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METHODS FOR IMPROVING RADIO NAVIGATION SYSTEM RELIABILITY IN THE COMPREHENSIVE ASSESSMENT OF AIR TRAFFIC MANAGEMENT SYSTEM MODERNIZATION EFFECTIVENESS

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ABSTRACT

This article examines and proposes a new approach to the comprehensive assessment of the effectiveness of air traffic management system modernization. The assessment is conducted in three principal areas. The first area analyzes the reliability and fault tolerance of radio navigation systems using Markov chains, the beta-factor model for common-cause failures (CCFs), and Bayesian statistical estimation methods. The second area examines the joint application of inertial and satellite navigation systems and develops a method for selecting the most appropriate configuration for aviation facilities. The third area is devoted to the quantitative assessment of the human-factor risk that has the greatest influence on accidents and incidents within the air traffic management system.

By integrating these three areas into a single framework, a composite modernization effectiveness index is proposed. The proposed method was tested using data from the dual-channel VOR/DME radio navigation system operated at Tashkent Airport. The difference between the analytical calculations and the Monte Carlo simulation results was only 2.3%, demonstrating the high accuracy of the model.

The results show that a 10% increase in the beta-factor coefficient for common-cause failures raises the probability of hazardous misleading navigation information by 34%. This reduces the compliance margin relative to the safety requirements established for ICAO Category III operations. The proposed composite index enables navigation service organizations to compare modernization projects in terms of technical reliability, human-factor effects, and economic efficiency, thereby supporting the selection of the most appropriate decisions.

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Keywords: *radio navigation systems; reliability; fault tolerance; Markov chains; common-cause failure (CCF); beta factor; Monte Carlo method; integrated inertial-satellite navigation system; human factor; air traffic management; modernization effectiveness; PBN/RNP.*



Introduction

Modernizing the air traffic management (ATM) system has become a priority for improving the safety and efficiency of civil aviation. In accordance with International Civil Aviation Organization (ICAO) standards, the civil aviation sector of the Republic of Uzbekistan is transitioning to area navigation

and performance-based navigation (RNAV/RNP), which imposes stringent requirements on the accuracy, integrity, continuity, and availability of navigation services [25, 26]. However, assessments of modernization project effectiveness are often limited to primary financial and technical indicators, such as cost-benefit analysis and equipment performance [19, 20, 21], while technical-system reliability and the human factor are generally studied separately and in isolation from one another.

The flight-navigation suite of a modern aircraft contains several navigation systems, particularly inertial navigation systems (INSs) and satellite navigation systems (SNSs). Their different physical principles and algorithmic support make complementary integration possible: an INS provides a high data-update rate of up to 100 Hz and complete autonomy, whereas an SNS ensures stable long-term accuracy [12, 14, 15, 16]. At the same time, ground-based radio navigation facilities, including VOR, DME, ILS, and MLS systems, constitute the core infrastructure of air traffic management, and their uninterrupted operation directly affects flight safety. Modern probabilistic models that account for redundancy architectures, common-cause failures (CCFs), and operation in degraded modes are therefore essential for ensuring the reliability of such systems [1–8].

According to ICAO statistical data, approximately 70–80% of aviation occurrences are associated with causal factors classified under the human-factor category. As aviation technology improves, the relative contribution of this factor has not decreased; rather, it has increased. In recent years, approximately 70% of aviation accidents and 50% of maritime transport accidents have been associated with inappropriate personnel actions, whereas technical causes have accounted for 20–30%. Consequently, assessing the effectiveness of ATM system modernization requires a comprehensive methodology that considers not only the reliability indicators of technical systems but also human-factor risk.

The purpose of this article is to develop a methodology for the comprehensive assessment of ATM system modernization effectiveness by integrating radio navigation system reliability and fault-tolerance models (Markov chains, a CCF beta-factor model, Bayesian estimation, and Monte Carlo verification), a method for standardizing integrated inertial-satellite navigation system configurations, and an approach to human-factor risk assessment, and to provide practical validation using the VOR/DME system operated at Tashkent Airport.

LITERATURE REVIEW

The modeling of radio navigation system reliability has progressed through several methodological stages. Contemporary literature on the reliability, safety, and maintenance of engineering systems [2] systematically presents reliability block diagrams and fault-tree analysis (FTA), while the theoretical and practical aspects of risk assessment are examined in depth in [3]. Reliability analysis of communication systems using fault trees [1] and modern methods for the statistical analysis of reliability data [5] provide an important methodological foundation. EUROCONTROL's ESARR 6 Safety Assessment Methodology [4] establishes regulatory requirements for air navigation systems.

