# Studies on the Disasters Criticality Assessment in Aviation Information Infrastructure

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**Abstract.** 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 (disasters criticality) 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 disaster criticality and 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, criticality, risk, disaster, 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 and problem statement

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]. 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. In general, FMECA requires the identification of the following basic information: Item, Function, Failure, Effect of Failure, Cause of Failure, Current Control fn the Recommended Actions.

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

## 3 Proposed method description

Let`s consider in detail step by step of implementation of the proposed method study. One CAIS from each of the categories defined in [12] were selected, these are: one air navigation system; one aircraft onboard information system; one airlines and airports system.

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

*Step 1.1-1.2* 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:

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

where $\mathbf{S}_1 = \mathbf{S}_{\text{ISAO}}$ is set of information systems of air navigation services; $\mathbf{S}_2 = \mathbf{S}_{\text{BSPS}}$ is set of onboard aircraft information systems; $\mathbf{S}_3 = \mathbf{S}_{\text{ISAA}}$ is set of airline and airport information systems, $\mathbf{S}_{1.1} = \mathbf{S}_{\text{SAE}}$ are aviation telecommunication systems; $\mathbf{S}_{1.2} = \mathbf{S}_{\text{RZZP}}$ are radio navigation aids; $\mathbf{S}_{1.3} = \mathbf{S}_{\text{SSP}}$ are surveillance systems; $\mathbf{S}_{1.4} = \mathbf{S}_{\text{SOD}}$ are data processing systems; $\mathbf{S}_{1.5} = \mathbf{S}_{\text{SMZ}}$ are meteorological support systems , $\mathbf{S}_{2.1} = \mathbf{S}_{\text{SPS}}$ are air signal system; $\mathbf{S}_{2.2} = \mathbf{S}_{\text{SZV}}$ are communication systems; $\mathbf{S}_{2.3} = \mathbf{S}_{\text{NAVS}}$ are navigation systems; $\mathbf{S}_{2.4} = \mathbf{S}_{\text{SSPZ}}$ are collision monitoring and prevention systems; $\mathbf{S}_{2.5} = \mathbf{S}_{\text{OSL}}$ are computing systems of aviation; $\mathbf{S}_{2.6} = \mathbf{S}_{\text{SVI}}$ are information display systems; $\mathbf{S}_{2.7} = \mathbf{S}_{\text{ABSK}}$ are automatic onboard control systems; $\mathbf{S}_{3.1} = \mathbf{S}_{\text{CRS}}$ is computer reservation system; $\mathbf{S}_{3.2} = \mathbf{S}_{\text{GDS}}$ is global reservation system (reservation); $\mathbf{S}_{3.3} = \mathbf{S}_{\text{BSP}}$ is mutual calculations system; $\mathbf{S}_{3.4} = \mathbf{S}_{\text{DCS}}$ are dispatch management systems.

*Step 1.3.* To determine subsystem sets, we arbitrarily select one set of systems from each class, for example $\mathbf{S}_{\text{SOD}}, \mathbf{S}_{\text{SSPZ}}, \mathbf{S}_{\text{GDS}}$ and according to (3) in [13] we present subsystem sets with $r_{1.4}=5, r_{2.4}=4, r_{3.2}=18,$ where $S_{1.4.1} = S_{\text{ASYPR}}$ are automated air traffic control systems (AATCS); $S_{1.4.2} = S_{\text{SPPP}}$ are automated airspace use planning systems; $S_{1.4.3} = S_{\text{ESAN}}$ are centralized surveillance and distribution systems for the surveillance data of the European Aviation Safety Organization Eurocontrol; $S_{1.4.4} = S_{\text{SOPD}}$ are flight data processing and transmission systems; $S_{1.4.5} = S_{\text{SOAD}}$ are aeronautical information processing and transmission systems; $S_{2.4.1} = S_{\text{TRA}}$ are transponders; $S_{2.4.2} = S_{\text{TCAS}}$ 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].

*Step 1.4.* To determine the set of components, we arbitrarily select one subsystem from each set of subsystems, for example $S_{\text{SOAD}}$, $S_{\text{TCAS}}$, $S_{\text{AMDS}}$.

