Experimental FMECA-based Assessing of the Critical Information Infrastructure Importance in Aviation

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Abstract. Up-to-date information and communication technologies (ICT) implementation in various industries, on the one hand, increases the efficiency of different business processes and, on the other hand, generates new threats and vulnerabilities in ICT. Critical infrastructures (CI) need principal new effective methods and means for cybersecurity ensuring. In the situation with limited resources, CI objects defining and ranking is an important task. To rank objectively, CI objects should be assessed using some criteria. Previously, authors have proposed a FMECA-based method to assess importance level for state critical information infrastructure, which allows ranking and evaluating the importance of CI objects using both quantitative and qualitative parameters. This paper presents a complex experimental study of the proposed method using the aviation industry as an example. An experimental technique was introduced and using it, the adequacy of method response to changing input data was checked. It confirmed the possibility of importance level assessment of critical aviation information systems related to various categories: information systems for air navigation services; on-board information systems for aircraft; information systems for airlines and airports.

Keywords: critical information infrastructure, importance level assessment, critical aviation information systems, experimental study, cybersecurity, aviation.

1 Introduction

Information and communication technologies (ICT) rapid development has led to significant and sometimes revolutionary changes in all spheres of people's lives in most states of the world. This has significantly increased the vulnerability of various networks, systems and ICT objects and has made it difficult to ensure their protection and security. All these factors have caused the world's leading states to pay significant attention to the protection of critical facilities, systems and resources, as well as to the identifying critical infrastructures (CI) [1-2], assessing their criticality level and impact of possible functional interruptions (failures). However, today there is no universal method that could be used to assess the criticality level of CI in different industries using both quantitative and qualitative parameters.

2 Related papers analysis

Increasing concentration of means and resources for protecting CI of different types necessitated the ranking of CI objects, the selection of the most important ones and the emergence of the CI concept [3-4]. ICT is important part of CI called critical information infrastructure (CII). In order to protect the most important CII objects, it is necessary to first identify these objects by certain criteria [5] and then determine the criticality (assess the importance) of the identified objects [6]. Particular attention needs to be given to aviation, where, in accordance with the guidance documents [7], so-called critical aviation information systems (CAIS) need to be identified and protected against various cyberthreats. In works [8-10] the FMECA-based (Failure Mode, Effects and Criticality Analysis) approach for assessing CII objects in different industries of CI was presented and studied.

3 Problem statement

In the study [1] authors have proposed a FMECA-based method of assessing the importance level of CII objects in aviation, which makes it possible to evaluate the importance level and to rank the CAIS [10]. This method uses the introduction of a basic set of systems and corresponding sets of subsystems, components, functions, violations of continuity of work (interruption of work, loss of functionality), their features and consequences, as well as the construction of a three-dimensional criticality matrix.

The main results of the implementation of the proposed method are presented in the form of a report, which summarizes such information as: a list of system components, their functions, types of interruptions for each component of the system; information on the causes and consequences of interruptions for each component of the system; calculations of criticality rankings, ranking results are a list of the most significant (critical) interruptions of work, which are displayed in a formalized and convenient for experts form. Other output data was obtained at different stages of the method implementation: criticality matrix, which according to the collected preliminary data graphically reflects the criticality of the system components (stage 7); Pareto diagram which shows the level of criticality inside the system and makes it possible to compare several different systems (stage 9); Ishikawa's cause and effect diagram that allows to identify priority areas for developing appropriate corrective measures (stage 10).

The previously proposed method by authors in [1] is implemented in the following stages: 1) identification of system components and setting the level of detail; 2) defining the functions of each detected system component; 3) determining the list of possible interruptions of each system component; 4) determining the consequences of each possible work interruption; 5) identification of interruption detection signs; 6) identification of methods for detecting work interruptions; 7) construction of a three-dimensional criticality matrix; 8) calculation of the criticality rank of probable interruptions; 9) selection of the list of the most significant (critical) work interruptions; 10) forming a list of corrective measures; 11) report generation.

The main task of this work is experimental study of method for importance level assessing of the CII objects in aviation (CAIS). This method was proposed by authors before [1] and it is based on FMECA technique with proposed improvements for effective quantitative and qualitative assessment.

4 The main part of the study

A. Experimental technique descryption

The first step of experimental research is the creation of *an experimental program*, which contains the following components:

1. The purpose and objectives of the experiment. The purpose of the experiment is to investigate the adequacy of the developed method.

Objectives:

1.1. Investigate the proposed method of assessing the importance of CII objects in aviation (by modeling its operation using developed software).

1.2. Check the adequacy of the developed method’s response to changing the input data.

1.3. Check the adequacy of the developed severity weight coefficients of the interruption consequences for the developed method.

2. Selection of input and output parameters:

2.1. Input parameters for solving problem 1.1. are: structural and functional diagrams of the analyzed system and its components; information on the functioning of each process or system component; a detailed description of all the parameters that may affect the functioning of the system; information about the results of work interruption; chronological work interruption data, including available work interruption intensity data. Output parameters: a report listing the types of interruptions for each system component; information on the causes and consequences of interruptions for each system component; criticality matrix; Pareto diagram; Ishikawa's cause and effect diagram; a list of corrective measures to reduce the criticality of the most significant work interruptions.

2.2. Input parameters for solving problem 1.2. are: a list of all types of system component interruptions and their estimated criticality level. Output parameters: summarized results of the study of each system interruptions.

2.3. Input parameters for solving problem 1.3 are: metrics tables B_{1i}, B_{2i}, B_{3i}, and calculated values for the weighting coefficients of work interruption consequences.

Output parameters: results of the study of the developed weight coefficients of work interruption consequences.

3. The order of actions:

3.1. Determining the set of system $\mathbf{C}$ components with the help of set of classes of systems $\mathbf{S}$, set of systems $\mathbf{S}_i$, set of subsystems $\mathbf{S}_{ij}$, and setting of level of detail $Det_{\min}$ (using accordingly (6), (1), (2) and (4) in [1]).

3.2. Determining the set of functions $\mathbf{F}$, and the set of work interruptions $\mathbf{D}$ (using accordingly (7) and (8) in [1]).

3.3. Determining the set of consequences $\mathbf{E}$, signs of detection $\mathbf{O}$, ways of detecting work interruptions $\mathbf{W}$ (using accordingly (9), (10) and (12) in [1]) and building a three-dimensional criticality matrix.

3.4. Calculating of the set of criticality ranks of possible interruptions $\mathbf{R}$, with the help of sets $\mathbf{B}_1, \mathbf{B}_2, \mathbf{B}_3$, selecting the list of most significant work interruptions $criticality\ (D_i)$, (using accordingly (13) – (18) in [1]), of set $\mathbf{VK}$ (see stage 8 of experimental research) and construction of the Pareto diagram.

3.5. Constructing a cause-and-effect diagram of Ishikawa, determining the set of corrective measures $\mathbf{K}$ and evaluating the effectiveness of implementing corrective measures by recalculating the criticality ranks $\mathbf{R}$ (using accordingly (19), (14) in [1]).

3.6. Systematizing data in a form of a report for all levels of analysis.

4. Choosing a factor change step.

S_{ijk} $(i=\overline{1,n},\ j=\overline{1,m_i},\ k=\overline{1,r_{ij}})$ according to (4) in [1]; C_i $(i=\overline{1,b})$ according to (6) in [1]; F_i $(i=\overline{1,l})$ according to (7) in [1]; D_i $(i=\overline{1,p})$ according to (8) in [1]; E_i $(i=\overline{1,q})$ according to (9) in [1]; O_i $(i=\overline{1,r})$ according to (10) in [1]; W_i $(i=\overline{1,s})$ according to (12) in [1]; R_i $(i=\overline{1,w})$ according to (13) in [1]; B_{1j} $(j=\overline{1,z})$ according to (15) in [1]; B_{2j} $(j=\overline{1,x})$ according to (16) in [1]; B_{3j} $(j=\overline{1,c})$ according to (17) in [1]; VK_{ij} $(i=\overline{1,n},\ j=\overline{1,m_i})$, (see stage 8 of experimental research); K_i $(i=\overline{1,g})$ according to (19) in [1].

5. Analyzing results.

The second step after the approval of the research plan is to determine the amount of experimental research and the necessary software.

The third step is the direct conduct of the experiment; the fourth step is the processing of experimental data, the systematization of all numerical data, the construction of matrices, diagrams and tables.

B. An experimental study of proposed method in aviation

Let`s consider in detail step by step of implementation of the proposed method study (one CAIS from each of the categories defined in work [12] are selected):

Stage 1*. *Identifying system components and setting the level of detail

<u>*Step 1.1*</u> For CAIS according to [12], with $n=3$ considering (1) in [13] we define the complete set of classes of CAIS systems as follows:

$$\mathbf{S}_{\mathrm{CAIS}} = \{\bigcup_{\mathbf{i}=1}^{3}\mathbf{S}_{\mathbf{i}}\} = \{\mathbf{S}_1, \mathbf{S}_2, \mathbf{S}_3\} = \{\mathbf{S}_{\mathrm{ISAO}}, \mathbf{S}_{\mathrm{BSPS}}, \mathbf{S}_{\mathrm{ISAA}}\}, \quad (1)$$

where $\mathbf{S}_1 = \mathbf{S}_{\mathrm{ISAO}}$ is set of information systems of air navigation services; $\mathbf{S}_2 = \mathbf{S}_{\mathrm{BSPS}}$ is set of onboard aircraft information systems; $\mathbf{S}_3 = \mathbf{S}_{\mathrm{ISAA}}$ is set of airline and airport information systems, according to [12].

