Prediction of main factors’ values of air transportation system safety based on system dynamics

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Abstract. On the basis of the system-dynamic approach [1-8], a set of models has been developed that makes it possible to analyse and predict the values of the main safety indicators for the operation of aviation transport systems.

1. Introduction
Research in the field of improving the safety of air transport is currently being intensively pursued at an intersection of many sciences: aircraft construction, engineering, instrumentation, computer science, management theory. Further development of aviation transport systems (ATS) is impossible without ensuring an adequate level of safety of their operation. Accidental catastrophes cause not only material damage, but also reputational losses for aviation companies.

The statistics for catastrophes for 100 000 flight hours is one of the important indicators that allow us to assess the safety of the operation of ATS. This indicator is indicated in the reports of the IAC (Figure 1).

Figure 1. Number of accidents in civil aviation in IAC countries for 100 000 flight hours.

The reason for a significant part of aviation accidents are critical combinations of events: failures of equipment, environmental influences and errors of crews and dispatchers.

One of the most promising ways to address the issue of aviation safety is associated with the application of the theory of system analysis and modern means of information processing to improve the software reliability of the ATS management, which directly affects flight safety.

There is a necessity for the application of modern automated software systems based on mathematical algorithms, due to several reasons, including:
a large number of dependencies between the variables that affect safety, which are difficult to construct manually;
- the need to quickly choose the right solution based on the analysis of a large number of solutions and large amounts of calculations;
- the need to visualise the results obtained.

The above reasons determine the relevance of the study on the improvement of the software used in the management of ATS systems, through the development of new models, algorithms and information systems of the programs to predict values of parameters affecting the safety of systems.

The developed model of system dynamics made it possible to obtain an assessment of the safety of the ATS on this basis, to identify the variables that exert the strongest influence on safety. The obtained results will allow assessing the state of the ATS safety from the resource point of view and determining indicators, the insufficient value of which leads to the occurrence of accidents and catastrophes.

2. **Approach to forecasting the security status of the functioning of aviation transport systems**

It is required to develop a model of system dynamics that allows one to predict the values of the main safety indicators of the ATS functioning at different time intervals. To predict the values of these indicators it is proposed to use the system dynamics model, the construction of which contains the following stages:

- a choice of variables that characterise the security of the operation of ATS and external factors that affect these variables;
- the construction of a graph of cause-effect relationships, reflecting the interrelations of variables and the influence of external factors on them;
- drawing up equations of system dynamics, the solution of which will allow the values of variables at given time intervals to be determined;
- getting solution of the system of equations;
- checking the constructed model for adequacy.

3. **Variables characterising the safety of functioning ATS**

A study of the peculiarities of the functioning of ATS allowed us to determine the following list of variables that allow us to characterise the level of safety of the functioning of these systems:

- $X_1$ – the time of training pilots on modern certified simulators (hours per year);
- $X_2$ – the average number of aircraft accidents per 100 000 flight hours per year (GOST B 23743-88);
- $X_3$ – frequency of occurrence of accidents;
- $X_4$ – the average number of violations of instructions by pilots for 100 thousand flight hours;
- $X_5$ – the proportion of obsolete aircraft (over 15 years);
- $X_6$ – an indicator of the activity of the bodies controlling the turnover of counterfeit goods;
- $X_7$ – the number of private aircraft in aviation;
- $X_8$ – the number of staff involved in meteorological services;
- $X_9$ – the total number of dispatchers.

In addition, the model includes the external factors that affect the variables of the system:

- `Res` – average for aircraft development of the resource before write-off (GOST B 23743-88);
- `For` – amount of foreign aircraft;
- `Exper` – average flight experience of pilots;
- `Price` – the cost of aviation fuel;
- `Port` – the average service life of aerodrome equipment;
- `Gov` – the number of regulations related to aviation (the level of control by the state).

4. **The graph of cause-effect relations**
Based on statistical data and expert analysis, dependencies between variables and external factors of systems are revealed (Table 1). The cell of the table contains the plus sign if the value from the corresponding column positively affects the value from the corresponding row of the table and the minus sign if it is negative.

