Chapter

# Risk and Economic Analysis Methods of Commercial Aero Engines

*Sherkhan Aitugan and Longbiao Li*

## Abstract

This chapter outlines the results of risk analysis and economic analysis of commercial aero engines during aircraft operation. Risk analysis is the procedure for identifying risk factors and assessing their significance, in essence, analysis of the likelihood that certain undesirable events may occur and as such adversely affect operation. Risk analysis includes risk assessment and methods to reduce risks or reduce adverse effects associated with it. Furthermore, economical analysis is a scientific way of understanding the essence of economic phenomena and processes, which in turn are based on dividing them into their constituent parts. In doing so, the variety of relationships and dependencies aimed at improving the associated work through the development and implementation of optimal solutions is studied. The purpose of the economic analysis is to give management of the actual state, and for persons who are not directly working with it, but are interested in its financial condition, the information necessary for an impartial judgment.

**Keywords:** aircraft, risk analysis, economic analysis

## 1. Introduction

Safety is one of the main characteristics of all human activities. In particular, safety issues are principally acute in activities and industries that are considered dangerous. Air transport may be regarded as falling within this category, as failures of aviation-related equipment, flight support services and human factors-specific errors increase the likelihood and the potential of a disaster, which in turn yields financial losses. At the same time, losses from catastrophes in civil aviation are significantly less than in many other hazardous industries [1]. It may be stated that this level is attained due to continuous investment in methods and techniques as well as maintaining high reliability levels, which cover the entire organization. Today, the available risks influencing activity of the developed economic conditions, it is necessary to have the effective tools for risk and economic analysis. This equally includes aviation industry as well as enterprises operating aircraft equipment. One of such tools is risk analysis and economic analysis [2–5].

As stated by Cruse et al. [6], the way in which organizations such as Pratt and Whitney and Rolls-Royce find that the safe life of an aircraft engine depends on the design. The safety factor is applied in order to improve various configurations so as to empower safety. In order for equipment manufacturers to increase the associated safety level of their products, the number of flight cycles is determined. Different problems have prompted investigating the manageability of an aircraft's engine life. Indeed, since 1984, resistance to damage has been a vital part of the ENgine Structural Integrity Program (ENSIP) contained in MIL-STD-1783. Currently, there is a program in the U.S. that uses probabilistic methods for gas turbine engines in ENSIP.

To reproduce the probability estimates important for hazard or failure assessment, various computing strategies are used, including Monte Carlo simulation. Monte Carlo simulation reproductions have been included in the probabilistic study, as they tend to be used in failure analysis and can give high accuracy. This strategy has been used in numerous aviation-specific electronics and hazard assessment schemes. The disadvantages of this methodology are the enormous estimated time and the dependence of the measured estimate on the size of the sample.

Economic analysis of aircraft and its components is one of the most important functions of airline management, the implementation of which is necessary to ensure its effective operation. As a matter of fact, economic analysis is known to represent numerous methods of economic theory. As such, economic analysis of aircraft and its components can be defined as an application of the theoretical foundations of the economy of the airline company and analytical sections of accounting to justify management-specific decisions.

This chapter will consider methods of risk analysis and economic analysis of one of the most important components of a commercial aircraft - the power plant or engine.

## 2. Main risk analysis process

To improve the efficiency and objectivity of risk analysis and to ensure comparability with other risk analysis outcomes, the following general rules should be observed. The risk analysis process should follow the following steps:

a. Defining the scope of application

b. Hazard identification and preliminary impact assessment

c. Evaluation of the risk value

d. Verification of the analysis results

e. Documentary substantiation;

f. Adjustment of the results of the analysis taking into account the latest data.

This process is shown in **Figure 1**. Risk assessment includes frequency analysis and consequence analysis. While **Figure 1** shows the documentation as a separate unit, it is developed at each stage of the process. Depending on the application, only certain elements of the process presented are considered. For example, in some cases it may not be necessary to go beyond the original hazard and impact analysis.

A necessary requirement is a thorough knowledge of the system and the analysis methods used. If the results of a risk analysis for a similar system are available, they can be used as a reference. It is necessary to prove that the processes are similar and that the changes do not make significant differences in the results. Conclusions should be based on a systematic assessment of the changes and how they may affect the existing hazards.

