Numerical Risk Analyses of the Impact of Meteorological Conditions on Probability of Airport Runway Excursion Accidents

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Abstract. A continuous growth in air transport industry over the recent decades increases the probability of occurrence of accidents and consequently the need of aviation risk and safety assessments. In order to assess the risks related to aircraft ground operations, all the influencing variables that can affect the safety of maneuvers should be determined. Generally, catastrophic accidents that occur inside an aerodrome are assigned to the runway incursions and excursions. Incursions are dedicated to all events happening inside the runway (e.g. existence of an obstacle or accident of two aircraft) and excursions are considered for an unsuccessful aircraft operation which leads to surpassing the designated thresholds/borders of the runway. Landing and take-off overruns, as the main excursion events, are responsible for the major recorded incidents/accidents over the past 50 years. Many variables can affect the probability of runway-related accidents such as weather conditions, aircraft braking potential, pilot's level of experience, etc. The scope of this study is to determine weather-wise parameters that amplify the probability of excursion events.

In order to quantify the probability of each type of accidents, the effect of each meteorological variables on the aircraft operation is simulated by RSARA/LRSARA© simulators, released by Aircraft Cooperative Research Program (ACRP). In this regard, specific airports with diverse characteristics (i.e.; landlocked airport, extreme annual operations, extreme runway geometries and weather conditions) are selected as case studies in the analyses. Gusts and wind forces, specifically cross-wind, turned out to be the most dominant weather-wise influencing parameters on the occurrence of runway excursions.

Keywords: Numerical risk analysis · RSA · Meteorological conditions

1 Introduction

Air transportation has the major influence on facilitating economic growth. Around 2 billion passengers annually are transported by this industry in 10 years period. One of the main reasons is the high demand for these services, as a result of that, enhancing

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rapid movement of passengers, goods and services to the domestic and global market. The demand for air transport has increased steadily over the past years. Passenger numbers have grown by 50% over the last decade and have more than doubled since the 1990s [1]. Therefore, extra attention should be paid to the safety of aviation because of its tremendous demanding potential.

Aviation risk can be dedicated to the measurements of the events frequency and the severity level of the possible consequences. Therefore, risk assessment is the interaction between aerodrome related hazards, airport's components vulnerability and the total exposure of the system. Risk can be defined as a measurement of the threat to safety of a complex posed by the accident scenarios and their consequences [2].

Identification of aerodrome related scenarios, their probability of occurrence and severity classification of the possible consequences (e.g. fatalities, aircraft damages, etc.) are the main sub-models that risk assessment methodologies in the field of air transport should cover.

Runway related events as results of aircraft operations can be classified into incursion and excursion accidents. Runway incursions are collisions of one aircraft with an accidental obstacle or another aircraft inside the runway.

On the other hand, runway excursions is dedicated to the any exit from the runway borders such as aircraft veers-off or overruns during takeoff or landing phases of flights. According to the recorded accidents/incidents statistics from all over the world, runway excursions are the most common type of events reported annually. These types of events can result in loss of life and/or damage to aircraft, buildings, etc. These facts prove the criticality of excursion events and the necessity to investigate them more. Runway excursions can be divided into following categories:

- Landing Overrun (LDOR), Under-Shoot (LDUS), Veer-Off (LDVO),
- Take-Off Overrun (TOOR), Veer-Off (TOVO) [3].

Runway Safety Areas (RSAs) are essential to be designed in order to mitigate the consequences of aircraft ground-operation events. These specific areas are categorizing depending on the accident scenario that may occur in the proximity of the runway; paved areas located after the runway ends, which are called Runway End Safety Areas (RESAs) and the longitudinal safety strips which are surrounding laterally the runway. RESAs mitigate the possible consequences in events of runway overrun or undershoot, while, lateral safety strips reduce the severity of aircraft veer-off incidents. The main scope of this study is to analyze numerically the impact of various meteorological conditions on the probability of the occurrence of runway-related events and to investigate the mitigating effects of RSAs on the severity of the consequences by simulating three case studies.

