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Quantifying civilian aircraft vulnerability: A data-driven approach in geo-political conflict zones for improved risk assessment of aircraft shot-down

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ABSTRACT

Current risk analysis methods for quantifying the risk of the shooting down of commercial aircraft rely on the use of risk matrices and risk categorisation classes. We show that these processes are not effective, subject to bias and not adequate to help aviation companies decide whether to fly to or over conflict areas.

Information concerning terror attacks, wars or conflicts is instantly available through various internet channels, and we argue that this enables more innovative accurate data-driven aircraft shoot down risk assessment. We propose a generalised linear model with logit link to estimate the likelihood of an aircraft being shot down based on technical and geo-political environmental factors. We use our model to estimate the probability of aircraft being shot down in all countries that are currently affected by military conflict. We demonstrate that probability of shooting down civilian aircraft depends on economic indicator such as GDP per capita, type and intensity of the conflict. We validate our model using out-of-sample tests with cross-validation.

The method proposed in this paper uses data available in open sources, it is easy to implement and utilize in aviation company or other industry bodies for prediction of aircraft shooting risks. It significantly improves currently existing methodologies of aircraft shooting risk assessment.

1. Introduction

Despite COVID pandemic effect, civil aviation remains a popular means of transportation and demonstrated good signs of growth and recovery – 2.3 billion passengers were transported on passenger flights worldwide in 2021 and 3.2 billion passengers in 2022 (ICAO, 2023).

Considering this high number of passengers and a large lumber of conflict zones around the globe nowadays (EASA, 2022), the chances of a civilian aircraft being shot down in the vicinity of a conflict zone are significant.

The most notable recent examples of civilian aircraft downing were Malaysia Airlines flight MH 17 that was shot down by a Buk surface-to-air missile on July 17, 2014 during the armed conflict in Eastern Ukraine (Board, 2015) and Ukraine International Airlines flight PS 752 that was shot down by two Tor M1 missiles launched by an Iranian Air Defence Unit as a result of misidentification amid escalation of conflict between Iran and the United States (Aviation Safety Network, 2022). Later the same year, on 4 May, also as a result of misidentification, an Embraer EMB-120 of African Express Airways was shot down in Somalia by anti-aircraft artillery used by Ethiopian peacekeepers (Aviation Safety Network, 2022), killing six people.

This paper critiques the current qualitative or semi-qualitative approaches to security risk assessments widely used in the aviation industry and proposes a more predictive quantitative data-driven methodology.

This paper is organised as follows. In Section 1 we provide an overview of current industry regulations and practices of security risk assessment, followed by a review of the literature on risk assessments in aviation safety and security. In section 2 we develop hypotheses concerning the factors influencing national and aviation security. In section 3 we introduce predictive quantitative data-driven methodology for assessing the probability of an aircraft being shot down by a surface to air missile and present the results of applying the methodology in section 4. We discuss these results in section 5 and present our conclusions in section 6.

1.1. Current processes for aviation security risk assessment

The Convention on International Civil Aviation (also known as the Chicago Convention) Annex 17 is an international legislative document that contains Standards and Recommended Practices for international civil aviation. It requires the relevant national authority of the country

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to conduct risk assessment for its civil aviation (ICAO, 2017). Guidelines for the implementation of this requirement are provided in the Aviation Security Manual that recommends countries to establish a risk management system which contains tools to obtain information about threats to aircraft and to conduct risk assessments. It is suggested that threat information should be received from intelligence authorities and thoroughly analysed in a systematic manner (ICAO, 2014). The applications of these recommendations are non-standardised and vary between countries. As a rule, the state's security services define several threat levels associated with different levels of severity. For example, in the United Kingdom, there are five levels of threat set by the Joint Terrorism Analysis Centre and the Security Service (MI5), each identifying the possibility of an attack: low (unlikely), moderate (possible but not likely), substantial (strong possibility), severe (highly likely), and critical (expected imminently) (GOV.UK, 2022). The United States uses a two-level threat alert system: imminent threat alert (credible, specific impending threat) and elevated threat alert (credible terror threat) (US Department of Homeland Security, 2011). France uses a three-level alert system: attack emergency (vigilance and maximum protection due to imminent threat of attack), heightened security/risk of attack (high level of terrorist threat), and vigilance (permanent posture of security) (Gouvernement.fr, 2022). Belgium uses a four-level system: level 1 (low, no threat), level 2 (medium, unlikely threat), level 3 (severe, threat is possible and probable), and level 4 (very serious, threat is serious and imminent) (Belgium.be, 2022). Clearly, countries have different systems of indication and interpretation of security threat level which makes it difficult to undertake a flight security risk estimation across more than one state.

The International Air Transport Association (IATA) recommends an air carriers' risk management approach that consists of the following seven steps: (1) communication and consultation (consultative team of all related stakeholders to understand the basis of decisions made and reasons for the required actions throughout the risk management process); (2) establishing the context; (3) identifying the risk (setting up objectives and detailing possible occurrences); (4) analysing; (5) prioritising; (6) treating the risk or risks; and, finally, (7) monitoring and reviewing implemented mitigation actions (IATA, 2013). For the analysis of the risk IATA suggests using Eq. (1).

$$\textit{Risk rating} = \textit{Consequence x Likelihood} \quad (1)$$

A similar approach is used in the International Civil Aviation Organization (ICAO) Manual Risk Assessment Manual for Civil Aircraft Operations Over or Near Conflict Zones, Doc 10084 (ICAO, 2018a), and in the ICAO Safety Management Manual, Doc 9859 (ICAO, 2018b).

Consequences are categorised as catastrophic, major, moderate, minor, or insignificant (IATA, 2013) or catastrophic, hazardous, major, minor, or negligible (ICAO, 2018b). The meaning of each consequence is defined in terms of its impact on financial performance of the entity, human lives, damage of equipment, and influence on brands and reputation of the company. IATA uses following categories of *Likelihood* values – *almost certain* (inevitable to occur, or mostly certain), *likely* (will occur in most of the circumstances), *possible* (possibility to occur under certain circumstances), *unlikely* (possible, but "surprised if it happens"), and *rare* (may occur in exceptional circumstances, unexpected) (IATA, 2013).

It is recommended that the values of the *Severity (Consequence)* and the *Likelihood* are combined in a standard risk matrix. A "traffic light" system associated with the table helps to assess risks and categorise those into one of three categories – acceptable, tolerable and intolerable (ICAO, 2018b). This is aimed at helping the entity to prepare structured and detailed mitigating actions to each level of the risk.

The ICAO and IATA matrices methodologies are widely used in aviation safety and security. However, a number of authors have highlighted several limitations associated with this methodology. Risk matrices have been criticised for poor resolution and errors (Anthony Cox Jr, 2008; Baybutt, 2018); ambiguous inputs and outputs (Anthony Cox Jr, 2008; Duijm, 2015), low flexibility as it is limited to a small number of levels and options and, hence, possible outcomes (ICAO, 2014), ignoring dependencies between risks (ICAO, 2018b) and use of generally accepted categories (Renooij and Witteman, 1999).

These limitations may have catastrophic implications in aviation security risk assessment. For example, there is an inability to quantify the impact of mitigations. In a given assessment, experts may consider that mitigating actions reduce the risk from 'high' to 'medium'. This does not provide a good assessment for residual risk (ICAO, 2014). In addition, ICAO delegates the risk assessment to states. This results in inconsistent use of risk matrices for security risk assessment (ICAO, 2018a).