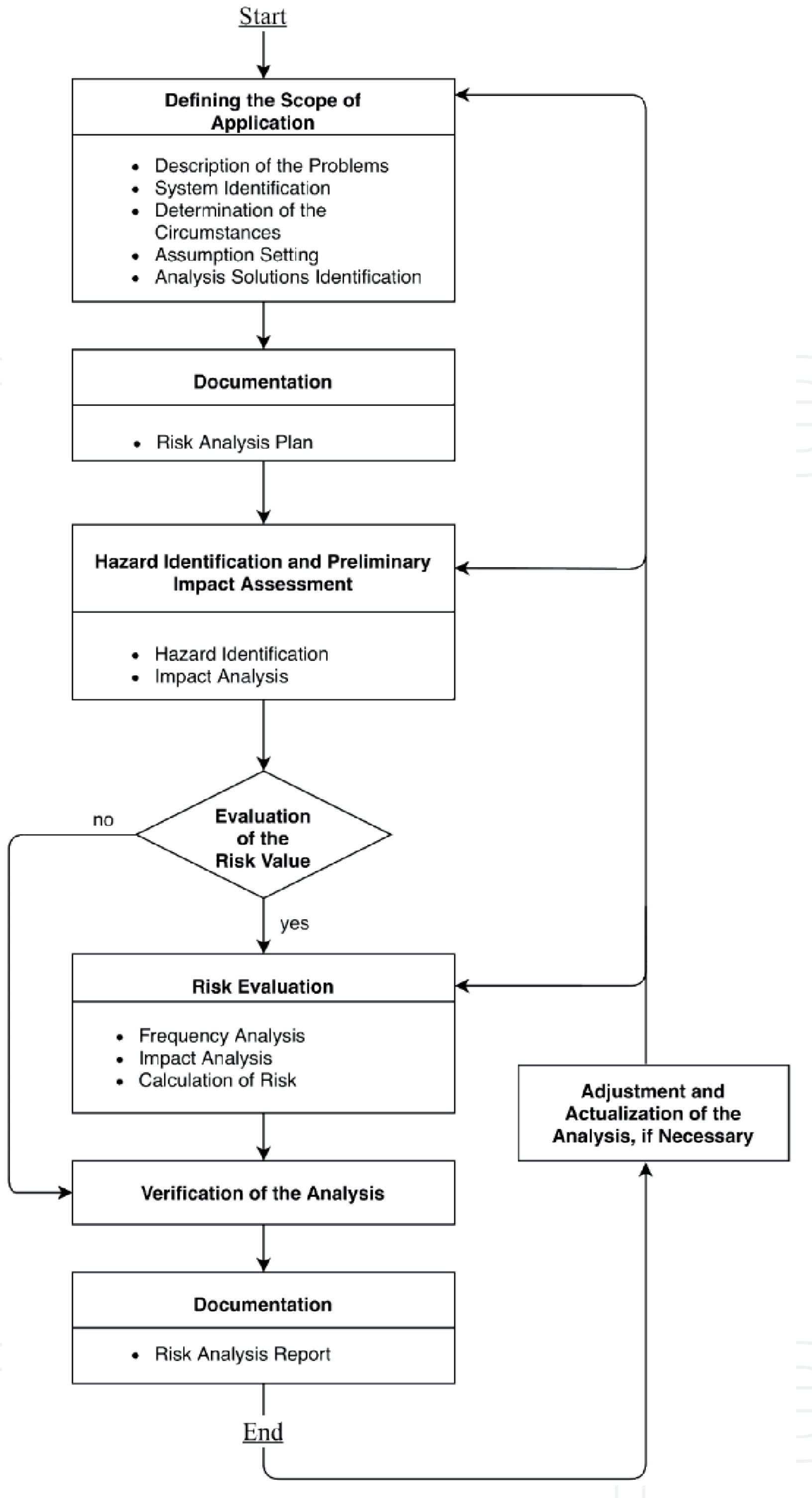


**Figure 1.**
*Risk analysis process.*

### 2.1 Risk analysis methods

A list of the most common methods is presented in **Table 1**. The list given in **Table 1** is not exhaustive. The list of additional methods is presented in **Table 2**. Sometimes it may be necessary to use more than one analysis method.

#### *2.1.1 Analysis of a chart of possible consequences of an event (event tree analysis) (ETA)*

The Event Tree Analysis, ETA is a set of quantitative or qualitative techniques that are used to identify possible outcomes of an initiating event and, if required,

| | Method | Description and application |
|---|---|---|
| 1 | Event tree analysis | A set of techniques for hazard identification and frequency analysis that uses an inductive approach to translate various initiating events into possible outcomes |
| 2 | Failure mode and effect analysis, as well as failure mode effects and criticality analysis | A set of methods for identifying the main sources of danger and frequency analysis, with the help of which all the emergency conditions of a given piece of equipment are analyzed for their influence on other components and on the system as a whole |
| 3 | Fault tree analysis | A set of techniques for hazard identification and analysis of frequencies of an undesirable event, with the help of which all ways of its implementation are determined. A graphical image is used |
| 4 | Study of hazards and related problems | A set of fundamental hazard identification techniques by which each part of the system is assessed to determine whether there may be deviations from the design intent and what consequences this may have |
| 5 | Human factor analysis | The set of methods consider influence of errors of the person on reliability |
| 6 | Preliminary hazard analysis | A set of techniques for hazard identification and frequency analysis used at an early stage of design to identify hazards and assess their criticality |
| 7 | Structural reliability scheme | A set of methods of frequency analysis, on the basis of which the system model and its reserves are created to assess the system reliability |

**Table 1.**
*List of the most common methods used in risk analysis.*

| | Method | Description and application |
|---|---|---|
| 1 | Classification of risk groups by category | Classification of risk types by categories in order of priority of risk groups |
| 2 | Inspection reports | Inventory of generic hazardous substances and/or sources of potential accidents that need to be addressed. These can be used to assess compliance with laws and standards |
| 3 | General failure analysis | A method designed to determine whether an accidental failure (accident) of a number of different parts or components within a system is possible and to evaluate its likely cumulative effect |
| 4 | Impact description models | Assessment of the impact of an event on people, property or the environment. Both simplified analytical approaches and complex computer models are used |
| 5 | Delphi's method | The method presents expert assessments that can provide frequency analysis, impact modeling and/or risk assessment |
| 6 | Hazard indices | A set of hazard identification/assessment techniques that can be used to rank different system options and identify less hazardous options |
| 7 | Monte Carlo method and other modeling methods | A set of methods for frequency analysis that uses the system model to estimate variations in baseline conditions and assumptions |
| 8 | Paired comparisons | A way to assess and rank the universal risk by means of paired comparison |
| 9 | Operation data review | A set of techniques that can be used to identify potentially problematic areas and for frequency analysis based on accident data, reliability data, etc. |
| 10 | Covert process analysis | A method for identifying hidden processes and paths that could lead to unexpected events |

**Table 2.**
*List of additional methods used in risk analysis.*

their probabilities. ETA is widely used for project-specific facilities that contribute to the reduction of accidents and identify sequences of events that, in turn, lead to certain consequences of the initiating event. Each event in the sequence is assumed to be either a failure or a fault.

Note that the probabilities in the event tree are conditional probabilities. For example, the probability of the sprinkler functioning is not a probability derived from tests under normal conditions but is a probability of functioning under fire conditions caused by an explosion.

The ETA provides a relationship between the functioning (or failure) of a variety of systems and the hazardous event following the single initiating event. The ETA is very useful for identifying events that require further analysis using the FTA (i.e. the tip of the fault tree events). In order to be able to make a comprehensive risk assessment, all potential initiating events need to be identified. With this method, however, it is always possible to overlook some important initiating events. Moreover, in the case of event trees, we are only dealing with success and failure states. It is difficult to include delayed success or return events.

ETA can be used both for hazard identification and for probabilistic evaluation of the sequence of events leading to hazardous situations.

### *2.1.2 Failure modes and effects analysis (FMEA)*

FMEA is a predominantly qualitative method, although it can be presented in a quantitative form that systematically identifies the consequences of each individual component of an emergency condition. An indispensable feature in any FMEA is to consider each major component/particle of the system as to how it achieves the emergency state and how this affects the emergency state of the system. The analysis is usually descriptive and is organized in the form of a table or worksheet intended for information. The FMEA certainly refers to the emergency conditions of a system component, the causal factors and the effects of this condition on the system as a whole and presents them in a "user-friendly" form.

FMEA is a bottom-up approach and addresses the consequences of component failures in a "one-at-a-time" manner. This method is capable of processing sufficient data. In addition, the results can be easily double-checked by another person familiar with the system.

The main disadvantages of the method are redundancy, the exclusion of recovery and repair activities and the focus on single component accidents.

FMEA can extend to performing what is called Failure Type, Function and Criticality Analysis (FMEA). In FMEA, each identified failure is ranked according to the likelihood of its occurrence and the severity of its consequences.

FMEA and FMESA provide input to analyses such as Fault Tree Analysis (a diagram analysis of all possible consequences of a failure or system crash). In addition to their application to system components, FMEA and FMECA can also be used in relation to human error; they can be used both for hazard identification and probability assessment (unless there is a limited level of redundancy in the system).