For system $S_{\text{SOAD}}$, 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 $S_{\text{TCAS}}$ according to [14], and $S_{\text{AMDS}}$ according to [15-16], with $b = 5$ та $b = 4$ while using (4) in [13] respectively, 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.

*Step 1.5.* 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 $S_{\text{SOAD}}$, 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:

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

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

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 $S_{\text{TCAS}}$ according to [14] and $S_{\text{AMDS}}$ 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], 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.

***Stage 3. Determining the list of possible disasters for each system component.*** For system $S_{\text{SOAD}}$ set of components $\mathbf{C}_{\text{SOAD}}$, with $p = 9$, while using (6) in [13], we present the set of work interruptions (disasters) 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 $S_{\text{TCAS}}$ according to [14] and $S_{\text{AMDS}}$ 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], were $D_{10} = D_{\text{VNA}}$ 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.

***Stage 4. Determining the consequences of each possible disasters.*** For each possible work interruption (disaster) 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], 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.

***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 in the following way (3):

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

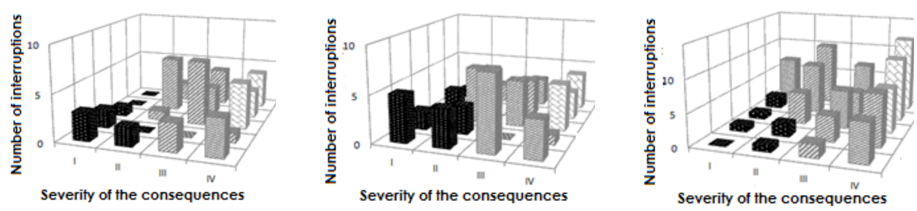
where $O_1 = O_{\text{VSI}}$ is VSI/TRA display; $O_2 = O_{\text{TIM}}$ is Timetable (general schedule screen); $O_3 = O_{\text{AUS}}$ is Amadeus Access Update/Amadeus Access Sell; $O_4 = O_{\text{SCH}}$ is Schedule (schedule screen). Taking into account (9) in [13], $E(O_{\text{VSI}}, D_i) = E(O_{\text{TIM}}, D_i) = E(O_{\text{AUS}}, D_i) = E(O_{\text{SCH}}, D_i) = 1$.

***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 in the following way:

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

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.

***Stage 7. Construction of a three-dimensional criticality matrix.*** For the system $S_{\text{SOAD}}$ 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 $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ we form a criticality table and construct a three-dimensional matrix (Fig. 1 b and Fig. 1 c, respectively).




*a)* *b)* *c)*

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

***Stage 8. Calculation of the criticality rank of probable disasters***

<u>*Step 8.1-8.3.*</u> For the $S_{\text{SOAD}}$ system, work interruptions $D_1 = D_{\text{VNIS}}$, let's define an indicator $B_{1j}, B_{2j}, B_{3j}$ as (13)-(15) in [13], where value of $z, x, c$ is going to be found according to tab. 5,7,9 in [1]. Similarly, for every possible work interruption of $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ systems, let's define an indicator $B_{1j}, B_{2j}, B_{3j}$ as (13)-(15) in [13], tab.. 5,7,9 in [1] and add obtained figures to the report (stage 11, Table 1).

<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):

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

where $\mathbf{VK}_1=\mathbf{VK}_{\mathrm{KZG}}$ is number of citizens involved (health and social consequences); $\mathbf{VK}_2=\mathbf{VK}_{\mathrm{EKON}}$ is economic effect; $\mathbf{VK}_3=\mathbf{VK}_{\mathrm{VNNS}}$ is impact on the environment; $\mathbf{VK}_4=\mathbf{VK}_{\mathrm{POLN}}$ is political implications; $\mathbf{VK}_5=\mathbf{VK}_{\mathrm{MZT}}$ is territorial reach; $\mathbf{VK}_6=\mathbf{VK}_{\mathrm{TRV}}$ is duration; $\mathbf{VK}_7=\mathbf{VK}_{\mathrm{VSKI}}$ 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:

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

where $VK_{1.1}=VK_{0-5}$ is 0-5 deceased; $VK_{1.2}=VK_{6-20}$ is 6-20 deceased; $VK_{1.3}=VK_{\mathrm{D100}}$ is 21-100 deceased; $VK_{1.4}=VK_{\mathrm{D499}}$ is 101-499 deceased; $VK_{1.5}=VK_{\mathrm{B500}}$ is ≥ 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, where $VK_{2.1}=VK_{\mathrm{D100M}}$ is < 100 mil.; $VK_{2.2}=VK_{\mathrm{D499M}}$ is 100-499 mil.; $VK_{2.3}=VK_{\mathrm{D2,9M}}$ is 500 mil. – 2,9 bil.; $VK_{2.4}=VK_{\mathrm{D6,9M}}$ is 2,9 bil. – 6,9 bil.; $VK_{2.5}=VK_{\mathrm{B7M}}$ is > 7 bil.; $VK_{3.1}=VK_{\mathrm{M1G}}$ is <1 ha. or 0,0001% of water resources; $VK_{3.2}=VK_{\mathrm{D10G}}$ is 1-10 ha, or 0,0001-0,001 % of water resources; $VK_{3.3}=VK_{\mathrm{D100G}}$ is 10-100 ha, or 0,001-0,01 % of water resources; $VK_{3.4}=VK_{\mathrm{D1000G}}$ is 100-1000 ha, or 0,01 - 0,1 % of water resources; $VK_{3.5}=VK_{\mathrm{B1000G}}$ is > 1000 ha, or > 0,1 % of water resources; $VK_{4.1}=VK_{\mathrm{MIN}}$ is minimal; $VK_{4.2}=VK_{\mathrm{SOCN}}$ is social discontent; $VK_{4.3}=VK_{\mathrm{MITG}}$ are rallies, protests; $VK_{4.4}=VK_{\mathrm{MASZ}}$ are riots; $VK_{4.5}=VK_{\mathrm{REV}}$ are revolutions, wars; $VK_{5.1}=VK_{\mathrm{OBYD}}$ is separate building; $VK_{5.2}=VK_{\mathrm{SEL}}$ is village; $VK_{5.3}=VK_{\mathrm{RGN}}$ is district, city; $VK_{5.4}=VK_{\mathrm{OBL}}$ is region; $VK_{5.5}=VK_{\mathrm{DER}}$ is country; $VK_{6.1}=VK_{\mathrm{DGOD}}$ is less than an hour; $VK_{6.2}=VK_{\mathrm{DOBA}}$ is day; $VK_{6.3}=VK_{\mathrm{3DOB}}$ are 3 days; $VK_{6.4}=VK_{\mathrm{5DOB}}$ are 5 days; $VK_{6.5}=VK_{\mathrm{10DIB}}$ are 10 days; $VK_{7.1}=VK_{\mathrm{MVID}}$ is almost no; $VK_{7.2}=VK_{\mathrm{NVR}}$ are causes no destruction; $VK_{7.3}=VK_{\mathrm{VR1S}}$ are causes destruction of one sector; $VK_{7.4}=VK_{\mathrm{VR2S}}$ are causes destruction of two sectors; $VK_{7.5}=VK_{\mathrm{VR3S}}$ are causes destruction of three and more sectors [18].

*Step 8.4.3.* For the $S_{\text{SOAD}}$ 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:

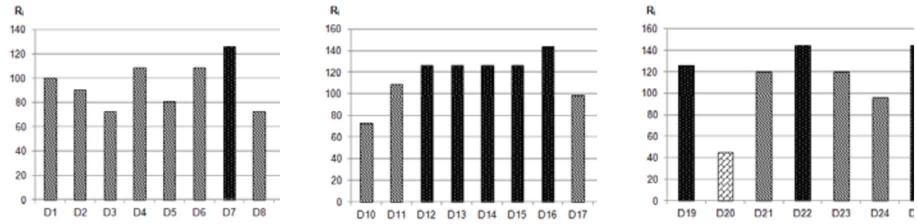
$$VK_{VNIS} = \frac{1}{7}\left(\frac{28}{35} + \frac{18}{30} + \frac{5}{25} + \frac{16}{20} + \frac{15}{15} + \frac{4}{10} + \frac{5}{5}\right) = \frac{24}{35} \approx 0,7,$$

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

Similarly, for every possible work interruption of $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ systems, let's calculate values $B_3'$ taking into account weighting coefficients $VK_i$, and add obtained figures to the Table 1 and report (stage 11, Table 1).