Some air carriers have operations and subsidiaries registered in multiple countries that may lead to inconsistency in security risk assessments by security agencies of several countries. The methodology provided by ICAO is most likely to prove more useful to a "flag carrier" – an air carrier legally bound by and clearly associated with one state. For the reasons mentioned above, the ICAO and IATA aviation security risk assessment processes are not suitable for air carries that operate across different borders.

1.2. Existing methods for assessment aviation security risks

Aviation security risk analysis research focuses mainly on the risks of passengers' security screening, risks related to certain flights and narrow industry niches such as air traffic management. For example, aviation security risk analysis research has focused on security risk problems such as passenger and hand baggage screening (Barnett, 2004; Nikolaev et al., 2012), quantification of risk of a specific flight based on mitigating actions applied to this flight, such as air marshals, airspace waivers, and other security actions (Bolczak and Forman, 2010), use of aircraft flight monitoring systems as a part of a risk management system in order to transmit information about security incidents to navigation services (Anderegg and Fong, 2007).

Risk models have been developed to build robustness to cyberattacks with the help of Adversarial Risk Analysis. The high level of digitalisation in aviation creates significant vulnerability – for example, for air traffic management (ATM). The proposed adversarial risk analysis method uses a Bayesian model for decision making for *the Defende*r that needs to forecast actions of the adversary, *the Attacker*, considering possible uncertainties. The Defender will deploy protective measures that can be monetised (quantified) to measure the impact of the attack as total cost (Cano et al., 2016). This methodology can be used in the airport where, in a real-life scenario, the Defender can be an airport operator, and the Attacker the group of criminals or terrorists. The set of protective measures for the airport – both default and extraordinary – can be relatively easily pre-defined and quantified (capital investments in airport boundary and protective means, operating costs of the personnel and equipment, extra costs of additional personnel, and so on). Despite its benefits, Adversarial Risk Analysis methodology is not suitable for risk analysis of an aircraft being shot down as, in a number of cases, aircraft are shot down as a result of error and not as a result of a strategy to attack a point of vulnerability in the system.

Ancel et al. (2015) proposed a causal model to analyse safety risks contributing to aviation safety event by application of an object-oriented Bayesian network. Authors provide statistics of accident occurrence stating that in-flight loss of control of the aircraft is the biggest contributor to fatal aviation accidents. The root-causes of such events were grouped into three categories: related to *human factors* (both in flight and on ground), *system components*, and *external factors* (environment). The model was used to compare historical loss-of-control incidents and quantified the probabilities for each of the contributing factors leading to loss of control (Ancel et al., 2015). Although the subject of this research has similarities to the issue of assessing the risk of an aircraft being shot down, the goal of the model is to analyse which contributing factors are leading to an undesirable event more often and define the significance of these factors rather than to define a risk of an undesirable event.

Rios Insua et al. explore application of risk matrices in respect of aviation safety at a state level. They examine a range of events and consequences identified by the Spanish Aviation Safety and Security Agency, including fatalities, minor and serious injuries, delays, and cancelations of flights, maintenance, and repair operations due to safety occurrences, loss of aircraft, and reputational losses. They propose a framework that predicts the number of events and the number of potential consequences. Although authors acknowledge the downsides of the usage of risk matrices, they still advocate their use. This approach employs safety information provided by analysis of aircraft technical parameters and this is not suitable for assessing security where the threat comes from external (adversary) factors (Rios Insua et al., 2018).

The most common methodology used both in aviation safety and security is the risk matrix – a simple qualitative methodology based on the opinion of experts. However, to the best of our knowledge, there is no common methodology for quantify aviation security risk. In the research reviewed in this section, authors either use the same methodology based on risk matrices or provide specific tailored approaches for the niche target of their research (e.g., air traffic management or analysis of safety events).

Air carriers are in a situation where risk assessment is vital and required by international legislation, but currently the methodologies employed in this regard are limited. Consequently, it is imperative to explore new methods to quantify the likelihood of an aircraft being shot down that addresses the various limitations identified above. This should help in reassuring those involved in aviation security today (ICAO, 2018a). The United Nations identifies factors that may influence the risk of a security threat in the aviation industry. However, to the best of our knowledge, these factors are currently only used for qualitative risk assessment of aircraft being shot down. In this paper we present a data-driven approach to quantify this risk and we apply this approach to the problem of quantifying the probability of an aircraft being shot down by a surface-to-air missile.

This paper has three aims: (i) demonstrate significant limitations and inadequacy of methodologies currently used in aviation industry for risk assessment of commercial flight shooting down; (ii) research which factors influence this risk and (iii) propose new probabilistic methodology for the prediction of aircraft shooting incidents using historical data available in open sources.

2. Hypothesis development

In this section we analyse what economic, geo-political, or social factors influence aviation security. These factors form the basis for the hypotheses that we develop. First, we explore the possibility of approaching aviation security as a part of national security that potentially provide more data of economic and geopolitical factors influencing it. Second, we study armed conflicts to identify the factors that might influence aircraft shooting-down risk. Third, we discuss to what extent economic indicators of a country might influence aircraft shooting-down risk. Finally, we provide a brief assessment of types of flight characteristics which are relevant for the research model.

2.1. National security

To understand the major factors that may influence aviation security in a given country, we first need to establish whether we can approach aviation security as a part of the national security apparatus of the state.

The ICAO considers actions against international civil aviation as a threat to general security. As stated in the preamble to the Convention on International Civil Aviation (Chicago Convention):

> *"whereas the future development of international civil aviation can greatly help to create and preserve friendship and understanding among the nations and peoples of the world, yet its abuse can become a threat to the general security"*
>
> (ICAO, 2006)

In 1996, the United States President Clinton established a Commission to study possible improvements in safety and security including air traffic control of both international and domestic civil aviation (Gore, 1997). From the security perspective, this study analysed the increasing threat of terrorism, in particular, a terror attack called the "Bojinka plot", where a group of terrorists led by Ramzi Yusuf (later convicted for the first attempt to destroy the World Trade Centre building in New York, USA in 1993) planned a terror attack with mid-air explosions on 11 USA-bound aircraft enroute from South Asia (Stewart and Mueller, 2020). Recommendation No. 3.1 of the Report indicates: *"The federal government should consider aviation security as a national security issue"* (Gore, 1997). The terror attacks of September,11 (9/11) have drastically changed the definition and the scope of national security in the US. The Patriot Act signed on October 26, 2001 (initially the called Anti-Terrorism Act) significantly increased the powers of law enforcement authorities, increased information-sharing for the protection of critical infrastructure, enhanced domestic security and surveillance procedures, and strengthened criminal laws against terrorism including terror attacks and violence against transportation systems (Congress, 2002). The Homeland Security Act, 2002 was another security policy document published in the aftermath of the September 11. This Act defined terrorism as *"… dangerous to human life or potentially destructive of critical infrastructure …"*. To prevent terror attacks the Act has established a new governmental department – the Department of Homeland security. Although the debate about the definition of *"homeland security"* and its correspondence to a widespread term *"national security"* was ongoing for some time (Reese, 2013), it is widely accepted that within the borders of the United States the meaning of the two is equal.