### *2.1.3 Analysis of a diagram of all possible consequences of a failure or system crash (fault tree analysis (FTA))*

Fault Tree Analysis, FTA is a set of qualitative or quantitative methods which are built into a logical chain and graphically presented those conditions and factors that may contribute to a certain undesirable event (called the top of events). Malfunctions or accidents identified in the "tree" can be events associated with damage to a component's mechanical structure, personnel errors, or any other event that may cause an undesirable incident. Starting at the top of the events, possible causes or alarm states of the next, lower functional level of the system are identified. Subsequent step-by-step identification of undesired system operation in the direction of successively decreasing system levels leads to the desired system level, which is the alarm condition of the component. An example of a "fault tree" for an emergency generator is shown in **Figure 2**.

The FTA provides an approach that is highly systematic, but at the same time flexible enough to allow for the analysis of multiple factors, including human interactions and physical phenomena. The top-down approach, implicit in its methodology, focuses on those effects of a failure or accident that are directly related to the top of events. The FTA is particularly useful for analyzing systems with multiple areas of contact and interaction. Graphical representation makes it easy to understand the behavior of a system and the behavior of the factors included in it, but since the size of trees is often large, the processing of fault trees may require the use of computer systems. This feature also makes it difficult to check the trouble tree.

FTA can be used to identify hazards, although it is primarily used in risk assessment as a tool to assess the probability or frequency of faults and accidents.

### *2.1.4 Hazard and operability analysis (HAZOP)*

HAZOP is a form of Failure Types and Consequences Analysis. HAZOP research was originally developed for the chemical industry. It is a procedure for detecting possible hazards across the entire facility. It is particularly useful for

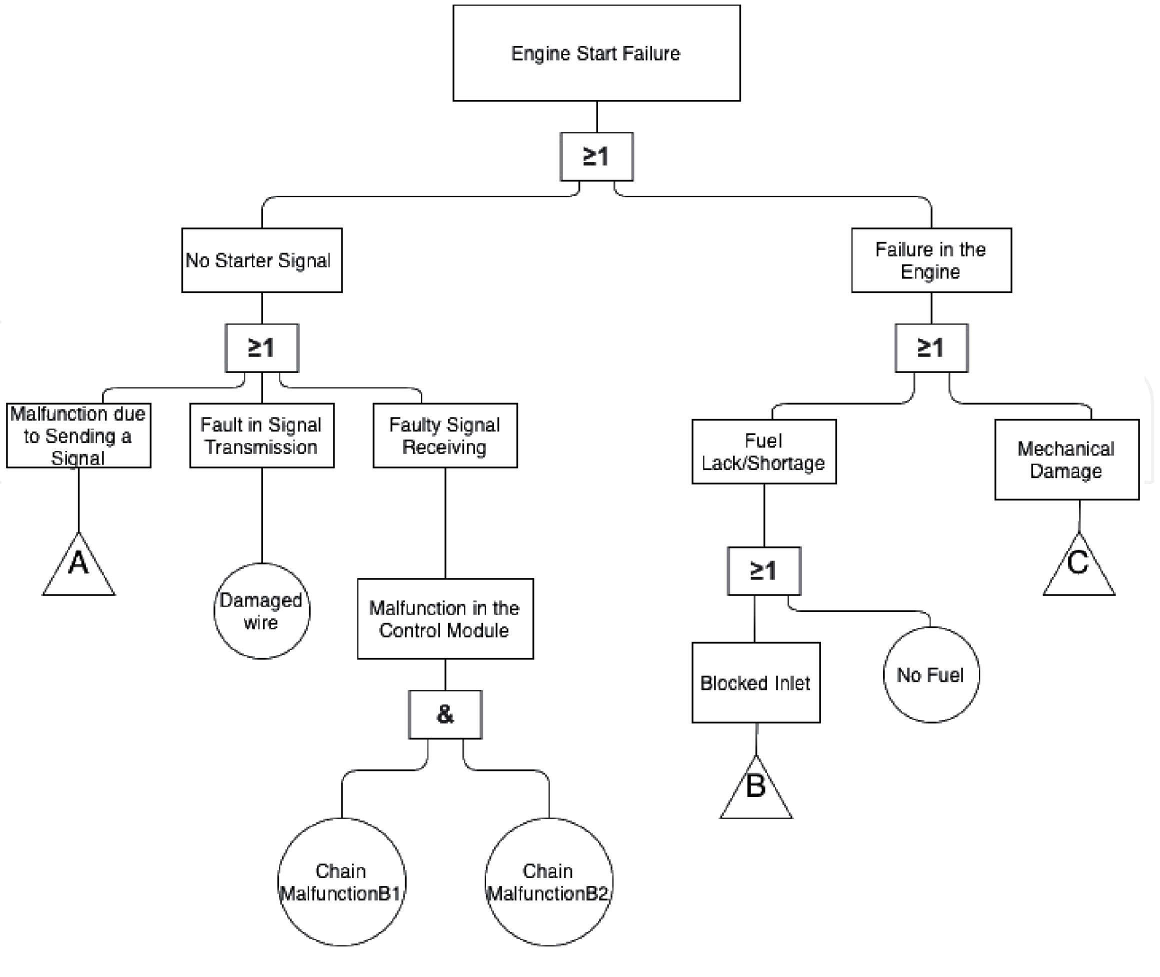


**Figure 2.**
*Example of a "fault tree."*

identifying unforeseen hazards in a facility due to lack of development information, or hazards that manifest themselves in existing facilities due to irregularities in their operation.

The main tasks of the method are:

a. To compile a complete description of the object or process, including estimated design conditions;

b. To systematically check each part of the facility or process in order to identify ways in which deviations from the design intent may occur;

c. To decide whether hazards or problems associated with these deviations may occur.

The HAZOP research principles may be applied to technical facilities during their operation or at various design stages. HAZOP research performed during the initial design stage can be performed by the project manager.

The most common form of HAZOP research is during the working design stage and is called HAZOP II research.

