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**OPTIMIZATION OF AIRCRAFT TECHNICAL
OPERATION PARAMETERS TO IMPROVE
FLIGHT REGULARITY**

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

Faculty of Civil and Mechanical Engineering
Institute of Mechanical, Aerospace and Transport Engineering

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Anvar Zabirov: _____ (signature)

Date:

The Doctoral Thesis has been written in English. It contains an annotation, introduction, four chapters, summary, conclusions, 142 figures, seven tables, and appendices; the total number of pages is 146, including appendices. The bibliography contains 75 titles.

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ANNOTATION

This study focuses on improving the operational management of aircraft maintenance processes to enhance flight regularity. The relevance of the topic stems from increasing demands for reliability and punctuality in air transportation, especially under conditions of limited resources and intensive fleet operation. The object of the research is the activity of the airline RAF-AVIA, which operates a regional network of flights with various types of airports and maintenance forms.

In Chapter 1, an analysis of the causes of flight delays related to aircraft technical condition is presented, along with a review of the specifics of operational maintenance management, airport classification, and the key factors affecting flight regularity. Additionally, public data was used to analyze punctuality statistics.

Chapter 2 presents a mathematical model for delay formation based on the dynamics of aircraft technical states and probabilistic characteristics of recovery processes. The model accounts for state transition probabilities, flight network structure, and specific airport parameters. The developed application tool, implementing the proposed mathematical models, enables the calculation of key flight regularity indicators and allow to evaluation of the influence of various operational parameters.

Chapter 3 includes an in-depth analysis of aircraft state dynamics at both base and non-based airports, proposes a method for evaluating the significance of operational factors on departure delay durations, and presents practical recommendations for RAF-AVIA aimed at optimizing maintenance processes and reducing the expected duration of flight delays.

Chapter 4 develops an objective-function-based optimization framework for AOG-critical defect scenarios, linking probabilistic state dynamics with recovery and logistics parameters to evaluate and select delay-mitigation strategies at the route level.

This Thesis is aimed at improving the efficiency of aircraft maintenance management through modeling, quantitative analysis, and the application of evidence-based decisions tailored to the operational context of a specific airline.

The application tool operates solely on airline-provided input parameters and accumulated operational statistics, ensuring that all calculations are based on real empirical data.

INTRODUCTION

Modern airlines operate under strict safety constraints and increasing pressure to maintain high levels of schedule reliability. In regional airline networks, technical disruptions often propagate across multiple routes, creating cumulative delays and operational instability. Despite the importance of operational aircraft maintenance management, quantitative tools for evaluating recovery processes and predicting technical delay formation remain limited.

This Thesis develops a probabilistic model of aircraft technical state evolution and recovery processes within an airline route network. The model integrates defect occurrence probability, MEL-based operational constraints, airport technical capability, and recovery time parameters. The proposed approach enables quantitative assessment of technical delay formation and

supports data-driven operational decision-making. The model is implemented in the FlightSync application tool and validated using real operational data from the Latvian airline RAF-AVIA.

Research relevance

The relevance of this research is driven by the need to improve flight regularity through quantitative optimization of operational aircraft maintenance within airline networks.

- Flight regularity depends on how effectively aircraft maintenance and technical operations are managed.
- In an airline network, technical delays are caused not only by failures and technical malfunctions, but also by organizational factors such as recovery time, resource logistics, staff availability, and spare parts support.
- Airlines differ in fleet structure, resources, and maintenance organization; therefore, standardized solutions cannot ensure stable performance.
- Improving flight regularity requires a systematic approach based on mathematical modeling and optimization of aircraft technical operation parameters, considering resource availability.

Research objectives

Improving flight regularity through optimization of operational aircraft maintenance parameters based on mathematical models of recovery processes within the airline route network.

To achieve this goal, the following research tasks were defined:

- 1) to analyze the current state of the flight regularity problem in civil aviation and its impact on airline network operations;
- 2) to analyze aircraft failures and technical malfunctions during operation, assess recovery capability within the airline network, and determine operational factors influencing technical delay probability;
- 3) to develop mathematical models of aircraft state assessment and recovery processes in accordance with MEL (Minimum Equipment List) requirements within airline network airports, aimed at reducing both the probability and duration of departure delays;
- 4) to develop an application tool for implementing the proposed mathematical models within operational maintenance management;
- 5) to test and validate the developed application tool using operational and statistical data from the RAF-AVIA airline.

Methods of the research

The following methods were applied:

- 1) methods of probability theory for the development of mathematical models;
- 2) matrix method of analysis and modeling;
- 3) statistical method;
- 4) method of aircraft technical condition identification.

Scientific novelty of the research

The scientific novelty of this Thesis is the following contributions:

- 1) developed graphical models of aircraft states and state transitions within an airline network, including both base and outstation airports, in the framework of aircraft technical operations;
- 2) proposed mathematical models for aircraft state assessment in accordance with Minimum Equipment List (MEL) requirements for airline network airports in the event of in-flight failures and subsequent recovery, aimed at minimizing both the probability and duration of departure delays and improving flight regularity;
- 3) developed and implemented an application tool, FlightSync, based on the proposed mathematical models and cumulative technical delay calculation algorithms. The application tool enables analysis of key factors affecting flight regularity and improves the efficiency of aircraft technical operations within the airline network. Testing on real operational data from RAF-AVIA confirmed the practical applicability and effectiveness of the solution.

Practical significance

The practical use of the developed models in airline operations significantly reduces both the probability and average duration of flight delays within the airline network in the event of technical failures. This is achieved through optimization of recovery processes, ensuring efficient allocation of maintenance resources, and forecasting of technical delays within the aircraft technical operation.

Theses to be defended

1. Graphical models of aircraft states and state transitions during failures and technical defects, for both base and outstation airports within the airline network in the aircraft technical operations.
2. Mathematical models for aircraft state assessment in accordance with MEL (Minimum Equipment List) requirements within airline network airports during failures and technical defects, as well as recovery models aimed at reducing both the probability and duration of departure delays and improving flight regularity.
3. Application tool that implements the developed mathematical models and provides calculation and forecasting of expected technical delays at airports within the airline network.

Results of the work

1. A comprehensive analysis of the current state of the flight regularity problem in civil aviation and its impact on airline network operations was conducted. The analysis examined existing approaches to flight regularity management and clarified the role of operational aircraft maintenance in maintaining stable performance within an airline network.
2. Aircraft failures and technical malfunctions during operation were analyzed using operational data. Recovery capability within the airline network was assessed, and

operational factors influencing technical delay probability were determined. The study established the relationship between defect occurrence, recovery conditions at network airports, and delay formation within the airline network.

3. Mathematical models of aircraft state assessment and recovery processes in accordance with MEL (Minimum Equipment List) requirements within airline network airports were developed. The models describe aircraft state transitions under failure conditions and defined recovery scenarios, and are aimed at reducing both the probability and duration of departure delays.
4. The FlightSync application tool was developed to implement the proposed probabilistic mathematical models within operational aircraft maintenance management. The application enables the calculation of cumulative technical delays and the practical application of the developed models within airline operations.
5. The FlightSync application tool was tested and validated using operational and statistical data from the RAF-AVIA airline. The validation confirmed the correctness of the implemented probabilistic models and their applicability in supporting operational aircraft maintenance management within the airline network.

Accuracy of research results

All research results are based on practical developments carried out by the author, including regulatory, technical, and organizational documentation, as well as actual operational data and interaction with airports within the RAF-AVIA airline network.

Thesis approbation

The research findings have been published in six scientific papers and presented at nine international scientific conferences held in Latvia and Poland, including a SCOPUS-indexed publication.