2 Background Review and Scope

The safety strips around the runway are designed with the primary motive of mitigating the possible consequences of incidents/accidents when aircraft surpasses the designated runway borders. In particular, RESA should be constructed in order to reduce the severity of the events consequences. Furthermore, aircraft veer-off, as a result of

numerous variables such as crosswinds, is probable to occur therefore, longitudinal strips along the runway lateral edges can minimize the consequences. According to the recent updates on the recommendations by International Civil Aviation Organization (ICAO), the 90 m RESA longitudinal dimension is now converted to 240 m. Plus, the total longitudinal protection after the runway threshold, including the 60 m strip, has been doubled from 150 to 300 m [4] (see Fig. 1).

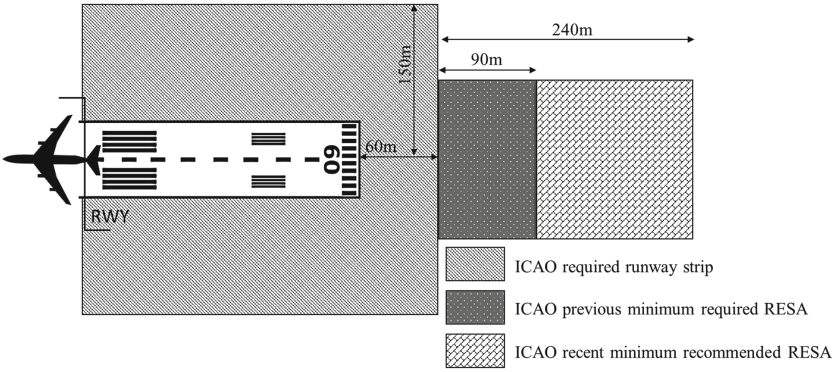


Fig. 1. Reference scheme for ICAO; geometry recommendations for RSAs [5]

Due to spatial circumstances (e.g. landlocked fields), applying the recommended practices prescribed by ICAO is restricted for some airports. In other words, changing the RSA geometry in some cases is not feasible because the runway can be surrounded by different forms of obstacles such as water surfaces (e.g. sea, rivers), residential areas, roads, unfavorable terrain, railroads and etc. Flat and even terrains without interfering obstacles are the ideal field scenarios for application of current RSAs standards. Where it is not possible to respect the RSA geometry by neither standard nor recommended practices, as the matter of safety, other mitigation strategies such as Engineered Material Arresting System (EMAS) can be considered.

According to ICAO Annex 14, any type of objects existing in RESA, which may endanger the safety of aircraft maneuvers, is considered as an obstacle and should be removed as far as practicable. Safety strips that are located before and after the runway should provide a cleared and graded area for aircraft. These areas are intended to serve in the event of undershoot or overrun excursions in various phases of flight. In these scenarios, these safety strips should be designed as to reduce the severity of the possible consequences to the aircraft and passengers by enhancing the aircraft deceleration and facilitate the movement of rescue and fire fighting vehicles [5].

Lateral safety strips that are surrounding the runway should be designed to reduce the severity of the consequences associated with potential lateral aircraft veering-off by providing an even and levelled area, respecting the certain cross slope of the runway

surface. These lateral strips should be constructed clear from any obstacles in order to protect aircraft overflying them during failed take-off and landing operations. ICAO prohibits objects in these areas except frangible mountings visual aids [6]. In other words, no fixed objects, other than frangible visual aids required for air navigational purposes, shall be permitted on the lateral runway strips [5].

Different national and international accidents/incidents databases from all over the world are collected to get used in the process of numerical risk analyses in order to determine the contributory meteorological parameters that affect the probability of occurrences of aviation ground operations accidents. In this regard, three airports with different characteristics (e.g. runway geometry, weather conditions, etc.) are simulated, by means of Runway Safety Area Risk analysis (RSARA/LRSARA©) software.