**Table 1. Minimum sections of a state graph**

|   | X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 | X9 |
|---|----|----|----|----|----|----|----|----|----|
| X1 | -  |    |    |    |    |    |    |    |    |
| X2 | +  | +  | -  | -  | +  | +  | -  | +  | -  |
| X3 | -  | +  | -  | +  | -  | -  | +  | -  | -  |
| X4 | -  | +  | -  | -  | +  | -  | +  | -  | -  |
| X5 | +  |    |    |    |    |    |    |    |    |
| X6 | +  | -  |    |    |    |    |    |    |    |
| X7 | +  | +  |    |    |    |    |    |    |    |
| X8 | -  | -  | -  | -  | -  | -  | -  | -  |    |

For example, as follows from the table for the variable, X_2 (the average number of aircraft accidents per 100 000 flight hours) is reduced:
- with an increase in the dispatchers and meteorological services staff;
- with an increase in the average pilots' experience;
- with an increase of control by the state.

Variable X_2 increases:
- with an increase in the number of violations;
- with an increase in the number of counterfeit parts;
- with an increase in the percentage of private aircraft;
- with an increase in the average time between the launch to the write-off of the aircraft and aerodrome equipment;
- with an increase in the percentage of foreign aircrafts;
- with an increase in the price of aviation fuel.

### 5. System of differential equations

According to the principles of the system-dynamic approach, based on the table and the cause-effect relationship graph for each variable model X_i, a differential equation of the form:

\[
\frac{dX_i}{dt} = F_i^+ - F_i^-, \tag{1}
\]

where:

\[
F_i^+ (\bullet) = S_i^+ \Pi_i^+, \tag{2}
\]

\[
F_i^- (\bullet) = S_i^- \Pi_i^-, \tag{2}
\]

The general form of the equations of system dynamics:

\[
\frac{dX_i}{dt} = S_i^+ \Pi_i^+ - S_i^- \Pi_i^- . \tag{3}
\]

On the basis of this relation, the following system of differential equations (4) is constructed:
\[ \begin{align*}
\frac{dX_1}{dt} &= \text{Exper} - f_{2.1}(X_2) f_{3.1}(X_3) f_{4.1}(X_4) \\
\frac{dX_2}{dt} &= f_{2.2}(X_4) f_{6.2}(X_6) f_{7.2}(X_7) \left( \text{Res} + \text{For} + \text{Price} \right) - f_{8.2}(X_8) f_{9.2}(X_9) \left( \text{Exper} + + \text{Gov} \right) \\
\frac{dX_3}{dt} &= f_{3.3}(X_7) \text{Price} - f_{1.3}(X_1) f_{9.3}(X_9) \left( \text{Exper} + \text{Gov} \right) \\
\frac{dX_4}{dt} &= f_{2.4}(X_2) f_{4.4}(X_4) \text{For} - f_{1.4}(X_1) f_{9.4}(X_9) \left( \text{Exper} + \text{Gov} \right) \\
\frac{dX_5}{dt} &= f_{2.5}(X_2) \text{Gov} \\
\frac{dX_6}{dt} &= f_{2.6}(X_2) \text{For} - \text{Gov} \\
\frac{dX_7}{dt} &= f_{2.7}(X_2) f_{3.7}(X_3) f_{4.7}(X_4) \text{For} - \text{Exper} \\
\frac{dX_8}{dt} &= f_{2.8}(X_2) \text{Gov} \\
\frac{dX_9}{dt} &= -f_{2.9}(X_2) f_{3.9}(X_3) f_{4.9}(X_4) \text{Gov}
\end{align*} \]

Expressions of form \( f_{\alpha,\beta}(X_\alpha) \) describe the dependence of variable \( X_\beta \) from \( X_\alpha \) determined on the basis of regression models. Taking into account these expressions, system (4) takes the form:

\[ \begin{align*}
\frac{dX_1}{dt} &= \text{Exper} - (0.3176 X_2 + 1.421) (0.09383 X_3 + 1.1098) (0.354 X_4 + 1.4926) \\
\frac{dX_2}{dt} &= (0.321 X_4 + 0.2349) (0.155 X_6 - 0.23) (0.3159 X_7 - 0.4636) 0.155 \left( \text{Res} + \text{For} + + \text{Price} \right) - (1.5727 X_8 - 0.411) (1.9307 X_9 - 0.7765) 0.155 \left( \text{Exper} + \text{Gov} \right) \\
\frac{dX_3}{dt} &= (0.7981 X_7 + 0.7458) 0.1 \text{Price} - (0.4889 X_1 - 1.5998) (0.4884 X_9 + 1.2446) \times \times 0.01 \left( \text{Exper} + \text{Gov} \right) \\
\frac{dX_4}{dt} &= (0.4616 X_2 + 0.4431) (0.9276 X_2 - 0.8953) 0.01 \text{For} - (0.4862 X_1 + + 0.3038) (0.7902 X_9 - 0.9651) 0.01 \left( \text{Exper} + \text{Gov} \right) \\
\frac{dX_5}{dt} &= (0.7039 X_2 + 1.1345) 0.01 \text{Gov} \\
\frac{dX_6}{dt} &= (0.00529 X_2 + 1.022) 0.01 \left( \text{For} - \text{Gov} \right) \\
\frac{dX_7}{dt} &= (0.059 X_2 + 0.9112) (0.00714 X_3 + 0.95) (0.064X_4 + 0.8986) 0.01 \left( \text{For} - \text{Exper} \right) \\
\frac{dX_8}{dt} &= (0.05865 X_2 + 0.9112) 0.05 \text{Gov} \\
\frac{dX_9}{dt} &= -((-0.08061 X_2 + 0.8845) (0.03905 X_3 + 0.9877) (0.097 X_4 + 0.859) 0.2 \text{Gov})
\end{align*} \]

where external factors:

\[ \begin{align*}
\text{Res} &= 1 + 0.7 \sin(t) \\
\text{Price} &= 0.25t^2 - 1.1t + 2 + 0.5t \sin(t) \\
\text{For} &= 0.1t^2 - 0.1t + 0.22 \\
\text{Exper} &= 0.3 + 0.7 \cos(t) \\
\text{Port} &= 0.1 + 0.1 \sin(t) \\
\text{Gov} &= 0.1t + 0.01
\end{align*} \]

for 2003-2004 years:

\[ \begin{align*}
\text{Res} &= 1 + 0.7 \sin(t) \\
\text{Price} &= 0.25t^2 - 1.1t + 2 + 0.5t \sin(t) \\
\text{For} &= 0.1t^2 - 0.1t + 0.22 \\
\text{Exper} &= 0.3 + 0.7 \cos(t) \\
\text{Port} &= 0.1 + 0.1 \sin(t) \\
\text{Gov} &= 0.1t + 0.27
\end{align*} \]

In the compilation of system equations, the values of variables and external factors are normalized for the corresponding year. Time is calculated by the number of years, for moment \( t=0 \), the year 2000 is adopted. The value of external factors (6 and 7) is substituted into the systems of equations (5). The obtained systems of nonlinear differential equations are solved by the fourth order Runge-Kutta method.

6. Analysis of solutions of the system of differential equations

Figure 2 shows the catastrophe chart of ATS for the time interval of 2000-2010, obtained on the basis of the solution of the system of equations (5) with external factors (6 and 7).

This chart does not have a clear tendency to a smooth decrease in the number of disasters. This means that the ever-increasing number of more economical foreign aircraft and increased training time of crews in simulators offset the impact of the cost of aviation fuel, which has a periodic component,
generally adversely affecting the number of catastrophes, during retraining and advanced training. Numerous changes in ATS occur simultaneously, chaotically balancing each other.

**Figure 2.** The graph of the number of disasters in the operation of ATS.
First column – data from official data from IAC; second column – data from model.

The smallest number $X_2$ was recorded in 2004, which is explained by the minimum frequency of incidents and the increased time spent on training pilots on certified simulators. The maximum value $X_2$ for 2006 is explained by the highest value of obsolete aircraft (over 15 years old), since 2006 this value (according to IAC statistics) has tended to decrease. The results of this analysis are supported by statistical data. Comparison of the data obtained with the help of the model with the statistical data of the IAC is shown in Figure 2.

7. Conclusion
A model of system dynamics has been developed that makes it possible to predict the safety parameters of ATS operation. Reflecting the interrelations between the variables of the system was prepared mathematical model of differential equations. The solution of system can be useful to analyse and predict the safety parameters of the ATS at specified intervals of their operation. The tendencies of the change in the predicted parameters are revealed, which is necessary to make managerial decisions to ensure the safety of ATS.

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