Other countries similarly consider aviation security as part of national security. The UK National Security Strategy and Strategic Defence and Security Review of 2015 lists aviation security among priority items that require good intelligence and coordination between airlines, airports, and governments. The Review stated that the UK government planned to increase its expenditure in aviation security worldwide and strengthen aviation security with UK experts at certain locations (Government, 2015). Security of the transportation systems and prevention of threats against transport is also a part of the national security strategies of Germany (Schockenhoff, 2008), and Australia (Dupont and Reckmeyer, 2012). Based on the above, we can positively assume that aviation security, including protection against civil aircraft being shot down, is an integral component of the national security of many countries. Therefore, we formulate our hypothesis:

H1. *A country's security situation is a significant factor when quantifying the risk of a civilian aircraft being shot down.*

This gives us an opportunity to undertake a fuller examination of the importance of a country's security level in relation to risk of civil aircraft being shot down.

2.2. Economic, social, and geo-political factors

The threats to international security categorised and summarised in the United Nations (UN) High-level Panel "Report on Threats, Challenges and Change. A more secure world: our shared responsibility" are as follows: 1) Economic and social threats, poverty, infectious diseases, and environmental degradation; 2) Inter-state conflict; 3) Internal conflict, including civil war, genocide, and other large-scale crimes; 4) Nuclear, radiological, chemical, and biological weapons; 5) Terrorism; and 6) Transnational organised crime (United Nations, 2004). The UN also highlights the concept of human security which it suggests can be achieved by protecting people and fundamental freedoms from critical threats, such as war and violent conflicts and by reducing poverty and achieving economic growth; the latter two factors also positively influencing national security (UNDP, 2005).

Giacomo defines national security as the ability to withstand aggression from abroad, where aggression is defined as an active use of force by an invading army occupying a part of national territory. Thus, aggression is always related to the use of military force and its context is related to the land, borders or, in other words, territorial disputes. Territorial integrity or possession of the land, therefore, are key interests of national security and are essential for the wellbeing of the nation. Giacomo's narrower definition of security relates only to military or territorial matters, while the broader definition links national security with economic prosperity. Under the broad definition, Giacomo argues that deterioration of the economy can be considered as a threat to national security and, in extreme cases, be equal to aggression (Giacomo, 1988).

Based upon both the UN and Giacomo's views, it could be concluded that wealthy nations with stable economies have stronger national security– economic poverty and instability being considered threats to national security. The econometric evidence supports the conclusion that a low level of GDP per capita can serve as a predictor of civil war: for example, nations with GDP per capita of 250 USD have a 0.15 probability of civil war, while nations with GDP per capita of 2,500 USD have a less than 0.01 probability of civil war (Humphreys, 2003). The definition of GDP per capita as per the Cambridge dictionary is the following: "The total value of all the goods and services produced by a country in a particular year, divided by the number of people living there". GDP is also an important parameter of economic performance and an indicator of economic wellbeing as predicted by the US Bureau of Economic Analysis (The U.S. Bureau of Economic Analysis, 2021).

Since aviation security is an integral part of the national security of a state, threats to the national security may affect aviation security. In particular, one of the significant threats to national security is war. However, as indicated above, a strong economy, measured by GDP per capita is likely to increase the strength of national security and, in turn, increase aviation security. We examine this view by testing our second hypothesis:

H2. *The GDP* per capita *of the state is a significant and important geopolitical factor for quantifying the risk of a civilian aircraft being shot down.*

2.3. Conflicts in the context of security

The type of war or conflict in a given country must be considered when assessing the risk of civil aircraft being shot down, since the type of war or conflict will inform the type of armour deployed by the different parties. There are several definitions of conflict, and it is important to define how we measure the conflict type and intensity. The Uppsala Conflict Data Program of Uppsala University (Pettersson and Wallensteen, 2015) proposes the following categorisation of armed conflict:

- *Interstate* conflict – a conflict between two or more states;
- *Internal* conflict – a conflict between government and internal opposition groups;
- *Internationalised* armed conflict –conflict between the state and opposition groups with the intervention of another state;
- *Extra systemic* conflict – a rarely used category, this refers to a conflict between a state and an opposition group outside of the territory of that state (e.g., colonial conflicts). However, these types of conflicts have not been registered by researchers since 1974, although they can still be observed in historical datasets.

The intensity of armed conflicts have been categorised by Pettersson and Wallensteen, (2015) as:

- Minor – the number of deaths is below 1000; and
- Major – 1000 and more deaths.

This categorisation includes battle-related deaths – both civil and military fatalities that occurred directly in the conflict – on the battlefield, due to bombing and crossfire (Pettersson and Wallensteen, 2015).

Conflicts can be divided into two categories – *interreligious* armed conflict, where the two sides of the conflict differ in their religious belonging and affiliation (i.e., Christian vs. Muslim, Buddhist vs. Hindu) and *theological* armed conflict – where the state and rebel group(s) are incompatible concerning religious affiliation (Basedau et al., 2016). Dividing conflicts on a basis of religion is quite a narrow approach and not all the conflicts have religious background, hence we look into other approaches, for instance a categorisation of armed conflicts from the perspective of international humanitarian laws (Vite, 2009):

- *International*– all cases of declared war between states;
- *Internationalised* – one side of the conflict sends troops to support opposing groups in another state;
- *Occupation* – when the territory of one of the sides of the armed conflict appears under the authority of the other side's army;
- *Non-international*– a conflict between the state and armed non-governmental groups;
- *Other conflicts* – including, for example, control of the territory without presence of the army, intervention of one or more states in non-international conflict, intervention of multinational forces in non-international conflict (Vite, 2009).

In classification of Vite (2009) a definition of "Other conflicts" is too wide, while "Occupation" can be a part of other conflicts. It has similarities with the classification of the Uppsala Conflict Data Program, however due to more precise and universal definitions of conflicts the latter better fits our research. Considering the fact that it is possible to categorise different types of conflict and that armed conflicts are among the top six threats to international security (United Nations, 2004), we test our third hypothesis:

H3. *The type of conflict and its intensity are significantly important for civil aircraft shooting risk quantification.*

2.4. Type of commercial air operation

Another important factor to consider in a model to assess the risk of being shot down is the nature of the flight, or type of commercial air operation. There are studies that indicate that number of safety occurrences is related with the type of operations, or nature of conducted flights (Kharoufah et al., 2018). We can assume that relation to security occurrences also exist. In the case of an intended shooting (e.g., terror attack) the adversary would be likely to target certain aviation activities, such as passenger flights to increase media impact and exposure. In the case of an unintended shooting (i.e., accidental shooting over the conflict zone) non-scheduled flights of any nature are more likely targets. The classification of civil flight activities is available in ICAO review of the classification and definitions used for civil aviation activities (ICAO, 2009). We suspect that the nature of a flight will impact the risk of being shot down and examine this view by testing a fourth hypothesis:

H4. *Type of commercial air operation or nature of the flight is important for shooting risk quantification.*

3. Methodology

This section of the paper provides information regarding selection of the variables and the model for the research.