The HAZOP II study has the following stages:

Stage 1 – identification of the goals, objectives and scope of the study, for example, the identification of hazards characterized only by non-local effects or only local effects, areas of the industrial facility to be considered, etc.;

Stage 2 – completing the HAZOP research team. This group should consist of designers and operators who have sufficient competence to assess the consequences of deviations from the conditions of the system operation;

Stage 3 – gathering the necessary documentation, drawings and descriptions of the technological process. This includes graphs of the sequence of technological operations; drawings of pipelines and measuring equipment; technical specifications for equipment, pipelines and measuring equipment; logical diagrams of process control related technology; design diagrams; operation and maintenance methods; emergency response methods, etc.;

Stage 4 – analysis of each main unit of equipment and all auxiliary equipment, pipelines and measuring equipment using documents collected at step 3. First of all, the purpose of the process design is determined; then, in relation to each line and unit of equipment with respect to such process variables as temperature, pressure, flow, level and chemical composition, the words-indicators are used (according to **Table 3**). (It is the author's view that these indicator words stimulate individual thinking and encourage collective discussion);

Stage 5 – document any deviation from the norm and the corresponding states. In addition, ways to detect and/or prevent deviations are identified. This documentation is usually indicated on HAZOP worksheets.

#### *2.1.5 Assessing the impact on human reliability factor (HRA)*

The assessment is related to the impact of human factor, namely operators and maintenance personnel, on system operation and can be used to assess the effect of personnel errors on safety and productivity.

Many processes contain potential for personnel errors, especially when the time available for the operator to make decisions is limited. The likelihood that problems will develop in a negative way is often low. Sometimes actions from outside personnel's jurisdiction are limited in their ability to prevent an initial fault progressing in the direction of an accident.

| Word pointer | Rejection | Possible reasons | Consequences | Action required |
|---|---|---|---|---|
| No, not | No expense | 1. Absence of submitted material | The output of the molded polymer will be reduced | a. Ensure good communication with the operator<br>b. Provide a low level signal on the installation tank |
| | | 2. The pump is faulty (many reasons) | The output of the molded polymer will be reduced | Provide for a low level signal on the installation tank |
| | | 3. A line is blocked or a control valve is erroneously closed or not closed | The pump will overheat. | Install a recirculation line on each pump |

**Table 3.**
*HAZOP II indicator words.*

The HRA identifies the various types of error actions that may occur, including the following:

a. Error by mistake, an oversight resulting in the failure to perform the required action;

b. An error of non-conformity, which may include:

1. A situation in which the action required is performed in a non-conforming manner;

2. An action performed with too much or too little force or without the required accuracy;

3. An action performed at a time not appropriate for it;

4. An action (or actions) performed in an incorrect order;

c. An extra action, an unnecessary action performed instead of or in addition to the required action.

The result of HRA identifies actions that can re-create previous errors.

The HRA methodology is a mixed discipline involving researchers and practitioners who are typically specialists in either the theory and practice of reliability or psychology and human factors.

The importance of HRA has been illustrated by various accidents in which critical human errors have contributed to a catastrophic sequence of events. Such accidents are a warning against risk assessments that focus exclusively on the mechanical design and software in the system. They illustrate the risk of ignoring human error. Moreover, HRAs are useful in considering errors that reduce productivity and in identifying the ways in which these errors and other faults (mechanical design and software) can be "replicated" by people, operators and maintenance personnel.

The HRA can include the following steps: (1) task analysis; (2) identification of personnel error; (3) quantitative determination of the impact of the human factor on reliability.

The task analysis and personnel error detection should be started at the concept stage and the early stages of design and development. They should be updated at later stages of the system development.

The purpose of the task analysis in the HRA process is to describe and characterize the task to be analyzed in detail in order to identify human error and/or quantify the impact on human reliability. The task analysis can also be performed for other purposes, such as evaluating the person's interaction with the machine or planning a procedure.

At this stage, possible errors in the task are identified and described. The identification of personnel error may include:

- The detection of the possible consequences and causes of the erroneous actions
- The proposal of measures to reduce the probability of the error,
- The improvement regarding the prospects for correction and/or the reduction of the consequences of erroneous actions. Thus, HRA results provide a valuable contribution to risk management, even if no quantitative assessment is made.

The purpose of HRA is to assess the probability of correct execution of the task or the probability of erroneous actions. Some techniques may also include steps to assess the probability or frequency of certain sequences of unwanted events or undesirable outcomes.

### *2.1.6 Preliminary hazard analysis (PHA)*

Preliminary Hazard Analysis, PHA is an inductive method of analysis whose purpose is to identify hazards, hazardous situations and events that may harm a given activity, facility or system. It is most often used at an early stage of project development when there is little information on design details and working procedures, and it can often be a precursor to subsequent research. In addition, it may be useful where existing systems or prioritize hazards where circumstances prevent the use of a wider range of techniques.

When conducting PHA, a list of hazards and general hazards is developed by considering such characteristics as:

a. The materials used or produced and their ability to react;

b. The equipment used;

c. Environmental conditions;

d. Location scheme;

e. Areas of contact and interaction between system components, etc.

The implementation of this method concludes with the determination of the potential for an accident, a qualitative assessment of the magnitude of the possible harm or health damage that may have been caused, and the identification of possible corrective measures. The PHA must be adjusted at the design, manufacturing, and testing stages to detect, correct, and improve new hazards. The results obtained can be presented in various ways, such as tables and "trees."

### 2.2 Hazard identification

The detection of hazard assumes a systematic check of the investigated system with the purpose of identification of type of present unrecoverable dangers and ways of their display. Statistical records of accidents and experience of previous risk analyses can provide a useful contribution to hazard identification processes. It should be recognized that there is an element of subjectivism in hazard thinking and that identified hazards may not always be exhaustive hazards that could pose a threat to the system. It is necessary that identified hazards are reviewed when new data are available. Hazard identification methods are broadly divided into three categories:

a. Comparative methods, examples of which are inspection sheets, hazard indices and operational data review;

b. Fundamental methods, which are constructed in such a way as to encourage a group of researchers to use a prediction in combination with their knowledge of the hazard identification task by asking a series of questions such as "what if ...?". Examples of this type of methodology are Hazard and Related Problem Research (HAZOP) and Failure Analysis (FMEA);

c. Methods of inductive approach, such as logic diagrams of possible consequences of a given event ("event tree" logic diagrams).

Other techniques can be used to improve hazard identification (and risk assessment capabilities) for certain problems. For example: hidden fault analysis, the Delphi method and human factor analysis.

Regardless of the techniques used, it is important that the overall hazard identification process pays due attention to the fact that human and organizational errors are significant factors in many accidents. It follows that accident scenarios involving human and organizational error should also be included in the hazard identification process, which should not focus exclusively on technical aspects.

## 3. Economic analysis

Economic analysis as a science is a system of specialized knowledge linked:

with the study of economic processes in their interrelation, formed under the influence of objective economic laws and factors of subjective order;

- With scientific justification of business plans, and with objective assessment of their implementation;

- With identification of positive and negative factors and quantitative measurement of their action;

- With disclosure of trends and proportions of economic development, with recognition of unused intra-economic reserves;

- Generalization of the best practices,

- With the adoption of optimal management decisions.