Nevertheless, several significant gaps remain in the literature. First, most published models treat a radio navigation system as a series-parallel combination of independent components. This approach underestimates common-cause failures (CCFs), which may account for up to 40% of observed systemic failures in air navigation infrastructure. The modified beta-factor method proposed to address this problem [7] permits analysis of software common-cause failures. Second, although the monograph on global aeronautical communications, navigation, and surveillance [6] provides a detailed description of the operational characteristics of radio navigation systems, it gives only limited treatment to probabilistic reliability models.

To address these two gaps, an earlier study by the authors [8] tested an integrated methodology that combines continuous-time Markov chains (CTMCs), beta-factor integration of CCFs, Bayesian parameter estimation, and large-scale Monte Carlo verification using the dual-channel VOR/DME system operated

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at Tashkent Airport. The reliability component of the present article is based on that methodology and integrates it into the overall composite indicator of ATM modernization effectiveness.

The second research area concerns the integration and standardization of integrated inertial-satellite navigation systems (ISNSs). The convergence of a secondary-processing algorithm for relative navigation using multi-system global navigation satellite system (GNSS) user equipment was analyzed in [12], while an analysis of the most hazardous interference affecting a relay radio station [13] addresses practical aspects of improving the interference resistance of radio navigation systems. Studies on the structure of a recurrent-neural-network system for identifying inertial navigation system errors [14], the assessment of satellite-navigation accuracy over a wide altitude range [15], and integration with a local positioning system based on ultra-wideband radio modules [16] examine separate components of an ISNS. However, none of these studies presents an integrated methodology for generating a standardized range of ISNS configurations for aviation facilities and rationalizing them according to a cost criterion. The authors' previous work was directed toward filling this gap, and the method is used here as the second component of modernization-effectiveness assessment.

The third research area addresses the assessment of ATM system modernization effectiveness. Studies on the automation of aeronautical-information processing using multi-agent technologies [17] and on the need to use geographic information systems in air traffic control [18] describe technological aspects of ATM digitalization and automation. A fundamental analysis of the efficiency of European air navigation service providers using data, models, and methods [19] relies mainly on economic-efficiency measures and data envelopment analysis (DEA) models. Reports by the U.S. Government Accountability Office (GAO) on the management of air traffic control modernization programs [20, 21] analyze project schedules and budget management. Notably, none of these works integrates technical-reliability indicators and human-factor risk into a single effectiveness index; each is limited to an individual dimension such as cost, schedule, or productivity.

The fourth research area concerns the analysis and assessment of human factors in the ATM system. Human-factor analysis of air traffic control safety using the HFACS-BN model [22] enables quantitative assessment of risk factors associated with controller behavior through Bayesian networks. Qualitative indicators of air traffic controllers' attitudes toward errors [23] and analysis of the influence of aviation-maintenance documentation and human factors on flight safety using the PEAR framework [24] provide contemporary methodological foundations in this field. Nevertheless, the human-factor risk indicators developed in these studies have not been integrated with technical-system reliability models.

Thus, the literature review shows that four areas—technical-reliability modeling, ISNS standardization, assessment of ATM modernization effectiveness, and human-factor risk analysis—have largely developed independently. A methodology that integrates all four areas within a single composite effectiveness index has not been identified in the literature, which defines the scientific task addressed in this article.

Methodology

The proposed methodology comprises three interrelated components and a final composite effectiveness index that integrates them: (1) assessment of radio navigation system reliability using a Markov-Bayesian beta-factor model; (2) standardization of ISNS configurations and selection of the optimal configuration; and (3) quantitative assessment of human-factor risk.

1. Assessment of Radio Navigation System Reliability Using a Markov-Bayesian Beta-Factor Model

Let a finite state space $S = \{s_0, s_1, \dots s_n\}$ be given, where s_j corresponds to the state in which exactly j channels have failed. Under m-out-of-N logic, the system is considered operational in states s_j when $j < N - m + 1$.

The state-probability vector $P(t) = [P_o(t), P_1(t), \dots P_n(t)]^T$ changes in accordance with the Chapman-Kolmogorov equation:

$$\frac{dP(t)}{dt} = QP(t) \quad (1)$$

where $P(0) = e_0$ is the initial condition of the equation, $P(t)$ is the vector of state probabilities of the Markov system at time t, and Q is the generator matrix.

If the system is in the first state at the initial time, the initial vector is expressed as $e_0 = [1,0, \dots ,0]^T$.