3.1. Regression model

3.1.1. Dependent variable

To select the dependent variable to employ when testing the hypotheses, we turn to industry practices. Specifically, ICAO Safety Management Manual and ICAO Risk Assessment Manual for Civil Aircraft Operations Over or Near Conflict Zones suggest using probability and severity (ICAO, 2018a, 2018b). Defining an objective level of severity is extremely difficult as it involves a range of qualitative factors. However, the probability of an attack can be objectively measured. Consequently, to test the hypotheses we employ the probability of the shooting attack $P_{Attack}(C, Y)$ in the given country C in given year Y, and this is calculated as follows:

$$P_{Attack}(C, Y) = \frac{N_{Incidents}\ (C, Y)}{N_{Departures}\ (C, Y)}, \tag{1}$$

where $N_{Incidents}\ (C, Y)$ is the number of incidents in the given country C in given year Y and $N_{Departures}\ (C, Y)$ is the number of flight departures in the given country C in given year Y.

3.1.2. Independent variables

To test hypotheses 2-4, we employ, respectively, the following independent variables: *GDP_PC_1000* – GDP per capita, thousands USD; *Conflict_Type* – type of armed conflict as per Table 5 and *Conflict_Intensity* – intensity of armed conflict as per Table 4; *Nature* – nature of the flight (see Table 1 for details).

The set of independent variables is summarised in Table 1:

After merging the datasets *security occurrences – aircraft shot down* (Aviation Safety Network, 2022) with *safe flights dataset,* the dataset of all registered airline departures in a given country in a given year (The World Bank, 2019), *GDP PC dataset* (Bank, 2020b), and *conflict dataset* (Uppsala Conflict Data Program, 2020; Pettersson and Wallensteen, 2015), we obtained 178 datapoints.

Table 1
Independent variables.

	Variable	Variable description and type	Variable code	Source (dataset)
1	GDP per capita	GDP per capita in the given country in given year, thousands of USD. The variable is introduced as a descriptor of economic wealth and stability that influences the level of national security. Scale variable	*GDP_PC_1000*	The World Bank national accounts data
2	Intensity of the conflict	Intensity of the conflict where 1 and 2 represents minor conflict and war, respectively. Presence of the conflict and its intensity are factors significantly influencing the national security. Categorical nominal variable	*Conflict_Intensity*	Uppsala Conflict Data Program
3	Type of the conflict	Type of the conflict, where 1, 2, 3 and 4 represents extra-systemic conflict, interstate, internal and internationalised internal conflict, respectively. For the prediction of the risk of shooting down civilian aircraft it is important to consider what kind of conflict was registered in the area. Categorical nominal variable	*Conflict_Type*	Uppsala Conflict Data Program
4	Nature of the flight	Nature of the flight, where 1–8 represents scheduled flights, other passenger, cargo, military, aerial works, other, special flights, and non-scheduled flights, respectively. The variable is introduced to capture possible relation of type of commercial operations and probability of shooting down the flight. Similar relation exists in air safety. Categorical nominal variable	*Nature_Of_Flight*	Aviation Safety Network

3.2. Model selection process

The set of independent variables that were selected for the model is a combination of scale (*GDP_PC_1000*) and categorical nominal variables (*Conflict_Intensity*, *Conflict_Type, Nature_Of_Flight).* The dependent variable (P_{Attack}) is also a scale variable. Studies show that for the analysis of combination of categorical and scale variables, especially where dependent (or response) variable is continuous we shall employ a Generalised linear model (Myers et al., 2012). It has the advantage of being appropriate if the dependent variable is non-normally distributed (Agresti, 2012) which is the case here, and catering for the possibility of a non-linear relation between the dependent and independent variables (Hoffmann, 2016), which we suspect may be the case here. Generalised linear modelling (GLM) methodology is used where other regression models are more restrictive, for instance, in insurance where data is assumed not to be normally distributed. In case where scale dependent variable is concentrated on non-negative axis studies recommend utilizing gamma GLM (de Jong and Heller, 2008), that corresponds to this research since we use probability having values between 0 and 1 as dependent variable.

3.3. Data sources

The dataset of aviation security incidents provided by the Aviation Safety Network (Aviation Safety Network, 2022), covering the period 1931–2018, contains 619 cases of aircraft being shot down. We use data of aircraft being shot down in the post-World War II period, a time of development of modern civil aviation under ICAO regulation. Throughout the remainder of the paper. We refer to this dataset as "*security occurrences – aircraft shot down*" (see Table 2 for details of the data contained in this dataset).

For the purpose of testing the hypotheses we combine a number of the flight categories specified in the security occurrences - aircraft shot down dataset, into those specified in Table 3.

We obtain economic indicator GDP per capita data from the World Bank national accounts data (Bank, 2020b). The dataset contains 12,507 records of GDP (in USD) per capita for 264 countries and territories, covering the period from 1960 until 2018 (we refer to this as the *GDP PC dataset*). In those cases, where GDP per capita was missing from the data were obtained from the countryeconomy.com website.

Historical data concerning wars and conflicts was obtained from the webpage of the Uppsala Conflict Data Program, Uppsala University (Uppsala Conflict Data Program, 2020) hereinafter, referred to as the–*conflict dataset*). This contains details of the location of the conflict, sides of the conflict, territory name (if relevant), year of conflict, intensity level, type of the conflict, start and finish date of the conflict, and other service data. The categorisation we employed of intensity and type of conflict are provided in Tables 4 and 5, respectively.

Information concerning departures of the flights per country per year is clearly important in assessing the overall risk of aircraft being shot

Table 2
Data record attributes (columns) of security occurrences-aircraft shot down dataset.

Column title	Explanation
Date	Date of the event
Short type	Aircraft type
Operator	Air carrier that operated affected flight
Total_casualties	Number of casualties
Damage	Damage that aircraft sustained
Fate	The fate of the aircraft (whether the aircraft was written off or repaired)
Location_near	Distance from geographical location point
Location	Geographical location point
Country_name	Country of the incident
Phase	Phase of the flight where shooting occurred (enroute, take-off, landing etc)
Nature	Nature of the flight[a]
Airport-export. airportname	Airport of departure
Airport-export_1. airportname	Scheduled/planned airport of arrival
Flight number	Flight number
Narrative	Detailed explanation of occurrence
Accident_cause	The cause of the accident if known
ASN_id	Internal service number of the case

[a] The nature of the flight (column *Nature*) can take one of the 33 following values (e.g., Cargo, Ambulance, training etc.).

Table 3
Values of nature of the flight.

	Flight nature	Category (numeric)
1.	Scheduled	1
2.	Other passenger	2
3.	Cargo	3
4.	Military	4
5.	Aerial works	5
6.	Other	6
7.	Special flight	7
8.	Non-scheduled	8

down. The "*security occurrences – aircraft shot downs*" dataset contains details of flights that were shot down due to different reasons. In order to calculate the probability of a flight being shot down, we need to know the total amount of flights in that country/region in the given time ("*safe flights*"). We obtained this data for 264 countries and territories during the period 1970–2018 from The World Bank World Bank repository (The World Bank, 2019).

4. Results

We first present results of normality tests to ensure that the variables meet the requirements for regression modelling. Second, we present results obtained from error analysis and out-of-sample validation results. Finally, we present the spatial model that effectively assesses the risk of an aircraft being shot down when flying across different territories.

4.1. Model selection

The descriptive statistics associated with each of the independent variables are shown in Table 6 and the results of Pearson correlation analysis related to these variables (using the SPSS Statistics software package) are presented in Table 7.

Table 4
Intensity of the conflict.

Intensity of the conflict	Category
Minor – 25–999 deaths	1
War – more than 1000 deaths	2

4.2. Normality test

For the results of conducting a univariate normality test using SPSS on the dependent variable P_{Attack} are shown in Fig. 1 and confirm, as suspected, that this does not follow a normal distribution.