Step 1.2. For example, with $n = 1$, $m_1 = 5$ while using (2) in [13], we present the set of systems of class $\mathbf{S}_1$ in the following way:

$$\mathbf{S}_1 = \mathbf{S}_{\mathrm{ISAO}} = \{\bigcup_{\mathrm{j}=1}^{5}\mathbf{S}_{1\mathrm{j}}\} = \{\mathbf{S}_{1.1}, \mathbf{S}_{1.2}, \mathbf{S}_{1.3}, \mathbf{S}_{1.4}, \mathbf{S}_{1.5}\} = \{\mathbf{S}_{\mathrm{SAE}}, \mathbf{S}_{\mathrm{RZZP}}, \mathbf{S}_{\mathrm{SSP}}, \mathbf{S}_{\mathrm{SOD}}, \mathbf{S}_{\mathrm{SMZ}}\}, \quad (2)$$

where $\mathbf{S}_{1.1} = \mathbf{S}_{\mathrm{SAE}}$ are aviation telecommunication systems; $\mathbf{S}_{1.2} = \mathbf{S}_{\mathrm{RZZP}}$ are radio navigation aids; $\mathbf{S}_{1.3} = \mathbf{S}_{\mathrm{SSP}}$ are surveillance systems; $\mathbf{S}_{1.4} = \mathbf{S}_{\mathrm{SOD}}$ are data processing systems; $\mathbf{S}_{1.5} = \mathbf{S}_{\mathrm{SMZ}}$ are meteorological support systems [12].

Similarly for sets of classes $\mathbf{S}_2$ and $\mathbf{S}_3$, with $n = 2$, $m_2 = 7$ and with $n = 3$, $m_3 = 4$ respectively, while using (2) in [13], we will present the set of systems, where $\mathbf{S}_{2.1} = \mathbf{S}_{\mathrm{SPS}}$ are air signal system; $\mathbf{S}_{2.2} = \mathbf{S}_{\mathrm{SZV}}$ are communication systems; $\mathbf{S}_{2.3} = \mathbf{S}_{\mathrm{NAVS}}$ are navigation systems; $\mathbf{S}_{2.4} = \mathbf{S}_{\mathrm{SSPZ}}$ are collision monitoring and prevention systems; $\mathbf{S}_{2.5} = \mathbf{S}_{\mathrm{OSL}}$ are computing systems of aviation; $\mathbf{S}_{2.6} = \mathbf{S}_{\mathrm{SVI}}$ are information display systems; $\mathbf{S}_{2.7} = \mathbf{S}_{\mathrm{ABSK}}$ are automatic onboard control systems; $\mathbf{S}_{3.1} = \mathbf{S}_{\mathrm{CRS}}$ is computer reservation system; $\mathbf{S}_{3.2} = \mathbf{S}_{\mathrm{GDS}}$ is global reservation system (reservation); $\mathbf{S}_{3.3} = \mathbf{S}_{\mathrm{BSP}}$ is mutual calculations system; $\mathbf{S}_{3.4} = \mathbf{S}_{\mathrm{DCS}}$ are dispatch management systems [12].

The sets of CAIS classes and systems according to [12], with $n = 1, n = 2, n = 3$ and $m_1 = 5, m_2 = 7, m_3 = 4$ taking into account (1) - (2) and (1) in [13] were determined in the following way:

$$\mathbf{S}_{\mathrm{CAIS}} = \{\mathbf{S}_1, \mathbf{S}_2, \mathbf{S}_3\} = \{\mathbf{S}_{\mathrm{ISAO}}, \mathbf{S}_{\mathrm{BSPS}}, \mathbf{S}_{\mathrm{ISAA}}\} =$$
$$= \{\{\mathbf{S}_{1.1}, \mathbf{S}_{1.2}, \mathbf{S}_{1.3}, \mathbf{S}_{1.4}, \mathbf{S}_{1.5}\}, \{\mathbf{S}_{2.1}, \mathbf{S}_{2.2}, \mathbf{S}_{2.3}, \mathbf{S}_{2.4}, \mathbf{S}_{2.5}, \mathbf{S}_{2.6}, \mathbf{S}_{2.7}\}, \{\mathbf{S}_{3.1}, \mathbf{S}_{3.2}, \mathbf{S}_{3.3}, \mathbf{S}_{3.4}, \mathbf{S}_{3.5}\}\} =$$
$$= \{\{\mathbf{S}_{\mathrm{SAE}}, \mathbf{S}_{\mathrm{RZZP}}, \mathbf{S}_{\mathrm{SSP}}, \mathbf{S}_{\mathrm{SOD}}, \mathbf{S}_{\mathrm{SMZ}}\}, \{\mathbf{S}_{\mathrm{SPS}}, \mathbf{S}_{\mathrm{SZV}}, \mathbf{S}_{\mathrm{NAVS}}, \mathbf{S}_{\mathrm{SSPZ}}, \mathbf{S}_{\mathrm{OSL}}, \mathbf{S}_{\mathrm{SVI}}, \mathbf{S}_{\mathrm{ABSK}}\}, \{\mathbf{S}_{\mathrm{CRS}}, \mathbf{S}_{\mathrm{GDS}}, \mathbf{S}_{\mathrm{IDS}}, \mathbf{S}_{\mathrm{BSP}}, \mathbf{S}_{\mathrm{DCS}}\}\}.$$

Step 1.3. To determine subsystem sets, we arbitrarily select one set of systems from each class, for example $\mathbf{S}_{\mathrm{SOD}}, \mathbf{S}_{\mathrm{SSPZ}}, \mathbf{S}_{\mathrm{GDS}}$ and according to (3) in [13] we present subsystem sets with $r_{1.4} = 5, r_{2.4} = 4, r_{3.2} = 18,$ and record the obtained data in table 1, where $S_{1.4.1} = S_{\mathrm{ASYPR}}$ are automated air traffic control systems (AATCS); $S_{1.4.2} = S_{\mathrm{SPPP}}$ are automated airspace use planning systems; $S_{1.4.3} = S_{\mathrm{ESAN}}$ are centralized surveillance and distribution systems for the surveillance data of the European Aviation Safety Organization Eurocontrol; $S_{1.4.4} = S_{\mathrm{SOPD}}$ are flight data processing and transmission systems; $S_{1.4.5} = S_{\mathrm{SOAD}}$ are aeronautical information processing and transmission systems; $S_{2.4.1} = S_{\mathrm{TRA}}$ are transponders; $S_{2.4.2} = S_{\mathrm{TCAS}}$ are onboard collision avoidance systems (TCAS); $S_{2.4.3} = S_{\text{SRPZ}}$ are early warning systems for dangerous land rapprochement; $S_{2.4.4} = S_{\text{BMR}}$ is airborne radar onboard; $S_{3.2.1} = S_{\text{AMDS}}$ is Amadeus; $S_{3.2.2} = S_{\text{TGDS}}$ is Travelport GDS; $S_{3.2.3} = S_{\text{SAB}}$ is Sabre; $S_{3.2.4} = S_{\text{TRES}}$ is TameliaRES; $S_{3.2.5} = S_{\text{APSS}}$ is Avantik PSS; $S_{3.2.6} = S_{\text{ABCS}}$ is Abacus; $S_{3.2.7} = S_{\text{ACA}}$ is AccelAero; $S_{3.2.8} = S_{\text{AXS}}$ is Axess; $S_{3.2.9} = S_{\text{IBE}}$ is Internet Booking Engine; $S_{3.2.10} = S_{\text{KUI}}$ is KIU; $S_{3.2.11} = S_{\text{MER}}$ is Mercator; $S_{3.2.12} = S_{\text{NAV}}$ is Navitaire; $S_{3.2.13} = S_{\text{PATH}}$ is Patheo; $S_{3.2.14} = S_{\text{RAD}}$ is Radixx; $S_{3.2.15} = S_{\text{AKF}}$ is Akeflite; $S_{3.2.16} = S_{\text{TTI}}$ is Travel Technology Interactive; $S_{3.2.17} = S_{\text{WSMS}}$ is WorldTicket Sell-More-Seats; $S_{3.2.18} = S_{\text{SIR}}$ is Siren according to [12].