Publications

1. A. Zabiroy, V. Šestakovs, J. Maklakovs, N. Krontals, I. Blumbergs. (2025). Recovery Model for Aircraft at Airports Within the Airline Network of the Airline Company. *International Review of Aerospace Engineering (IREASE)*. DOI: <https://doi.org/10.15866/irease.v18i1.25566>, SCOPUS.
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8. A. Zabirov, Z. Zabirov, V. Šestakovs. (2020). Optimization of the Strapdown Inertial Navigation System Structure of Aircraft. 61ST INTERNATIONAL SCIENTIFIC CONFERENCE OF RTU.
9. A. Urbahs, P. Trifonovs-Bogdanovs, A. Zabirov, K. Mamay. (2019). Error Analysis of the Modern Aircraft Navigation Systems. The 2nd Aviation and Space Congress.

List of abbreviations

MCC – Maintenance Control Center
 CAMO – Continuing Airworthiness Management Organization
 OCC – Operations Control Center
 MEL – Minimum Equipment List
 AOG – Aircraft on Ground
 MPD – Maintenance Planning Document

AMP – Approved Maintenance Program
IATA – International Air Transport Association
ICAO – International Civil Aviation Organization
EASA – European Union Aviation Safety Agency
FAA – Federal Aviation Administration
A/C – Aircraft
TO – Technical Operation

Structure of the Thesis

The Thesis comprises an annotation, an introduction, four chapters, a summary, conclusions, 42 figures, 7 tables, and appendices; the total number of pages is 146. The bibliography contains 75 references.

The main parts of the Thesis

1. **The Annotation** summarizes the purpose of the research: to improve flight regularity by enhancing operational management of aircraft maintenance. It highlights the use of probabilistic modeling and application tool implementation based on RAF-AVIA operations.
2. **The Introduction** explains the relevance of flight delays due to technical issues and defines the research goal, objectives, methods, and the practical significance of the study for regional airline operations.
3. **Chapter 1** analyzes causes of delays related to aircraft technical condition and operational management. It describes airport classifications, airline network structure, and introduces the concept of technical state transitions.
4. **Chapter 2** presents a probabilistic model of aircraft state degradation and restoration. It introduces dual-level MEL logic, recovery/delivery time modeling, and integrates these into an application tool (FlightSync) for scenario analysis.
5. **Chapter 3** applies the model to RAF-AVIA operations. It identifies key operational factors affecting delays and provides prioritized recommendations for improving maintenance processes based on simulation results.
6. **Chapter 4** formulates an objective-function-based approach to optimizing operational aircraft maintenance management. The chapter introduces a quantitative criterion representing the expected total technical delay of a route, analyzes the influence of managerial measures through adjustments of probabilistic and temporal model parameters, and demonstrates the effectiveness of combined strategies using a detailed route-based case study for the RAF-AVIA airline network.
7. **Conclusions** confirm that the research objectives were achieved. The developed model and application tool support data-driven decision-making to reduce technical delays and improve flight regularity.
8. **Bibliography** contains a structured list of 67 sources, including ICAO, EASA, FAA, and academic publications on reliability, maintenance, and airline operations.
9. **Appendices** provide the program code of FlightSync application tool and AOG Statistics Data.

1. ANALYSIS OF FACTORS AFFECTING FLIGHT REGULARITY AND THE EFFICIENCY OF OPERATIONAL MANAGEMENT IN AIRCRAFT MAINTENANCE

Introduction

This chapter analyzes the operational, technical, and probabilistic factors influencing flight regularity and formulates a structured framework for evaluating technical delay risk within an airline network.

Flight regularity is a key performance indicator of airline operational effectiveness. Delays generate network propagation effects, reduce passenger satisfaction, and cause direct financial losses that increase with delay duration. Airport Collaborative Decision-Making systems improve pre-departure coordination through real-time information exchange between airlines, ground handlers, and air traffic control. Airlines implementing integrated delay management demonstrate improved punctuality performance. IATA standardizes delay reporting through unified operational categories (Table 1.1).

Table 1.1

Percentage Distribution of All Departure Delay Causes by IATA Categories in 2025

IATA Code	Definition
0–9	Others & Airline internal codes
11–18	Passenger and baggage handling
21–29	Cargo and mail
31–39	Aircraft and ramp handling
41–48	Technical and aircraft equipment
51–58	Damage to aircraft and automated equipment failure
61–69	Flight operations and crewing
71–77	Weather
81–89	Air traffic flow management/airport and governmental authorities
91–96	Reactionary delay
97–99	Miscellaneous

Disruption management focuses on schedule recovery and efficient resource reallocation. Rolling-horizon maintenance planning and predictive estimation of MEL-related workload improve operational stability. Delay data are processed within centralized ATM systems, and flow regulation mechanisms defined by EUROCONTROL mitigate network-level delay propagation.

Aircraft reliability directly affects regularity, since technical failures introduce restoration time and potential schedule disruption. The economic impact of delays exceeds €1.25 billion annually in Europe and \$32.9 billion in the USA. Effective mitigation, therefore, requires probabilistic risk assessment methods.

The present research addresses the limited development of formal models for technical delay evaluation and proposes an operational control framework aligned with ICAO safety priorities and standardized technical documentation principles (ATA Spec 100 / iSpec 2200).

1.1. Analysis of the state of flight regularity in civil aviation

Flight delays arise from uncontrollable factors such as weather and ATC restrictions, as well as controllable operational and technical factors. European statistics indicate that reactionary delays dominate long-duration disruptions, while technical causes significantly contribute to medium and long delay brackets (Table 1.2) (Fig. 1.1).

Table 1.2

Causes and Duration of Delays (%) in 2017 (Europe)

Cause of delay/duration	< 15 min	15–30 min	31–60 min	1:01–2:00 hrs	> 2:00 hrs
Uncategorized delays (various causes) [%]	32.61	5.98	2.99	2.77	2.38
Airline operational causes [%]	2.20	4.36	4.76	4.76	2.79
Passenger and baggage-related delays [%]	2.97	3.46	1.68	0.81	0.55
Delays caused by aircraft servicing by suppliers (loading, refueling, catering) [%]	2.44	2.83	0.95	0.53	0,20
Delays caused by aircraft maintenance or defects [%]	1.85	3.98	5.08	6.72	12.83
Delays due to operational control and crew duty regulations [%]	3.24	4.43	2.96	2.46	2.00
Delays caused by air traffic management [%]	12.76	15.24	8.58	4.60	2.50
Delays caused by airport restrictions [%]	10.81	6.09	2.06	1.02	0.67
Delays caused by previous flight delay (reactionary delay) [%]	31.12	53.64	70.94	76.41	76.08

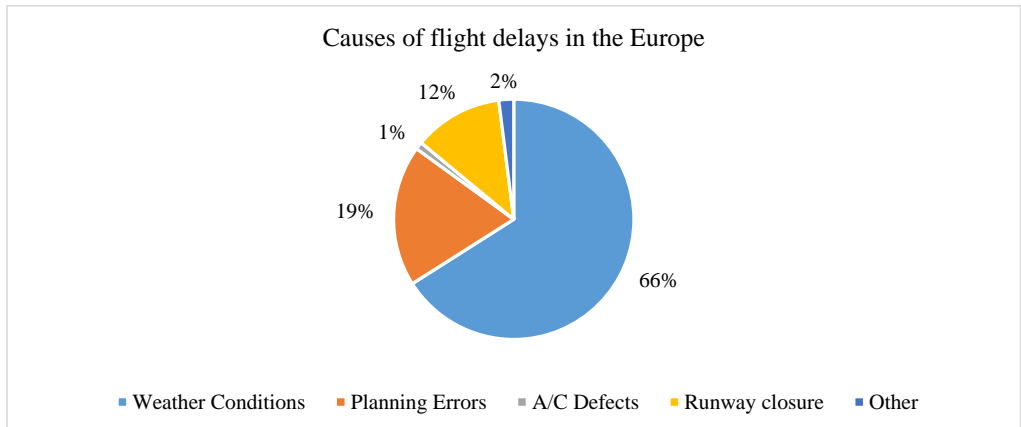


Fig. 1.1. Causes of flight delays in Europe.