3 Data Collection and Numerical Analyses

In order to analyze the impact of each meteorological condition on the aviation risks, statistical databases consist of accident/incident records in the national and international scales are required that cover the main reasoning for each type of events. The output of this attempt can be also useful for the authorities in charge to prioritize their mitigation actions and setting monitoring operations on the design and execution of airport infrastructures. Accidents/incidents that are recorded annually can be misleading since the chances of irregularity in records are high. In this regard, the trend of the statistics over a period of years is fundamental, not annual variation. This point of view demonstrates the evolution rate of the air transport safety which is necessary in setting right priorities for the required actions and developing the right predictions for the years to come [7].

Figure 2 is extracted from the accidents/incidents reports published by Airbus, Boeing, National Transportation Safety Board (NTSB), and Aviation Safety Network (ASN) as the four major aviation databases for a period of 15 years. In the process of collecting the data, it turned out that as the aircraft operations increase, the number of events are also increase. Event statistical records by these four references aviation databases apparently demonstrate a steady decrease annual rate of incidents/accidents for recent years respect to the past. It should be also noted that hull loss incidents are always more probable to occur respect to the fatal accidents for the corresponding time span. Furthermore, it can be interpreted that the majority of the incidents/accidents occur during the landing/approach and take-off phases of flights and in form of runway excursions [8]. Beside the human errors (e.g. pilot incapability, misleading operational data, etc.), meteorological conditions may noticeably affect the safety of the operations by compromising the ground operations (e.g. low visibility, inadequate skid resistance and pavement friction, etc.). In this regard, further investigation is carried out by this study to assess numerically and separately the impact of each weather parameter and meteorological condition on the safety of the maneuvers.

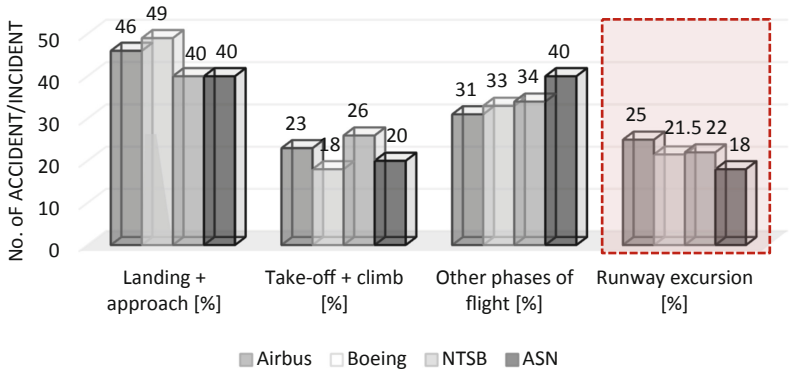


Fig. 2. Accident/incident records from 4 major databases (5-year timespan)

Each of the meteorological variables has a contributory index that needs to be numerically analyzed because of the large number of accidents it has contributed to. For this matter, the statistical records of runway-related events for a five-year time span are collected and the trend is analyzed. NTSB databases are selected for the following numerical analysis according to higher recorded events respect to other databases. Totally, 8,657 aviation incidents/accidents from all over the world are collected that in 1,740 (20%) of these accidents meteorological conditions are contributing factors [9]. According to NTSB [10], Wind, visibility/ceiling, high density altitude, turbulence, carburetor icing, updrafts/downdrafts, precipitation, icing, thunderstorms, temperature extremes, and lightning are the triggering factors in most weather-caused accidents. Weather and non-weather-related accidents for a 5-year time span extracted from NTSB records are depicted in Table 1.

Table 1. Meteorological related and non-related worldwide accidents according to NTSB

Recording year	No. of weather-related accidents	No. of non-weather-related accidents	% of weather-related accidents
2003	409	1463	21.85
2004	378	1344	21.95
2005	336	1444	18.88
2006	303	1289	19.03
2007	314	1377	18.57

According to Table 1, aviation accidents in general, have shown an overall descending trend over 5-year time span. In the final NTSB report for each accident in which meteorological conditions were found to be a triggering cause or contributing factor, a subject modifier is cited to designate the specific weather condition(s) encountered during the accident. In fact, multiple meteorological parameters can

overlap and have a complex effect on the occurrence of one event. For total 1,740 accidents records, there are 2,230 citations of meteorological subject modifiers. The breakdown of these statistic records based on various meteorological variables is presented in Fig. 3.