Table 1. Presentation of the subsystems set

System	Value r_{ij}	Subsystems set	Name of subsystems set
$\mathbf{S}_{\text{SOD}}$	$r_{1.4} = 5,$	$S_{1.4.1}, S_{1.4.2}, S_{1.4.3}, S_{1.4.4}, S_{1.4.5}$	$S_{\text{ASYPR}}, S_{\text{SPPP}}, S_{\text{ESAN}}, S_{\text{SOPD}}, S_{\text{SOAD}}$
$\mathbf{S}_{\text{SSPZ}}$	$r_{2.4} = 4,$	$S_{2.4.1}, S_{2.4.2}, S_{2.4.3}, S_{2.4.4}$	$S_{\text{TRA}}, S_{\text{TCAS}}, S_{\text{SRPZ}}, S_{\text{BMR}}$
$\mathbf{S}_{\text{GDS}}$	$r_{3.2} = 18,$	$S_{3.2.1}, S_{3.2.2}, S_{3.2.3}, S_{3.2.4}, S_{3.2.5}, S_{3.2.6},$ $S_{3.2.7}, S_{3.2.8}, S_{3.2.9}, S_{3.2.10}, S_{3.2.11}, S_{3.2.12},$ $S_{3.2.13}, S_{3.2.14}, S_{3.2.15}, S_{3.2.16}, S_{3.2.17}, S_{3.2.18}$	$S_{\text{AMDS}}, S_{\text{TGDS}}, S_{\text{SAB}}, S_{\text{TRES}}, S_{\text{APSS}}, S_{\text{ABCS}},$ $S_{\text{ACA}}, S_{\text{AXS}}, S_{\text{IBE}}, S_{\text{KUI}}, S_{\text{MER}}, S_{\text{NAV}},$ $S_{\text{PATH}}, S_{\text{RAD}}, S_{\text{AKF}}, S_{\text{TTI}}, S_{\text{WSMS}}, S_{\text{SIR}}$

Step 1.4. To determine the set of components, we arbitrarily select one subsystem from each set of subsystems (Table 1), for example S_{SOAD}, S_{TCAS}, S_{AMDS}.

For system S_{SOAD}, with $b = 7$, while using (4) in [13], we present the set of components in the following way:

$$\mathbf{C}_{\text{SOAD}} = \{\bigcup_{i=1}^{7} C_i\} = \{C_1, C_2, ..., C_7\} = \{C_{\text{ODSS}}, C_{\text{OPD}}, C_{\text{MKS}}, C_{\text{ZVI}}, C_{\text{KGZ}}, C_{\text{PPR}}, C_{\text{ZBP}}\},$$

where $C_1 = C_{\text{ODSS}}$ is data processing of the surveillance system; $C_2 = C_{\text{OPD}}$ is flight data processing; $C_3 = C_{\text{MKS}}$ is system monitoring and control; $C_4 = C_{\text{ZVI}}$ is recording and reproduction of information; $C_5 = C_{\text{KGZ}}$ is commutation of voice communication; $C_6 = C_{\text{PPR}}$ is decision support; $C_7 = C_{\text{ZBP}}$ is ensuring the safety of flights.

Similarly for systems S_{TCAS} according to [14], and S_{AMDS} according to [15-16], with $b = 5$ та $b = 4$ while using (4) in [13] respectively, we present the set of components (Table 2), where $C_8 = C_{\text{ANT}}$ are antennas; $C_9 = C_{\text{BLO}}$ is calculator unit; $C_{10} = C_{\text{VRS}}$ is respondent mode S; $C_{11} = C_{\text{IND}}$ are indicators (installed in the cockpit); $C_{12} = C_{\text{PYL}}$ is control panel; $C_{13} = C_{\text{ATIM}}$ is Amadeus Timetable; $C_{14} = C_{\text{AAV}}$ is Amadeus availability; $C_{15} = C_{\text{ASCH}}$ are Amadeus schedules; $C_{16} = C_{\text{ADA}}$ is Amadeus direct access.

Table 2. Presentation of the set of components

System / Subsystem	Set of subsystem components	Value of b	Subsystem components	Name of subsystem components
S_{SOAD}	$\mathbf{C}_{\text{SOAD}}$	7	$C_1, C_2, ..., C_7$	$C_{\text{ODSS}}, C_{\text{OPD}}, ..., C_{\text{ZBP}}$
S_{TCAS}	$\mathbf{C}_{\text{TCAS}}$	5	$C_8, C_9, ..., C_{12}$	$C_{\text{ANT}}, C_{\text{BLO}}, ..., C_{\text{PYL}}$
S_{AMDS}	$\mathbf{C}_{\text{AMDS}}$	4	$C_{13}, C_{14}, ..., C_{16}$	$C_{\text{ATIM}}, C_{\text{AAV}}, ..., C_{\text{ADA}}$

<u>*Step 1.5.*</u> Let us set the minimum level of detail $Det_{\min}$ to describe and decompose the system. The purpose of the analysis $\mathbf{S}_{ij} / S_{ijk}$ is to determine the level of criticality of possible types of components interruptions that cause loss of their functionality, to find out their causes, consequences, methods of detection and recommendations for reducing their criticality.

Therefore, the description and decomposition are limited by level "system class" / "system" / "subsystem" / "component" $(\mathbf{S}_i / \mathbf{S}_{ij} / S_{ijk} / C_i)$ and concern only the effects of possible interruptions of certain components C_i. Meaning that $Det_{\min} = C_i$, however, a more detailed study of the more complex components (subsystems) of CAIS may consider the case of $Det_{\min} = C_{ij}$, where C_{ij} are parts of components C_i $\left(Det_{\min} = S_{ij} \vee S_{ijk} \vee C_i / C_{ij}\right)$ etc.

The selected systems are limited by level $\mathbf{S}_{\text{ISAO}} / \mathbf{S}_{\text{SOD}} / S_{\text{SOAD}} / \mathbf{C}_{\text{SOAD}}$; $\mathbf{S}_{\text{BSPS}} / \mathbf{S}_{\text{SSPZ}} / S_{\text{TCAS}} / \mathbf{C}_{\text{TCAS}}$; $\mathbf{S}_{\text{ISAA}} / \mathbf{S}_{\text{GDS}} / S_{\text{AMDS}} / \mathbf{C}_{\text{AMDS}}$ i and concern only the effects of possible interruptions of certain components C_i.

Stage 2. Defining the functions of each detected system component. For system S_{SOAD}, containing a set of components $\mathbf{C}_{\text{SOAD}}$, with $l = 15$, while using (5) in [13], we present the set of functions in the following way:

$$\mathbf{F}_{\text{SOAD}} = \{\bigcup_{i=1}^{15} F_i\} = \left\{F_1, F_2, ..., F_{15}\right\} =$$

$$= \left\{F_{\text{OSG}}, F_{\text{POI}}, F_{\text{VOI}}, F_{\text{OPD}}, F_{\text{KPOL}}, F_{\text{PPAT}}, F_{\text{VYI}}, F_{\text{DVI}}, F_{\text{ZDGZ}}, F_{\text{APR}}, F_{\text{PZIT}}, F_{\text{VPI}}, F_{\text{VVKS}}, F_{\text{PAP}}, F_{\text{ZBP}}\right\},$$

where $F_1 = F_{\text{OSG}}$ is signal processing; $F_2 = F_{\text{POI}}$ is primary information processing; $F_3 = F_{\text{VOI}}$ is secondary information processing; $F_4 = F_{\text{OPD}}$ is flight data processing; $F_5 = F_{\text{KPOL}}$ is flight control; $F_6 = F_{\text{PPAT}}$ is air patrol; $F_7 = F_{\text{VYI}}$ is display and management of information; $F_8 = F_{\text{DVI}}$ is documentation and reproduction of information; $F_9 = F_{\text{ZDGZ}}$ is providing air traffic controllers with land and voice communications; $F_{10} = F_{\text{APR}}$ is automation of decision making; $F_{11} = F_{\text{PZIT}}$ is collision prevention; $F_{12} = F_{\text{VPI}}$ is use of planned information; $F_{13} = F_{\text{VVKS}}$ is identifying and resolving potential conflict situations; $F_{14} = F_{\text{PAP}}$ is aviation events warning; $F_{15} = F_{\text{ZBP}}$ is ensuring the safety of flights [12].

Similarly for systems S_{TCAS} according to [14] and S_{AMDS} according to [16], sets of components $\mathbf{C}_{\text{TCAS}}$ and $\mathbf{C}_{\text{AMDS}}$, with $l = 14$ and $l = 4$, while using (5) in [13], we present sets of functions (Table 3), where $F_{16} = F_{\text{PPR}}$ are receiving and transmitting radio waves; $F_{17} = F_{\text{ZIL}}$ is request of other aircraft responders; $F_{18} = F_{\text{OMRL}}$ is calculating the location of aircraft; $F_{19} = F_{\text{VTL}}$ is aircraft trajectory tracking; $F_{20} = F_{\text{PPRD}}$ is transmitting warnings and recommendations on the VSI / TRA display or other indicators; $F_{21} = F_{\text{PMPP}}$ is the transmission of voice messages to the pilot through the airplane located in the cockpit of the sound notification system; $F_{22} = F_{\text{VNZ}}$ is responding to requests in Mode-A, Mode-C and Mode-S from radar systems of the air traffic control service, as well as from other aircraft equipped with TCAS; $F_{23} = F_{\text{ODSS}}$ is data exchange with compatible systems; $F_{24} = F_{\text{VPZ}}$ is establish a direct connection using a unique address assigned; $F_{25} = F_{\text{PDBV}}$ is transfer of data from the barometric height sensor and from the control panel to the TCAS computer unit; $F_{26} = F_{\text{VVI}}$ is display of vertical speed indicator (VSI) information with the display of air-condition warnings and recommendations for conflict resolution (TRA); $F_{27} = F_{\text{YRT}}$ is setting TCAS mode and responding mode-S; $F_{28} = F_{\text{YKV}}$ is setting the UPR radar response codes; $F_{29} = F_{\text{PRS}}$ is system operation check; $F_{30} = F_{\text{PIZ}}$ is providing (general) flight information on all airlines during the week; $F_{31} = F_{\text{FIPP}}$ is generating flight information that has at least one available class for sale or a waiting list; $F_{32} = F_{\text{VGVR}}$ is display all scheduled flights; $F_{33} = F_{\text{MODI}}$ is the ability to access specific airline information for sale or to complete a waitlist.