Technical unavailability at departure is associated with defect identification, extended inspections, aircraft replacement, and incomplete preparation. Recent European performance reports confirm that ATM bottlenecks, airport restrictions, technical failures, and crew constraints significantly influence punctuality.

Reliability-Centered Maintenance enables prioritization of maintenance actions according to failure criticality. Statistical analysis of delay distributions reveals peaks associated with turnaround inefficiencies and coordination failures.

These findings confirm the necessity of probabilistic modeling for evaluating and mitigating delay risk within airline operational control systems.

1.2. Operational planning and control in airline service systems

Airline management operates at strategic and operational levels, where the operational level governs daily flight execution and directly determines regularity. The Daily Flight Plan coordinates departures, arrivals, and transit operations, while real-time monitoring activates corrective feedback mechanisms. Compliance with FAA and EASA requirements ensures procedural stability. Integration of flight planning and maintenance improves aircraft utilization efficiency.

Departure delays frequently originate within the aircraft preparation cycle, which includes airline maintenance actions and ground handling procedures. Lean maintenance principles reduce process inefficiencies and improve turnaround performance. Regulatory oversight (FAA Order 8900.1) defines maintenance compliance standards.

Even minor coordination failures may propagate through the operational loop and accumulate into measurable schedule disruptions.

1.3. Departure delays in the aircraft preparation cycle

Departure delays frequently originate within the aircraft preparation cycle, which includes:

- airline maintenance actions;
- ground handling procedures.

Lean maintenance principles reduce waste and improve turnaround efficiency. Regulatory oversight (FAA Order 8900.1) defines maintenance compliance standards.

Minor coordination failures (fueling delay, tool unavailability, dispatch miscommunication) may propagate through the operational loop and accumulate into measurable schedule disruptions.

1.4. Route-based operational control and aircraft technical states

Aircraft technical operation is modeled as alternating ground and flight phases within a route network. Airports are classified by technical capability:

- B – base airport (equipped for full maintenance and turnaround);
- T – transit airport (limited/no maintenance capability);
- TB –tTransit-base airport (partial maintenance capacity).

This classification determines restoration feasibility and influences delay probability.

Each flight route is represented as a sequence of flights with turnarounds at airports of different types. The structure of flight routes in the RAF-AVIA airline network is presented in Table 1.3.

Table 1.3

Structure of the Flight Network of the RAF-AVIA Airline

№	Flight Structure (Graphical)	Flight Parameters
1	$B-T-B$	1/2
2	$B-T-T-B$	1/3
3	$B-T-TB-B$	1/3
4	$B-T-T-T-B$	1/4
5	$B-T-T-TB-B$	1/4
6	$B-T-TB-T-B$	1/4
7	$B-TB-TB-T-TB-B$	1/5
8	$B-TB-B-TB-TB-B$	1/5
9	$B-TB-T-TB-T-TB-B$	1/6
10	$B-T-T-T-TB-T-TB-B$	1/7
11	$B-TB-T-TB-T-T-TB-B$	1/7
12	$B-TB-T-T-TB-T-TB-B$	1/7

The distinguishing characteristics of airports are presented in Table 1.4.

Table 1.4

Characteristics of Airports in the Airline Network

#	Characteristics	Airport type			Notes
		T	TB	B	
1	Probability of availability of spare parts necessary for aircraft recovery	P_{SP}^T	P_{SP}^{TB}	P_{SP}^B	-
2	Probabilistic characteristics of aircraft recovery time (T_R)	$F^T(t)$	$F^{TB}(t)$	$F^B(t)$	May be specified using alternative methods
3	Probabilistic characteristics of operational delivery time of necessary spare parts if unavailable at the airport (T_D)	$G^T(t)$	$G^{TB}(t)$	$G^B(t)$	May be specified using alternative methods
4	Probability of aircraft loop-back on the next flight at the base airport	-	-	P_{LB}	-
5	Probability of availability of a reserve aircraft at the base airport for flight execution	-	-	P_{RES}	-
6	Availability of specialists for aircraft recovery work	No	Yes	Yes	-
7	Average aircraft turnaround time at the airport	T_{AT}^T	T_{AT}^{TB}	T_{AT}^B	For type "B" in case the aircraft is loop-back into the next flight

1.5. Aircraft states and transitions across the stages of its utilization process at the operational management loop level

The technical operation of an aircraft within the airline's operational control system is divided into distinct stages reflecting its physical and functional status within the route network:

- 1) presence at the base airport;
- 2) active in-flight operation;

- 3) turnaround at a transit airport;
- 4) stay at a transit base with limited maintenance capacity;
- 5) placement outside the operational control loop for scheduled or unscheduled maintenance.

The evolution of aircraft state across these stages can be represented as a Markov chain with conditional transition probabilities determined by operational constraints.

The corresponding state-transition structure is presented in Fig. 1.2.

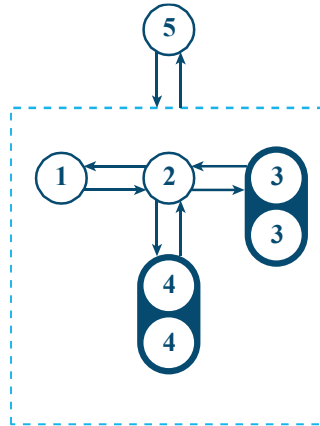


Fig. 1.2. State-transition graph of the aircraft across the stages of the technical operation process (at the operational management loop level).

Let us examine in more detail the content and structure of the stages of the aircraft technical operation system in accordance with the sequence of transitions and states of the aircraft at the operational management loop level.

1.6. Aircraft maintenance on the ground during pre-flight preparation

Pre-flight preparation includes ground maintenance procedures, ensuring continued airworthiness and dispatch readiness. For formal analysis of interdependencies between operations, a graph-theoretic representation is applied.

As shown by Lee et al., coordinated logistics planning, spare availability, and time-sensitive scheduling directly influence ground-time performance. Graphical models enable the identification of quantitative relationships between technological operations and provide a basis for statistical analysis.

The network-based process flow chart for a transit flight is presented in Fig. 1.3.

1.7. Process flow chart of comprehensive preparation of the aircraft for departure at a transit airport

All aircraft undergo ground handling during preparation for departure at a transit airport. The comprehensive preparation process includes aircraft reception, pre-flight servicing, and dispatch procedures, in accordance with FAA maintenance guidance.

Aircraft reception comprises apron guidance, installation of wheel chocks, and post-flight inspection. Towing is required when taxiing under own power is impractical or when repositioning without crew involvement is necessary.

Pre-flight preparation includes ground power supply connection, cabin conditioning, loading and refueling operations, and cleaning. External power reduces onboard system load, while environmental control ensures passenger comfort. Fueling and servicing with required fluids are completed prior to boarding. Cabin and cockpit cleaning is performed before passenger embarkation.

The process flow chart establishes standardized task organization aimed at minimizing turnaround time and reducing delay risk. The chart is represented as a time-scaled linear diagram (“operation-time” coordinates), with task parameters summarized in Table 1.5.

The network-based structure defines chronological task sequencing and specifies earliest and latest permissible start times, allowing analysis of operational constraints and dependencies.

Connections between events are represented by:

- 1) solid lines – real tasks with defined duration;
- 2) dashed lines – logical dependencies without physical execution time.

