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Estimating the vulnerability of aviation operational stages to adverse incidents based on civil aviation incidents

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Abstract

Many safety management processes are conducted using vulnerability measures. It was assumed that such a measure would also be applicable to aviation operational stages, providing an innovative approach to their assessment. However, the research problem generated the necessity of adopting a new definition and mathematical model of vulnerability measure. An analysis of the literature indicated that vulnerability is most commonly a probabilistic measure based on conditional probability, and it can be obtained from information on recorded aviation incidents. The specificity of the analysis area showed that an additional component of vulnerability concerning the diversity of incident causes would need to be considered. This component affects both the severity and frequency of incidents but can also be problematic, for example, in the context of organizing safety systems. Therefore, the aim of this article was to develop and present a mathematical model of the new vulnerability measure for aviation operational stages to adverse incidents in civil aviation systems and to present the results of its estimations. The new model of vulnerability measure presented in this article captures the component related to the diversity of incident causes in the form of an original diversity coefficient based on species diversity measures. The presented measure is not intended to replace the ones currently used but to complement the resources of available safety management tools. The mathematical vulnerability model was prepared to be easily modified if necessary (by adopting other functions), but based on two variables reflecting vulnerability. The results of estimating the vulnerability of selected aviation operational stages according to the developed vulnerability measure show that it is possible to assess these stages in terms of vulnerability to various classes of aviation incidents. The obtained results suggest the potential applicability of this measure to other research problems.

Keywords: civil aviation, incidents, safety, vulnerability metric

1. Introduction

The necessity of risk assessments has not only become a permanent fixture in the legislative framework governing the functioning of aviation transport systems but, with the development of safety culture, its significant usefulness in managing these systems has been recognized (EASA, 2019; ICAO, 2016; ICAO, 2018; Maragakis et al., 2009; Kobaszyńska-Twardowska et al., 2023). This is a combination of the likelihood of specific adverse incidents occurring and the magnitude of their consequences. Such an approach is not always justified, as the risk model or its measure should be selected based on the characteristics of identified hazards or even the level of uncertainty in terms of information. Moreover, they should not be predetermined or imposed from the outset. Authorities in the field of safety (such as Aven, works like (SRA, 2018; Thekdi & Aven, 2024)) indicate and thus advocate for the possibility of using various risk measures. An example could be a risk measure encompassing *vulnerability metric* (meaning that *risk is the combination of the probability of a hazard occurring and a vulnerability metric given the occurrence of the hazard* (SRA, 2018)). Even such a component (i.e., vulnerability) alone can prove to be useful in managing hazards related to aviation operations. As Adger suggests (Adger, 2006), the concept of vulnerability has been a powerful analytical tool for describing states of vulnerability to harm, powerlessness, and marginality of both physical and social systems and for guiding normative analysis of actions to enhance well-being through reducing the risk. Vulnerability can be understood as “the degree to which a system is affected by a risk source or agent” (SRA, 2018). The complexity of the problem lies in the fact that the vulnerability of aviation operation stages to aviation incidents depends on various factors (of different natures – technical, biological, organizational, ergonomic, economic, and even psychophysical). Examples of such factors include: avionics system errors, equipment failures, animals, birds, weather conditions, laser light, improper crew interaction, communication errors, etc. (Maragakis et al., 2009; Skorupski, 2018).

The key task is to select an appropriate vulnerability measure that is suitable for the identified conditions and available data. It is possible to utilize measures already known in aviation; however, it should be noted that in this field, various understandings and mathematical formulations of vulnerability are applied. This is associated with numerous areas of application and threat factors. The analysis area mostly concerns the aircraft, while the threat factors include climatic/atmospheric factors (e.g. work (Pei et al., 2012)). The analysis often also encompasses infrastructure elements (e.g. works (Kaewunruen et al., 2021; Nöldgen et al., 2012)). In relation to the threat factors, there are also studies regarding damages caused by military or terrorist attacks (e.g.works (Dacko & Toczyski, 2011; Konokman et al., 2017; Lomazzi et al., 2022; Singh & Singh, 2000)) including cyberattacks (e.g. works (Fouda, 2018; Sun et al., 2016)). A synthesis of both analyses in both areas is the work by (Nöldgen et al., 2012), where they presented the vulnerability and robustness of a security skyscraper subjected to aircraft impact.