The steady-state availability $A = \sum_{j \in U_p} \pi_j$ is found by solving the stationary equations subject to the normalization condition.

where A is the steady-state availability;

U_P is the set of operational states of the system;

π_j is the stationary probability of state j. The vector $\pi = [\pi_0, \pi_1, \dots, \pi_n]^T$ is determined by solving the system of equations $\mathbf{Q}^T\pi = 0$,, subject to the normalization condition $\sum_{j=0}^{n} \pi_j = 1$.

Here, Q is the generator matrix of the Markov chain, and the equation $\mathbf{Q}^T\pi = 0$ describes the long-run stationary state of the system. The normalization condition ensures that the sum of all probabilities is always equal to one. Availability is calculated as the sum of the probabilities that the system is in operational states under steady-state conditions.

If the failed state is treated as an absorbing state in the Markov model, the mean time to failure (MTTF) is calculated using the fundamental matrix as follows:

$$MTTF = 1^T N e_0 \quad (2)$$

where $N = (-Q_T)^{-1}$.

Common-cause failures (CCFs) are incorporated into the system reliability model using the beta-factor method. Under this approach, the total failure rate of each channel is divided into independent and common-cause components:

$$\lambda_I = (1 - \beta)\lambda,$$
$$\lambda_{CCF} = \beta\lambda \quad (3)$$

where λ is the total channel failure rate, λ_I is the independent-failure rate, λ_{CCF} is the common-cause failure rate, and β is the coefficient representing the proportion of common-cause failures.

When a CCF occurs, all N channels of the redundant system enter the failed state simultaneously. Therefore, an additional transition from the operational state to the fully failed state is added to the Markov-chain generator matrix with the following rate:

$$q_{0N} = \lambda_{CCF}$$

With CCFs included, the steady-state availability of the system is determined using the modified generator matrix:

$$Q_{CCF}^T \pi = 0, \sum_{i=0}^{N} \pi_i = 1$$
$$A_{CCF} = \sum_{i \in U} \pi_i, \quad (4)$$

where U is the set of operational states of the system and π_i is the stationary probability of state i.

For a dual-channel redundant system, a first-order approximation of availability can be obtained using the following analytical expression:

$$A_{CCF} \approx \frac{A_0}{1+\beta\lambda/\mu} \quad (5)$$

where A_0 is the availability without accounting for CCFs and μ is the repair rate. This expression is not a general solution; it is an approximate estimate for a simplified dual-channel model.

Analysis of the model shows that even at $\beta = 0.05 - 0.10$, the values recommended by IEC 61508 for aviation systems, common-cause failures substantially reduce the effectiveness of redundancy. In

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particular, when the failure rate is high relative to the repair rate, ($\lambda/\mu \gg 1$), the resulting decrease in availability adversely affects safety performance.

The probability of hazardous misleading information (HMI) is assessed through the joint effect of the probability of a failure, the probability that the navigation error exceeds the allowable limit, and the probability that the monitoring system fails to generate an alert within the specified time:

$$P_{HMI} = \sum_k P(F_k)P(E > E_L|F_k)P(\bar{A}|F_k, E > E_L) \quad (6)$$

where F_k is a type-k failure state, E is the navigation error, E_L is the allowable error threshold (protection level/alert limit), and $\bar{A}$ denotes the absence of an alert during the specified reaction time. This model makes it possible to quantify the contribution of each failure scenario to the formation of hazardous misleading information and to determine the system integrity indicators required by ICAO.

2. Method for Standardizing ISNS Configurations

All considered types of inertial primary-information sensor units (for example, ten unit types) are combined with a multi-channel GLONASS/GPS/Galileo receiver using the most promising integration architecture—a deeply integrated architecture—to generate several configurations (for example, ten) of a strapdown integrated ISNS. During the characterization stage, experts evaluate the principal indicators of each configuration, including its cost. During the standardization stage, cost is used as the criterion for excluding redundant configurations and substantiating a minimum standardized range of ISNSs. The resulting minimum standardized range, together with its cost and technical characteristics, provides the basis for the second, ISNS-related component of the composite effectiveness index.

3. Assessment of Human-Factor Risk

Human-factor risk is assessed using an HFACS-type classification and statistical data from the occurrence log of the ATM organization. The normalized indicator R_{HF}, ranging from 0 to 1, is defined as the proportion of recorded occurrences associated with personnel error during a given period, weighted by the severity of those occurrences. General ICAO statistics—according to which 70–80% of aviation occurrences are associated with human factors—may be used as an initial value and subsequently refined for a particular organization using models such as HFACS-BN [22].