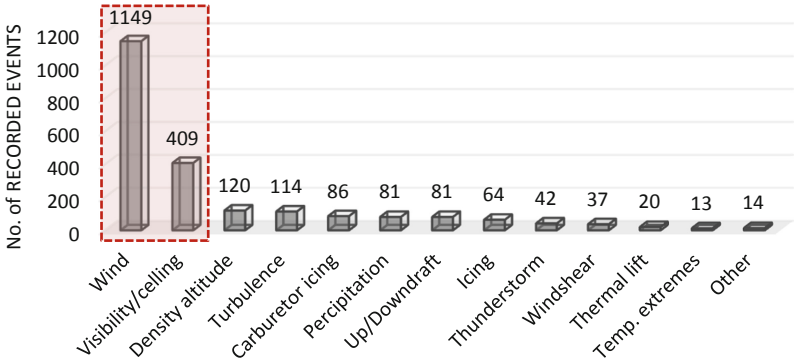


Fig. 3. Recorded meteorological conditions accidents (5-year timespan)

Wind (by 1149 citations) and visibility/ceiling (by 409 citations) impact factors can be considered as dominant contributing parameters in aviation risks compare to other meteorological modifiers and are going to be analyzed separately in continue.

3.1 Meteorological Break Down: Wind Impact Factor

As mentioned in Fig. 3, wind impact factor with 1,149 citations (51.52%) is responsible for more than half of the cause or contributing factor citations in the accidents database for 5-year time span that is broken down in Fig. 4.

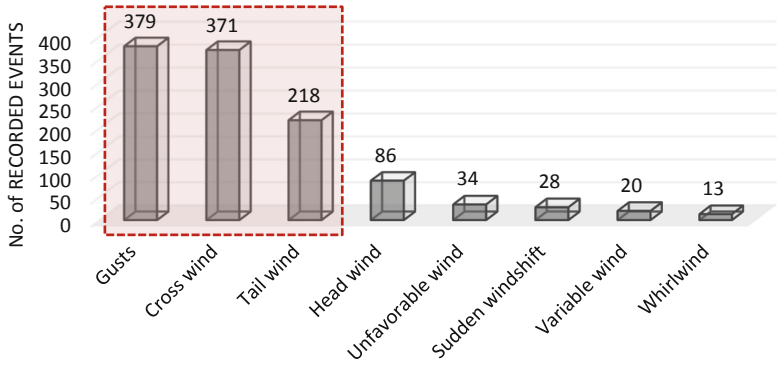


Fig. 4. Break down of recorded wind parameters affecting the accidents (5-year timespan)

According to Fig. 4, gusts, crosswind and tailwind are accounting for approximately 85% of the recorded events for 5-year timespan.

3.2 Meteorological Break Down: Visibility/Ceiling Impact Factors

Visibility radius and ceiling clearance are other principal causes or contributing factors in meteorological-related accidents according to the collected databases, with 409 citations over a 5-year timespan. Visibility refers to the greatest horizontal distance at which prominent objects can be viewed with the naked eye. Visibility can be compromised by precipitation, fog, haze and etc. In the field of aviation, a ceiling is considered as the lowest layer of clouds reported as being broken or overcast, or the vertical visibility into an obscuration like fog or haze. The breakdown of visibility into its related parameters shows low ceiling, clouds and fog to be the principal contributing factors, accounting for approximately 86% of the recorded events for 5-year timespan (See Fig. 5).