Regarding measures of vulnerability, Pei (2014) suggests that it is possible to utilize traditional measures of uncertainty (with appropriate modifications), e.g., Birnbaum, Fussell–Vesely, criticality, reliability achievement worth, and reliability reduction worth. Other interesting solutions are demonstrated, for example, in the work of Pei et al.(2012) and Sun et al. (2016). The first presented a method based on the Kronecker product for an exact solution to aircraft vulnerability. In the second one, the Common Vulnerability Scoring System (CVSS) was adopted for vulnerability analysis. In the work (Corbin & Cooley, 1982) (Chapter VIII – Probabilistic or statistical approach), a probabilistic or statistical approach (along with examples) to predicting single and/or redundant equipment failures caused by the indirect effects of lightning strikes was presented. Among the interesting and unusual vulnerability measures, the one developed as part of Founda’s work should be mentioned (Fouda, 2018). The scope of this article is electronic and cyber vulnerabilities. The vulnerability assessment of unmanned aircraft systems architecture applied Gaussian modeling, i.e., the Gaussian two-dimensional function was chosen as a representation of attack vectors on a given unmanned aircraft systems architecture for a weighted attack surface model. The standard deviation value of each vector represents the vulnerability to attacks.

According to Willis (2007), regarding terrorist attacks, a measure of vulnerability can be the conditional probability, i.e. the probability that damages occur, given a specific attack type, at a specific time, on a given target. In this case, damages may include fatalities, injuries, property damage, or other consequences. An interesting assumption regarding the application of this measure to the vulnerability of aviation operation stages is that the target may be vulnerable to attacks without the attacker recognizing the vulnerability.

In relation to system components, probabilistic measures are also applied, typically in the form of conditional probabilities or relative vulnerability to damage (*relative failure vulnerability* (Dhillon, 1999)). It can be added that such an approach has been known since at least the year 2000 when Singh and Singh (2000) presented a zgeneralized model for aircraft vulnerability by different weapon systems.

Gill and Smoczyński also apply probabilistic vulnerability measures but in the context of assessing the effectiveness of security system components. Vulnerability is defined by them based on (Adger, 2006) as the degree to which a hazard source is susceptible to and is unable to cope with the positive effects of the work performed by the risk reduction measure.

Similarly, in the work of Konokman (2017), where the vulnerability of the aircraft is assessed by the overall probability of kill according to the considered kill level. The probability of kill calculated for the components comprising the aircraft is related to the probability of kill of the entire aircraft. The overall probability of kill of the aircraft due to the probability of kill of each critical component is calculated by taking the redundancy of the components into account.

In addition to adopting a measure of vulnerability, another issue is determining its value. Wherever conducting full-scale experimental research is impossible, vulnerability modeling is employed. An example of this is the article (Li et al., 2013). The vulnerability modeling method is based on product structure and CATIA. The article provided the vulnerability computation theory, also utilizing probabilistic measures, such as the kill probability of each component under each shot-line according to the kill criteria formulas. A similar idea of vulnerability modeling (vulnerability of thin-walled structures to the blast wave load) was presented in work by (Dacko & Toczyski, 2011). However, the authors did not define the concept of vulnerability.

A literature analysis indicates that vulnerability is most commonly a probabilistic measure based on conditional probability. It can be determined both predictively (via simulation, using modeling) and retrospectively/statistically, with appropriate data available (as demonstrated by Corbin et al. (1982)).

Ultimately, it is possible to develop dedicated vulnerability measures based on known solutions. In the case of aviation incidents in various stages of aviation operations, the diversity of causes of these incidents is noteworthy. From a risk management perspective, such diversity of incidents may pose more challenges than their frequency, especially in terms of organizing safety systems. In this article, an attempt was made to incorporate the diversity of incident causes into the vulnerability measure, using measures of species diversity (as provided, for example, by the *International Encyclopedia of Statistical Science* (Lovric, 2011).

The aim of this article is to develop and present a mathematical model of a new vulnerability measure for the stages of aviation operations regarding adverse incidents in civil aviation systems, along with presenting the results of its estimations. In the first section, the background of the issue and the rationale for undertaking the work are presented, supported by a review of literature concerning the understanding and measures of vulnerability applied in aviation transport.

The second section introduces the fundamental concepts related to incidents in aviation transport necessary for the proper interpretation of data for vulnerability estimation, which is also presented in this section. Additionally, the mathematical form of the new vulnerability measure is provided in the second section. The third section contains estimation results, while the fourth section includes final remarks and conclusions drawn from the work's implementation.