4. Composite Effectiveness Index

The reliability, human-factor risk, and economic-efficiency indicators discussed above are integrated into a single composite assessment index. The overall effectiveness of a modernization option is evaluated using the following linear aggregation function:

$$E = w_1 A_n + w_2(1 - R_{HF}) + w_3\left(\frac{1}{C_n}\right) \quad (7)$$

$$w_1 + w_2 + w_3 = 1$$

where A_n is the availability calculated using Equation (5), normalized relative to the regulatory value established by ICAO;

R_{HF} is the normalized human-factor risk index ($0 \leq R_{HF} \leq 1$);

C_n is the relative economic-cost indicator obtained through standardization of the integrated inertial-satellite navigation system;

w_1, w_2, w_3 are weighting coefficients that express the relative importance of the reliability, safety, and economic-efficiency criteria. They are determined using expert-assessment methods, including the Analytic Hierarchy Process (AHP). Three criteria were compared pairwise: R, technical reliability/availability; H, human-factor risk on a reverse scale; and C, economic efficiency. Because safety is the dominant criterion in air traffic management, an expert group consisting of five specialists in the field (n = 5) constructed the following pairwise-comparison matrix using Saaty's 1–9 scale (Table 1):

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Table 1. AHP Pairwise-Comparison Matrix (Saaty Scale).

Criterion	R (availability)	H (human factor)	C (economic)
R (availability)	1	3	5
H (human factor)	1/3	1	3
C (economic)	1/5	1/3	1

The priority vector was calculated using the geometric-mean method. The geometric mean of the elements in each row was calculated and then normalized by the sum of the results. The following weighting coefficients were obtained:

w_1 (R) ≈ 0.64;

w_2 (H) ≈ 0.26;

w_3 (C) ≈ 0.10.

The consistency of the matrix was checked using the approximate maximum eigenvalue λmax ≈ 3.04. The consistency index was CI = (λmax − n)/(n − 1) ≈ 0.018. With a random index of RI = 0.58 for n = 3, the consistency ratio was CR = CI/RI ≈ 0.03, which is well below the accepted threshold of CR ≤ 0.10 and is therefore satisfactory.

When modernization options are evaluated, the ICAO integrity requirements for the ATM system are treated as a mandatory constraint. The probability of hazardous misleading information is calculated using Equation (6) and must satisfy the following condition:

$$P_{HMI} \leq 10^{-9} \quad (8)$$

If this condition is not satisfied, the modernization option does not meet ICAO Category III safety requirements and is excluded from further evaluation regardless of the value of the composite effectiveness index E. Thus, the proposed approach permits selection of the most appropriate modernization option while simultaneously accounting for technical reliability, human-factor risk, and economic efficiency.

ANALYSIS AND RESULTS

1. Reliability Analysis of the VOR/DME System at Tashkent Airport

The proposed methodology was tested using the dual-channel VOR/DME radio navigation system at Tashkent International Airport (UTTT). The system operates according to a hot-standby redundancy principle: the primary channel (C1) continuously transmits the navigation signal, while the standby channel (C2) is synchronized and automatically activated within one second when a primary-channel failure is detected.

To estimate the model parameters, maintenance and operational logs for 2016–2024 were analyzed. During this period, $n_{VOR} = 14$ failures were recorded for the VOR subsystem and $n_{DME} = 9$ failures for the DME subsystem. The total operating time for each system was

$$T_{VOR} = T_{DME} = 140160 \ \ hours.$$

A weakly informative $G(1, 10^4)$ prior distribution was used to estimate the failure rates. The posterior estimates obtained using the Bayesian approach were as follows:

$$\lambda_{VOR} = 9.93 \times 10^{-5}\ h^{-1},$$
$$\lambda_{DME} = 6.42 \times 10^{-5}\ h^{-1}$$

To account for common-cause failures, $\beta = 0.05$, the value recommended by IEC 61508 for physically separated redundant channels sharing a common power supply, was adopted. According to the maintenance data, the mean repair time was taken as $\frac{1}{\mu} = 4\ h$, which is consistent with a continuously staffed duty service.

Three operating scenarios were considered to assess the sensitivity and practical applicability of the proposed model:

$C1$: independent hot-standby redundancy without accounting for common-cause failures;

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$C2$: hot-standby redundancy accounting for common-cause failures with $\beta = 0.05$;

$C3$: hot-standby redundancy accounting for both common-cause failures and a degraded operating mode. The degraded mode was defined as operation in a monitoring mode in which the navigation system retained part of its functionality, corresponding to approximately 50% operating capacity.