When the dependent variable is non-normal and scale and the independent variables are a mix of categorical nominal (*Conflict_Intensity, Conflict_Type, Nature_Of_Flight*) and scale (*GDP_PC_1000*), it is recommended that a generalised linear model (Gamma with log link) be employed (Arbuckle, 2013; de Jong and Heller, 2008). Consequently, we employ such a model.

4.3. Model development

In order to test the model fit, we divided the dataset randomly, with 80% of the data-points being set aside as the training dataset and 20% as the test dataset. The results of estimating the model effects and the parameter values of a generalised linear model based on the training dataset (scale dependent variable P_{Attack}, independent categorical nominal variables *Conflict_Intensity, Conflict_Type, Nature_Of_Flight* and scale variable *GDP_PC_1000*) are shown in Tables 8 and 9, respectively.

Results displayed in Table 8 show that independent variables, other than *Conflict_Intensity* are highly significant, and even *Conflict_Intensity* is significant at 0.06. Similarly, the results presented in Table 9 indicate that the independent variable *Conflict_Intensity=1 (minor conflict)* has a slightly lower significance – its value is higher than 0.05, while *Conflict_Intensity=2 (war)* serves as the reference point. This observation makes sense as larger scale conflicts more influence on the economy and consequently security situation of the country (Humphreys, 2003). It also goes in line with earlier formulated hypothesis (H3).

Results presented in Table 9 suggest that the probability of an aircraft being shot down is negatively proportional to GDP per capita (coefficient B = −0.354). A similar result was discussed by Humphreys who found that the probability of civil war in the country depended on its GDP per capita, to the extent that the probability decreases as its GDP per capita increases (countries with GDP per capita of 250, 600, 1250 and 5,000 USD, having probabilities of civil war of 0.15, 0.06, 0.04 and 0.01.

Based on the coefficients of the model, presented in Table 9, we estimate that the natural log of the probability of an aircraft being shot down (i.e., ln (P_{Attack})) is given as follows:

$$\begin{aligned}\ln(P_{Attack}) = & -6.21 + (-0.589)Intensity_{Level_1} + (-0.560)Type_{Conflict_2} \\ & + (-0.668)Type_{Conflict_3} + (-1.19)Nature_{Flight_1} \\ & + (-0.911)Nature_{Flight_2} + (-0.906)Nature_{Flight_3} \\ & + (-0.570)Nature_{Flight_4} + (-1.91)Nature_{Flight_5} \\ & + (-3.32)Nature_{Flight_6} + (-0.556)Nature_{Flight_7} \\ & + (-0.354)GDP_{PC\_1000}\end{aligned} \quad (2)$$

Consequently, the probability of an aircraft being shot down over country C P_{Attack}.

$$P_{Attack}(C, Y) = e^{\ln(P_{Attack})}. \quad (3)$$

Table 5
Types of conflict.

Type of conflict	Category
Extra-systemic[a]	1
Interstate	2
Internal	3
Internationalised internal	4

[a] In order to ensure that the results of the analysis are relevant to current circumstances, extra-systemic conflicts were not included as those types of conflict have not been observed since 1974.

Table 6
Descriptive statistics of independent variables.

		Independent variables			
		GDP_PC_1000	Conflict_Intensity	Conflict_Type	Nature_Of_Flight
N	Valid	175	159	159	172
	Missing	384	400	400	387
Mean		.831	1.86	3.30	4.26
Median		.388	2.00	3.00	5.00
Std. Deviation		1.19	.353	.744	1.64
Minimum		.050	1	2	1
Maximum		7.88	2	4	8

Table 7
Correlation analysis.

		Independent variables			
		GDP_PC_1000	Nature_Of_Flight	Conflict_Intensity	Conflict_Type
GDP_PC_1000	Pearson Correlation	1	−.155*	−.245**	−.185*
	Sig. (2-tailed)		.045	.002	.021
	N	175	168	156	156
Nature_Of_Flight	Pearson Correlation	−.155*	1	.080	−.043
	Sig. (2-tailed)	.045		.322	.593
	N	168	172	155	155
Conflict_Intensity	Pearson Correlation	−.245**	.080	1	.143
	Sig. (2-tailed)	.002	.322		.072
	N	156	155	159	159
Conflict_Type	Pearson Correlation	−.185*	−.043	.143	1
	Sig. (2-tailed)	.021	.593	.072	
	N	156	155	159	159

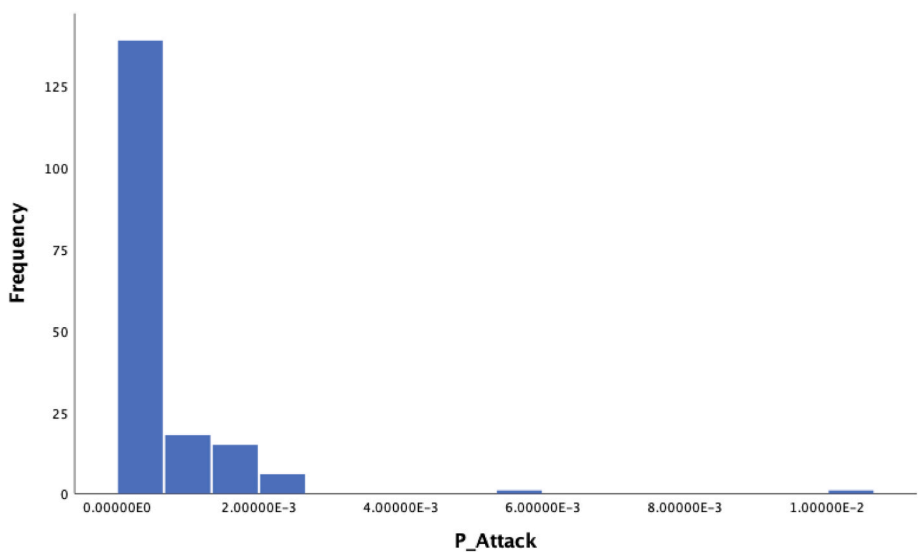

Fig. 1. Result of normality test of P_{Attack}.

Table 8
Test of model effects – generalised linear model.

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	1417	1	.000
Conflict_Intensity	3.64	1	.056
Conflict_Type	8.30	2	.016
GDP_PC_1000	22.3	7	.002
Nature_Of_Flt	17.3	1	<.001

Notes@ Dependent Variable: P_Attack.
Model: (Intercept), Conflict_Intensity, Conflict_Type, GDP_PC_1000, Nature_Of_Flt.

4.4. Out-of-sample validation

In order to validate the model we employed equations (2) and (3), using the 20% of the dataset which as set aside for out-of-sample testing (33 datapoints), to calculate probability of an aircraft being shot down and we compared the observed probability of attacks in a given year in a given country with the predicted number of attacks. The results, presented in terms of increasing GDP er capita of the various countries, are presented in Table 10.

The charts of observed and predicted probabilities in relation to GDP per capita are demonstrated in Fig. 2. The differences between the observed and predicted values are not immediately identifiable, hence detailed error analysis will be required.