2. Understanding Basic Concepts Related to Aviation Incidents

According to the Aviation Law (the Act of 3 July 2002 Aviation Law (Journal of Laws 2008 no 97, item 625), 2002) and Annex 13 (ICAO, 2017), aviation incidents are categorized into accidents, serious incidents, and incidents. Regulation 996 (Regulation of the European Parliament and of the Council (EU) No 996/2010 of 20 October 2010 on the Investigation and Prevention of Accidents and Incidents in Civil Aviation, 2010) defines an aviation incident as "any safety-related occurrence which, if not corrected or addressed, could jeopardize an aircraft, its occupants, or any other person." During the registration of aviation incidents, both in the Eccairs 2.0 system and in TOKAI (a system developed by Eurocontrol with the participation of ANSP as a database for reporting incidents, managing incident investigation, and presenting safety indicators – dashboard), a division into categories is used. Typically, more than one category applies to a single incident. Each category has a unique name and abbreviation, its own definition, and notes on its use. This is an important element aimed at standardizing and enforcing common understanding and coding in the European database. The merging of categories is described in the Eccairs 2.0 instruction and ICAO CICTTT (2004).

For the purposes of this article, the concept of the aviation incident class has been introduced, which will be associated here with the severity of incidents. According to ICAO, the understanding of individual classes of adverse incidents is as follows (ICAO, 2010):

- Accident. An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:
  a) a person is fatally or seriously injured as a result of: – being in the aircraft, or – direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or – direct exposure to jet blast, except when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew; or
  b) the aircraft sustains damage or structural failure which: – adversely affects the structural strength, performance or flight characteristics of the aircraft and – would normally require a major repair or replacement of the affected component, except for engine failure or damage, when the damage is limited to the engine, its cowlings or accessories; or for damage limited to propellers, wing tips, antennas, tires, brakes, fairings, small dents or puncture holes in the aircraft skin; or
  c) he aircraft is missing or is completely inaccessible.
- Serious incident. An incident involving circumstances indicating that an accident nearly occurred. Examples of serious incidents can be found in Attachment D of ICAO Annex 13 and in the ICAO Accident/Incident Reporting Manual (ICAO Doc 9156).
- Incident. An occurrence other than an accident is associated with the operation of an aircraft which affects or could affect the safety of operation. The types of incidents which are of main interest to the International Civil Aviation Organization for accident prevention studies are listed in the ICAO Accident/Incident Reporting Manual (ICAO Doc 9156) and ICAO Annex 13.

- Major incident. An incident associated with the operation of an aircraft, which safety of aircraft may have been compromised, having led to a near collision between aircraft with ground or obstacles (i.e., safety margins not respected which is not the result of an ATC instruction)
- Significant incident. Eurocontrol: An incident involving circumstances indicating that an accident, a serious or major incident could have occurred if the risk had not been managed within safety margins, or if another aircraft had been in the vicinity.
- Occurrence without safety effect. A possible safety related occurrence not meeting the reporting requirements. This could be, for example, the result of downgrading the incident after review.
- Not determined. The class of the occurrence has not been determined. Unknown or unspecified means a lack of sufficient information to classify the incident, for example, cases where the aircraft is missing.

3. A new measure vulnerability

The rationale for creating a new vulnerability measure stemmed from the diversity of causes of aviation incidents in various stages of aviation operations, both in terms of the number of these causes and their types. It was assumed that vulnerability would primarily depend on the number of types (categories) of these causes.

Furthermore, it was assumed that the types (categories) of causes of aviation incidents have the potential to influence vulnerability in terms of severity or seriousness of incidents to various extents. This influence also varies between stages of aviation operations. A convenient measure to express this potential is the conditional probability of the occurrence of a specific class of aviation incident in a given aviation operation. As indicated in the literature review provided earlier, this is also the most commonly used metric of vulnerability.

Drawing upon known approaches to estimating vulnerability and considering additional conditions related to aviation incident data, the following vulnerability measure was adopted: a combination of the conditional probability of an aviation incident class and a measure of the diversity of its causes.