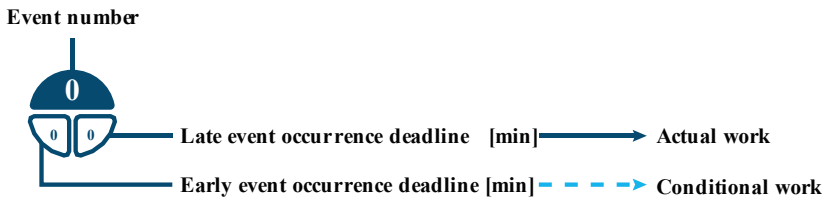
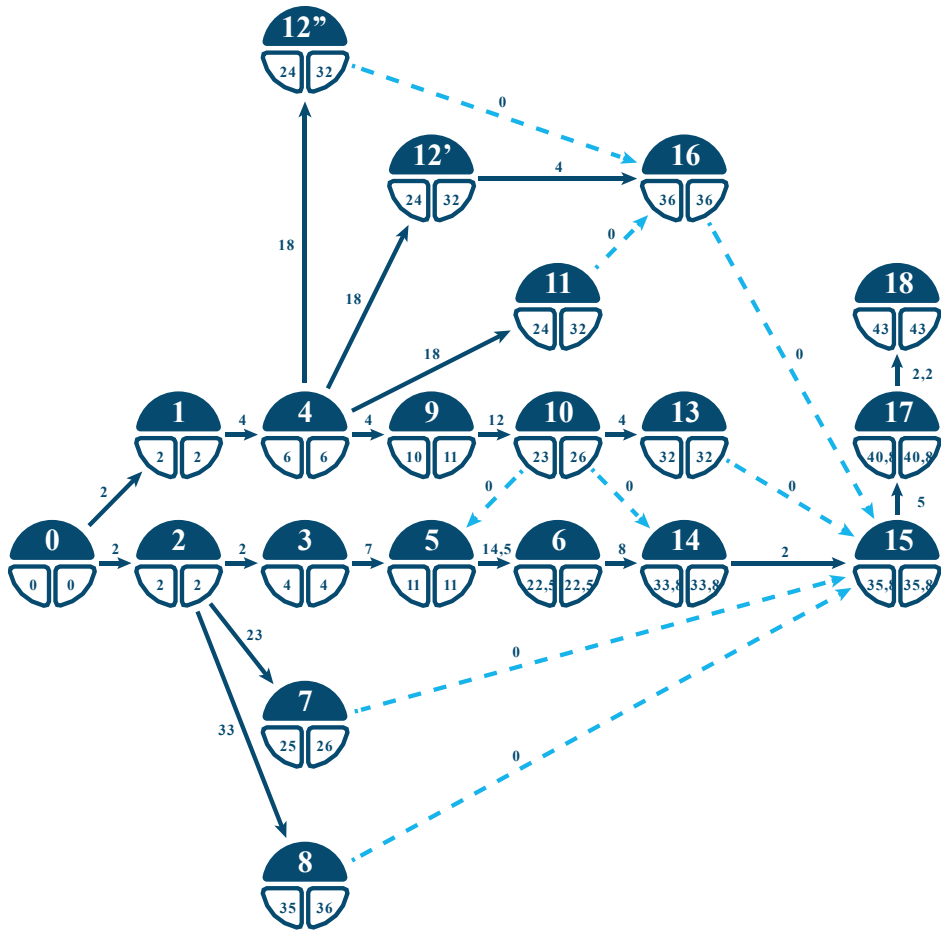


Fig. 1.3. Flow chart of comprehensive preparation of the aircraft for departure at a transit airport.

The parameters of the working technological process shown in Table 1.5 include the names of the tasks involved in this particular maintenance form; the start and end events between which the task is performed; and the duration of the task execution, based on general turnaround procedures.

Table 1.5

Table of Working Technological Process Parameters

Event number	Event description	Number of performers	Duration of work [min]
1	Establishing crew communication	1	<p>The Gantt chart displays the duration of 18 events. The critical path is highlighted in blue and includes events 1, 2, 3, 4, 7, 11, 12, 13, 14, 15, 16, 17, and 18. A 'Time reserve' of 8 minutes is shown for event 13. The total duration is 43 minutes.</p>
2	Installing wheel chocks	2	
3	Setting up the boarding stairs	1	
4	Preparatory maintenance work	3	
5	Disembarking passengers	1	
6	Cabin cleaning	12	
7	Unloading and loading baggage	3	
8	Turning on/off onboard power	2	
9	Preparatory fuel refueling work	1	
10	Fuel refueling	1	
11	Water system refueling	1	
12	Route inspection	2	
13	Draining waste	1	
14	Boarding passengers	1	
15	Removing the boarding stairs	1	
16	Final maintenance work	2	
17	Engine start-up	1	
18	Disconnecting the power supply	1	
Total time for comprehensive pre-flight preparation $T_{\text{sum}} = 43$ minutes.			

In a network-based process model, the critical path represents the longest chain of dependent tasks and determines the total duration of aircraft preparation. For transit operations, its length defines the minimum turnaround time required prior to departure, see Fig. 1.3. Tasks on the critical path have zero float, therefore any variation in execution time caused by resource availability, staffing, or maintenance efficiency directly affects aircraft ground time and departure punctuality. Events correspond to task completion nodes, see Table 1.5.

Dispatch includes preflight inspection, engine start monitoring, towing, and ATC clearance. After confirmation of system readiness, communication switches to visual signaling and the aircraft is integrated into the departure sequence. ATC sequencing efficiency significantly influences departure punctuality and taxi-out delays.

1.8. States and transitions of the aircraft

The aircraft “state” is defined as a condition arising when adverse factors affect normal operation and reduce the level of flight safety. In accordance with EASA Part M and Part CAMO requirements, continued airworthiness must be ensured through structured maintenance control and responsibility allocation within approved organizations. Situations in which the aircraft is not in a condition for safe operation are regulated by the MEL procedures.

Aircraft states are denoted by S_i , where $i = 0, 1, 2, 3, 4$, and reflect increasing severity of operational degradation:

- S_0 – normal flight condition;
- S_1 – deterioration of flight conditions;
- S_2 – hazardous or alert condition;
- S_3 – emergency condition;
- S_4 – catastrophic condition.

1.9. Probabilistic indicators used in the qualitative and quantitative analysis of failure states

In quantitative analysis, failure conditions are characterized by acceptable average probabilities per flight hour or per flight. These probability levels are established within regulatory design frameworks for multi-engine aircraft and reflect expected operating conditions and crew response capability.

Regulatory classification defines the following limits:

- S_{NR} – frequent – $P_{NR} < 10^{-3}$;
- S_1 – probable – $P_1 < 10^{-4}$;
- S_2 – remote – $P_2 < 10^{-5}$;
- S_3 – extremely remote – $P_3 < 10^{-6}$;
- S_4 – extremely improbable – $P_4 < 10^{-7}$.

Based on these limits, the scheme of possible aircraft state transitions within a single flight is represented by the graph shown in Fig. 1.4, consistent with regulatory safety definitions and risk models.

The model assumes that:

- during the flight, the state of the aircraft does not improve;
- departure on a flight (i.e., from an airport of type B) is permitted only in states S_0 , S_1 and S_2 ;
- departure on a flight from airports of types T and TB is permitted in states S_0 , S_1 , S_2 and S_3 .

