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Value Reconstruction and Management Optimization of Air Traffic Control Safety Training Archives in Digital Transformation

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Abstract: The safe operation of air traffic control (ATC) is critical to the aviation industry. Safety training archives, as critical documentation recording the training processes and outcomes of ATC personnel, play a pivotal role in ensuring ATC safety. This study conducts an in-depth analysis of the construction elements, management frameworks, and multidimensional value embedded in ATC safety training archives, aiming to provide both theoretical foundations and practical guidelines for enhancing ATC safety management practices.

Keywords: Air traffic control; Safety training archives; Safety assurance; Archive management

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1. Introduction

In recent years, global civil aviation traffic has continued to grow, yet safety risks persist. According to data from the Civil Aviation Administration of China (CAAC), while civil aviation flight operations in 2024 increased by 12.3% compared to 2019, the incident rate per 10,000 flight hours attributable to aviation liability causes decreased by 74.6%. This demonstrates notable progress in safety management measures while underscoring the imperative for continued vigilance against human factor risks. According to statistics, human factor-related incidents in global ATC still account for 60–80% of total accidents, with frequent occurrences such as runway incursions and communication errors, highlighting the disconnect between personnel capabilities and safety requirements. The International Civil Aviation Organization (ICAO) has explicitly identified human factors as a critical risk area in its Global Aviation Safety Plan, mandating member states to mitigate such risks through systematic training management. ICAO further emphasizes in DOC 9868 [1] and DOC 9941 [2] the necessity to establish standardized safety training archive systems, enabling full-cycle management from qualification certification to ongoing competency monitoring. China's Civil Aviation 14th Five-Year Plan further proposes a digital transformation

strategy [3], mandating the optimization of safety management through data integration and intelligent technologies, thereby providing policy support for the development of training archive systems. For instance, the plan explicitly requires promoting deep integration between civil aviation Safety Management Systems (SMS) and big data platforms to achieve a transition from "experience-driven" to "data-driven" decision-making.

Current traditional safety training management models exhibit systemic deficiencies. Firstly, incompatible data systems among airlines, ATC units, and training institutions result in fragmented training records, preventing the establishment of individualized competency profiles. For instance, critical metrics like decision-making latency and scenario response accuracy remain unquantified due to inconsistent data formats. Secondly, overreliance on periodic examinations and certificate-based validation neglects dynamic analysis of real-time behavioral data (e.g., simulator error correction rates, emergency protocol execution efficiency). This gap delays the identification of competency degradation, as evidenced by a 2023 ICAO report showing 68% of human-factor incidents involved personnel passing recent certifications. Thirdly, standardized training curricula fail to address individual learning curves and skill variances. A representative case occurred at a Category II airport where controllers with identical certifications exhibited a 40% performance divergence in low-visibility scenario handling, directly correlating to near-miss incidents. Additionally, the absence of lifecycle competency tracking creates "skill cliffs." In a runway incursion incident at an international hub, the involved controller held valid licenses but lacked recorded emergency drill data from the preceding 18 months. Management failed to detect declining stress response scores (measured by biometric sensors but unintegrated into training archives), missing critical intervention windows. This incident underscores the inherent flaw of current systems: without granular, longitudinal data (e.g., scenario-specific error patterns, adaptive training adjustments), human factor risks persist undetected until manifesting as operational failures. ICAO Doc 9941 [2] explicitly warns that "certification without continuous competency assurance constitutes systemic vulnerability."

2. Core components

As the cornerstone of aviation safety assurance, the quality of ATC personnel safety training directly impacts the operational integrity of the entire air transportation ecosystem. Establishing a scientifically rigorous safety training archive system constitutes not only a fundamental mandate under ICAO Annex 1 (Personnel Licensing) and Doc 9941, but also serves as a critical mechanism for achieving professionalized and systematic management of ATC human capital.

2.1. Multidimensional profiling of personnel baseline data

The foundational component of ATC safety training archives lies in the systematic collection and management of multidimensional personnel data. As mandated by ICAO DOC 10056 [4], A standardized template for ATC personnel files should be established, containing basic information such as name, age, gender, and contact details. This information not only serves as the fundamental basis for identity verification but also constitutes essential data for formulating personalized training plans. For example, statistical analysis of age distribution can facilitate the planning of technology transition programs for personnel from different generations, while gender data can provide references for staffing adjustments during special physiological periods. Additionally, career information, including employment start date, department affiliation, and job category, should be linked with basic information to form a database. This database, supported by a visual management system, enables real-time tracking of

personnel career trajectories. By establishing a job suitability analysis model, the matching degree between the skill profiles of equipment maintenance personnel and job requirements can be calculated, effectively enhancing personnel allocation efficiency.