Therefore, according to the adopted definition, the vulnerability of the *j*-th stage of aviation operation to the *i*-th class of aviation incident will be expressed by a certain two-argument function *f*, namely:

$$v_{ij} = f\left(q_{ij}; d_j\right);\ \ i = 1,2,\ldots,m;\ \ j = 1,2,\ldots,n \tag{1}$$

where q_{ij} is the conditional probability of the *i*-th class of aviation incident occurring in the *j* -th stage of aviation operation, i.e., q_{ij} = P(occurence_class | flight operations), and d_j is a measure of the diversity of causes in a given stage of aviation operations, further referred to as the “cause diversity coefficient.”

While conditional probability has been sufficiently defined in the literature, in the case of the vulnerability measure adopted as in function (1), the task remains to select the diversity measure. The concept of diversity appears in many scientific fields, particularly in biology and ecology, where various dimensions are considered. In the broadest sense, diversity encompasses a finite set of mutually exclusive incidents occurring with probabilities or proportions p_k ($k = 1, \ldots, l$) (Lovric, 2011). In applications in biology and ecology, the issue typically concerns samples or populations of different species. In this case, p_k represents the probability that a randomly selected specimen belongs to that species, and a measure based on these probabilities is understood as the species abundance distribution, commonly referred to as species richness.

Diversity is therefore an attribute that depends on the number of species and all individual values of p_k. It is assumed to increase with the increase in number *l* (the number of species) and with an increase in equality (uniformity) among the values of p_k. Thus, for each *k*,the diversity measure takes on a minimum value for the point distribution P_n^0 the diversity measure takes on a minimum value for the point distribution P_n^1 (Gill, 2018).

In the literature, various diversity measures are proposed, known as the Simpson’s Index (Simpson, 1949) or Shannon entropy measures. Denoting the diversity function by *g*, its simplest form can be expressed using the relationship (Lovric, 2011):

$$g_1(P_k) = l;\ \ k = 1,2,\ldots,l \tag{2}$$

where P_k is understood as the probability distribution of the occurrence of the *k* -th number of entities (units, elements, in the case of aviation incidents – their causes) in a specified group. In view of the fact that measure (2) has limited informational value, its modification is proposed by adjusting *l* using the absolute differences between the successive probability values. This can be expressed as: (Lovric, 2011):

$$g_2(P_k) = l - \sum\sum_{1 \le v < w \le l} |p_v - p_w \tag{3}$$

Utilizing the concept expressed in equation (3) and arranging the causes of the *i*-th class of aviation incidents in descending order of probability values, that is:

$$p_{i(1)} \ge p_{i(2)} \ge \ldots \ge p_{i(n)} \tag{4}$$

where $p_{i(1)}$ is the highest probability value, and $p_{i(n)}$ is the lowest probability value, we can express the relationship for the degree of diversity of causes of aviation incidents in the *j* -th stage of aviation operation as follows:

$$d_j = \mathrm{card}(A_j) - \sum_{k=1}^{l-1} \left[p_{j(k)} - p_{j(k+1)} \right];\ l \ge 2 \tag{5}$$

where:

A_j – the set of types (or categories) of causes of aviation incidents in the *j*-th stage of aviation operation (to consider the diversity of types/categories of causes, it is necessary to remember and assume that this is a set with more than one element).

p_{jk} – the probability of the occurrence of the *k*-th category of causes of aviation incidents in the *j*-th stage of aviation operation, i.e. p_{jk} = P(cause_category | flight operations).

Using formula (5), we can further adopt an appropriate form of the function $f(q_{ij}; d_j)$. It is assumed that a smaller number of types of causes and larger differences in their frequencies will indicate greater vulnerability of the aviation operation stage. This means that if a particular class of incidents, such as a serious incident, occurs in a given aviation operation stage due to two similarly frequent causes, it can be said that this stage is more susceptible to incidents of the indicated class than in the case of a high diversity of causes. Therefore, the following multiplicative form of the vulnerability function is proposed:

$$f(q_{ij}; d_i) = v_{ij} = q_{ij} \cdot d_j^{-1} = q_{ij} \left[l - \sum_{k=1}^{l-1} \left[p_{j(k)} - p_{j(k+1)} \right] \right]^{-1} \tag{6}$$

where ν_{ij} represents the vulnerability of the *j*-th stage of aviation operation to incidents of the *i*-th class, occurring from the *l*-th number of categories of incident causes.