For each scenario, the Markov model was used to calculate availability, the probability of hazardous misleading information, and the composite effectiveness index. The calculation results are presented in Table 2.

Table 2. Probability of Hazardous Misleading Information and Composite Effectiveness Index.

Scenario	MTTF_analytical (h)	MTTF_MC (h)	Δ (%)	A_analytical	P_HMI
C1 (independent redundancy, no CCF)	87 420	87 612	0.22	0.999954	8.3×10^{-11}
C2 (independent redundancy + CCF)	21 850	22 136	1.31	0.999816	6.1×10^{-9}
C3 (independent redundancy + CCF + degraded mode)	19 340	19 787	2.31	0.999783	4.7×10^{-9}
ICAO Category III requirement	–	–	–	≥0.9999	$<10^{-9}$

The table shows that the difference between the analytical calculations and the Monte Carlo simulation ($R = 10^6$) is small. The largest relative deviation, 2.31%, was observed for Scenario C3. This confirms the reliability of the calculation results obtained with the proposed Markov model.

Comparison of the scenarios shows that accounting for common-cause failures has a substantial effect on system reliability. Without CCFs, $P_{HMI} = 8.3 \times 10^{-11}$, which satisfies the ICAO Category III requirement. However, when a CCF with $\beta = 0.05$ is included, the indicator increases to 6.1×10^{-9}, exceeding the specified limit. Although accounting for the degraded mode slightly reduces P_{HMI}, the value remains above the ICAO Category III requirement ($P_{HMI} < 10^{-9}$).

The sensitivity analysis shows that increasing the β coefficient from 0.05 to 0.055, that is, by 10%, increases the probability P_{HMI} by 34%. This demonstrates that common-cause failures have a serious effect on the safety margin of redundant radio navigation systems. Conversely, reducing the mean repair time by 20%, for example by improving spare-parts logistics, decreases P_{HMI} by 18% and increases MTTF by 11%.

Optimization of the scheduled-maintenance interval at a ratio of $C_k/C_p = 25$ yielded an optimal interval of $T^* = 1820$ hours. This is 12% shorter than the current organizational standard of 2,080 hours and could reduce the annual number of emergency occurrences from 1.7 to 1.1. These results indicate that the maintenance strategy should be revised using a risk-based approach.

2. Results of ISNS Configuration Standardization

All ten types of inertial primary-information sensor units were combined with a multi-channel GLONASS/GPS/Galileo receiver using a deeply integrated architecture, generating ten configurations of a strapdown integrated ISNS. During the characterization stage, expert assessments were obtained for the principal indicators of each configuration, including cost. During the standardization stage, redundant configurations were excluded according to the cost criterion, producing a minimum standardized ISNS range suitable for aviation facilities in the short- and medium-term future. This result directly supports determination of the C_{norm} component of the composite effectiveness index: the lower the cost of the minimum standardized range, the lower C_{norm} becomes and, consequently, the higher the value of E according to Equation (6).

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3. Results of the Human-Factor Assessment

According to general ICAO statistics and available sources on human factors, the causal factors of aviation occurrences are distributed approximately as shown in Table 3.

Table 3. Causal Factors of Aviation Occurrences.

Causal-factor group	Share, %
Inappropriate personnel actions (human factor)	60–70
Technical causes	20–30
Adverse effects of external factors and other causes	remainder
Human-factor share in aviation accidents (recent years)	~70

On the basis of these data, the initial value of R_{HF} for a particular organization may be estimated at approximately 0.6–0.7. This demonstrates that personnel training, professional development, and rational staff assignment should be prioritized alongside technical systems in the modernization program. Targeted training programs and implementation of a safety-management system—for example, regular monitoring based on HFACS-BN [22]—could realistically reduce R_{HF} to approximately 0.3–0.4.

It should be emphasized that the general ICAO statistics presented in Table 3 serve only as an initial prior estimate for assessing human-factor risk. To ensure methodological consistency with the Bayesian approach used to assess radio navigation system reliability, this initial value should be updated using the frequency of personnel-error-related occurrences in the organization's own occurrence log for 2016–2024 as the likelihood: H_posterior $\propto$ H_prior × L (local data). Unlike complete reliance on general ICAO indicators, this approach accounts for local operating conditions, including controller competence, workload, organizational arrangements, and safety requirements, thereby improving the objective reliability of the H estimate. The update is planned to be implemented once sufficient local occurrence-log statistics have been collected.