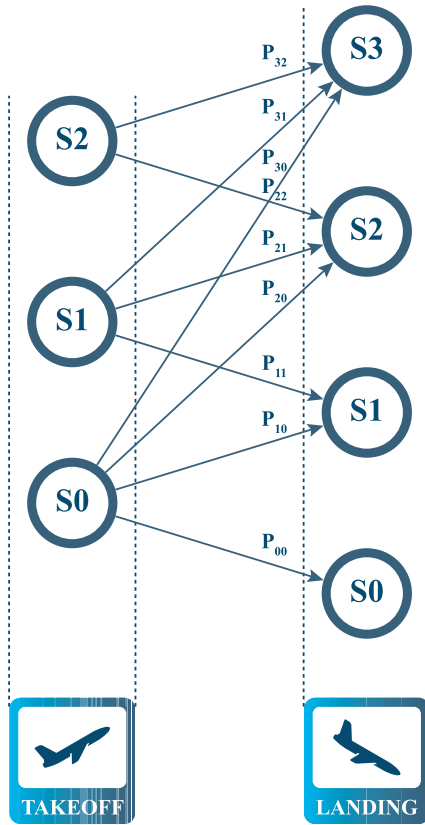


Fig. 1.4. Flow chart of comprehensive preparation of the aircraft for departure at a transit airport.

The state S_{NR} is excluded from the state transition graph because it does not affect flight safety or dispatch capability; the aircraft may continue operation in this state until a technical decision is taken.

At any stage within the airline network, failures may occur in flight or on the ground, requiring restoration before further operation. Aircraft are therefore classified as “fit” or “not fit” for continued flight; restoration is mandatory in the latter case. Such restoration introduces a risk of departure delay and must be included in the total aircraft downtime evaluation.

To evaluate departure delay risk within the operational control loop, three modeling levels are required:

- model of the aircraft state change during a single flight segment of a route;
- model of the aircraft state change throughout the entire route;
- model of the aircraft state change across a sequence of routes over the period of its presence within the operational control loop of the aircraft maintenance process.

2. DEVELOPMENT OF THE AIRCRAFT MAINTENANCE PROCESS MODEL AT THE LEVEL OF OPERATIONAL CONTROL LOOP

2.1. Graphical model

Structure of the aircraft maintenance process

To describe aircraft state changes within the airline network (Fig. 1.4), a unified graphical representation is introduced, covering transitions during a single flight, along a route, and across a sequence of routes within the operational control loop.

The model is based on operational assumptions reflecting dispatch limitations and maintenance constraints. Aircraft state is assumed not to improve during flight. Departure from a base airport (B) is permitted only in states S_0 and S_1 , while departure from transit (T) and transit-base (TB) airports is allowed in states S_0 , S_1 , and S_2 .

Recovery capability depends on airport type. At base airports, degraded states S_2 and S_3 may be restored to dispatchable conditions depending on spare parts availability, recovery time distribution $F(t)$, delivery time $G(t)$, and the availability of a reserve aircraft P_{RES} . At transit and transit-base airports, recovery is constrained by limited resources and depends primarily on the probability of spare availability P_{SP} , as well as recovery and delivery time distributions.

Two delay formation mechanisms are considered. At transit and transit-base airports, delay depends on whether recovery can be completed locally: if spare parts are available, recovery follows $F(t)$; otherwise, additional delivery time $G(t)$ is required. At base airports, delay formation is additionally influenced by the possibility of aircraft replacement using a reserve unit.

A delay occurs when total recovery time exceeds the available turnaround time T_{AT} , otherwise, departure is performed without delay. Thus, delay duration is determined by the excess of recovery time over the operational time window.

Aircraft state transition processes were developed for different airport types (B, T, TB). A representative case for a transit airport (T), where delay formation is most constrained by maintenance capability, is shown in Fig. 2.1.

The graphical model provides the basis for further mathematical formalization of aircraft recovery processes and probabilistic analysis of departure delays caused by state changes during flight and ground operations.



Fig. 2.1. State and transition graphs of the aircraft in a "TB"-type airport and the preceding flight.

2.2. Mathematical model of aircraft condition change per one flight

Let η denote the aircraft state at the start of the flight. The possible values of η (see Fig. 1.4) are $\{S_0, S_1, S_2\}$.

Let q_0, q_1, q_2 denote the probabilities that the aircraft is in states S_0, S_1, S_2 , respectively, at the beginning of the flight.

This can be expressed as

$$P\{\eta = S_j\} = q_j; \sum_j q_j = 1; j = 0,1,2. \quad (2.1)$$

The aircraft state at the beginning of the flight is thus a random variable with the set of possible states $\{S_0, S_1, S_2\}$ and a probability distribution (see Fig. 1.2).

Let us denote ξ as the state of the aircraft at the end of the flight. The possible values of ξ (see Fig. 1.4) are the states $\{S_0, S_1, S_2, S_3\}$.

Let us denote p_0, p_1, p_2, p_3 as the probabilities that the aircraft is in states S_0, S_1, S_2, S_3 , respectively, at the end of the flight. This is written as

$$P\{\xi = S_i\} = p_i; \sum_i p_i = 1; i = 0,1,2,3. \quad (2.2)$$

The aircraft's condition at the end of the flight is a random variable with four possible states S_0, S_1, S_2, S_3 , and a corresponding probability distribution (see Fig. 1.4).

Let us denote $p_{ij} = P\{\xi = \frac{S_i}{\eta} = S_j\}$ the conditional probability that the aircraft's state at the end of the flight is S_i , given that its state at the beginning of the flight was S_j . These conditional probabilities p_{ij} have the following property:

$$\sum_{i=0}^3 p_{ij} = 1; j = 0,1,2. \quad (2.3)$$

Some of the values p_{ij} , according to the state transition scheme shown in Fig. 1.4, will be equal to zero.

All the listed elements p_{ij} are arranged into a rectangular matrix P of size 4×3 , which is called the transition matrix or the matrix of transition probabilities describing the change of aircraft states from the beginning to the end of the flight.

$$P = \begin{pmatrix} 1 - p_{10} - p_{20} - p_{30} & 0 & 0 \\ p_{10} & 1 - p_{21} - p_{31} & 0 \\ p_{20} & p_{21} & 1 - p_{32} \\ p_{30} & p_{31} & p_{32} \end{pmatrix} \quad (2.4)$$

The state probabilities q_j and p_j are written in the form of state probability vectors as follows:

$$p = \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix}, q = \begin{pmatrix} q_0 \\ q_1 \\ q_2 \end{pmatrix}. \quad (2.5)$$

Then the relationship between the vectors p and q is given by the formula, which in matrix form is succinctly written as shown in classical Markov reliability modeling frameworks:

$$p = Pq. \quad (2.6)$$

Conditional probabilities p_{ij} are considered given and are related to the reliability level of the operated aircraft fleet, as well as to the justification of the list of allowable aircraft failures before reaching a base-type (B) airport and/or the next scheduled maintenance of the aircraft. Thus, the probabilities $(1 - p_{00}) = p_{10} + p_{20} + p_{30}$, $(1 - p_{11}) = p_{21} + p_{31}$, $(1 - p_{22}) = p_{32}$ represent the probabilities of failures occurring during flight or on the ground given that the aircraft departed in states S_0 , S_1 and S_2 , respectively. The probabilities p_{00} , p_{11} and p_{22} represent the probabilities of no failures occurring during flight or on the ground given that the aircraft departed in states S_0 , S_1 , S_2 , respectively.

The ratios $\frac{p_{32}}{p_{30}}$, $\frac{p_{31}}{p_{30}}$, $\frac{p_{21}}{p_{20}}$, which by definition are greater than or equal to one, can be considered as indicators of the validity of the list of allowable failures for states S_2 and S_1 , respectively. The lists are considered valid if these ratios are equal to 1 (one).

Using known reliability theory metrics, expressed for p_{00} , it can be written in the following form:

$$p_{00} = e^{-\omega T_{NSF}}, \quad (2.7)$$

where T_{AN} is the average duration of a non-stop flight (NSF) of the aircraft in the airline network, and ω is the failure rate parameter of the aircraft, given the aircraft departs in state S_0 .