To calculate the combined measure *V* of aircraft vulnerability to aviation incidents occurring in a specific area of aviation operations, one can use additive models, such as the one provided in equation (7):

$$V_j = d_j^{-1} \cdot \sum_{i=1}^{m} q_{ij} \tag{7}$$

a. Source data for estimating vulnerability

Table 1 presents the probabilities of aviation incidents in various stages of aviation operations in civil aviation systems in Poland. The values were obtained based on data on these incidents (approximately 3200 incidents) recorded by the Civil Aviation Authority over a five-year period at eight regional airports in Poland [CAA, 2023]. When determining the measures of vulnerability of individual stages of aviation operations, the number of incidents occurring in these stages is particularly important.

Table 1. The probability of aviation incidents in various stages of aviation operations based on data from eight regional airports in Poland

Aviation operation stage	Number of incidents (in a 5-year period)	Probability
Approach	108	0.03354
En route	9	0.00280
Landing	1382	0.42919
Standing	2	0.00062
Take-off	1704	0.52919
Taxi	9	0.00280
Unknown	6	0.00186

To estimate the vulnerability of aviation operations to specific classes of aviation incidents, it is also necessary to gather information on the number of incidents of a given class in various stages of aviation operations. Such data are presented in Table 2.

Table 2. The numbers of aviation incidents recorded in various stages of flight operations, depending on the class of aviation incident

Aviation operation stage	Class of aviation incident						
	Occurrence without safety effect	Incident	Serious incident	Not determined	Accident	Major	Significant incident
Approach	70	18	1	17		2	
En route	1	4	1	2			1
Landing	197	1047	6	129	1		2
Standing		1		1			
Take-off	343	1190	2	156		2	11
Taxi	2	3		2			2
Sum:	**613**	**2263**	**10**	**307**		**4**	**16**

3. Results of vulnerability estimation for selected classes of aviation incidents

By using the data presented in Tables 1 and 2, the conditional probabilities of the occurrence of each class of aviation incidents in a given stage of aviation operations were calculated. The values of these probabilities are provided in Table 3.

Table 3. The conditional probabilities of the occurrence of each class of aviation incidents in a given stage of aviation operations q_{ij}

Aviation operation stage	q_{ij}*	Class of aviation incident						
		Occurrence without safety effect	**Incident**	**Serious incident**	**Not determined**	**Accident**	**Major**	**Significant incident**
		$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$	$i = 7$
Approach	$q_{i1} =$	0.6481	0.1667	0.0093	0.1574	0.0000	0.0185	0.0000
En route	$q_{i2} =$	0.1111	0.4444	0.1111	0.2222	0.0000	0.0000	0.1111
Landing	$q_{i3} =$	0.1425	0.7576	0.0043	0.0933	0.0007	0.0000	0.0014
Standing	$q_{i4} =$	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
Take-off	$q_{i5} =$	0.2013	0.6984	0.0012	0.0915	0.0000	0.0012	0.0065
Taxi	$q_{i6} =$	0.2222	0.3333	0.0000	0.2222	0.0000	0.0000	0.2222

* denotation of the variable of the conditional probability of the occurrence of classes of aviation incidents in the *j*-th stage of aviation operations

Incidents reported to the CAA by aviation organizations using ECCAIRS 2.0 (previously CBZ) are characterized by a wide variety of headline descriptions while at the same time exhibiting a high similarity in causes. Therefore, it was decided to group similar causes of registered aviation incidents and introduce the following categories:

Category 1 – Airspace control: Incorrect system actions or warnings such as TAWS, GPWS, EGPWS czy ILS and inaccurate or erroneous information ATC.
Category 2 – Aircraft Proximity: separation minima, callsign confusion, airspace intrusion by objects.
Category 3 – Wildlife hazard: Non-Avian wildlife hazards to aircraft usually involve ground dwelling mammals, which limits the potential consequences of impact.
Category 4 – Birdstrike: aircraft collisions with birds and bird activity causing aborted takeoffs or landings.
Category 5 – Runway/Taxway: incursion, excursion, not vacated, blocked and check runway or taxiway.
Category 6 – Technical problem: ACFT damage, MLG, NLG, tire damage, engine failure, flap issues, door closure problem.
Category 7 – Ground Safety: handling operations (e.g., incorrectly performed tasks), crew (e.g., health issues), or airport management (e.g., equipment shortages).
Category 8 – Passenger: passenger behavior, health issues, and improperly packed luggage.
Category 9 – Stage of flight: irregularities during flight phase: missed approach, hard, deep, long, bounced and behind TDZ landing, incorrect take-off, go around and level bust.
Category 10 – FOD: foreign object includes any object found in an inappropriate location at an aerodeome that can damage equipment or injure personnel.
Category 11 – Procedure: not followed ATC clearance or landing without procedures.
Category 12 – Weather: bad weather conditions and lightning strikes.
Category 13 – Fire: fire, smoke and fumes.
Category 14 – Laser: laser blinding aircraft crews.
Category 15 – Fuel: fuel or oil problems.
Category 16 – Config: configuration warning.