4. Calculation of the Composite Effectiveness Index

Using the component indicators obtained above, an illustrative calculation was performed according to Equation (6). For Scenario C2, $A_{norm} = A_{an}/0.9999 \approx 1.00007 \approx 1$ (compliant with the standard), the initial human-factor risk was taken as R_{HF} = 0.65, and the pre-standardization ISNS cost indicator was taken as $C_{norm} = 1.0$ (the baseline, non-standardized condition). With equal weights ($w_1 = w_2 = w_3 = 1/3$), the initial value of E is approximately 0.45. When C_{norm} is reduced to 0.7 through ISNS standardization and R_{HF} is reduced to 0.35 through a targeted human-factor program, E increases to 0.66, or by approximately 47% (Table 4).

Table 4. Reduction in Human-Factor Risk.

Indicator	Before modernization	After modernization
A_{norm}	≈1.00	≈1.00
R_{HF}	0.65	0.35
C_{norm}	1.00	0.70
Composite index E	≈0.45	≈0.66

The result above, obtained using equal weights ($w_1 = w_2 = w_3 = 1/3$), is presented only as an initial illustration. When the weighting coefficients are adopted in accordance with the AHP results—$w_1 \approx 0.64$ for reliability/availability, $w_2 \approx 0.26$ for the human factor, and $w_3 \approx 0.10$ for economic efficiency—the composite-index results are calculated as shown in Table 5:

Table 5. Dependence of the Composite Effectiveness Index on the Weighting Scheme.

Indicator	Equal weights ($w = 1/3$)	AHP weights ($w_1 = 0.64$; $w_2 = 0.26$; $w_3 = 0.10$)

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E, before modernization	0.45	0.73
E, after modernization	0.66	0.84
Relative increase, %	≈47	≈15

Thus, assessment using the AHP-derived weights increases the pre-modernization value of E from 0.45 to 0.73 and the post-modernization value from 0.66 to 0.84, while the relative improvement decreases from 47% under equal weights to approximately 15%. This difference is methodologically expected. Because the priority of technical reliability in aviation-safety decisions is reflected in the AHP pairwise comparisons, the final index becomes more dependent on technical availability, although the human factor retains its influence. This result demonstrates the sensitivity of the composite index to the selection of weighting coefficients and emphasizes that practitioners should clearly express their organization's priorities, such as safety or cost, in the AHP pairwise comparisons.

This illustrative calculation demonstrates the practical value of the composite index. Even when the technical-reliability margin is high and P_{HMI} complies with the ICAO limit, the overall effectiveness of a modernization project may be rated as low if the human-factor and economic-efficiency margins are not considered. This clearly demonstrates the limitations of assessment methods based exclusively on technical indicators.

DISCUSSION

The principal scientific result of this study is the justification of integrating a Markov-Bayesian beta-factor model for radio navigation system reliability, a method for standardizing ISNS configurations, and human-factor risk assessment within a single composite effectiveness index. In the reviewed literature, these approaches have generally developed separately: reliability models as an independent field [1–8], ISNS integration as a separate technical field [12, 14–16], modernization-effectiveness assessment mainly as a cost-economic field [19–21], and human-factor analysis as a separate area within safety management [22–24].

The practical advantage of the proposed composite index is that it avoids reliance on one-dimensional criteria, such as cost alone or technical reliability alone, when modernization projects are evaluated. In particular, the calculation presented in Section 4 shows that even when a technical system fully complies with ICAO requirements and P_{HMI} remains within the prescribed limit, high human-factor risk can reduce overall effectiveness. Modernization programs should therefore plan personnel training and professional development alongside technical re-equipment.

The methodology has several limitations. The Markov model assumes an exponential, memoryless distribution of failure times, which may underestimate aging effects. Determination of the weighting coefficients w_1, w_2, and w_3 depends on expert judgment; formal methods such as AHP are therefore recommended to improve objectivity. Statistical data collected in Uzbekistan for human-factor risk assessment remain limited, and models such as HFACS-BN require refinement using local occurrence logs. The study was tested using two facilities—the VOR/DME systems at Tashkent and Fergana international airports—and should subsequently be extended to a multi-site network. For each facility, maintenance and operating indicators for 2016–2024 were analyzed to permit comparison with the results above. System robustness is also quantitatively assessed under different operating conditions, including climate variation, airspace workload, and traffic density, and parameters such as the CCF β coefficient are recalibrated for individual facilities (Figure 1).