Table 3. Presentation of the set of functions

System / Subsystem	Set of subsystem components	Value of l	Functions of components sets	Names of functions of components sets
S_{SOAD}	$\mathbf{C}_{\text{SOAD}}$	*15*	$F_1, F_2, ..., F_{15}$	$F_{\text{OSG}}, F_{\text{POI}}, ..., F_{\text{ZBP}}$
S_{TCAS}	$\mathbf{C}_{\text{TCAS}}$	*14*	$F_{16}, F_{17}, ..., F_{29}$	$F_{\text{PPR}}, F_{\text{ZIL}}, ..., F_{\text{PRS}}$
S_{AMDS}	$\mathbf{C}_{\text{AMDS}}$	*4*	$F_{30}, F_{31}, ..., F_{33}$	$F_{\text{PIZ}}, F_{\text{FIPP}}, ..., F_{\text{MODI}}$

Stage 3. Determining the list of possible interruptions of each system component. For system S_{SOAD} set of components $\mathbf{C}_{\text{SOAD}}$, with $p = 9$, while using (6) in [13], we present the set of work interruptions in the following way:

$$\mathbf{D}_{\text{SOAD}} = \{\bigcup_{i=1}^{9} D_i\} = \{D_1, D_2, ..., D_9\} = \{D_{\text{VNIS}}, D_{\text{NOPS}}, D_{\text{PFOD}}, D_{\text{PNI}}, D_{\text{VZZ}}, D_{\text{NSD}}, D_{\text{VRTZ}}, D_{\text{VPKS}}, D_{\text{VAF}}\},$$

where $D_1 = D_{\text{VNIS}}$ is detecting a nonexistent signal; $D_2 = D_{\text{NOPS}}$ is incorrect estimation of signal parameters; $D_3 = D_{\text{PFOD}}$ is data processing and distribution breaches; $D_4 = D_{\text{PNI}}$ is suspension of receipt of information on flights of aircraft; $D_5 = D_{\text{VZZ}}$ is loss or destruction of a recording device; $D_6 = D_{\text{NSD}}$ is unauthorized access to the recording device; $D_7 = D_{\text{VRTZ}}$ is loss of radio or telephone communication with crews, related dispatch points and other traffic participants;

$D_8 = D_{\text{VPKS}}$ is the occurrence of potential conflict situations of the PCC; $D_9 = D_{\text{VAF}}$ is detection of an emergency factor [14].

Similarly for systems S_{TCAS} according to [14] and S_{AMDS} according to [15-16], set of components $\mathbf{C}_{\text{TCAS}}$ and $\mathbf{C}_{\text{AMDS}}$, with $p = 9$ and $p = 17$ respectively, while using (6) in [13], we present the set of work interruptions (Table 4), де $D_{10} = D_{\text{VNA}}$ is directional antenna failure; $D_{11} = D_{\text{VOBS}}$ is failure of the system computing unit; $D_{12} = D_{\text{TCF}}$ is "TCAS FAIL", if there is a failure of the equipment that is the minimum required for the operation of the TCAS system; $D_{13} = D_{\text{XPF}}$ is "XPNDR FAIL" failure of the respondant mode-S, occurs in the event of termination of the receipt of reliable data on the altitude from the barometric altimeter on the respondant mode-S; $D_{14} = D_{\text{TCO}}$ is "TCAS OFF" (TCAS system is disabled, or problems occur inside the system; $D_{15} = D_{\text{VSF}}$ is "VSI FAIL" (failure of the vertical speed indicator), when the vertical speed arrow is not displayed on the VSI display; $D_{16} = D_{\text{TDF}}$ is "TD FAIL" (failure of air condition indicator) appears when the system TCAS-2000 is unable to display air warnings; $D_{17} = D_{\text{RAF}}$ is "RA FAIL" (refusal to issue RA messages) appears when TCAS system is unable to display recommendations for resolving a conflict situation; $D_{18} = D_{\text{NPY}}$ is malfunction or failure of the control panel; $D_{19} = D_{\text{ZSD}}$ is failure to update dates (periods); $D_{20} = D_{\text{NIPA}}$ is incompleteness of information about airlines; $D_{21} = D_{\text{NZI}}$ is providing outdated information; $D_{22} = D_{\text{NNI}}$ is unreliability of the information provided; $D_{23} = D_{\text{NIMP}}$ is failure to provide landing information (only schedule is displayed, regardless of availability); $D_{24} = D_{\text{VMPK}}$ is the inability to buy a ticket unless the airline has an agreement to sell with Amadeus; $D_{25} = D_{\text{NZD}}$ is inability to find airline information to alert you to potential threats or to obtain necessary information.

Table 4. Presentation of sets of work interruptions

System / Subsystem	Set of subsystem components	Value of p	Work interruptions	Names of work interruptions
S_{SOAD}	$\mathbf{C}_{\text{SOAD}}$	9	$D_1, D_2, ..., D_9$	$D_{\text{VNIS}}, D_{\text{NOPS}}, ..., D_{\text{VAF}}$
S_{TCAS}	$\mathbf{C}_{\text{TCAS}}$	9	$D_{10}, D_{11}, ..., D_{18}$	$D_{\text{VNA}}, D_{\text{VOBS}}, ..., D_{\text{NPY}}$
S_{AMDS}	$\mathbf{C}_{\text{AMDS}}$	7	$D_{19}, D_{20}, ..., D_{25}$	$D_{\text{ZSD}}, D_{\text{NIPA}}, ..., D_{\text{NZD}}$

Stage 4. Determining the consequences of each possible work interruption. For each possible work interruption of the set $\mathbf{D}_{\text{SOAD}}$ with $q = 10$, while using (7) in [13], we present the set of interruption consequences in the following way:

$$\mathbf{E}_{\text{SOAD}} = \{\bigcup_{i=1}^{10} E_i\} = \{E_1, E_2, ..., E_{10}\} = \{E_{\text{NPR}}, E_{\text{PRSY}}, E_{\text{VVPS}}, E_{\text{VRLP}}, E_{\text{NODD}}, E_{\text{VRTZ}}, E_{\text{PRVZ}}, E_{\text{VNM}}, E_{\text{ZPS}}, E_{\text{PRS}}\},$$

where $E_1 = E_{\text{NPR}}$ is wrong decision-making, due to incorrect analysis of the air situation; $E_2 = E_{\text{PRSY}}$ is malfunction of control systems, power supply, communication, piloting, lack of fuel, interruptions in the life support of the crew and passengers, failure of engines, destruction of individual aircraft structures; $E_3 = E_{\text{VVPS}}$ is lack of ability to track aircraft; $E_4 = E_{\text{VRLP}}$ is loss of opportunity to investigate a flight incident FI; $E_5 = E_{\text{NODD}}$ is inability to evaluate the actions of the operator; $E_6 = E_{\text{VRTZ}}$ is no radio or telephone connection; $E_7 = E_{\text{PRVZ}}$ is violation of recommendations on solving the collision threat; $E_8 = E_{\text{VNM}}$ is choosing the wrong maneuver; $E_9 = E_{\text{ZPS}}$ are aircraft collisions; $E_{10} = E_{\text{PRS}}$ is malfunction of control systems, power supply, communication, piloting, lack of fuel, interruptions in the life support of the crew and passengers, failure of engines, destruction of individual aircraft structures [14].

Similarly, for each possible work interruption of sets $\mathbf{D}_{\text{TCAS}}$ according to [14] and $\mathbf{D}_{\text{AMDS}}$ according to [16], with $q = 3$ and $q = 6$ respectively, while using (7) in [13], we present the set of work interruptions (Table 5), where $E_{11} = E_{\text{NVVP}}$ is TCAS 2000 system may be temporarily unable to determine the relative bearing of the conflicting aircraft due to the large roll angle, which causes the directional antenna to shade; $E_{12} = E_{\text{NVP}}$ is inability to display recommendations for conflict resolution; $E_{13} = E_{\text{NVPY}}$ is inability to use the control panel accordingly; $E_{14} = E_{\text{NRS}}$ is system inability to work in real time; $E_{15} = E_{\text{VIA}}$ is lack of information on airlines; $E_{16} = E_{\text{NOOI}}$ is inability to get online flight booking information; $E_{17} = E_{\text{MZGP}}$ is a possible malfunction in the flight schedule or the need to reformat it; $E_{18} = E_{\text{VPZD}}$ are problems with refueling, the possibility of a collision threat; $E_{19} = E_{\text{NSP}}$ is lack of awareness of employees, which could lead to the wrong decision.