*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 $S_{\text{SOAD}}$ 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 $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$, let's calculate interruptions criticality rank and add obtained figures to the report (stage 11, Table 1).

***Stage 9. Selection of the list of the most significant (critical) disasters.*** For the $S_{\text{SOAD}}$ 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 1) 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 1 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 $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ systems, let's rank calculated values of criticality level as (20) in [13] and add obtained figures to the report (stage 11, Table 1). Moreover, on this stage a Pareto bar chart (Fig. 2) is used to spot the list of most significant (critical) $D_i$.

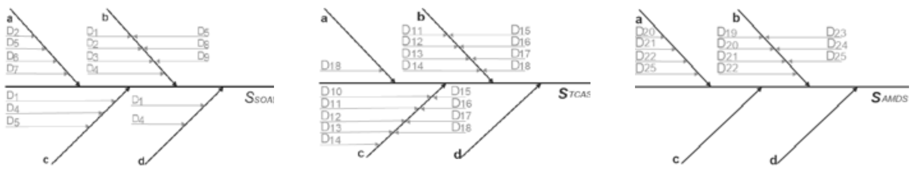



*a)* *b)* *c)*

**Fig. 2.** Calculation results of $R_i$ for $S_{\text{SOAD}}$ (a), $S_{\text{TCAS}}$ (b) and $S_{\text{AMDS}}$ (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 $S_{\text{SOAD}}$ 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 $S_{\text{TCAS}}$ 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 $S_{\text{AMDS}}$ 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 $S_{\text{TCAS}}$ system is the most critical.

***Stage 10. Forming a list of corrective measures.*** To make a a list of corrective measures for $S_{\text{SOAD}}$ , $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ 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.




*a)* *b)* *c)*

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

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 $S_{\text{SOAD}}$ and $S_{\text{AMDS}}$ systems are elimination of software errors causes and user errors (*b* and *a* on Fig. 3 a and Fig. 3 c), for $S_{\text{TCAS}}$ system – elimination of hardware and software related causes (*b* and *c* on Fig. 3 b).

Whereafter for every possible work interruption of $S_{\text{SOAD}}$ , $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ 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.

The list of necessary corrective measures for $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ systems, is presented in [1]. 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]. Also, we can see which corrective measures can be implemented and for how much they reduce criticality rank.

***Stage 11 – Report generation.*** At this stage, data obtained in the previous stages is systematized, visualization of qualitative and calculation of quantitative values of CAIS criticality is carried out. An example of report creation for $S_{\text{SOAD}}$, $S_{\text{TCAS}}$ and $S_{\text{AMDS}}$ systems is presented in Table 1.

Novelty of the paper defines by proposed improvements of the FMECA technique (set-theoretical approach, criticality matrix, Pareto diagram, Ishikawa's cause and effect diagram etc.). The practical values of this study define by verification of the ability of different CAIS assessment and potential efficiency to assess criticality of infrastructures in different industries.

**Table 1.** Report for all levels of analysis

| $S_i$ / $S_{ij}$ / $S_{ijk}$ | $C_i$ | $F_i$ | $D_i$ | $E_i$ | $O_i$ | $W_i$ | R | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $B_1$ | $B_2$ | $B_3$ | $R_i$ |
| $S_{1.4.5}$ | $C_1$ | $F_1$ | $D_1$ | $E_1$ | 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 |

## 4 Conclusions

In this paper experimental study of proposed by authors FMECA-based method for importance level assessing of the CII objects in aviation based on criticality analysis of systems (subsystems) disaster risks 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): $S_{\text{SOAD}}$ (aeronautical information processing and transmission system), $S_{\text{TCAS}}$ (onboard collision avoidance system, TCAS) and $S_{\text{AMDS}}$ (Amadeus system).

Three-dimensional criticality matrix as well as Pareto bar charts shows that $S_{\text{TCAS}}$ system is the most critical among selected CAIS (5 critical disasters and 3 critical components). Ishikawa cause and effect diagrams shows that priority areas for developing corrective measures for $S_{\text{SOAD}}$ and $S_{\text{AMDS}}$ systems are elimination of software errors causes and user errors, but for $S_{\text{TCAS}}$ 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 risks in different industries (power energy, communications etc).

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