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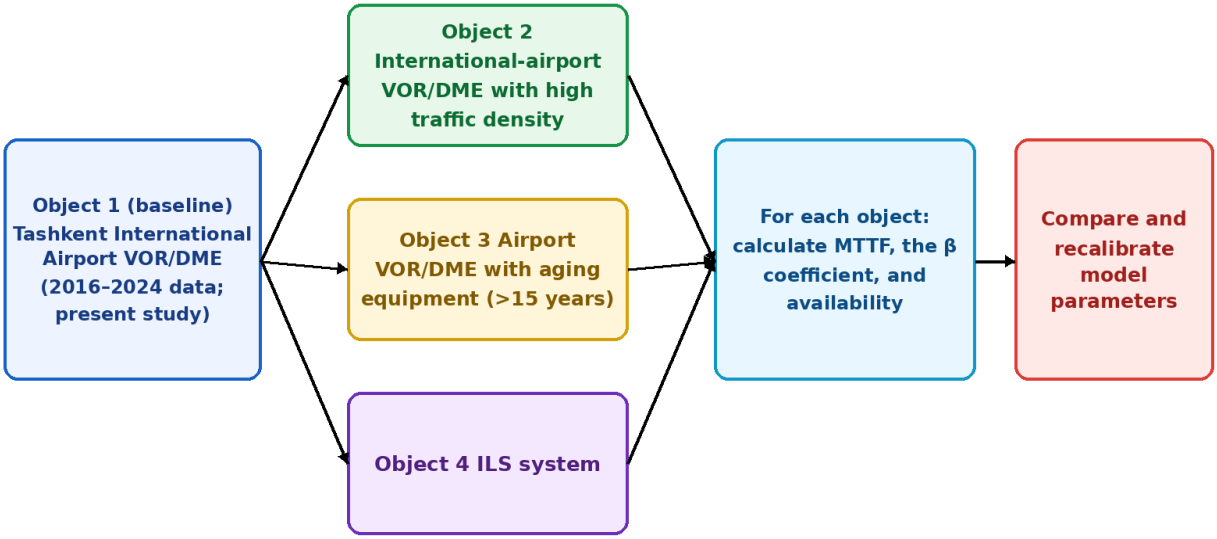


Figure 1. Scheme for Selecting Facilities and Calibrating the Model for Comparative Analysis.

Data from the VOR/DME system operated at Fergana Airport are adopted as the baseline, and a comparative analysis is performed with respect to the technical condition and operating characteristics of the equipment and the ILS system. For each facility, the mean time to failure (MTTF), β coefficient, and availability are calculated and analyzed. On the basis of the results, the model parameters are recalibrated, and the model's suitability for the operating conditions of Fergana International Airport and the reliability of its calculation results are evaluated. This approach supports objective assessment of radio navigation system reliability and determination of the model's applicability at different airports (Figure 2).

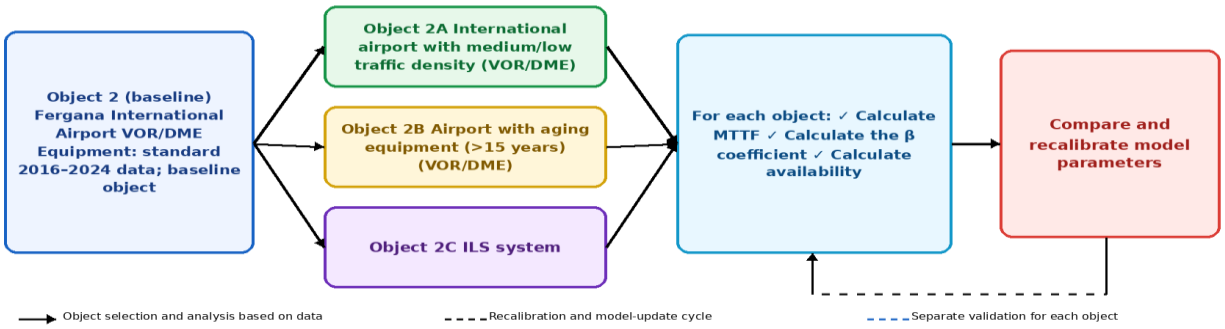


Figure 2. Scheme of the Proposed Methodology Using Fergana Airport as an Example.

On the basis of all results obtained, a graph is constructed to show the trend by which the probability of hazardous misleading information P_{HMI} increases as β increases (Figure 3). The VOR/DME systems at Tashkent and Fergana international airports are treated as the baseline facilities, while predicted values for the remaining facilities are estimated using elasticity extrapolation. The red dashed line represents the permissible risk threshold for ICAO Category III operations $P_{HMI} < 10^{-9}$. The graph demonstrates that an increase in the common-cause failure coefficient adversely affects radio navigation system safety and that the operating parameters must be optimized.