Economic analysis of aircraft and its components is one of the most important functions of airline management, the implementation of which is necessary to ensure its effective operation. As a matter of fact, economic analysis is known to represent numerous methods of economic theory.

Modern management theories determine the necessity of substantiation of all-important management decisions by means of analytical process called "rational problem solving". This process, the analytical part of which is identical to economic analysis, includes the following seven stages:

### 3.1 Classification of analysis methods and techniques

The method of analysis should mean the methods of investigation of the object of analysis, and the method of analysis acceptance - one or more mathematical or logical operations aimed at obtaining a specific result of analysis.

Mathematical methods are objective, as they yield the same results when applied by different analysts. In complex analysis, these methods are usually combined. Thus, the type of a mathematical model is often chosen intuitively, and the model parameters are determined by methods of mathematical statistics.

Mathematical models: mathematical economy models - theoretical and applied models - are widely used in the analysis. Theoretical models allow studying general properties of economy and its separate elements by deduction of conclusions from formal preconditions. They are important for understanding possible properties of the object of analysis. They are macroeconomic and microeconomic models, including models of firm theory and market theory. Applied models provide an opportunity to estimate parameters of functioning of a concrete economic object and to formulate specific recommendations for decision making. Applied models include, first of all, econometric models, which operate with numerical values of economic variables and allow statistically significant evaluation on the basis of available observations.

Mathematical models, besides, are subdivided into equilibrium models, which describe steady-state conditions and are therefore called descriptive, and optimization models, which allow establishing optimal, i.e. the best parameters of the system according to a certain criterion. Static models that describe the object state at a particular moment or period of time and dynamic models that include interrelationships of variables in time are distinguished.

Methods of applied mathematical statistics - econometrics, should be used as much as possible first of all in the analysis, since almost all data used in economic analysis contain a random component. Note that the results obtained by statistical processing of data may differ in the degree of accuracy and probabilistic validity. Estimates can be considered reasonable if their probability and accuracy are determined, otherwise they may not be credible.

Multidimensional methods: These methods provide objective quantitative tools to investigate data similarity, proximity, grouping or classification. Data can be presented as a set of indicators, variables that characterize objects or a single object at different points in time, e.g., an enterprise in different years. Most methods are designed to reduce the number of variables and highlight the most important characteristics. The following methods underline the most important ones:

The method of cluster analysis, which allows building a classification of several objects by combining them into groups or clusters, based on the criterion of minimum distance in space of certain indicators describing the objects, as well as the classification of objects by a given number of groups – clusters. Probabilistic justification of the clustering results can be obtained by discriminant analysis.

Factor analysis: variables, whose values provide statistical or accounting data, are often quite conditional for the object or phenomenon under study. They can only indirectly reflect its internal structure, driving forces or factors. The analyst is limited to the set of indicators traditionally used in accounting and statistics. If an unknown factor manifests itself in changes of several variables, there is a correlation between these variables. The number of independent, initially hidden factors that can be detected by factor analysis is often significantly less than the number of traditional indicators.

In addition, there are two levels of use of expert judgments: quantitative, in which experts make estimates in the form of quantitative indicators, and qualitative, in which experts make comparative estimates, for example, "better and worse."

### 3.2 Comparison method in economic analysis

Comparison is a scientific method of knowledge, in the process of its unknown phenomenon; subjects are compared with already known, studied earlier cases, in order to determine common features or differences between them. By means of comparison the general and specific in the economic phenomena, changes of the objects under study, tendencies and lawfulness of their development are studied. Hence, the following evaluations in the area of economic analysis and comparisons are used for identifying observed problems and suggest a course of action(s):

1. Comparison of planned and actual indicators to assess the extent to which the plan has been implemented. This comparison allows the user to determine the extent to which the plan has been completed in a specific timeframe, such as a month, quarter, or year.

2. Comparing the actual indicators with the normative ones allows cost monitoring and promotes the implementation of resource saving technologies. The practice of analytical work also uses comparisons with approved norms (for example, consumption of materials, raw materials, energy, etc.). Such a comparison is necessary to identify savings or over-expenditure of resources for production, to assess the efficiency of their use during operation.

3. Comparison of actual indicators with those of previous years to determine trends in economic processes.

4. Comparison with the best results, i.e. with the best samples, best practices. New achievements of science and technology can be carried-out both within the framework of the enterprise under study and outside. Inside the enterprise the average level of indicators achieved in general is compared with indicators of advanced sites. This allows identifying best practices and new opportunities for production and operation.

5. Comparison of the indicators of the analyzed form with the average indicators of the zone/area to assess the results achieved and identified unused reserves.

6. Comparison of parallel and dynamic series to study the relationship of the studied indicators. This is used to identify and justify the form and direction of the relationship between different indicators. For this purpose the numbers, which characterize one of the indicators, should be placed in ascending or descending order and consider how in this connection other investigated indicators change: ascending or descending and to what extent.

7. Comparison of different variants of managerial decisions in order to choose the most optimal of them.

8. Comparison of the results of activity before and after the change of any factor is applied in the calculation of the influence of factors and calculation of reserves.

The following types of comparative analysis are also distinguished in the economic analysis: horizontal, vertical, trend, as well as one-dimensional and multi-dimensional.

1. Horizontal comparative analysis is used to determine the absolute and relative deviations of the actual level of the studied indicators from the basic (planned, past period, average level, scientific achievements and best practices).

2. With the help of vertical comparative analysis the structure of economic phenomena and processes is studied by calculating the specific weight of parts in general, the ratio of parts of the whole among themselves, as well as the impact of factors on the level of performance indicators by comparing their values before and after changing the relevant factor.

3. Trend analysis is used to study relative growth rates and growth of indicators over a number of years to the level of a base year, i.e. to study the dynamics series.

4. In one-dimensional comparative analysis comparisons are made on one or several indicators of one object or several objects on one indicator.

5. By means of the multi-dimensional comparative analysis the results of activity of several operating enterprises (divisions) are compared on a wide spectrum of indicators.

### 3.3 Factor analysis methodology

The sequence of performing factor analysis includes the following stages:

1. Selection of factors that determine the performance indicators under study and their systematization in order to ensure the capabilities of the system approach;

2. The establishment of modeling and transformation of the factor systems

3. Calculation of the influence of factors and assessment of the role of each of them in changing the value of the resultant indicator;

An important methodological issue in factor analysis is the determination of the relationship between factors and performance indicators: functional or stochastic, forward or backward, straight or curved. Here, theoretical and practical experience as well as methods of comparison of parallel and dynamic series is used in conjunction with analytical groups of initial information, graphic and others.

The modeling of economic indicators (deterministic and stochastic) is also a complex methodological problem in factor analysis, the solution of which requires special knowledge and practical skills in this branch.