2.2. Modular development of training curriculum systems

Modern ATC safety training has developed a trinity curriculum system integrating "theory–practical operation–emergency response." The basic safety theory curriculum should cover aviation regulations, human factors analysis, and the cultivation of a safety culture. Tools such as the development of a 3D visualized aircraft separation standards teaching system can be utilized to enhance controllers' mastery of theoretical knowledge. Emergency response courses need to include modules for handling special situations like radar failure and communication disruptions, employing scenario-based immersive training methods to strengthen practical skills. In new equipment training, a stepped curriculum structure of "theoretical instruction–simulated operation–internship" should be constructed. For example, introducing augmented reality devices for navigation station maintenance training can significantly reduce operational error rates. Training records should be precise down to minute-level credit hour statistics, with weight allocations for blended (online and offline) training methods clearly indicated, providing data support for the attribution analysis of training effectiveness.

2.3. Holistic construction of assessment systems

The ATC safety training evaluation system needs to transcend the traditional single-mode written examination format and establish a three-dimensional "knowledge-skill-competency" assessment model. Theoretical assessments can utilize a dynamic question bank system, where intelligent test paper generation software automatically creates differentiated examination papers based on job characteristics to enhance assessment reliability. Practical assessments should establish standard operating procedure evaluation scales, set key performance indicators in ATC simulator evaluations, and employ motion capture systems for high-precision assessments. It is noteworthy that "non-technical skills" should be incorporated into the assessment framework, such as by developing a team resource management assessment matrix that rates behaviors across multiple dimensions, including situational awareness and decision-making quality. A normal distribution model should be established for comprehensive assessment ratings, with a special competency enhancement plan initiated for individuals whose assessments rank in the bottom 10% for two consecutive years.

2.4. Closed-loop mechanisms for training quality enhancement

The training feedback system is a value-sublimation link in the archives system. A "dual-loop feedback mechanism" can be established. On the one hand, multi-dimensional evaluations from trainees regarding the course content, the instructors' proficiency levels, and the facility conditions are collected in real-time through mobile terminals. On the other hand, big data technology is employed to conduct regression analysis on the assessment scores and training elements. For example, the correlation between the duration of simulation training and the success rate of handling special situations can be discovered. To implement the improvement suggestions, a PDCA cycle mechanism needs to be established. By analyzing the feedback from trainees, the course duration can be adjusted reasonably to reduce the operation error rate. At the same time, a cross-cycle tracking function for training archives should be established to conduct longitudinal comparisons of the historical data of retrained personnel and accurately identify the ability decay curve.

3. Management model

Amidst the advancement of information technologies and escalating safety governance requirements, the archival management model must integrate traditional methodologies with cutting-edge innovations to establish a "dual-track convergence, real-time synchronization, and multidimensional cybersecurity" framework. This system ensures end-to-end integrity, traceability, and security.

3.1. Dual-track practice for archive storage and maintenance

Currently, ATC safety training archives are universally managed through a dual-track storage model combining physical (paper) and digital formats. Physical archives, as the original legally binding carriers, must be classified and filed based on three dimensions: personnel ID, training year, and course category. For example, a "one-person-one-file" physical archive cabinet system can be established, utilizing a color-coded management approach to distinguish job roles (e.g., red labels for controllers, blue for equipment maintenance personnel), significantly enhancing archive retrieval efficiency. Physical archive repositories must be equipped with temperature and humidity control systems to maintain humidity levels between 45% and 55%, and acid-free paper archive boxes should be employed to delay material aging, thereby markedly reducing the annual damage rate of physical archives.

The electronic archive management system is based on a distributed storage architecture and achieves server cluster deployment through virtualization technology. The training archive database can adopt a "dual-active storage" model [5], where the primary and backup data centers synchronize data in real time to ensure zero service interruption in the event of a single-point failure. Data backup follows the "3-2-1" strategy (3 copies, 2 media types, 1 offsite storage), with incremental backups performed daily at midnight and full backups conducted every Sunday. The SHA-256 encryption algorithm is used to ensure the integrity of backup files.

3.2. Dynamic operationalization of archival updating mechanisms

Archive updates must adhere to the principle of "training completed, data recorded immediately" by establishing a direct connection channel for training data. A mobile-based training data entry system can be developed, enabling trainees to automatically capture assessment results after completing simulator evaluations and synchronize them with electronic archives, with data latency controlled within 15 minutes [6–8]. For archive updates triggered by job promotions, when a controller advances from tower control to area control, the system automatically links to the radar control specialized training module and initiates the archive upgrade process.

Dynamic tracking management achieves visual monitoring through a data dashboard. A "training history heatmap" can be established to visually display personnel participation frequency in training courses over three years, fluctuations in assessment scores, and areas of skill weakness, providing data support for the formulation of retraining plans.

3.3. Multi-level prevention and control for archive security assurance

At the physical security level, archive storage facilities must meet the Class III protection standards stipulated in the Civil Aviation Security Regulations [9]. Archive repositories can be equipped with biometric access control systems that employ dual-factor authentication (fingerprint + iris) and installed with millimeter-wave radar monitoring devices to achieve alarm response within 0.5 seconds of unauthorized intrusion.