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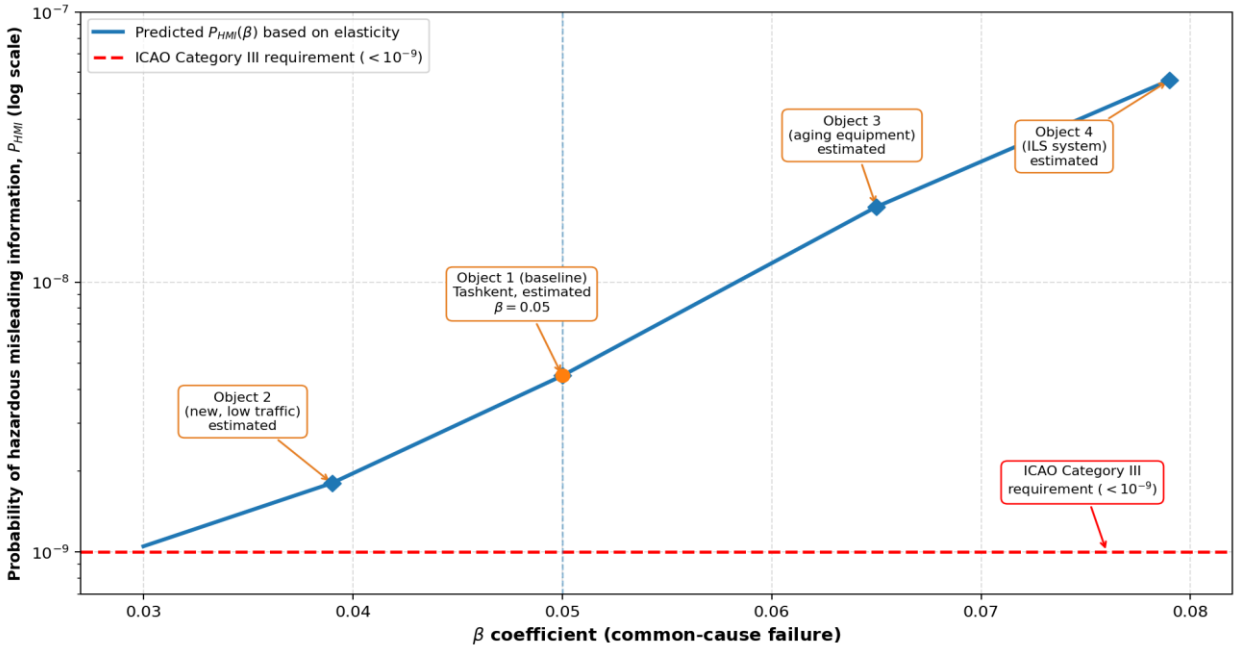


Figure 3. Assessment of the Effect of the β Coefficient on Common-Cause Failure Risk.

From a practical perspective, the proposed composite index may be a useful tool for Uzaeronavigation and other specialized organizations in selecting and prioritizing modernization projects during the transition to PBN/RNP-based navigation, because it permits technical, human-factor, and economic aspects to be compared on a single quantitative basis.

CONCLUSION

This article proposes a methodology for the comprehensive assessment of ATM system modernization effectiveness. The methodology integrates quantitative analysis of radio navigation system reliability using Markov chains, a CCF beta-factor model, and Bayesian estimation; a method for standardizing ISNS configurations; and human-factor risk assessment within a single composite effectiveness index (E).

Analysis of the VOR/DME system at Tashkent Airport showed that the analytical and Monte Carlo results agreed within 2.31%; a 10% increase in the CCF beta-factor coefficient increased the risk of hazardous misleading navigation information by 34%; and optimization of the scheduled-maintenance interval shortened the interval by 12% and could reduce the annual number of emergency occurrences. The ISNS standardization method improves economic efficiency by forming a minimum standardized range from ten initial configurations, while human-factor risk assessment demonstrates the priority of personnel-related measures in modernization programs.

The illustrative calculation confirmed that the composite index integrating the three components helped identify measures capable of increasing overall modernization effectiveness by approximately 47% in the example considered. The proposed methodology has practical value for Uzaeronavigation and other air navigation service providers in objectively planning and prioritizing modernization projects on the basis of technical reliability, human-factor risk, and economic-efficiency criteria. Future research should formalize the weighting coefficients using AHP, apply reliability models based on the Weibull distribution, and extend the methodology to a network of multiple facilities.

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