Table 5. Presentation of the sets of work interruptions

Work interruption	Value of q	Work interruption consequences	Names of work interruption consequences
$\mathbf{D}_{\text{SOAD}}$	*10*	$E_1, E_2, ..., E_{10}$	$E_{\text{NPR}}, E_{\text{PRSY}}, ..., E_{\text{PRZ}}$
$\mathbf{D}_{\text{TCAS}}$	*3*	E_{11}, E_{12}, E_{13}	$E_{\text{NVVP}}, E_{\text{NVP}}, E_{\text{NVPY}}$
$\mathbf{D}_{\text{AMDS}}$	*6*	$E_{14}, E_{15}, ..., E_{19}$	$E_{\text{NRS}}, E_{\text{VIA}}, ..., E_{\text{NSP}}$

Stage 5. Identifying signs of work interruption detection. For possible work interruptions $\mathbf{D}_{\text{SOAD}}$, while using (8)-(9) in [13], with $r = 0$ (the selected set of interruptions of work did not show any sign O_i), and for the set $\mathbf{D}_{\text{TCAS}}$, according to [14] and $\mathbf{D}_{\text{AMDS}}$, according to [15-16], with $r = 1$ and $r = 3$ respectively, while using (8)-(9) in [13], we present the set of signs of work interruption detection (Table 6) in the following way (3):

$$\mathbf{O} = \{\bigcup_{i=1}^{4} O_i\} = \{O_1, O_2, ..., O_4\} = \{O_{VSI}, O_{TIM}, O_{AUS}, O_{SCH}\}, \tag{3}$$

where $O_1 = O_{\text{VSI}}$ is VSI/TRA display; $O_2 = O_{\text{TIM}}$ is Timetable (general schedule screen); $O_3 = O_{\text{AUS}}$ is Amadeus Access Update/Amadeus Access Sell; $O_4 = O_{\text{SCH}}$ is Schedule (schedule screen).

Taking into account (9) in [13], $E(O_{\text{VSI}}, D_i) = E(O_{\text{TIM}}, D_i) = E(O_{\text{AUS}}, D_i) = E(O_{\text{SCH}}, D_i) = 1$.

Table 6. Presentation of the set of signs of work interruption detection

Work interruption	Value of r	Work interruption consequences	Names of work interruption consequences
$\mathbf{D}_{\text{TCAS}}$	1	O_1	O_{VSI}
$\mathbf{D}_{\text{AMDS}}$	3	O_2, O_3, O_4	$O_{\text{TIM}}, O_{\text{AUS}}, O_{\text{SCH}}$

Stage 6. Identifying ways of detecting work interruptions. For each possible work interruption of the set $\mathbf{D}_{\text{SOAD}}$ according to [13], $\mathbf{D}_{\text{TCAS}}$ according to [14] and $\mathbf{D}_{\text{AMDS}}$ according to [15], while using (10) in [13], with $s = 7$, $s = 1$, $s = 1$ respectively, we present the set of ways of detecting work interruptions (Table 7) in the following way:

$$\mathbf{W}_{\text{SOAD}} = \{\bigcup_{i=1}^{9} W_i\} = \{W_1, W_2, W_3, W_4, W_5, W_6, W_7, W_8, W_9\} = \\ = \{W_{\text{SAZS}}, W_{\text{SOPD}}, W_{\text{ASAZ}}, W_{\text{BBRP}}, W_{\text{SGZ}}, W_{\text{AZS}}, W_{\text{SZBP}}, W_{\text{TCAS}}, W_{\text{AAIR}}\} \quad (4)$$

where $W_1 = W_{\text{SAZS}}$ is automatic dependent surveillance systems; $W_2 = W_{\text{SOPD}}$ is flight data processing system (FDPS); $W_3 = W_{\text{ASAZ}}$ are automated aviation security systems; $W_4 = W_{\text{BBRP}}$ are on-board multi-channel “black box” flight recorders; $W_5 = W_{\text{SGZ}}$ are voice communication systems; $W_6 = W_{\text{AZS}}$ are automated surveillance, communications, information processing and on-board collision avoidance systems; $W_7 = W_{\text{SZBP}}$ are flight safety systems; $W_8 = W_{\text{TCAS}}$ are TCAS system; $W_8 = W_{\text{AAIR}}$ is Amadeus AIR.

Table 7. Presentation of the set of ways to detect interruptions

Work interruption	Value of s	Work interruption consequences	Names of work interruption consequences
$\mathbf{D}_{\text{SOAD}}$	*7*	$W_1, W_2, ..., W_7$	$W_{\text{SAZS}}, W_{\text{SOPD}}, ..., W_{\text{SZBP}}$
$\mathbf{D}_{\text{TCAS}}$	*1*	W_8	W_{TCAS}
$\mathbf{D}_{\text{AMDS}}$	*1*	W_9	W_{AAIR}

Stage 7. Construction of a three-dimensional criticality matrix. For the system S_{SOAD} we form a criticality table according to such parameters as “probability – weight – number of interruptions of system operation” and construct a three-dimensional criticality matrix (Fig. 1 a). Similarly, for systems S_{TCAS} and S_{AMDS} we

form a criticality table and construct a three-dimensional matrix (Fig. 1 b and Fig. 1 c, respectively).

Stage 8. Calculation of the criticality rank of probable interruptions

<u>*Step 8.1.*</u> For the S_{SOAD} system, work interruptions $D_1 = D_{\text{VNIS}}$, let's define an indicator B_{1j} (frequency assessment) as (13) in [13], where value of z is going to be found according to table 5 in [1]. Thus let's define an indicator $B_1 = 5$. Similarly, for every possible work interruption of S_{SOAD}, S_{TCAS} and S_{AMDS} systems, let's define an indicator B_{1j} as (13) in [13], table. 5 in [1] and add obtained figures to the report (stage 11, table 11).

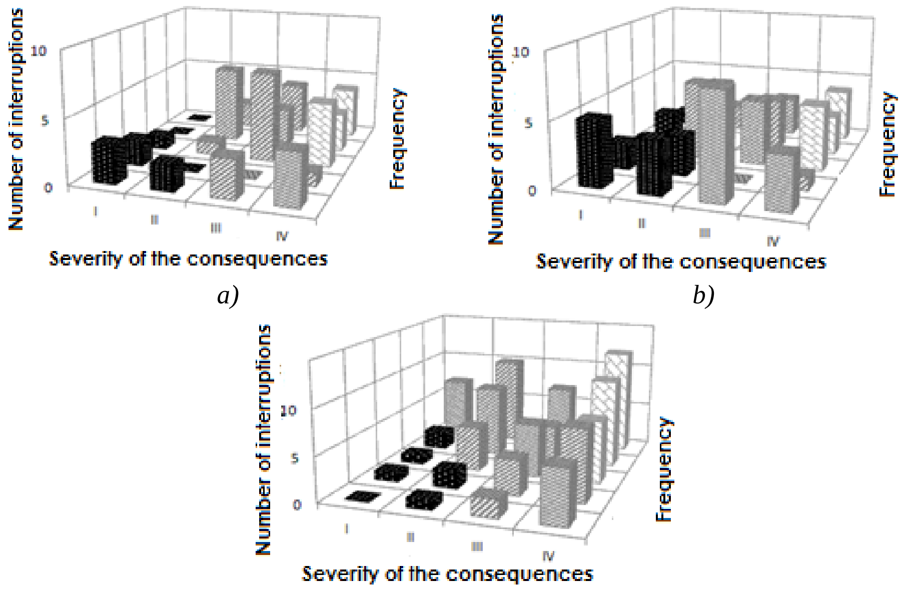

Fig. 1. Three-dimensional criticality matrix for S_{SOAD} (a), S_{TCAS} (b) and S_{AMDS} (c)

<u>*Step 8.2.*</u> For the S_{SOAD} system, work interruptions $D_1 = D_{\text{VNIS}}$, let's define an indicator B_{2j} (probability assessment of D_i component detection of C_i before it's appearance) as (14) in [13], where x value is found similarly according to table 7 in [1]. Therefore, let's define an indicator $B_2 = 4$. Similarly, for every possible interruption of systems S_{SOAD}, S_{TCAS} and S_{AMDS}, let's define an indicator B_{2j} as (14) in [13], table 7 in [1] and add obtained figures to the report (stage 11, table 11).

<u>*Step 8.3.*</u> For the S_{SOAD} system, work interruptions $D_1 = D_{\text{VNIS}}$, let's define an indicator B_{3j} (weight assessment of D_i component of C_i) as (15) in [13], where c value is found similarly according to table 9 in [1]. Therefore, let's define an indicator $B_3' = 7$. Similarly, for every possible interruption of S_{SOAD}, S_{TCAS} and

S_{AMDS} systems, let's define an indicator B_3' as (15) in [13], table 9 in [1] and add obtained figures to the report (stage 11, Table 11).

<u>*Stage 8.4.*</u> Calculation of values for the weighting coefficients of work interruption consequences. Mentioned coefficients are introduced according to [18].