To assess whether there is any significant difference between the predicted and observed values we test the null hypothesis that – *there is*

Table 9
Parameter estimates – generalised linear model.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	−6.21	.337	−6.87	−5.55	339	1	.000
[Conflict_Intensity = 1]	−.589	.309	−1.19	.016	3.64	1	.056
[Conflict_Intensity = 2]	0[a]	.	.	.	.	.	.
[Conflict_Type = 2]	−.560	.276	−1.10	−.018	4.10	1	.043
[Conflict_Type = 3]	−.668	.250	−1.16	−.178	7.15	1	.007
[Conflict_Type = 4]	0[a]	.	.	.	.	.	.
[Nature_Of_Flt = 1.00]	−1.19	.416	−2.01	−.376	8.21	1	.004
[Nature_Of_Flt = 2.00]	−.911	.606	−2.10	.276	2.26	1	.133
[Nature_Of_Flt = 3.00]	−.906	.419	−1.73	−.085	4.68	1	.031
[Nature_Of_Flt = 4.00]	−.570	.355	−1.27	.126	2.58	1	.108
[Nature_Of_Flt = 5.00]	−1.91	.752	−3.39	−.441	6.48	1	.011
[Nature_Of_Flt = 6.00]	−3.32	1.02	−5.31	−1.32	10.6	1	.001
[Nature_Of_Flt = 7.00]	−.556	.604	−1.74	.627	.847	1	.357
[Nature_Of_Flt = 8.00]	0[a]	.	.	.	.	.	.
GDP_PC_1000	−.354	.085	−.521	−.187	17.3	1	<.001
(Scale)	.859[b]	.099	.685	1.08			

Notes: Dependent Variable: P_Attack.
Model: (Intercept), Conflict_Intensity, Conflict_Type, GDP_PC_1000, Nature_Of_Flt.
[a] Set to zero because this parameter is redundant.
[b] Maximum likelihood estimate.

Table 10
Observed and expected (predicted) values of P_{Attack} .

GDP_ PC_1000	$P_{Attack\_Observed}$	$P_{Attack\_Predicted}$	*Error*	$\frac{(P_{Attack\_Observed} - P_{Attack\_Predicted})^2}{P_{Attack\_Predicted}}$
0.05	0.002500	0.001121	0.001379	0.001697
0.056	0.000800	0.001118	−0.000318	0.000091
0.064	0.000101	0.000637	−0.000536	0.000451
0.071	0.000345	0.000635	−0.000291	0.000133
0.071	0.000345	0.000635	−0.000291	0.000133
0.084	0.001111	0.000406	0.000705	0.001226
0.229	0.000847	0.001052	−0.000205	0.000040
0.229	0.000847	0.001052	−0.000205	0.000040
0.249	0.001500	0.001045	0.000455	0.000199
0.273	0.000238	0.001036	−0.000798	0.000614
0.278	0.000469	0.001034	−0.000565	0.000309
0.388	0.000588	0.000711	−0.000122	0.000021
0.388	0.000588	0.000711	−0.000122	0.000021
0.424	0.000405	0.000890	−0.000485	0.000264
0.441	0.000357	0.000358	0.000000	0.000000
0.484	0.000220	0.000493	−0.000273	0.000151
0.493	0.000465	0.000273	0.000193	0.000136
0.527	0.000230	0.000677	−0.000447	0.000295
0.577	0.000208	0.000930	−0.000722	0,000560
0.642	0.000133	0.000909	−0.000776	0.000662
0.642	0.000133	0.000650	−0.000516	0.000410
0.685	0.000182	0.000640	−0.000458	0.000328
0.698	0.000016	0.000180	−0.000164	0.000150
0.711	0.000156	0.000477	−0.000320	0.000215
0.714	0.000337	0.000454	−0.000117	0.000030
0.948	0.000290	0.000418	−0.000128	0.000039
0.948	0.000625	0.000418	0.000207	0.000102
1.242	0.000015	0.000013	0.000002	0.000000
1.363	0.000088	0.001245	−0.001157	0.001074
1.7	0.000119	0.000229	−0.000110	0.000053
1.851	0.002000	0.000338	0.001662	0.008158
1.851	0.002000	0.000338	0.001662	0.008158
3.105	0.000083	0.000380	−0.000297	0.000231
4.245	0.000057	0.000145	−0.000088	0.000054

no significant difference between observed and predicted values of probability of attack. We calculate the *p-value using the MS Excel function CHISQ.DIST (x, df, cumulative)= 1 - cdf(x)* where x is calculated as follows: $\chi^2 = \sum\frac{(P_{Attack\_Observed} - P_{Attack\_Predicted})^2}{P_{Attack\_Predicted}}$, with *df* is the degrees of freedom (33 in our case), and *cdf* is cumulative distribution function.

We find that $cdf\ (x) < 0.05$, confirming that there is no significant difference between observed and predicted values of probability of attack.

4.5. Error analysis

To assess the fit of the model, we also examine the goodness of fit statistics and the deviance parameter values developed using SPSS. These results are displayed in Table 11.

The value of Deviance shown in Table 9, divided by the degrees of freedom (*Value/df*) is close to 1, suggesting that the model fit is appropriate (McCullagh and Nelder, 1989).

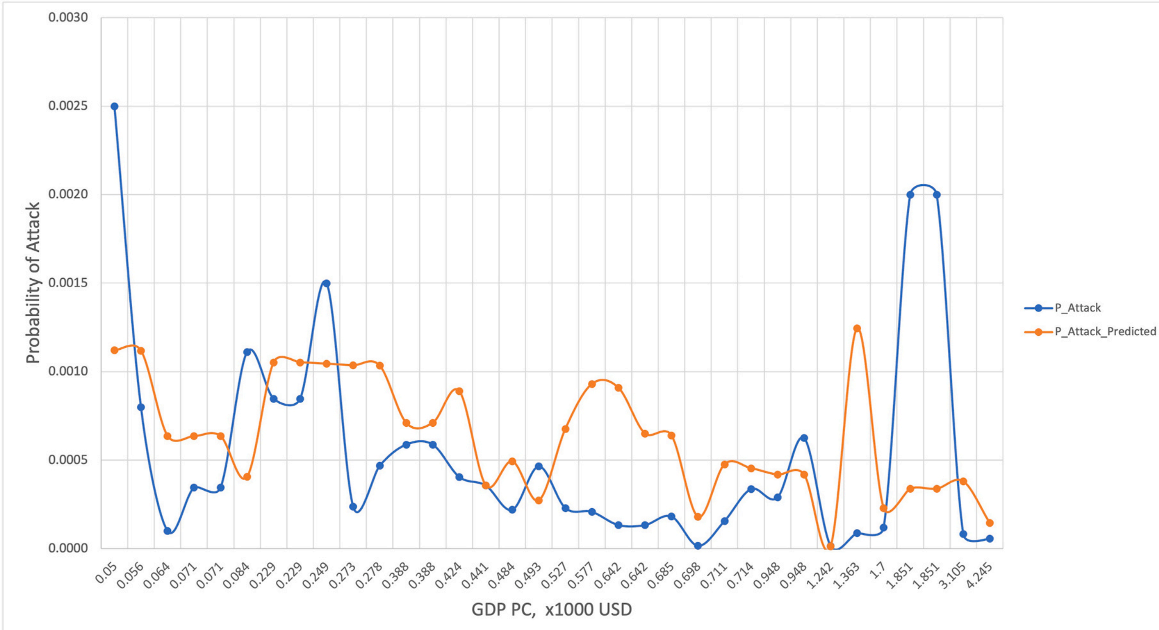

Fig. 2. Observed and expected (predicted) probability of the attack dependent from GDP per capita.