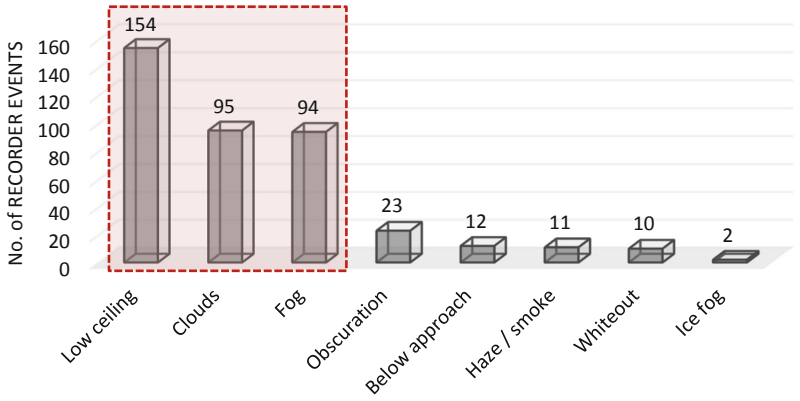


Fig. 5. Break down of recorded visibility/ceiling parameters (5-year timespan)

Carried out analyses prove that among all meteorological related elements, wind and visibility/ceiling are responsible for the majority of events (51.52% and 18.34% respectively). From those, more than half of wind-related accidents occurred during the landing phase (57.7%) and around half of the visibility/ceiling related accidents occurred during approach, maneauvering and cruise phases (combined 51.43%). Among all wind components, the most influencing ones are gusts, crosswind and tailwind (combined 85%), and the principal components of visibility/ceiling are low ceiling condition and existence of clouds and fog (combined 86%).

4 Numerical Risk Analyses of Aircraft Ground Operations

In order to numerically compute the probability of occurrence of runway-related accidents/incidents RSARA© aircraft ground movement simulator is utilized. This software, which was developed as part of ACRP Project 4-08 [11], evaluates the overruns, veers-off and undershoots risks associated with landing and take-off phases of flight operations.

4.1 Case Studies Selection

Three specific airports are selected according to their unique meteorological characteristics in order to carry out sensitivity analyses. These unique modifiers consist of Historical weather data (HWD) covering historical operations period (wind, temperature, visibility, etc.), RSAs (geometry, type of surface, and existence of EMAS and obstacles) and annual traffic volumes. General specifications of the airports are compiled and displayed in Table 2.

Table 2. Technical specifications summary of selected Case Studies CS1, CS2, and CS3

Case study	CS1	CS2	CS3
RWY dimension	2440 × 30 m	1508 × 30 m	2450 × 46 m
DTHR[1]	RWY 33 (305 m)	RWY 09 (97 m) RWY 27 (72 m)	RWY 06 (120 m)
Elevation	2389 m	6 m	103 m
ASDA[2]	RWY 15 (2135.4 m) RWY 33 (2440.3 m)	RWY 09 (1319 m) RWY 27 (1319 m)	RWY 06 (2450 m) RWY 24 (2450 m)
LDA[3]	RWY 15 (2135.4 m) RWY 33 (2135.4 m)	RWY 09 (1319 m) RWY 27 (1319 m)	RWY 06 (2330 m) RWY 24 (2450 m)
Pavement	Asphalt	Grooved concrete	Concrete
RESA	RWY15 (61 × 43 m) RWY33 (61 × 43 m)	RWY09 (56 × 61 m) RWY27 (90 × 61 m)	RWY06 (90 × 90 m) RWY24 (180 × 90 m)
NAVAIDs[4]	CAT II[5] on side	CAT II both sides	CAT II one side
Selection	Strong wind, gusts, small dimension RESA	Short runway, steep approach, water-locked	Heavy rain/fog, low visibility, valley-locked

1 DTHR: Displaced Threshold
2 ASDA: Accelerate-Stop Distance Available
3 LDA: Landing Distance Available
4 NAVAIDs: Navigational Aid Systems
5 CAT II: Instrumental Landing System category 2

4.2 Input Variables

Following variables are required in order to simulate the aircraft take-off and landing operations and assess numerically the probabilities of occurrence of any possible excursion events.