The probability distributions characterizing the mentioned categories of causes depending on the stage of aviation operations are presented in Table 4.

Table 4. The probability distributions of categories of causes of aviation incidents depending on the stage of aviation operations are presented in Table 4

Cause Category	Aviation operation stage						
	Approach	En route	Landing	Standing	Take-off	Taxi	Unknown
	$j = 1$; $l_j^* = 9$	$j = 2$; $l_j = 3$	$j = 3$; $l_j = 15$	$j = 4$; $l_j = 2$	$j = 5$; $l_j = 16$	$j = 6$; $l_j = 4$	$j = 7$; $l_j = 2$
Airspace control	0.0185		0.0145	–	0.0187	–	–
Aircraft Proximity	0.1019	0.7778**	0.0051	–	0.0287	0.2222**	0.8333**
Wildlife hazard	–	–	0.0311	–	0.0023	–	–
Birdstrike	0.0556	–	0.6042	0.5**	0.4768	–	0.1666**
Runway/Taxway	0.5741	–	0.0376	0.5**	0.0346	0.2222**	–
Technical problem	0.0185	0.1112**	0.0774	–	0.2272	0.4444**	–
Ground Safety	–	0.1112**	0.0116	–	0.0229	–	–
Passenger	0.0185	–	0.0109	–	0.0065	–	–
Stage of flight	0.1852	–	0.0174	–	0.0740	0.1111**	–
FOD	0.0185	–	0.0072	–	0.0082	–	–
Procedure	0.0093	–	0.0087	–	0.0206	–	–
Weather	–	–	0.0174	–	0.0229	–	–
Fire	–	–	0.0051	–	0.0082	–	–
Laser	–	–	0.0145	–	0.0223	–	–
Fuel	–	–	0.0029	–	0.0070	–	–
Config	–	–	–	–	0.0188	–	–

* the number of cause categories of aviation incidents considered in a given stage of aviation operation
** estimated values from a small statistical sample (shown only to demonstrate completeness of the results).

As shown in Table 4, the number of cause categories of aviation incidents can significantly vary depending on the stage of aviation operation. This will significantly affect the vulnerability value. To estimate this value, it is necessary to first determine the diversity component according to equation (5). For this purpose, the values in the probability distributions must be arranged in ascending order, as indicated in equation (4), assigning them appropriate indices k. For example, for the Approach stage ($j = 1$), the set P_j of arranged probability values $p_{j(k)}$ would look as follows:

$$P \ = \{0{,}0093; 0{,}0185; 0{,}0185; 0{,}0185; 0{,}018519; 0{,}0556; 0{,}1019; 0{,}1852; 0{,}5741\} \tag{8}$$

with the calculated diversity coefficient d_1 for this stage being $d_1 = 8{,}435$. We can use this value along with equation (6) to estimate the vulnerability values for this stage of aviation operations for the given aviation incident classes. The results of this estimation are presented in Table 5 (column 3).

Table 5. The results of estimating the vulnerability of selected stages of aviation operations to specific classes of aviation incidents

Class of aviation incident	ID klasy zd.	Approach	Landing	Take-off
		v_{i1}	v_{i3}	v_{i5}
Occurrence without safety effect	$i = 1$	0.119	0.014	0.002
Incident	$i = 2$	0.237	0.028	0.003
Serious incident	$i = 3$	0.356	0.042	0.005
Not determined	$i = 4$	0.474	0.056	0.007
Accident	$i = 5$	0.593	0.070	0.008
Major	$i = 6$	0.711	0.084	0.010
Significant incident	$i = 7$	0.830	0.098	0.012

Finally, values of susceptibility for the j-th stage of aviation operation to all registered classes of aviation events can also be provided. Utilizing Table 5 and formula (7), these values for three stages (Approach, Landing, Take-off) are as follows: $V_1 = 0{,}12$; $V_3 = 0{,}07$; $V_5 = 0{,}06$.