4.6. Spatial model

It is possible to build a spatial model (graphic mapping linked to geographical information system) for civil aircraft shooting down risk using Equations (2) and (3). To achieve this, we consider the data from actual armed conflicts for 2020 (independent variables *Conflict_Intensity, Conflict_Type*) from the Uppsala Conflict Data Program, Uppsala University (Uppsala Conflict Data Program, 2020) and data of GDP per capita (independent variable *GDP_PC_1000*) for 2020 from the World Bank and other open sources (Bank, 2020b; Economics, 2020) The spatial risk model is obtained for scheduled flights (independent *Nature_Of_Flight =1*) for countries where conflicts were registered.

The spatial model is developed using the open-source geographic information system application QGIS 3.4.14 and the Eurostat map dataset (Geoportal of the European Commission, Cartographer, E., 2020). The probabilities of an aircraft being shot down are displayed with different colours for visualisation in Fig. 3.

It is clear from the spatial model displayed in Fig. 3 that the most critical countries are those with low levels of GDP per capita and ongoing conflicts: for example, Somalia (GDP per capita 309 USD), Afghanistan (GDP per capita 509 USD), Yemen (GDP per capita 632 USD), Syria (GDP per capita 870 USD), and Ethiopia (GDP per capita 936 USD). The first four of these countries have ongoing conflicts defined as *Conflict_Intensity,* = *2* (major) and *Conflict_Type* = *4* (internationalised internal conflict). In Ethiopia the conflict is *Conflict_Type* = *3* (internal).

Visualisation of high-risk areas can support safety and security decision-makers of air carriers at the stage of route feasibility assessment and navigation services at the stage of route planning. Clearly, this enables high-risk areas to be avoided, and alternate routes to be planned.

For the insurance purposes, this methodology can be used to calculate risk exposure for flight operations in a region. Clearly, if a significant number of flights are affected by a high-risk area, a decrease in this number will reduce risk exposure.

When it is not possible to avoid a high-risk area (e.g., where the route must pass over the conflict zone due to aircraft range, fuel capacity, terrain, or other limitations) other risk mitigating actions are be implemented, including deeper analysis of the specific risk in the affected area. This can consider types of weaponry available in the conflict zone, more specific high-risk areas within the country, the pattern of attack, or the usage of weapons including time of day when attacks were observed.

The methodology adopted in this paper can also be employed to assess how the probability of surface-to-air shooting attack would alter should a change occur in the nature of a conflict or a geo-political environment. For example, Yemen is a country in the Arab Peninsula with a population of 29.9 million (Bank, 2020a), a very low GDP per capita (Bank, 2020b), and an ongoing internationalised internal conflict (Uppsala Conflict Data Program, 2020), so we can perform an out-of-sample forecasting. The data related to the independent variables for this case are as follows:

GDP_PC_1000 = *0.632 x 1000 USD; Conflict_Intensity,* = *2* (major)*; Conflict_Type* = *4* (internationalised internal). This results in P_{Attack} = *0,000490185.*

If the intensity of the conflict in Yemen decreased to level 1 but all other factors remained unchanged, the predicted probability of aircraft being shot down would decrease to P_{Attack} = *0.000271995.* However, if the conflict intensity remained at 2, but the GDP per capita increased to the level of Oman (a country bordering Yemen), the predicted probability of an aircraft being shot down would significantly decrease to P_{Attack} = *2.94316E-06* – significant decrease of probability. This example

Table 11
Goodness of fit.

	Value	df	Value/df
Deviance	148	140	1.06
Scaled Deviance	173	140	
Pearson Chi-Square	179	140	1.28
Scaled Pearson Chi-Square	209	140	
Log Likelihood[b]	1009		
Akaike's Information Criterion (AIC)	−1992		
Finite Sample Corrected AIC (AICC)	−1989		
Bayesian Information Criterion (BIC)	−1952		
Consistent AIC (CAIC)	−1939		

Notes: Dependent Variable: P_Attack.
Model: (Intercept), Conflict_Intensity, Conflict_Type, Nature_Of_Flt, GDP_PC_1000[a]
[a]Information criteria are in smaller-is-better form.
[b]The full log likelihood function is displayed and used in computing information criteria.

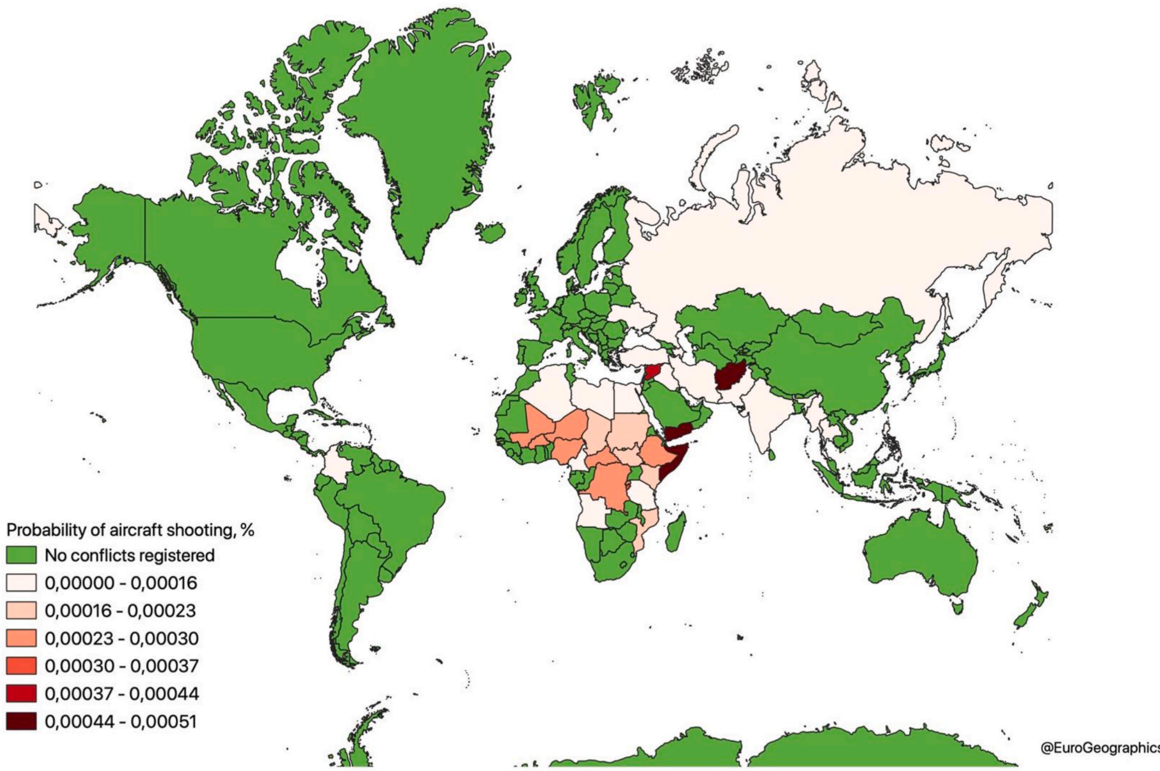

Fig. 3. Spatial model – visualisation of probability of surface-to-air shooting attack.

clearly shows that the probability of an aircraft being shot down over a country decreases with the level of conflict intensity and with an increase in GDP per capita.