- Airport characteristics: above sea level elevation, annual traffic and expected annual growth, type of flights (commercial, cargo, taxi/commuter or general aviation), and being international hub or not;
- Risk criteria: the value of 1.0E−6 is selected as the Target Level of Safety (TLS) in this study (one failure in one million operations);
- Runway configuration: runway designation, ASDA, LDA, and approach category (types of available approach instruments);
- RSA geometry, obstacles and OFA distance: designing the RESA geometry and declaring the existing lateral Obstacle Free Area (OFA). This distance is the clearance from the runway edge to the nearest obstacle, fixed or movable. The drawings are in the form of cells matrixes. Each cell corresponds to a coordinate that is referenced to the runway centerline. According to these drawings (see Fig. 6 and 7), the green (#G) is related to the grass, the yellow (#Y) is related to instrumental landing system (frangible obstacles), the pink (#P) is related to unpaved area, the gray (#Gr) is paved area, and the red (#R) area is related to water/mountain (catastrophic obstacles);

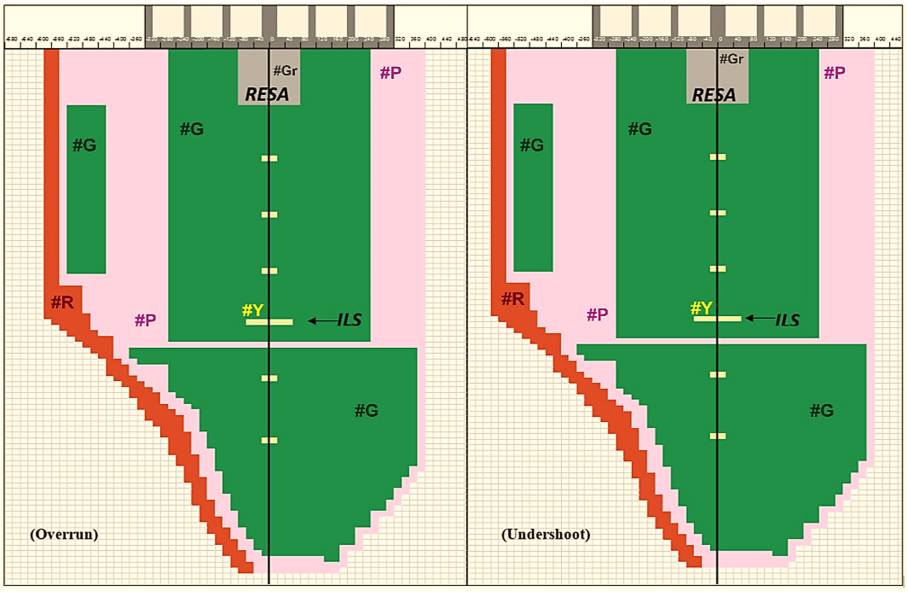


Fig. 6. Example of input scheme of RSA geometry and existing obstacles (CS1 RWY head)