Step 8.4.1. For example, for the weighting coefficients of work interruption consequences according to [18], having $n = 7$ considering (16) in [13], let's define a complete set of criteria of weighting coefficients as follows (5):

$$\mathbf{VK} = \{\bigcup_{i=1}^{7} \mathbf{VK}_i\} = \{\mathbf{VK}_1, \mathbf{VK}_2, ..., \mathbf{VK}_7\} = \tag{5}$$
$$= \{\mathbf{VK}_{\text{KZG}}, \mathbf{VK}_{\text{EKON}}, \mathbf{VK}_{\text{VNNS}}, \mathbf{VK}_{\text{POLN}}, \mathbf{VK}_{\text{MZT}}, \mathbf{VK}_{\text{TRV}}, \mathbf{VK}_{\text{VSKI}}\},$$

where $\mathbf{VK}_1 = \mathbf{VK}_{\text{KZG}}$ is number of citizens involved (health and social consequences); $\mathbf{VK}_2 = \mathbf{VK}_{\text{EKON}}$ is economic effect; $\mathbf{VK}_3 = \mathbf{VK}_{\text{VNNS}}$ is impact on the environment; $\mathbf{VK}_4 = \mathbf{VK}_{\text{POLN}}$ is political implications; $\mathbf{VK}_5 = \mathbf{VK}_{\text{MZT}}$ is territorial reach; $\mathbf{VK}_6 = \mathbf{VK}_{\text{TRV}}$ is duration; $\mathbf{VK}_7 = \mathbf{VK}_{\text{VSKI}}$ is interdependence of sectors CI (the consequence of the destruction of one is the destruction of the others) according to [18].

It also should be noted that, criteria of weighting coefficients of work interruption consequences are placed from most important – "7" to least important – "1".

Step 8.4.2. For example, if $n = 1$, $m_1 = 5$ using (17) in [13], let's represent the set of coefficients $\mathbf{VK}_1$ as follows:

$$\mathbf{VK}_1 = \mathbf{VK}_{\text{KZG}} = \{\bigcup_{\text{j}=1}^{5} VK_{1\text{j}}\} = \{VK_{1.1}, VK_{1.2}, VK_{1.3}, VK_{1.4}, VK_{1.5}\} =$$
$$= \{VK_{0-5}, VK_{6-20}, VK_{\text{D100}}, VK_{\text{D499}}, VK_{\text{B500}}\},$$

where $VK_{1.1} = VK_{0-5}$ is 0-5 deceased; $VK_{1.2} = VK_{6-20}$ is 6-20 deceased; $VK_{1.3} = VK_{\text{D100}}$ is 21-100 deceased; $VK_{1.4} = VK_{\text{D499}}$ is 101-499 deceased; $VK_{1.5} = VK_{\text{B500}}$ is $\geq$ 500 according to [18].

Similarly, for sets of coefficients $\mathbf{VK}_2, \mathbf{VK}_2, ..., \mathbf{VK}_7$, if $n = \overline{2,7}$ and $m_2 = m_3 = m_4 = m_5 = 5$ accordingly, using (17) in [13] let's represent all sets of coefficients and add them to the table 8, where $VK_{2.1} = VK_{\text{D100M}}$ is < 100 mil.; $VK_{2.2} = VK_{\text{D499M}}$ is 100-499 mil.; $VK_{2.3} = VK_{\text{D2,9M}}$ is 500 mil. – 2,9 bil.; $VK_{2.4} = VK_{\text{D6,9M}}$ is 2,9 bil. – 6,9 bil.; $VK_{2.5} = VK_{\text{B7M}}$ is > 7 bil.; $VK_{3.1} = VK_{\text{M1G}}$ is <1 ha. or 0,0001% of water resources; $VK_{3.2} = VK_{\text{D10G}}$ is 1-10 ha, or 0,0001-0,001 % of water resources; $VK_{3.3} = VK_{\text{D100G}}$ is 10-100 ha, or 0,001-0,01 % of water resources; $VK_{3.4} = VK_{\text{D1000G}}$ is 100-1000 ha, or 0,01 - 0,1 % of water resources; $VK_{3.5} = VK_{\text{B1000G}}$ is > 1000 ha, or > 0,1 % of water resources; $VK_{4.1} = VK_{\text{MIN}}$ is minimal; $VK_{4.2} = VK_{\text{SOCN}}$ is social discontent; $VK_{4.3} = VK_{\text{MITG}}$ are rallies, protests; $VK_{4.4} = VK_{\text{MASZ}}$ are riots; $VK_{4.5} = VK_{\text{REV}}$ are revolutions, wars; $VK_{5.1} = VK_{\text{OBYD}}$ is separate building; $VK_{5.2} = VK_{\text{SEL}}$ is village; $VK_{5.3} = VK_{\text{RGN}}$ is district, city; $VK_{5.4} = VK_{\text{OBL}}$

is region; $VK_{5.5} = VK_{\text{DER}}$ is country; $VK_{6.1} = VK_{\text{DGOD}}$ is less than an hour; $VK_{6.2} = VK_{\text{DOBA}}$ is day; $VK_{6.3} = VK_{\text{3DOB}}$ are 3 days; $VK_{6.4} = VK_{\text{5DOB}}$ are 5 days; $VK_{6.5} = VK_{\text{10DIB}}$ are 10 days; $VK_{7.1} = VK_{\text{MVID}}$ is almost no; $VK_{7.2} = VK_{\text{NVR}}$ are causes no destruction; $VK_{7.3} = VK_{\text{VR1S}}$ are causes destruction of one sector; $VK_{7.4} = VK_{\text{VR2S}}$ are causes destruction of two sectors; $VK_{7.5} = VK_{\text{VR3S}}$ are causes destruction of three and more sectors [18].

Table 8. Sets of coefficients representation

Weighting coefficients	Coefficients' names	Value m_i	Set of coefficients	Names' of sets of coefficients
$\mathbf{VK}_1$	$\mathbf{VK}_{\text{KZG}}$		$VK_{1.1}, VK_{1.2}, VK_{1.3}, VK_{1.4}, VK_{1.5}$	$VK_{0-5}, VK_{6-20}, VK_{\text{D100}}, VK_{\text{D499}}, VK_{\text{B500}}$
$\mathbf{VK}_2$	$\mathbf{VK}_{\text{EKON}}$		$VK_{2.1}, VK_{2.2}, VK_{2.3}, VK_{2.4}, VK_{2.5}$	$VK_{\text{D100M}}, VK_{\text{D499M}}, VK_{\text{D2,9M}}, VK_{\text{D6,9M}}, VK_{\text{B7M}}$
$\mathbf{VK}_3$	$\mathbf{VK}_{\text{VNNS}}$		$VK_{3.1}, VK_{3.2}, VK_{3.3}, VK_{3.4}, VK_{3.5}$	$VK_{\text{M1G}}, VK_{\text{D10G}}, VK_{\text{D100G}}, VK_{\text{D1000G}}, VK_{\text{B1000G}}$
$\mathbf{VK}_4$	$\mathbf{VK}_{\text{POLN}}$	5	$VK_{4.1}, VK_{4.2}, VK_{4.3}, VK_{4.4}, VK_{4.5}$	$VK_{\text{MIN}}, VK_{\text{SOCN}}, VK_{\text{MITG}}, VK_{\text{MASZ}}, VK_{\text{REV}}$
$\mathbf{VK}_5$	$\mathbf{VK}_{\text{MZT}}$		$VK_{5.1}, VK_{5.2}, VK_{5.3}, VK_{5.4}, VK_{5.5}$	$VK_{\text{OBYD}}, VK_{\text{SEL}}, VK_{\text{RGN}}, VK_{\text{OBL}}, VK_{\text{DER}}$
$\mathbf{VK}_6$	$\mathbf{VK}_{\text{TRV}}$		$VK_{6.1}, VK_{6.2}, VK_{6.3}, VK_{6.4}, VK_{6.5}$	$VK_{\text{DGOD}}, VK_{\text{DOBA}}, VK_{\text{3DOB}}, VK_{\text{5DOB}}, VK_{\text{10DIB}}$
$\mathbf{VK}_7$	$\mathbf{VK}_{\text{VSKI}}$		$VK_{7.1}, VK_{7.2}, VK_{7.3}, VK_{7.4}, VK_{7.5}$	$VK_{\text{MVID}}, VK_{\text{NVR}}, VK_{\text{VR1S}}, VK_{\text{VR2S}}, VK_{\text{VR3S}}$

Step 8.4.3. For the S_{SOAD} system, work interruptions $D_1 = D_{\text{VNIS}}$, indicator $B_3 = 7$, and value of weighting coefficient as (19) in [13], is calculated as follows:

$$VK_{VNIS} = \frac{1}{7}\left(\frac{28}{35} + \frac{18}{30} + \frac{5}{25} + \frac{16}{20} + \frac{15}{15} + \frac{4}{10} + \frac{5}{5}\right) = \frac{24}{35} \approx 0,7,$$

hence, according to (18) in [13] $B_3' = 0,7 \cdot 7 = 4,9 \approx 5.$

Similarly, for every possible work interruption of S_{SOAD}, S_{TCAS} and S_{AMDS} systems, let's calculate values B_3' taking into account weighting coefficients VK_i, and add obtained figures to the Table 9 and report (stage 11, Table 11).