The cybersecurity protection framework adopts a "zero-trust" architecture [10]. The electronic archive system

implements three-tiered access permissions: general personnel are restricted to viewing their own archives, training supervisors possess departmental data retrieval privileges, and system administrator operations require dual-verification mechanisms.

4. Application value

The construction and management of ATC safety training archives serve not merely as a repository for information recording but as a core tool for enhancing aviation safety management efficiency [11]. By systematically integrating full-cycle personnel training data, they exhibit multi-dimensional application value in areas such as qualification assessment, training optimization, and risk prevention and control, providing critical support for the sustainable development of the ATC safety system.

4.1. Scientific transformation of personnel qualification assessment and certification

In the realm of personnel qualification assessment and certification, training archives provide accurate and comprehensive evidence. Detailed evaluation scores within the archives visually demonstrate ATC personnel's mastery of knowledge and skills, while training records comprehensively showcase their participation in various training programs [12]. By synthesizing this information, assessors can accurately determine whether personnel meet the job qualification requirements for corresponding positions, offering objective and reliable data support for the certification process.

Furthermore, training archives possess the capability to dynamically track changes in personnel qualifications. Over time, as personnel accumulate new knowledge through continuous training or gain experience through work practice, their qualifications improve, with these positive changes updated in real time within the archives [13]. Conversely, if personnel fail retraining assessments or encounter other qualification-reducing circumstances, this information is also documented. Leveraging this feature of archives, human resources departments can promptly capture personnel qualification dynamics, adjust job assignments reasonably, and ensure that all personnel consistently possess the competence required for their roles.

4.2. Data-driven training effectiveness evaluation and optimization

Training effectiveness evaluation and optimization also heavily rely on safety training archives. By leveraging comparative data on evaluation scores within the archives, it is possible to clearly observe the extent to which personnel's knowledge and skill levels have improved before and after training [14]. Feedback on personnel work performance further reflects, from the perspective of real-world work scenarios, the effectiveness of training content in practical applications. Through in-depth analysis of this data, quantitative evaluation of training program outcomes can be achieved, clarifying whether training has met its intended objectives.

Based on personnel feedback and training effectiveness evaluation results contained in the archives, targeted improvements to training content and methods can be implemented. If feedback indicates that certain course content lacks sufficient depth or that training methods fail to effectively convey knowledge, adjustments can be made to the depth and breadth of course content, more advanced simulation training equipment can be adopted to enhance the authenticity of hands-on training, or teaching methods can be refined to improve knowledge transfer efficiency, thereby comprehensively enhancing training quality.

4.3. Decision support for safety risk warning and accident investigation

In the fields of safety risk warning and accident investigation, training archives also play a pivotal role [15]. By leveraging big data analytics technology to conduct in-depth mining of archive data, potential safety risk points can be identified. For example, analyzing fluctuations in personnel training scores can reveal trends; if scores show a sustained decline or training participation significantly drops, these anomalies may indicate issues in knowledge retention or work attitude, potentially leading to safety risks. In such cases, early warnings can be issued to prompt relevant departments to take preventive measures promptly.

In the unfortunate event of an ATC accident, training archives serve as a critical source of clues. Investigators can review the training archives of involved personnel to gain detailed insights into their training history and skill mastery, providing robust evidence for in-depth accident cause analysis. This, in turn, enables the formulation of more targeted improvement measures to prevent similar accidents from recurring.

5. Discussion and conclusion

The safety training archives of the ATC system are of paramount importance in safeguarding its secure and stable operation. These archives provide precise data for personnel management, facilitating competency assessments and job allocations; they offer guidance for training optimization, enhancing quality through feedback and effectiveness evaluations; and they serve as a critical component of safety assurance, enabling risk warnings and supporting accident investigations, thereby acting as the cornerstone for maintaining normal ATC system operations. Establishing a well-structured and scientifically managed safety training archive system can effectively elevate ATC safety management standards and strengthen the system's capacity to navigate complex operational environments.

As aviation technology advances at an unprecedented pace and artificial intelligence (AI) gradually integrates into the ATC domain, new challenges emerge for personnel capabilities. The scope of safety training archives must expand to include AI-related knowledge and operational training records. Management technologies also demand innovation, leveraging big data analytics and blockchain to ensure efficient utilization and secure storage of archive information.

Against the backdrop of industry convergence and collaborative development, the prospects for sharing and exchanging ATC system safety training archives with training materials from airlines, airports, and other departments are promising. By sharing critical information, the aviation industry can integrate training resources, learn from advanced practices, and establish collaborative mechanisms to comprehensively elevate safety standards across the sector, laying a solid foundation for the sustained development of aviation.

Disclosure statement

The author declares no conflict of interest.

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