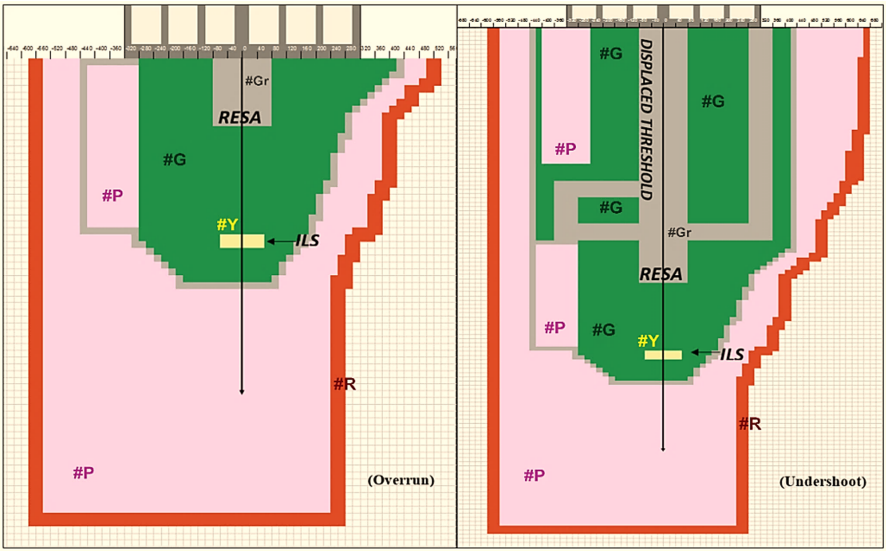


Fig. 7. Example of input scheme of RSA geometry and existing obstacles (CS1 RWY end)

- HOD: for each case studies operation data for a period of one year are collected, which cover the date and time of operation, runway designation, arrival/departure, aircraft FAA code, flight category (commercial, general aviation, commuter/taxi or cargo) and flight type (international or domestic).
- HWD: it should be noted that the periods of the collected weather data and operations data must be synced. Normally weather data are collected on an hourly basis for more accurate results, which cover visibility, wind direction, wind speed, air temperature, ceiling, and existence of rain, snow, snow showers, rain showers, thunderstorms, ice crystals, ice pellets, snow pellets, pellet showers, freezing rain, freezing drizzle, wind gusts and fog. After collecting the required data, each HWD should be coupled with one HOD and the probability of associated accidents should be simulated for each historical operation [12].

4.3 Adopted Frequency Model for Numerical Computation

The probability of occurrence of each runway-related event is adopted from the frequency model in a logistic format that offered by ACRP [11], which is described by the following equation:

$$P = \frac{1}{1 + e^{-(b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \ldots)}} \tag{1}$$

Where, P is the probability of occurrence of one specific event, X_i is independent binary variable such as ceiling, visibility, crosswind, precipitation, etc.; b_i is the regression coefficient [13]. According to Eq. (1), average probability of the occurrence

of the event outside the RSA, average number of years expected between incident/accidents, and the percentage of movements with risk higher than adopted TLS can be achieved as the outputs of the numerical simulations.

5 RSARA/LRSARA© Numerical Sensitivity Analyses

In order to assess the impact level of each meteorological condition various aircraft operation scenarios are defined to get simulated by RSARA© and Lateral Runway Safety Area Risk analysis (LRSARA©) simulators. Meteorological components are altered for each of the scenarios in order to simulate critical weather conditions for sake of sensitivity analyses. The outputs cover the average probability of excursions under selected boundary conditions. Three meteorological scenarios are designed for these sensitivity analyses, which consist of extreme weather conditions:

- Favorable weather condition, which is expected when there is perfect visibility, mild air temperature, no extreme cloud coverage, no precipitation, no thunderstorms, etc.;
- Unfavorable weather condition, which involves extreme forms of precipitation, presence of dense fog, heavy wind gusts, thunderstorms, maximum cloud density, low visibility, wet runways with thick water-film, etc.

Respect to the defined meteorological scenarios, the sensitivity analyses are carried out for each case study separately and the average probability of runway excursion events are presented in the following. According to Fig. 8, the average probabilities of LDOR and LDVO are higher than other types of accidents. Landing is a critical phase, in some cases more critical than take-off. There is a difference of one order of magnitude between the extreme weather scenarios and normal (state of art) condition.

