results indicate that the implementation of a Category II Precision Approach Lighting System (PALS) with a 900-meter ALSF-II configuration can improve the quality of visual guidance for pilots during the final approach phase. This system consists of centerline lights, crossbar lights, sidebar lights, and sequential flashing lights that work in an integrated manner to help pilots maintain the approach path, glide path, and aircraft position relative to the runway.

The integration of the PALS CAT II system with the Instrument Landing System (ILS), Precision Approach Path Indicator (PAPI), and Runway Lighting System enhances the effectiveness of aviation safety systems through the synchronization of visual and instrument guidance. This integration supports flight operations under low-visibility conditions and minimizes the risk of go-arounds and pilot visual disorientation.

This research introduces a novel approach by applying the Tri Hita Karana concept in the development of an aviation safety system rooted in Bali's environment and culture. This approach is realized through the harmonization of operational safety, energy efficiency of the lighting system, and environmental management of the runway approach area.

The implementation of PALS CAT II at I Gusti Ngurah Rai Airport in Bali not only supports improved flight safety but also strengthens the development of a sustainable airport that aligns with Bali's identity as a culture- and environment-based international tourist destination.

ADVANCED RESEARCH

Based on the results of the research conducted, there are several areas for further research that can be pursued to improve aviation safety systems at I Gusti Ngurah Rai Airport in Bali and other airports, as follows:

Further research could focus on developing an Internet of Things (IoT)-based Airfield Lighting System (AFL) to monitor the condition of approach lights in real time. This system can help airport technicians detect light malfunctions, power outages, and decreases in light intensity more quickly and efficiently (Chang et al., 2025).

Subsequent research could examine the integration of the Precision Approach Lighting System (PALS) with smart airport technology and artificial intelligence (AI) to enhance the automation of lighting system control based on weather conditions, Runway Visual Range (RVR), and air traffic density.

Further research is needed on the energy efficiency analysis of LED-based PALS systems and the utilization of renewable energy sources, such as solar panels, to support the concepts of green airports and sustainable airport infrastructure.

Further research could also explore visual approach simulations using aviation software or flight simulators to analyze the effectiveness of CAT II PALS on pilot performance during landings under various weather conditions and visibility levels.

Research grounded in local culture can be developed by more broadly integrating the Tri Hita Karana concept into airport management systems, including coastal environmental control, obstacle area management, and the development of sustainable and environmentally friendly aviation infrastructure.

Future research could also conduct a comparative analysis of the PALS CAT I, CAT II, and CAT III systems at international airports in Indonesia to determine the effectiveness of each system in enhancing flight safety under different operational conditions.

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