Table 8. Calculation of weighting coefficients values

System / Subsystem	Value p	Name	Calculated value VK_i	Value B_3'	Value B_3
S_{SOAD}	9	$VK_{VNIS}, VK_{NOPS}, ..., VK_{VAF}$	*0,7;0,7;0,7;0,8;0,6; 0,7;0,8;0,7;0,6*	*7;8;9;8;8; 8;9;9;8*	*5;6;6;6;5; 6;7;6;5*
S_{TCAS}	9	$VK_{VNA}, VK_{VOBS}, ..., VK_{NPY}$	*0,7;0,8;0,8;0,8;0,8; 0,8;0,7;0,8;0,8*	*9;8;7;7;9; 7;8;9;7*	*6;6;6;7;7; 6;6;7;6*
S_{AMDS}	7	$VK_{ZSD}, VK_{NIPA}, ..., VK_{NZD}$	*0,6;0,6;0,7;0,7; 0,7;0,6;0,7*	*8;5;5;8; 6;6;5*	*6;3;4;6; 4;4;4*

Step 8.5. Assessment of criticality rank of R_i each of work interruption types listed D_i according to (12) in [13]. For example, for the S_{SOAD} system, work interruption $D_1 = D_{VNIS}$, let's calculate the criticality rank $R_1 = 5 \cdot 4 \cdot 5 = 100$ and add obtained figures to the report (stage 11). Similarly, for every possible work interruption of systems S_{SOAD}, S_{TCAS} and S_{AMDS}, let's calculate interruptions criticality rank and add obtained figures to the report (stage 11, Table 11).

Stage 9. Selection of the list of the most significant (critical) work interruptions. For the S_{SOAD} system, work interruptions $D_1 = D_{VNIS}$, calculated interruptions criticality rank $R_1 = 5 \cdot 4 \cdot 5 = 100$, according to the criticality determination rule (20) in [13], $D_1 = D_{VNIS}$ reffers to the *Middle* level, requires the development of corrective measures to reduce criticality rank. Obtained figures are highlighted in the report (stage 11, Table 11) with the help of various colours, if D_i, according to (20) in [13], refers to the *High* criticality level, then R_i in Table 11 is highlighted in black, if D_i refers to the *Middle* level – in grey, if D_i refers to the *Low* level – in light grey.

Similarly, for every possible work interruption of S_{SOAD}, S_{TCAS} and S_{AMDS} systems, let's rank calculated values of criticality level as (20) in [13] and add obtained figures to the report (stage 11, Table 11). Moreover, on this stage a Pareto bar chart (Fig. 2) is used to spot the list of most significant (critical) D_i.

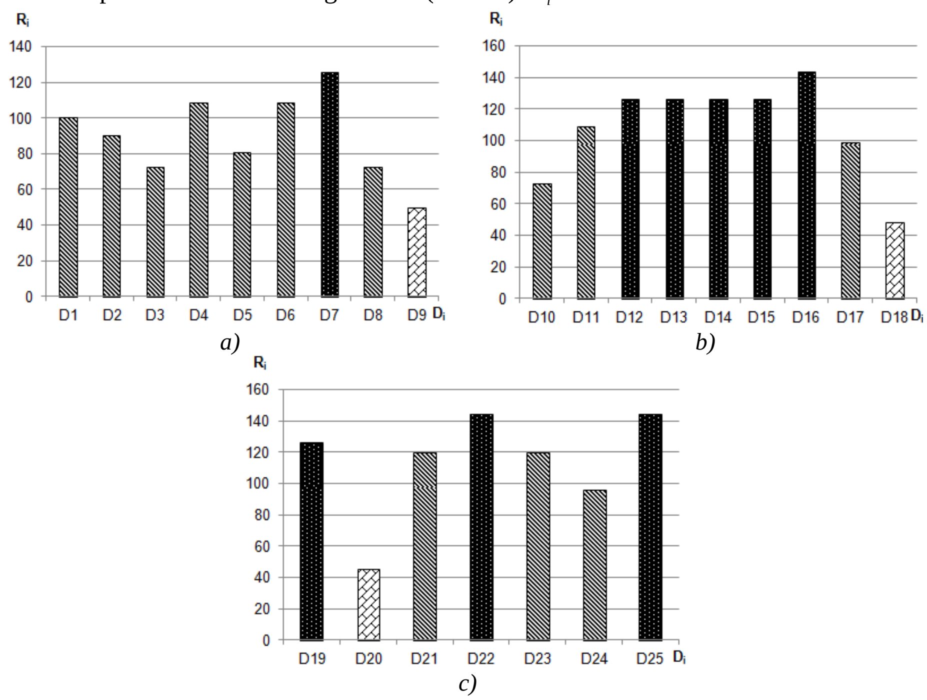

Fig. 2. Calculation results of R_i for S_{SOAD} (a), S_{TCAS} (b) and S_{AMDS} (c)

The diagram is created separately for each S_{ij} (to rank the most significant (critical) D_i, hence D_i are placed on the horizontal axis, and calculated values R_i are ont the vertical axis (like (12) in [13]), if $R_i > R_k$, then D_i is highlighted in black on the diagram, if $R_0 < R_i \le R_k$ – then D_i is highlighted in grey, if $R_i \le R_0$ – then D_i is highlighted in light grey. Patero bar charts help spot the list of most significant (critical) work interruptions. They also make it possible to compare separate systems by the calculated criticality rank and to identify the system which is the most critical among CAIS. For the S_{SOAD} system, the most critical work interruption is D_7, rank criticality calculations, carried out by (12) in [13], revealed the following result: $R_7 = 3 \cdot 6 \cdot 7 = 126 > R_k = 125$. For the S_{TCAS} system the most critical work interruption are values D_{12} – D_{16}, rank criticality calculations, carried out by (12) in [13], revealed the following result: $R_{12} = R_{13} = R_{14} = R_{15} = 126 > R_k = 125; R_{16} = 144 > R_k = 125.$ For the S_{AMDS} system most critical work interruptions are D_{19}, D_{22}, D_{25} rank criticality calculations, carried out by (12) in [13], revealed the following result: $R_{19} = 126 > R_k = 125$; $R_{22} = R_{25} = 144 > R_k = 125$. Patero bar charts also made it possible to compare the number of critical work interruptions of studied systems and found out that S_{TCAS} system is the most critical.

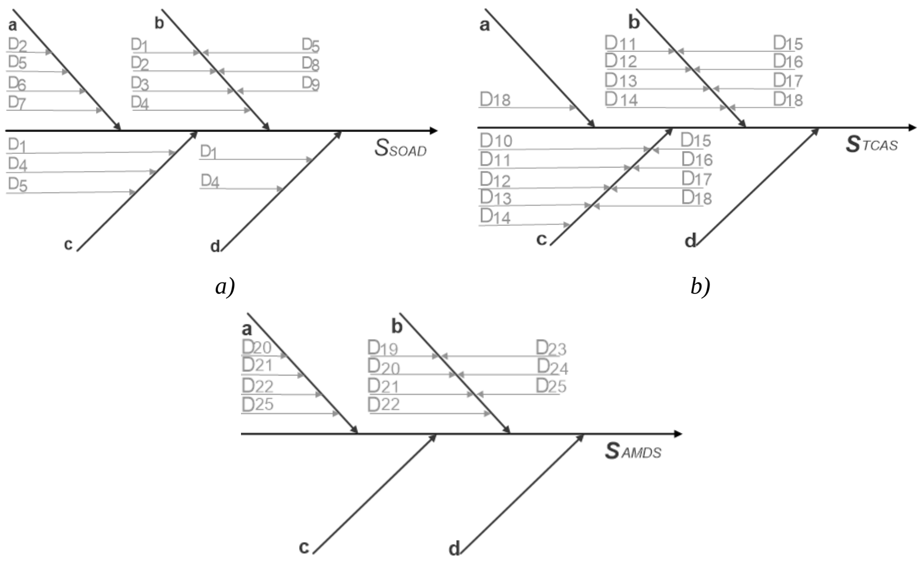

Fig. 3. Ishikawa cause and effect diagram for S_{SOAD} (a), S_{SOAD} (b) and S_{AMDS} (c)

Stage 10. Forming a list of corrective measures. To make a a list of corrective measures for S_{SOAD}, S_{TCAS} and S_{AMDS} systems let's create Ishikawa cause and effect diagrams [17, 19] (Fig. 3), that graphically reflect the characteristics that cause work interruptions D_i and increase the effectiveness of corrective measures development.

Ishikawa cause and effect diagrams for selected systems has devided all identified D_i by the main causes of their occurrence, namely due to errors of: users (a), software (b), hardware (c), network technologies (d). Therefore, priority areas for developing corrective measures for S_{SOAD} and S_{AMDS} systems are elimination of software errors causes and user errors (*b* and *a* on Fig. 3 a and Fig. 3 c), for S_{TCAS} system – elimination of hardware and software related causes (*b* and *c* on Fig. 3 b).