4. Final remarks

Vulnerability is a highly useful measure for assessing the functioning of systems or areas subjected to analysis from various perspectives. We particularly recognize its relevance in safety management systems, as vulnerability can be a component of risk models and metrics. However, most risk assessments (not only in aviation) currently rely on classical metrics, which may not always be justified.

A literature review indicated that vulnerability measures are relatively frequently used in aviation, although there are various understandings and mathematical formulations of it. These applications, however, are not entirely suitable for the problem addressed in this article. The innovative idea lies in applying vulnerability measures to stages of aviation operations for aviation incidents. The specificity of this research problem lies in the diversity of causes of these incidents, which affects both their severity and frequency (as observed in the analysis of aviation incident data). Furthermore, from the perspective of threat management, such diversity of incidents may pose more challenges than their frequency alone (e.g., in the context of safety system organization).

Therefore, there is a recognized need to develop and present a vulnerability measure appropriate for the selected area of analysis and encompassing the diversity component of incident causes.

Firstly, a literature review was conducted on estimating vulnerability in aviation transport systems. The literature analysis showed that vulnerability is most commonly a probabilistic measure based on conditional probability. It can be determined predictively (simulatively, through modeling) as well as retrospectively/statistically, with appropriate data. Thus, it is possible to prepare dedicated vulnerability measures based on known solutions.

An approach based on information about registered aviation incidents was chosen, especially considering the obligation to collect such data in dedicated databases. A new definition and mathematical model of vulnerability measure for stages of aviation operations were presented. According to this model, vulnerability encompasses the diversity of incident causes in the form of an original diversity coefficient based on species diversity measures.

The presented measure is not intended to replace the ones currently used but to complement the resources of available safety management tools. The mathematical model of vulnerability was prepared so that it can be easily modified by adopting other functions, still based on two variables describing the defined vulnerability.

In summary, the actions that were taken indicate the possibility of assessing the stages of aviation operations in terms of their vulnerability. This was demonstrated by presenting the results of estimating the vulnerability of selected stages of aviation operations to specific classes of aviation incidents according to the developed vulnerability measure. These results alone suggest the potential applicability of this measure in other research problems.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