The most important methodological aspect in economic analysis EA, is the calculation of the influence of factors on the value of effective indicators, for which the analysis uses a set of methods, the essence, name, scope of which and the procedure of calculation are considered in the following chapters.

Finally, the last stage of the factor analysis is the practical use of the factor model for calculation of reserves for the growth of the resultant index, for planning and forecasting its value in case of changes in the production situation.

### 3.4 Economic optimization of the airline's lifecycle

An increase in resource (durability), which is an integral part of reliability, accordingly, leads to an increase in the latter. Increasing reliability, as well as increasing resources (reliability component), requires a significant amount of work, significant cost and time. The past decades of aviation Gas Turbine Engines (GTEs) development have been marked by a continuous growth of resources: from several hundreds of hours to tens of thousands of hours.

When the engine resources did not exceed 1000 hours, there were no doubts about the economic expediency of their increase due to at least two circumstances: high expenses of the operating organizations and relatively small expenses for the works connected with the increase of resources (**Figures 3** and **4**).

A different situation occurs when justifying large resource values (>20,000 hours). On the one hand, the operating costs are already significantly reduced (operating costs per hour of motor operation), and with small operating costs, further reduction of the operating costs brings ever less economic benefit.

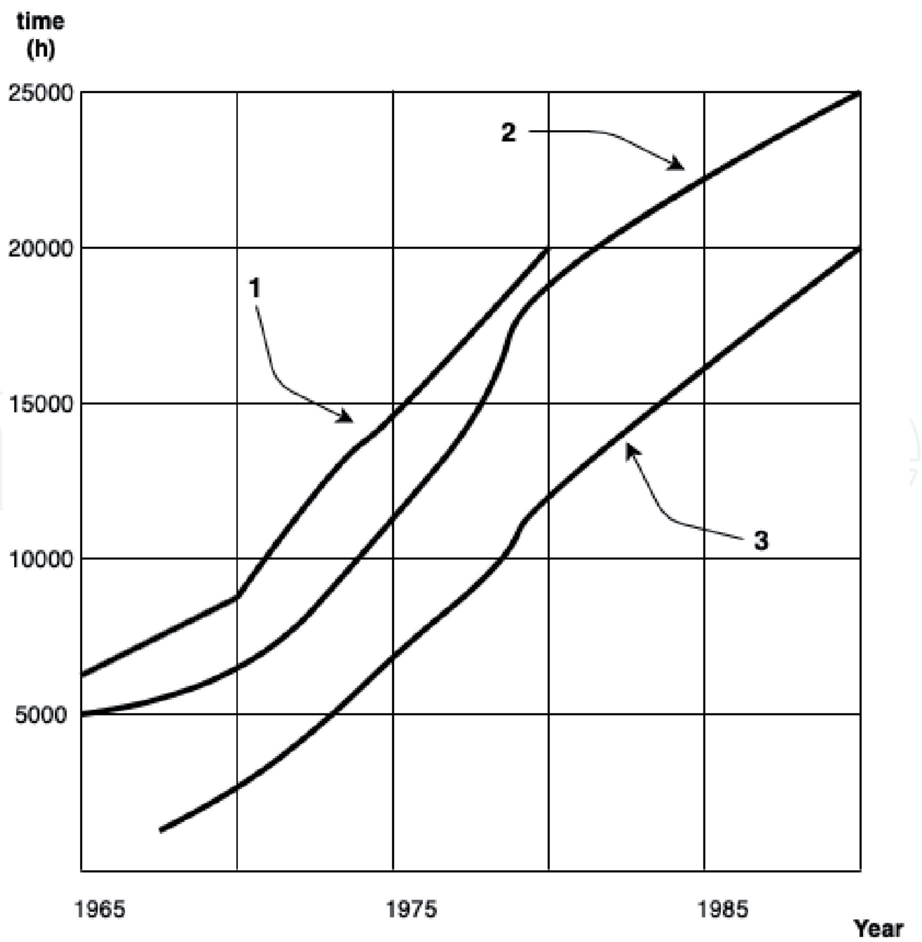


**Figure 3.**
*Growth of resources of engines AI-20 (1), AI-24 (2), AI-25 (3) on years of operation.*

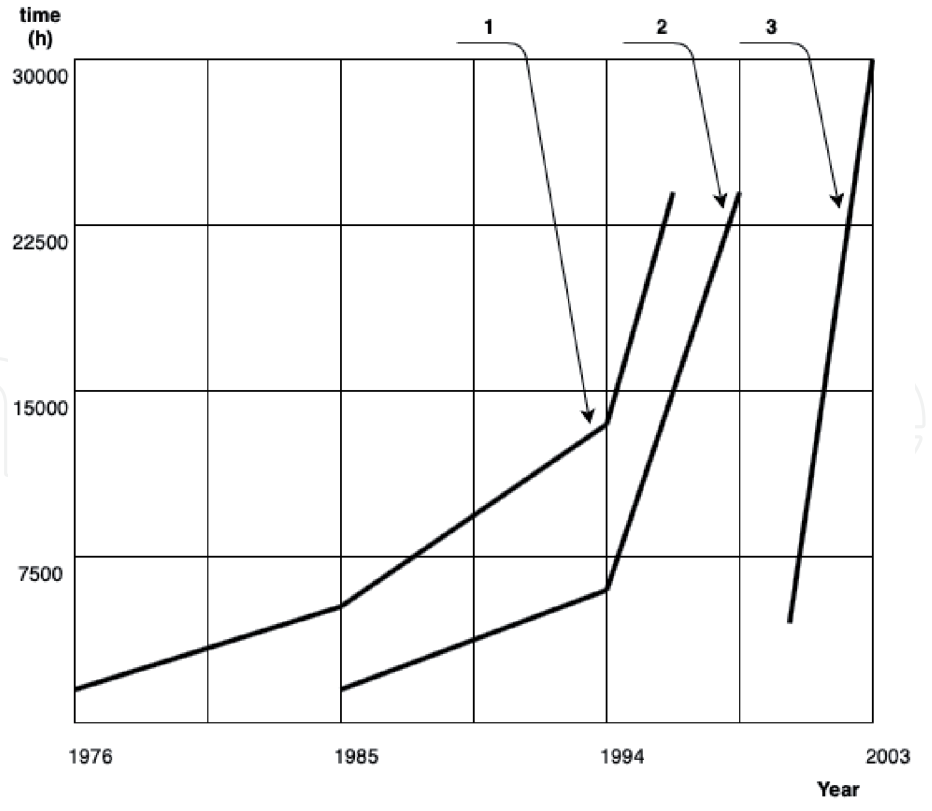


**Figure 4.**
*Growth of resources of engines with a large degree of dual circuit D-36 (1), D-18T (2), D436T1 (3).*

In addition, in accordance with the law of the dwindling limit value, the operating costs may increase starting from a certain service life.