5. Discussion

As demonstrated in section 4.3, the variable *Conflict_Intensity* demonstrated slightly lower significance than some other variables. This variable can take one of the two values – *Conflict_Intensity=1*, representing minor conflicts with 25–999 deaths, and *Conflict_Intensity=2*, indicating wars with more than 1000 deaths. The slightly lower significance of this variable may arise because a greater gradation of different types of conflict (beyond minor/major) is required and second, the assessment of conflict intensity based on a number of fatalities may be overall non-precise since exact numbers are not always reported, as mentioned by (Pettersson and Wallensteen, 2015). Therefore, the fact of a presence of a conflict as such can be more significant for the model than its intensity. Similarly, in parameter estimates, we observed that the independent variable *Conflict_Type* with the value of *2 (interstate conflict)* also had lower significance than the other conflict types. This may have arisen because historically, in the dataset, *interstate* conflicts had the smallest share – only 27 out of 178 records, while 77 *internal* and 74 *internationalised* conflicts were registered at the same time (Uppsala Conflict Data Program, 2020)

The model has demonstrated the significant influence of GDP per capita, an important economic variable, on the probability of an aircraft being shot down. However, one of the limitations of the research that the model does not capture the probability of a shooting event in "peaceful" countries (where no conflicts are registered at present), where no conflicts are registered, and does not consider possible mitigating actions. To calculate the probability of an aircraft being shot down in peaceful countries, a regression model may not be the best solution due to the lack of data.

Currently the model presented here is limited to providing the user with the expected probability of a surface-to-air attack. It certainly can be considered as an input of 'likelihood' in the equation proposed by the industry guidelines: *Risk rating = Consequence x Likelihood* (IATA, 2013). The consequence will need to be calculated based on the methodology accepted in the organization considering possible unintended outcomes of such mitigations. For example, changing the routing of the flight from an airspace due to security reasons may bring the flight to another airspace where safety concerns would prevail (high terrain, poor air traffic control coverage, etc).

Another limitation of the model is that the dataset used for calculation of the probability of the attack ("safe" flights) contains a number of departing flights from the given country in a given year. To calculate the probability of an aircraft being shot down over a certain country it would be beneficial to calculate this based on the number of overflying flights, which can be higher than the number of departing flights. However, such data are not available for public access.

Additional data such as type of the weapon (for example, MANPADS, surface to air missile and other), crime rate and so on can be introduced. However, this data is available in relatively short perspective – 10–20 years, which would shorten our available dataset. This absence of data can be solved by using the Monte Carlo simulation to increase the dataset. There are two challenges that emerge from this approach. First, the crime rate data generated by Monte Carlo would not necessarily lead to a model that is representative of the actual data. One would be assuming that the generated crime rate would be in the bounds of past data. The second challenge concerns the multicollinearity problem. Studies show that crime rate and economic indicators such as GDP per capita are correlated (Havi, 2014; Kathena and Sheefeni, 2017; Pereira and de Menezes, 2021). Therefore for current research crime rate can be excluded from the model considering that we already use GDP per capita variable. Alternatively the model can be approached from the perspective of intelligence adversary risk analysis and event trees that were already used for modelling of security events such as bioterrorism (Parnell et al., 2010).

The level of granularity of the model can be improved by capturing the risk of an aircraft being shot down for specific geographic locations within in a given country. A higher resolution geographic model may be required to capture this risk. In large countries, the security situation can vary within their borders. For example, UK travel advice does not recommend travel to parts of Jordan bordering Syria; however, the rest of the country is considered to be safe for travel (GOV.UK, 2021). The next stages of the research shall consider higher granularity of the geographical model for countries.

There are a few mitigation actions that can be put in place to reduce the risk of an aircraft being shot down. For example, the operator can change the flight route without changing the final destination, the operator can change the destination, or the operator can cancel the flight. There is a cost associated with each choice when multiple attributes (e.g., safety, fuel, supply chain financial implications) must be considered. Cost benefit analyses have been conducted for aviation security decisions such as the decisions to implement terrorism threat risk management (Stewart and Mueller, 2020) and baggage screening (Jacobson et al., 2006). Future work should explore the development of a model for cost benefit analysis of different risk mitigation actions for managing the risk aircraft being shot down.

6. Conclusions

There have been a number of fatal incidents with passenger aircraft caused by surface-to-air shooting in the past. Considering the number of conflict zones around the globe nowadays, the risk to civil aviation remains significant, therefore novel methodologies helping to predict such risks are very much relevant.

This paper had three aims. Firstly, it underlined limitations and inadequacy of currently existing methodologies, mostly unsophisticated, based on risk matrices where inputs are provided by one or several experts (ICAO, 2014). Such methods, although simple to implement, have two main flaws: the results of the assessment are highly dependent on the expertise of experts involved in the assessment and the limited classifiers of the risk obtained as the result of such assessment are not good, as different people have different understandings of these classifications (Renooij and Witteman, 1999). In addition, the quality of input data in widely used matrix methodology is subjective by those who make the assessments of severity and probability categories (Anthony Cox Jr, 2008) and the risk levels must be very precisely defined to ensure alignment between stakeholders (Duijm, 2015).

Secondly, we research what factors influence the risk of an aircraft shooting down. We conclude that presence of the conflict is among top threats influencing national security (United Nations, 2004) and the intensity and type of the conflict are good classificatory and descriptors of the wars and other armed conflict situation (Pettersson and Wallensteen, 2015). GDP per capita can serve as an indicator of economic stability of the country (The U.S. Bureau of Economic Analysis, 2021). Type of commercial air operation is influencing the number of safety occurrences (Kharoufah et al., 2018), so the nature of conducted flights is also an important factor to consider when assessing the risk of an aircraft being shot down. We use the above factors as independent variables for our model.

Finally, we propose new probabilistic methodology for assessing of the risk of the aircraft being shot down using regression model. We utilize data-driven approach to quantify aviation security risk, by using the dataset of aircraft shot downs. The probability of the attack is used as the dependent variable in a regression model. The algorithm based on the generalised linear model – gamma with log link – appeared to be the most suitable method for predictive threat analysis at this stage of the research. The model underwent out-of-sample testing that resulted in a good fit of the model. We additionally tested the model using relatively recent data of conflicts and GDP per capita from 2020 and visualized the outcome as a spatial model provided in Fig. 3.

The methodology is easy to use – the data that is utilized in the model is not restricted, regularly updated and available to download. The outcome can be presented as a "heat map" and help aviation company to plan its routes avoiding the areas with high probability of aircraft being shot down or develop appropriate mitigating actions to make flights over conflict areas possible. Proposed methodology can work as a standalone model or be a part of company accepted risk assessment methodology. For example, our method can be integrated into an existing qualitative or quantitative risk assuming method as an objective and unbiased input for risks related to overflying conflict zones.

The main benefit of the proposed methodology is that it removes the bias related to expertise of the experts. We use four independent variables for the model, it means that the methodology takes twice as many inputs as industry-recommended methodologies, and these inputs are quantitative, unbiased, originating from reliable sources, not dependent on an expert's view to assess the probability of the attack.

Further research can resolve current limitations of the model – consider the effect of mitigating measures and provide finer granularity and consider higher and lower risk areas within one country.

CRediT authorship contribution statement

Stanislav Bukhman: Writing – original draft, Methodology, Investigation, Conceptualization. **Mario P. Brito:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Ming-Chien Sung:** Writing – review & editing, Supervision.

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