Whereafter for every possible work interruption of S_{SOAD}, S_{TCAS} and S_{AMDS} systems, if $g=3, g=2, g=1$ accordingly, using (21) in [13], let's represent a set of methods to detect interruptions (that corrsespond to *High* and *Middle* according to rule (20) in [13],) as follows:

$$\mathbf{K} = \{\bigcup_{i=1}^{6} K_i\} = \{K_1, K_2, ..., K_6\} = \{K_{\text{PONA}}, K_{\text{OROB}}, K_{\text{OKPD}}, K_{\text{ZRTO}}, K_{\text{POBR}}, K_{\text{VOAA}}\}, \quad (6)$$

where $K_1 = K_{\text{PONA}}$ is directional antenna inspection and repair; $K_2 = K_{\text{OROB}}$ is inspection and repair of system's computer unit, $K_3 = K_{\text{OKPD}}$ are scheduled review and repair of data transmission channels; $K_4 = K_{\text{ZRTO}}$ is change of maintenance and repair regulations; $K_5 = K_{\text{POBR}}$ is scheduled review of flight recorders; $K_6 = K_{\text{VOAA}}$ are Amadeus AIR components update as scheduled.

Table 20. The list of corrective measures

S_{ij} / S_{ijk}	D_i	R_{begin}	K_i	R_{finish}
S_{SOAD}	D_1	100	K_{OKPD}	$5\cdot3\cdot5=75$
	D_2	90	K_{OKPD}	$3\cdot4\cdot6=72$
	D_3	72	K_{ZRTO}	$3\cdot3\cdot6=54$
	D_4	108	K_{OKPD}	$3\cdot5\cdot6=90$
	D_5	80	K_{POBR}	$2\cdot7\cdot4=56$
	D_6	108	K_{POBR}	$3\cdot5\cdot6=90$
	D_7	126	K_{ZRTO}	$3\cdot5\cdot7=105$
	D_8	72	K_{OKPD}	$3\cdot4\cdot6=72$
S_{TCAS}	D_{10}	72	K_{PONA}	$3\cdot3\cdot6=54$
	D_{11}	108	K_{OROB}	$3\cdot5\cdot6=90$
	D_{12}	126	K_{OROB}	$3\cdot6\cdot6=108$
	D_{13}	126	K_{OROB}	$3\cdot6\cdot6=108$
	D_{14}	126	K_{OROB}	$3\cdot5\cdot7=105$
	D_{15}	126	K_{OROB}	$3\cdot7\cdot5=105$

	D_{16}	144	K_{OROB}	$4\cdot5\cdot6=120$
	D_{17}	98	K_{OROB}	$2\cdot7\cdot7=98$
	D_{19}	126	K_{VOAA}	$3\cdot6\cdot6=108$
	D_{21}	120	K_{VOAA}	$4\cdot5\cdot4=80$
S_{AMDS}	D_{22}	144	K_{VOAA}	$4\cdot5\cdot6=120$
	D_{23}	120	K_{VOAA}	$4\cdot5\cdot4=80$
	D_{24}	96	K_{VOAA}	$2\cdot6\cdot4=48$
	D_{25}	144	K_{VOAA}	$5\cdot6\cdot4=120$

The list of necessary corrective measures for S_{SOAD}, S_{TCAS} and S_{AMDS} systems, is presented in Table 10. The effectiveness of corrective measures assessment is carried out by recalculation of R_i (stage 8). Next, we use the initial value R_{begin} (R_i before the K_i implementation) and final R_{finish} (R_i after the implementation of K_i): if $R_{finish} < R_k$ then corrective measures aimed to reduce the rank of criticality can be recommended for use to provide cybersecurity [20].

In Table 10 we can see which corrective measures can be implemented and for how much they reduce criticality rank (D_i highlighted in grey are those that became insignificant Low, while D_i highlighted in light grey are those that shifted from $High$ to $Middle$ criticality rank as a result of corrective measures implementation).

Stage 11 – Report generation. At this stage, data obtained in the previous stages ($\mathbf{S}_i, S_{ij}, C_i, F_i, D_i, E_i, O_i, W_i$ та R_i) is systematized, visualization of qualitative and calculation of quantitative values of CAIS criticality is carried out. The stage involves the systematization of all information in the form of a table. An example of report creation for S_{SOAD}, S_{TCAS} and S_{AMDS} systems is presented in Table 11.

Table 31. Report for all levels of analysis

$\mathbf{S}_i$ / S_{ij} / S_{ijk}	C_i	F_i	D_i	E_i	O_i	W_i	**R**			
							B_1	B_2	B_3	R_i
$\mathbf{S}_{1.4.5}$	C_1	F_1	D_1	E_1	0	W_1	5	4	5	100
	C_2	F_2	D_2	E_2	0	W_1	3	5	6	90
	C_3	F_3	D_3	E_3	0	W_2	3	4	6	72
	C_4	F_4	D_4	E_4	0	W_3	3	6	6	108
	C_5	F_5	D_5	E_5	0	W_4	2	8	5	80
	C_6	F_6	D_6	E_6	0	W_4	3	6	6	108
	C_7	F_7	D_7	E_7	0	W_5	3	6	7	126
		F_8	D_8	E_8	0	W_6	3	4	6	72

		F_9	D_9	E_9	0	W_7	2	5	5	50
		…		E_{10}						
		F_{15}								
$S_{2.4.2}$	C_8	F_{16}	D_{10}	E_{11}	$O_1 = 1$	W_8	3	4	6	72
	C_9	F_{17}	D_{11}	E_{12}	$O_1 = 1$	W_8	3	6	6	108
	C_{10}	F_{18}	D_{12}	E_{13}	$O_1 = 1$	W_8	3	7	6	126
	C_{11}	F_{19}	D_{13}		$O_1 = 1$	W_8	3	7	7	126
	C_{12}	F_{20}	D_{14}		$O_1 = 1$	W_8	3	6	7	126
		F_{21}	D_{15}		$O_1 = 1$	W_8	3	7	6	126
		F_{22}	D_{16}		$O_1 = 1$	W_8	4	6	6	144
		F_{23}	D_{17}		$O_1 = 1$	W_8	2	7	7	98
		F_{24}	D_{18}		0	W_8	2	4	6	48
		…								
		F_{29}								
$S_{3.2.1}$	C_{13}	F_{30}	D_{19}	E_{14}	$O_2 = 1$	W_9	3	7	6	126
	C_{14}	F_{31}	D_{20}	E_{15}	$O_2 = 1$	W_9	3	5	3	45
	C_{15}	F_{32}	D_{21}	E_{16}	$O_2 = 1$	W_9	5	6	4	120
	C_{16}	F_{33}	D_{22}	E_{17}	$O_3 = 1$	W_9	4	6	6	144
			D_{23}	E_{18}	$O_4 = 1$	W_9	5	6	4	120
			D_{24}	E_{19}	0	W_9	4	6	4	96
			D_{25}		$O_3 = 1$	W_9	6	6	4	144

5 Discussion

Thereby, Table 11 summarizes such information results of the proposed method as: a list of system components, their functions, types of interruptions for each component of the system; information on the causes and consequences of interruptions for each component of the system; calculations of criticality rankings, anking results are a list of the most significant (critical) interruptions of work, which are displayed in a formalized and convenient for experts form. Other output data was obtained at different stages of the method implementation: criticality matrix, which according to the collected preliminary data graphically reflects the criticality of the system components (stage 7); Pareto diagram which shows the level of criticality inside the system and makes it possible to compare several different systems (stage 9); Ishikawa's cause and effect diagram that allows to identify priority areas for developing appropriate corrective measures (stage 10).

Experimental study gives a possibility to determine the importance level of S_{SOAD} (aeronautical information processing and transmission system), S_{TCAS} (onboard collision avoidance system, TCAS) and S_{AMDS} (system Amadeus) systems in aviation and defined componetnts of these CAIS particularly:

– system S_{SOAD} has one critical component C_7 with one functional interruption D_7;

– system S_{TCAS} has three critical components C_{10}, C_{11} and C_{12} with five functional interruptions $D_{12} - D_{16}$;

– system S_{AMDS} has two critical components C_{13} and C_{16} with three functional interruptions D_{19}, D_{22}, D_{25}.

Three-dimensional criticality matrix and Patero bar charts shows that S_{TCAS} system is the most critical among selected CAIS (5 critical interruptions).

Ishikawa cause and effect diagrams shows that priority areas for developing corrective measures for S_{SOAD} and S_{AMDS} systems are elimination of software errors causes and user errors, for S_{TCAS} system – elimination of hardware and software related causes.

Conclusions

In this paper experimental study of proposed by authors FMECA-based method for importance level assessing of the CII objects in aviation was carried out. It was selected three CAIS from different categories (air navigation systems, aircraft on-board information systems as well as airlines and airports systems): S_{SOAD} (aeronautical information processing and transmission system), S_{TCAS} (onboard collision avoidance system, TCAS) and S_{AMDS} (Amadeus system).

Three-dimensional criticality matrix as well as Patero bar charts shows that S_{TCAS} system is the most critical among selected CAIS (5 critical interruptions and 3 critical components). Ishikawa cause and effect diagrams shows that priority areas for developing corrective measures for S_{SOAD} and S_{AMDS} systems are elimination of software errors causes and user errors, but for S_{TCAS} system – elimination of hardware and software related causes.

In the future research study it is planned to develop software that, based on the proposed method, will allow to conduct an experimental research and confirm the possibility of determining the importance of different categories of CAIS as well as to assess infrastructure in different industries.

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