2.3. Mathematical model of aircraft condition change over a route

The aircraft operation over a route is represented as a sequence of flight segments with intermediate ground operations. The state evolution across the route is modeled as a repeated application of the single-flight transition process with consideration of intermediate recovery effects.

The resulting state distribution after completion of a route depends on the cumulative effect of sequential transitions:

- degradation during each flight segment;
- partial restoration during turnaround;
- operational constraints associated with airport type.

The model incorporates route structure (sequence of B, T, TB airports) and evaluates the probability of reaching critical states over the entire route. Thus, the route-level model extends the single-flight model by introducing state accumulation and dependency between consecutive segments.

2.4. Mathematical model of aircraft state changes across a sequence of routes

To describe long-term aircraft operation within the airline network, the model is extended to a sequence of routes. In this case, the aircraft state evolution is considered over multiple operational cycles, forming a stochastic process with stationary characteristics.

The model evaluates:

- steady-state probabilities of aircraft technical conditions;
- long-term reliability indicators;
- cumulative probability of degradation across operational time.

The sequence of routes is treated as a chain of interconnected operational cycles, where the output state of one route becomes the input state of the next. This allows assessing the stability of the aircraft technical condition within the operational control loop and identifying trends in reliability degradation.

2.5. Models of aircraft recovery processes and departure delays

Aircraft recovery processes are modeled based on probabilistic characteristics of maintenance capability and logistics constraints. The recovery time depends on:

- probability of spare parts availability, P_{SP} ;
- recovery time distribution, $F(t)$;
- delivery time distribution, $G(t)$;
- availability of reserve aircraft, P_{RES} .

Two recovery mechanisms are considered.

1. At transit (T, TB) airports recovery is performed either immediately (if spare parts are available) or after delivery. The total recovery time is determined by a combination of maintenance and logistics processes.
2. At base (B) airports in addition to standard recovery, aircraft replacement with a reserve aircraft is possible, reducing delay probability.

Departure delay is formed when the total recovery time exceeds the available turnaround time T_{AT} . The delay duration is determined as a function of the aircraft recovery process parameters, including maintenance time and possible additional time associated with spare part delivery and operational constraints.

The corresponding analytical representation of delay formation is introduced in the model through the probabilistic characteristics of recovery time, allowing formal evaluation of delay occurrence and duration.

The model enables estimation of:

- probability of delay occurrence;
- expected delay duration;
- sensitivity of delays to maintenance and logistics parameters.

Thus, recovery processes act as a linking element between aircraft technical state evolution and operational performance indicators, directly influencing flight regularity.

2.6. Application tool implementation of the flight regularity assessment model

Purpose of the application tool

The FlightSync application tool was developed as a practical implementation of the mathematical model for assessing flight regularity proposed in Chapter 2. It functions as an

engineering decision-support instrument, enabling evaluation of delay formation under varying operational and maintenance conditions.

The application integrates the key elements of the model, including aircraft state distribution, state transition probabilities, airport-specific recovery capabilities, and route structure. Delay formation is analyzed through the interaction of reliability parameters and operational constraints such as turnaround time, spare part availability, and reserve aircraft logic.

The structure of the application follows the logic of the mathematical framework. Input parameters include:

- route configuration and probability distribution across the airline network;
- initial aircraft technical state distribution;
- state transition probabilities for a single flight;
- recovery and spare part delivery time characteristics;
- probability of spare availability at different airport types;
- base airport operational parameters, including reserve aircraft and loop-back logic.

The computational process evaluates delay formation at multiple levels: individual airport operations, route-specific performance, and overall network impact. For each route, delay values are calculated and weighted according to their probability, allowing estimation of total flight regularity within the airline system.

The application provides both aggregated and detailed analytical outputs, including delay distributions, sensitivity to input parameters, and the influence of maintenance logistics on operational performance. Results can be exported for further analysis or integration into reporting and decision-making processes.

Each functional component of the application corresponds directly to elements of the mathematical model described in Sections 2.1–2.5, ensuring consistency between theoretical formulation and practical implementation.

Unlike conventional OCC systems, which are primarily focused on monitoring and reactive operational control, the FlightSync application tool enables probabilistic modeling of aircraft technical states, recovery processes, and logistics constraints. This allows quantitative assessment of delay formation mechanisms and provides a more comprehensive understanding of how maintenance and operational factors influence flight regularity.

3. DEVELOPMENT AND JUSTIFICATION OF RECOMMENDATIONS FOR IMPROVING THE OPERATIONAL MANAGEMENT OF AIRCRAFT TECHNICAL OPERATION PROCESSES UNDER AIRLINE CONDITIONS

3.1. Analysis of the dynamics of aircraft states at airports within the airline network

In this chapter, an analysis of aircraft technical state dynamics within the airline network is carried out in order to assess the occurrence of situations requiring aircraft recovery and, consequently, the risk of departure delays. The analysis focuses on the influence of the Minimum Equipment List (MEL), route structure, and transition probabilities between aircraft states.

Due to differences in recovery processes and delay formation, the analysis is performed separately for non-base and base airports.

For non-base airports, the probability $P(A_0)$ of completing a flight in state S_0 is primarily determined by the structure of the airline network, represented by the parameter V_B/V . In the absence of MEL, or when only failures corresponding to state S_2 are included, the dynamics of $P(A_0)$ depend solely on this parameter. However, the inclusion of failures permitting continuation of flights until the next scheduled maintenance (state S_1) introduces additional dependence on the number of performed flights n , reflecting the accumulation of deferred failures (see Fig. 3.1).

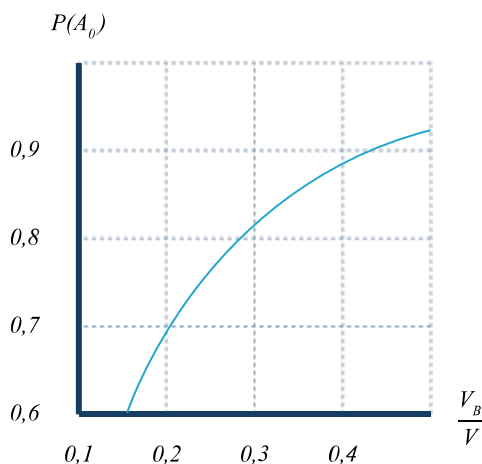


Fig. 3.1. Dynamics of state S_0 at $P_{10} = 0$ in non-base airports.

The analysis shows that the probability $P(A_1)$, corresponding to completion of a flight in states $S_0 \cup S_1$, remains independent of the number of flights n . Therefore, the decrease in $P(A_0)$ with increasing n indicates an increase in the probability of the aircraft being in state S_1 , i.e., the accumulation of allowable failures.

A key result of the analysis is that the expansion of the allowable failure list (introduction of state S_1) does not significantly reduce the probability of situations requiring recovery, but

redistributes them over time. This effect leads to the formation of latent risks, which materialize in subsequent transitions to state S_3 .

The probability of occurrence of situations requiring aircraft recovery at non-base airports is defined as $1 - P(A_2)$, corresponding to the probability of state S_3 . The analysis demonstrates that this probability is weakly influenced by the parameter P_{32}/P_{30} , which characterizes failures allowing continuation of flights to the base airport, but is highly sensitive to the parameter P_{31}/P_{30} , which defines failures allowing continuation until the next scheduled maintenance (see Fig. 3.2).