On the other hand, an ever-increasing amount of effort is required to increase resources.

There is an economically optimal resource value, at which the total cost of increasing the resource is the lowest (TOP 1).

The introduction of electronic engine designers, the use of numerical methods and high-level models, application software packages (e.g. ANSYS), combined with the accumulated experience in the creation of aircraft GTEs and the high qualifications of engineering staff have allowed the development and successful application of calculation methods for resource determination.

It has given the chance to lower expenses essentially and to reduce calendar terms of an establishment of resources. At the same time, the importance of an economically optimal resource to the right has shifted significantly [7] (**Figure 5**).

For different engines, and even for the same engine installed on different aircraft, there will be different values of optimal service life, as operating costs may vary depending on the engine type, aircraft type, operating company, etc.

The engine resource can be very large; however, it will be far from economic optimum. The indicator of optimum resource can serve as total value of expenses for 1 hour of established resource.

Deviation of a resource of the engine from economic optimum can be connected with special requirements to the engine, overlapping at designing. In this case, the efficiency of the design solutions used may "prove to be as efficient as possible under imposed constraints."

The desire to establish an economically optimal resource was one of the reasons why the notion of resource design appeared.

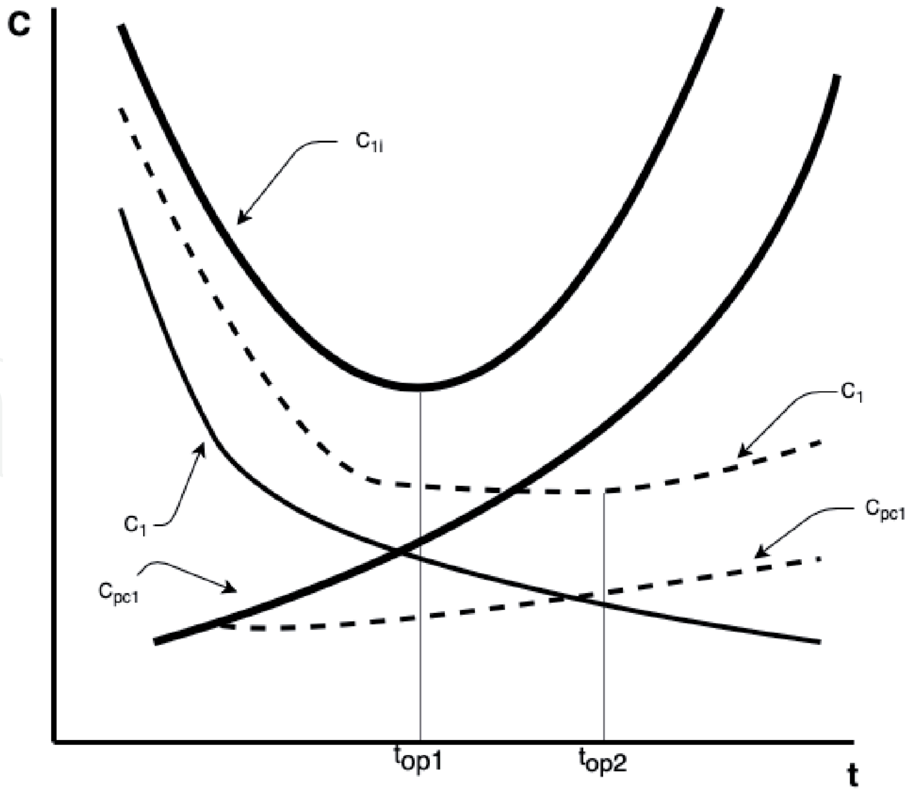


**Figure 5.**
*Dependence of change in costs on the value of the engine resource.*

Under resource designing of aviation GTEs, it is necessary to understand the durability details at a design stage of the engine. The full account of operating conditions is provided and optimization of a level of working parameters, indicators of effect and value of resource is made.

The development of technical (indiscriminate) diagnostics, modularity of design, content usability of engines and accumulated experience of operation allowed to carry-out the operation of aviation GTEs on technical condition. The economic effect from the exploitation according to the technical condition is very high:

- The number of spare parts is reduced by 20%;
- The number of spare engines is reduced by half;
- The cost of maintenance and repairs is reduced by approx. 25%.

The almost universal transition to maintenance-free operation, with the replacement of individual modules without removing the engines from the wing, has led to a review of the engine life as a whole.

For a complex, multi-component system, the concept of engine life becomes conditional. The economic purpose of engine reconditioning during repairs and the cost per hour of a life cycle are of paramount importance. The economic viability of engine reconditioning depends on the cost of repair and the cost of replacing parts that limit the life cycle (**Table 4**).

Using the data in **Table 4**, it is possible to determine repair costs per hour for a CFM56-3 engine with a thrust of 23,500 pounds (10,657 kG) using Eq. (1):

$$C_{ep} = \frac{C_p + C_d}{N_{\Sigma} t_z} \quad (1)$$

where $C_p$ is the cost of repairs; $C_d$ is the cost of replacing parts; $N_\Sigma$ – number of flight cycles worked out; $t_z$ – flight cycle time, hour.

Adding all the costs in columns 4 and 5 of **Table 4**, dividing by the number of flight cycles (28,000 cycles) and duration of flight (1.4 hours), yields $125.64. Adding to cost of a new engine, attributed to 1 hour of operation, and the cost of fuel consumption for 1 hour of engine operation, results in the cost of 1 hour of the life cycle of the CFM56-3 engine (Eq. (2)).

$$C_{hour} = \frac{C_{dv} + C_d + C_p}{t_\mu N_\Sigma} + C_{ud} R C_m \tag{2}$$

where $C_{dv}$ is the new engine price; $C_{ud}$ is the specific fuel consumption, $C_m$ – price of 1 kg of fuel; R is the engine thrust.

For each engine, there is an optimum operating time on the wing (before repair). For example, for the PW4000 engine, the optimum wing life is 3500–4500 flight cycles.

This is due to the ability to repair and rebuild the structure and properties of the fuel blades. Longer engine stay on the wing leads to a high degree of utilization of the blades. Therefore, it is very important to keep exact account of engine details operating time in hours and flight cycles. An error in the operating time can lead to a substantial increase in the cost of repairs.

Powder metallurgy, laser and micro-plasma welding methods are used in blade repairs. The limitations of the repair are related to cracks and thinning of the blade walls.

Modifying the structure and properties of the blade, allows the same blades to be used for a longer period of time in the engine. This results in significant cost savings. Based on performed research and the associated data, the recovery and repair of 30,000 work blades can bring savings of up to $80,000.