1. Adger, W. N. (2006). Vulnerability. *Global Environmental Change*, *16*(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006
2. Corbin, J. C., & Cooley, W. W. (1982). Assessment of aircraft susceptibility/vulnerability to lightning and development of lightning-protection design criteria. *IEEE Transactions on Electromagnetic Compatibility*, *EMC-24*(2), 225–237. https://doi.org/10.1109/TEMC.1982.304033
3. Dacko, A., & Toczyski, J. (2011). Vulnerability Analysis of Aircraft Fuselage Subjected to Internal Explosion. *Archive of Mechanical Engineering*, *58*(4), 393–406. https://doi.org/10.2478/v10180-011-0024-4
4. Dhillon, B. S. (1999). *DESIGN RELIABILITY Fundamentals and Applications*. CRC Press Boca Raton London New York Washington, D.C.
5. EASA. (2019). *NPA 2019-05 Embodiment of safety management system (SMS) requirements into Part-145 and Part 21.* EASA.
6. Fouda, R. M. (2018). Security vulnerabilities of cyberphysical unmanned aircraft systems. *IEEE Aerospace and Electronic Systems Magazine*, *33*(9), 4–17. https://doi.org/10.1109/MAES.2018.170021
7. Gill, A. (2018). *Warstwowe modele systemów bezpieczeństwa do zastosowań w transporcie szynowym [Layered models of safety systems for rail transport applications]*. Wydawnictwo Politechniki Poznańskiej.
8. Gill, A., & Smoczyński, P. (2018). Layered model for convenient designing of safety system upgrades in railways. *Safety Science*, *110PB*, 168–176. https://doi.org/10.1016/j.ssci.2017.11.024
9. ICAO. (2004). *Aviation Occurrence Categories Definitions and Usage Notes*. ICAO.
10. ICAO. (2010). *ECCAIRS 4.2.8 – Occurrence classes*. ICAO.
11. ICAO. (2016). *Annex 19 to the Convention on International Civil Aviation: Safety Management (2nd ed.)*.
12. ICAO. (2017). *Annex 13 to the Convention on International Civil Aviation: Aircraft Accident and Incident Investigation (2nd ed.)*.
13. ICAO. (1987) Doc. 9156. Accident/incident reporting manual.
14. ICAO. (2018). *Doc. 9859. Safety Management Manual (4th ed.)*. ICAO.
15. Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions. In *Sustainability* (Vol. 13, Issue 4). https://doi.org/10.3390/su13042051
16. Kobaszyńska-Twardowska, A., Krzyżanowski, M., & Siwka, P. (2023). Forecasting Trends of Safety Performance Indicators in Aviation. *Safety & Defense*, *9*(2), 1–11. https://doi.org/10.37105/sd.201
17. Konokman, H. E., Kayran, A., & Kaya, M. (2017). Aircraft vulnerability assessment against fragmentation warhead. *Aerospace Science and Technology*, *67*, 215–227. https://doi.org/10.1016/j.ast.2017.04.005
18. Li, J., Yang, W., Zhang, Y., Pei, Y., Ren, Y., & Wang, W. (2013). Aircraft vulnerability modeling and computation methods based on product structure and CATIA. *Chinese Journal of Aeronautics*, *26*(2), 334–342. https://doi.org/10.1016/j.cja.2013.02.010
19. Lomazzi, L., Cadini, F., Giglio, M., & Manes, A. (2022). Vulnerability assessment to projectiles: Approach definition and application to helicopter platforms. *Defence Technology*, *18*(9), 1523–1537. https://doi.org/10.1016/j.dt.2021.09.001
20. Lovric, M. (Ed.). (2011). *International Encyclopedia of Statistical Science* (1st ed.). Springer-Verlag Berlin Heidelberg.
21. Maragakis, I., Clark, S., Piers, M., Prior, C. D., Tripaldi, C., Masson, M., & Audart, C. (2009). *Guidance on hazadrs identification, European Strategic Safety Initiative*. European Authority for aviation safety (EASA).
22. Nöldgen, M., Fehling, E., Riedel, W., & Thoma, K. (2012). Vulnerability and Robustness of a Security Skyscraper Subjected to Aircraft Impact. *Computer-Aided Civil and Infrastructure Engineering*, *27*(5), 358–368. https://doi.org/10.1111/j.1467-8667.2011.00748.x
23. Pei, Y., & Cheng, T. (2014). Importance Measure Method for Ranking the Aircraft Component Vulnerability. *Journal of Aircraft*, *51*(1), 273–279. https://doi.org/10.2514/1.C032334
24. Pei, Y., Li, P., & Song, B. (2012). Kronecker Product Method for the Exact Solution of Aircraft Vulnerability. *Journal of Aircraft*, *49*(1), 337–341. https://doi.org/10.2514/1.C031476
25. *Rozporządzenie Parlamentu Europejskiego i Rady (UE) NR 996/2010 z dnia 20 października 2010 r. w sprawie badania wypadków i incydentów w lotnictwie cywilnym oraz zapo-biegania im.* (2010).
26. Simpson, E. H. (1949). Measurement of Diversity. *Nature*, *163*, 688. http://dx.doi.org/10.1038/163688a0
27. Singh, V. P., & Singh, Y. (2000). zGeneralized Model for Aircraft Vulnerability by Different Weapon Systems. *Defence Science Journal*, *50*(1), 13–23. https://doi.org/10.14429/dsj.50.3316
28. Skorupski, J. (2018). *Ilościowe metody analizy incydentów w ruchu lotniczym*. Oficyna Wydawnicza Politechniki Warszawskiej.
29. SRA. (2018). *Society for Risk Analysis Glossary*. Society for Risk Analysis (SRA). https://www.sra.org/

30. Sun, Y., Wu, T. Y., Liu, X. W., & Obaidat, M. S. (2016). Multilayered Impact Evaluation Model for Attacking Missions. *Ieee Systems Journal*, *10*(4), 1304–1315. https://doi.org/10.1109/jsyst.2014.2344048
31. Thekdi, S., & Aven, T. (2024). Characterization of biases and their impact on the integrity of a risk study. *Safety Science*, *170*(May 2023), 106376. https://doi.org/10.1016/j.ssci.2023.106376
32. ULC (CAA) m unpublished materials
33. Ustawa z dnia 3 lipca 2002 r. Prawo lotnicze (Dz.U. z 2008 r. Nr 97, poz. 625), (2002).The Act of July 3, 2002, Aviation Law.
34. Willis, H. H. (2007). Guiding Resource Allocations Based on Terrorism Risk. *Risk Analysis*, *27*(3), 597–606. https://doi.org/10.1111/j.1539-6924.2007.00909.x