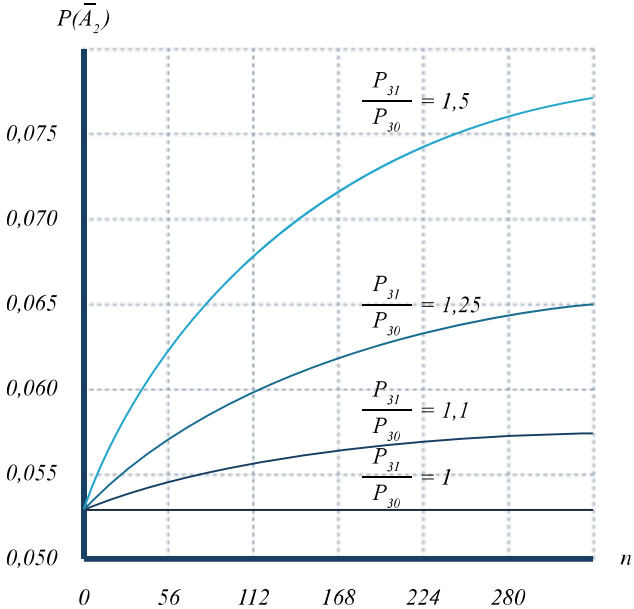


Fig. 3.2. Dynamics of changes in the probability of state S_3 at different values of the parameter P_{31}/P_{30} in non-base airports for $\frac{V_B}{V} = 0.5$.

3.2. Assessment of the significance of operational factors on the temporal indicators of flight regularity

At base airports, the dynamics of aircraft states are determined by recovery processes and represent the regeneration phase of the system.

The probability $P(B_2)$ of aircraft arrival in state S_2 is primarily influenced by the structure of the airline network (V_B/V) and increases with a higher number of landings at non-base airports. The influence of allowable failures permitting continuation to the base airport (parameter P_{32}/P_{30}) is moderate and comparable to its effect at non-base airports.

The probability $P(B_3)$, corresponding to arrival in state S_3 , depends mainly on the distribution of the total failure flow among states. The analysis shows that the parameter P_{31}/P_{30} has a dominant influence on $P(B_3)$, significantly exceeding the effect of P_{32}/P_{30} . Unlike non-base airports, this influence is weakly dependent on the network structure parameter V_B/V .

Thus, base airports act as recovery nodes within the airline network, where accumulated technical states are resolved, while the primary drivers of delay formation are formed at non-base airports.

Based on the obtained dependencies, the duration of departure delays is evaluated using the mathematical model developed in Chapter 2.

To quantify the influence of operational factors Y_i on the total delay duration T_D , the following method is applied:

$$\Delta T_D = T_D(Y_i + \Delta Y_i) - T_D(Y_i).$$

This approach allows ranking factors according to their impact on delay formation (see Fig. 3.3).

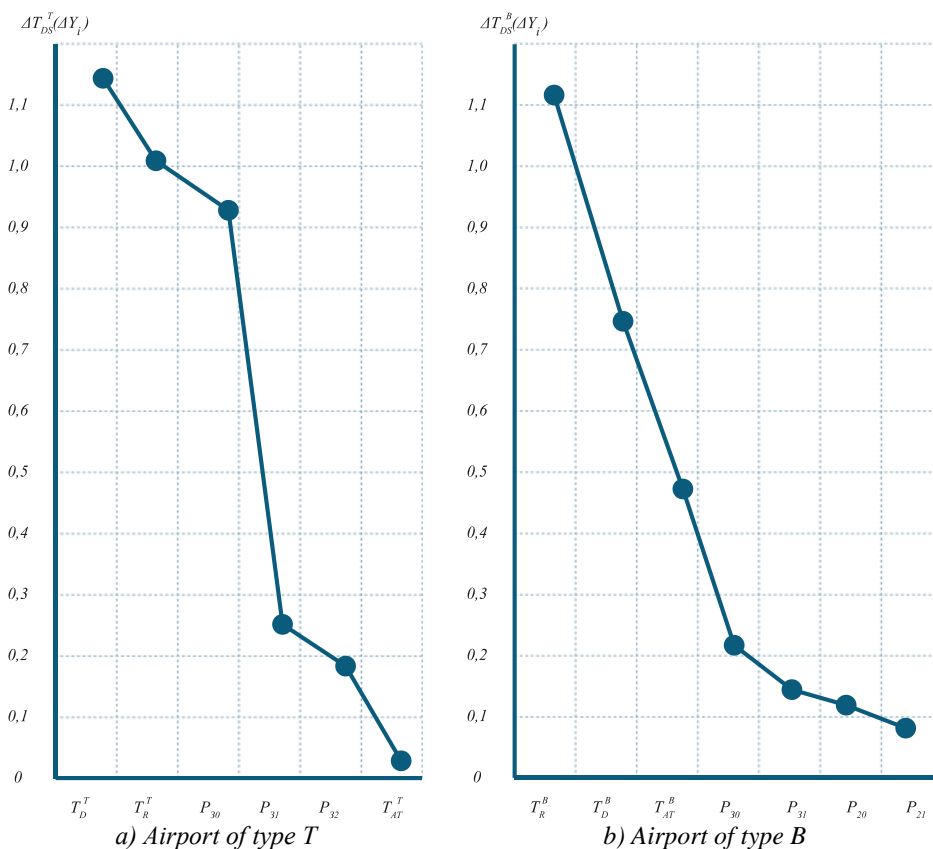


Fig. 3.3. Polygon of the distribution of significance of operational factors at the parameter value $\frac{V_B}{V} = 0.5$.

The analysis shows that the influence of operational factors is not uniform and depends on both the structure of the airline network and the baseline values of the parameters. Therefore, intuitive assessment of their significance is insufficient, and computational analysis is required.

3.3. Recommendations for improving the operational management of aircraft maintenance processes for the RAF-AVIA airline network

Development of recommendations for the RAF-AVIA airline is based on the ranking of operational factors that influence the duration of aircraft departure delays at airports within the airline's network.

Using real operational data from the RAF-AVIA airline, the developed model was applied to assess the significance of operational factors affecting departure delays (see Fig. 3.4).

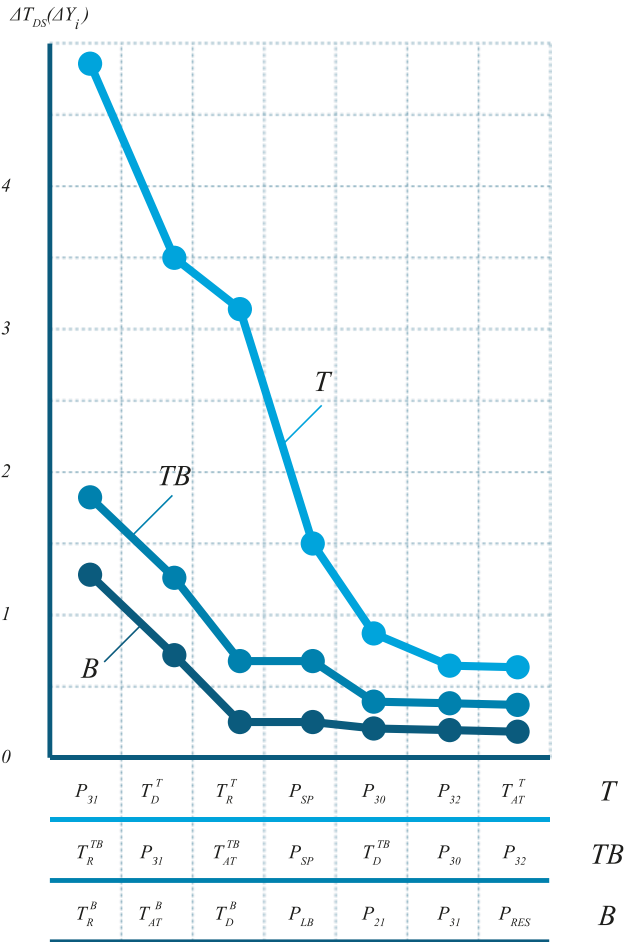


Fig. 3.4. Polygon of the distribution of the significance of operational factors for the RAF-AVIA airline network.