Resource of details is expedient to provide at designing so that replacement of basic details in operation was possible less. It is necessary to plan replacement of details (not concerning the basic), limiting a resource, by a combination of replacement with repair of engines (visit of workshop).

In order to avoid forced removal of the engine from the wing due to the end of the service life of the main parts, most airlines operating GTE maintain a "service life balance" policy (minimum life of parts). The essence of the case is that the majority of parts that limit the life produce their life span in the range of 1500–3000 flight cycles from their limit life.

For example, the front rotor shaft of a CF6-50 engine has a limit of 11,500 flight cycles but is likely to be disposed of after (9500–10,000) flight cycles (**Table 5**).

| Rental no | Working hours before renting, hour | Total earnings, hour | The cost of repair, $ | Cost of parts to be replaced, $ |
|---|---|---|---|---|
| 1 | 8500 | 8500 | 800.000 | — |
| 2 | 6500 | 15.000 | 900.000 | 650.000 |
| 3 | 6500 | 21.500 | 950.000 | 410.000 |
| 4 | 6500 | 28.000 | 950.000 | 265.000 |

**Table 4.**
*Costs of scheduled maintenance of the CFM56-3 engine with 23,500 lb thrust.*

| | Engine | Cost of main parts, million $ | Unused resource remnants, cycle |
|---|---|---|---|
| 1 | JT9D | 2.1 | 2000 |
| 2 | PW4000 | 2.44 | 2000–3300 |
| 3 | CF6-50 | 2.1 | 1400–2500 |
| 4 | CF6-80C2 | 2,.7 | 2000–2500 |

**Table 5.**
*Costs and unused balances of resources of the main details of aero engines.*

In this case, the cost of 1 hour of the engine's life cycle is reduced, which increases the competitiveness of the engine.

In addition to the planned reasons for removal (exhaustion of the reserve in terms of the temperature of exhaust gases, increase in the reserves of stability of the ATC, exhaustion of the service life of parts that limit the resource, etc.), a significant share is occupied by unplanned ones.

Unscheduled engine removals can make big corrections to the repair and replacement schemes of the parts that limit the service life. The number of unscheduled engine removals can be 50% of the total number of removals. For example, for the PW4000 family engines, unscheduled removals account for 35–45% of all removals. For CF6-50 engines the reason for 25% of removals is exhaust gas temperature exhaustion, other 25% of removals are caused by the necessity to replace the main parts, which have reached their end-of-life, and another 50% of removals are unplanned removals [8]. In order to increase the economic efficiency of aviation GTEs operation it is necessary:

- To install the engine parts with minimum expenses;
- To ensure optimal stay of the engine on the wing of the aircraft in a single operation;
- Ensure the timely replacement of parts that limit the engine's life (avoid early removal of the engine due to lack of service life of the main parts or exhaustion of gas reserves);
- Accurately determine the current damageability of parts in hours and cycles depending on the operating conditions (automated hours and cycles);
- Quickly determine the scope of work and necessary parts replacement during unscheduled engine stripping;
- Taking into account unplanned surveys to correct the scope of work for subsequent engine reconditioning, and remain the engine on the wing, etc.

It is most convenient to perform the above-mentioned works using ground automated systems of engine operation monitoring. One of the essential elements of such systems is the algorithms of calculating the developed resource.

The conducted analysis of aviation GTE resources allows drawing the following conclusions:

1. There is an economically optimal engine resource for the given operation conditions.

2. Economically optimal engine life can change significantly with changes in the cost of life.

3. To improve the economics of engine operation, ground-based automated engine performance monitoring systems should be used.

## 4. Conclusions

This chapter is the result of the study of a number of special disciplines, such as risk analysis and economic analysis of commercial aero engines during aircraft operation. Risk analysis includes risk assessment and methods to reduce risks or reduce adverse effects associated with it. The methods for risk analysis have been provided, including ETA, FMEA, FTA, HAZOP and PHA.

Furthermore, Economical analysis is a scientific way of understanding the essence of economic phenomena and processes, based on dividing them into its constituent parts and studying the variety of relationships and dependencies aimed at improving its work through the development and implementation of optimal solutions. The purpose of the economic analysis is to give management a picture of the actual state, and for persons who are not directly working with it, but are interested in its financial condition, the information necessary for an impartial judgment.

Aviation engineering as a commodity has its specificity. If one considers an aircraft as a whole, the aircraft operation efficiency is defined by perfection of the power plant. The engine may appear on the market as an independent product with a market price. But it must be taken into account that the aircraft engine is a subsystem of the aircraft, so its economic assessment should be carried out, if possible, taking into account the characteristics of the aircraft and its specifics of operation, which is a difficult task. Still, this is a necessary procedure, especially in the case of economic evaluation.

**Author details**

Sherkhan Aitugan* and Longbiao Li
Nanjing University of Aeronautics and Astronautics, Nanjing, China

*Address all correspondence to: sherkhan.aitugan@gmail.com

## References

[1] Jardine AKS, Anderson PM, Mann DS. Application of the Weibull proportional hazards model to aircraft and marine engine failure data. Quality and Reliability Engineering International. 1987;**3**(2):77-82

[2] Berens AP, Hovey PW, Skinn DA. Risk Analysis for Aging Aircraft Fleets. U.S. Air Force Wright Laboratory Report, WL-TR-91-3066, Vol. 1; 1991

[3] Cioclov DD. A model for fracture risk analysis. Revue Roumaine des Sciences Techniques. 1986;**31**(6):613-622

[4] Bigun ES. Risk analysis of catastrophens using experts' judgements: An empirical study on risk analysis of major civil aircraft accidents in Europe. European Journal of Operational Research. 1995;**87**(3):599-612

[5] Violette MG, Safarian P, Han N. Transport airplane risk analysis. Journal of Aircraft. 2015;**52**(2):395-402

[6] Cruse TA, Mahadevan S, Tryon RG. Fatigue reliability of gas turbine engine structures. NASA Report, No. NASA/CR-97-206215

[7] Butushin SV, Nikonov VV, Fejgenbaum Yu M, Shapkin VS. Obespechenie letnoy godnosti vozdushnyh sudov grazhdanskoy aviacii po usloviyam prochnosti. Collection of scientific papers of the 4th International scientific-technical conference "Modern scientific-technical transport problems" M., MGTU GA; 2013. p. 772

[8] Itskovich AA, Fainburg IA. Pokazateli effektivnosti processov podderzhaniya letnoy godnosti vozdushnyh sudov [indicators of the efficiency of process of maintenance of the aircraft air- worthiness]. Scientific Bulletin of the Moscow State Technical University of Civil Aviation. 2012;**178**:21-26