The results show that the most significant factors for transit airports (T), are

- P_{31}, T_D^T, T_R^T ;
- for transit-base airports (TB),

- T_R^{TB}, P_{31} ;
for base airport (B),
- T_R^B, T_{AT}^B .

The parameter P_{31}/P_{30} , reflecting the justification of allowable failures permitting continuation until the next scheduled maintenance, has the greatest influence on delay formation across all airport types. These results confirm the applicability of the developed model for real airline operations and demonstrate its effectiveness as a decision-support tool.

Thus, the improvement of aircraft maintenance logistics, reduction of recovery and delivery times, and careful justification of MEL policies represent the key directions for enhancing flight regularity.

4. OPTIMIZATION OF OPERATIONAL DECISIONS IN THE PRESENCE OF AOG-CRITICAL TECHNICAL DEFECTS

In this chapter, the developed models are applied to a practical operational task – the assessment and optimization of technical delays caused by AOG-critical defects (state S_3) under real airline conditions.

The analysis is performed using operational data from the RAF-AVIA airline. The route considered includes a sequence of flights between base (B), transit-base (TB), and transit (T) airports:

RIX (Riga, B) → **TLL** (Tallinn, TB) → **WAW** (Warsaw, TB) → **FRL** (Forli, T) →
SOF (Sofia, TB) → **RIX** (Riga, B).

The modeling approach combines:

- probabilistic estimation of the likelihood of AOG events along the route;
- assessment of expected delays depending on airport recovery conditions;
- integration of these components into a single objective function.

4.1. Practical application of the developed models and calculation of the objective function for a RAF-AVIA airline route

The probability of occurrence of an AOG event at each route position is determined using the probabilistic model of aircraft state evolution. As the number of performed flights increases, the probability of entering state S_3 accumulates along the route:

- $q_1 = 0.06500$ (TLL, TB);
- $q_2 = 0.12578$ (WAW, TB);
- $q_3 = 0.18260$ (FRL, T);
- $q_4 = 0.23573$ (SOF, TB);
- $q_5 = 0.28541$ (RIX, B).

These values show that the probability of an AOG event increases progressively along the route, reflecting the accumulation of technical risks.

The expected delay associated with recovery depends on airport type:

- base airport (B): 1.5 min;
- transit-base (TB): 153 min;
- transit (T): 591 min.

The most critical contribution is formed at transit airports due to long recovery and logistics times.

The expected delay at each route position is determined by combining the probability of an AOG event and the corresponding recovery conditions:

- TLL: 9.95 min;
- WAW: 19.24 min;
- FRL: 107.92 min;
- SOF: 36.07 min;
- RIX: 0.43 min.

The total expected technical delay for the route is defined as the sum of delays at all route positions:

$$J_0 \approx 2.8933 \text{ h} \approx 173.6 \text{ min.}$$

This value represents the baseline operational scenario and reflects the combined influence of:

- the probability of AOG events;
- recovery time;
- spare parts logistics;
- airport infrastructure limitations.

The analysis shows that the dominant contribution to delays is formed at the transit airport (FRL), while TB airports also significantly affect total delay.

4.2. Analysis of management measures

In this section, the optimization problem is interpreted in terms of practical management measures that affect the parameters of the developed model. Each management action is formalized as a controlled modification of either the probabilistic component of the model, describing the likelihood of an aircraft entering the S_3 state, or the temporal component, characterizing recovery and logistical processes at airports of different types.

To reduce delays, a set of operational measures is analyzed. Each measure corresponds to a modification of model parameters and is evaluated through its impact on the objective function.

Measure 1. Increase in turnaround time at TB airports

This measure introduces an operational buffer without changing recovery processes.

Result:

$$J_1 \approx 167.2 \text{ min.}$$

The effect is limited, as root causes of delays remain unchanged.

Measure 2. Improvement of recovery conditions at TB airports

Includes:

- increased spare parts availability;
- reduced recovery time.

Result:

$$J_2 \approx 155.7 \text{ min.}$$

Provides moderate improvement by reducing recovery duration.

Measure 3. Engineer on board

Reduces the probability of transition to the AOG state across the entire route.

Result:

$$J_3 \approx 104.2 \text{ min.}$$

This is the most effective **single measure**, as it reduces the frequency of critical events.

Measure 4. Express spare-part delivery to T airport

Targets the main bottleneck (FRL).

Result:

$$J_4 \approx 127.6 \text{ min.}$$

Significantly reduces delays at the most critical route segment.

Combining measures and the optimal combined strategy

Since different measures affect different components of delay formation, their combination produces a cumulative effect.

The most effective strategy includes:

- reduction of AOG probability (Measure 3);
- improvement of recovery at TB airports (Measure 2);
- reduction of logistics time at T airport (Measure 4).

Result:

$$J^* \approx 1.0967 \text{ h} \approx 65.8 \text{ min.}$$

This corresponds to a reduction of approximately **62 %** compared to the baseline scenario.

4.3. Final conclusions based on the case study

The performed analysis demonstrates that:

- technical delays are formed as a result of the interaction between probabilistic (AOG occurrence) and temporal (recovery and logistics) factors;
- the largest contribution to delays is generated at transit airports with limited recovery capabilities;
- the most effective single measure is the reduction of AOG probability (engineer on board);
- maximum effect is achieved through combined management strategies, affecting both probability and recovery processes.

The developed approach provides a quantitative framework for evaluating operational decisions and allows the selection of optimal strategies for improving flight regularity under real airline conditions.

RESEARCH RESULTS

1. A comprehensive analysis of the current state of the flight regularity problem in civil aviation and its impact on airline network operations was performed.
2. Aircraft failures and technical malfunctions during operation were analyzed, recovery capability within the airline network was assessed, and operational factors influencing technical delay probability were determined.
3. Mathematical models of aircraft state assessment and recovery processes in accordance with MEL (Minimum Equipment List) requirements within airline network airports were developed, aimed at reducing both the probability and duration of departure delays.
4. The FlightSync application tool was developed for implementing the proposed probabilistic mathematical models within operational aircraft maintenance management.
5. The FlightSync application tool was tested and validated using operational and statistical data from the RAF-AVIA airline.

CONCLUSIONS

This Thesis addresses the problem of improving flight regularity through the optimization of operational aircraft maintenance management within an airline route network.

The main results of the research are as follows.

1. A model of aircraft technical state evolution was developed based on discrete operational states and probabilistic transitions between them. The model accounts for in-flight degradation, ground-based recovery processes, and operational limitations related to MEL application.
2. A model of technical delay formation within the airline route network was constructed. The model integrates:
 - the probability of defect occurrence;
 - recovery time;
 - spare part availability;
 - airport type and its technical capability.
3. A parametric analysis was performed to assess the impact of key operational factors on expected technical delay. The most influential parameters affecting flight regularity were identified.
4. An objective function was developed to quantitatively evaluate management decisions under AOG-critical defect conditions. This made it possible to formally compare alternative operational strategies rather than relying on qualitative judgment.
5. The developed optimization approach was applied to a real airline route configuration of RAF-AVIA. The baseline expected total technical delay was quantified, and alternative management measures were formally evaluated. It was established that the greatest effect is achieved not by isolated actions, but by a coordinated combination of measures affecting both probabilistic and time-related parameters of the system, resulting in a reduction of expected technical delay by more than 60 % compared to the baseline scenario.
6. The developed models were implemented in the FlightSync application tool, designed to calculate cumulative technical delays and analyze alternative management scenarios. The application tool was tested using RAF-AVIA operational data and can be used as a decision-support tool for airline engineering and operations control departments.

The results of this research demonstrate that improving flight regularity should be treated as a problem of integrated management of interrelated operational parameters. The proposed approach provides a quantitative basis for selecting optimal strategies in the presence of technical defects and is applicable to real airline operations.



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