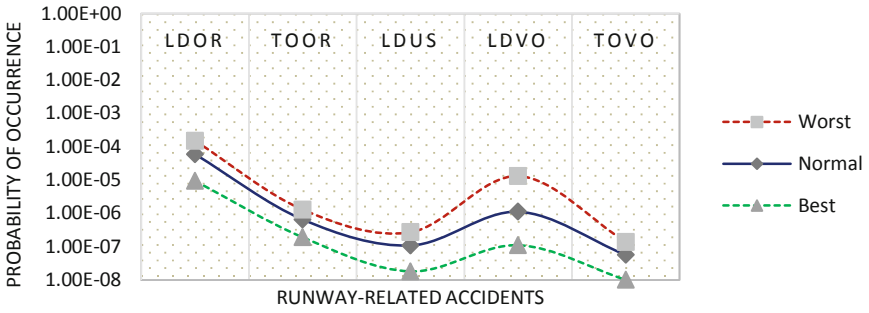


Fig. 8. Meteorological conditions sensitivity analyses for case study A1

According to Fig. 9, various meteorological conditions can be more crucial and have more critical impacts on the overruns and undershoots types of events rather than veer-off accidents, since the divergence of the veer-off probability values are less than the others.

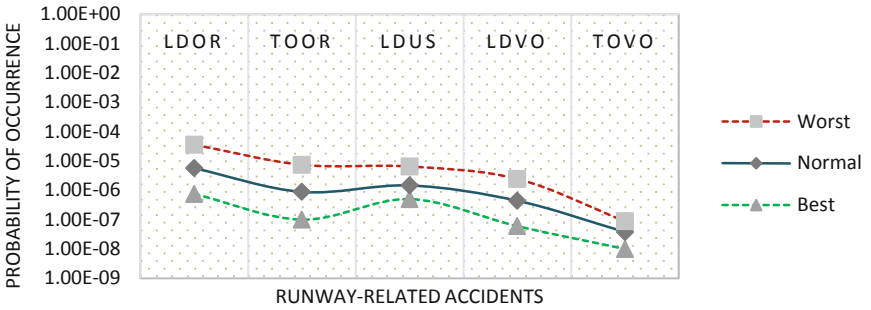


Fig. 9. Meteorological conditions sensitivity analyses for case study A2

According to Fig. 10, the average probability of all types of the runway excursion events undergo significant alteration by moving from unfavorable to favorable meteorological conditions, except for TOVO. Furthermore, LDVO experiences maximum rate of probability divergence due to available distance on either side of the runways.

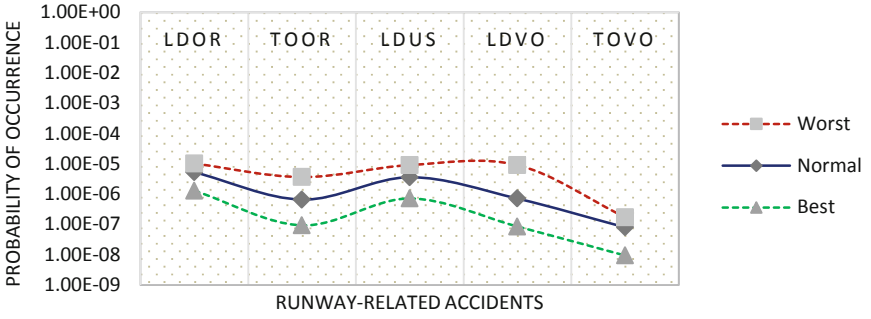


Fig. 10. Meteorological conditions sensitivity analyses for case study A3

6 Conclusion

This study evaluates the impact level of each meteorological parameter on the probability of occurrence or runway excursion events. In this regard, three weather condition scenarios are designed to be evaluated in numerical risk analyses. The principal scope of this investigation is based on general concept of risk and safety and quantifying the probability of each possible runway-related accident by simulating three

selected case-studies with unique topographical and meteorological characteristics. RSARA and LRSARA© software, which are developed according to the ACRP methodology of aircraft ground operation risk assessment, are adopted for further sensitivity analyses.

As it can interpreted by analyzing the collected database of worldwide accident/incident records, the total recorded incidents are noticeably lower than the accidents, which can be mainly due to the tendency of airport authorities to avoid releasing minor incidents records to the public for the sake of their publicity. Moreover, it should be noted that meteorological conditions affect noticeably the number of accidents during visual meteorological condition (VMC). Runway excursion records during VMC are higher than those recorded during instrumental meteorological condition (IMC). Airports equipped with Instrumental Landing Systems (ILSs) facilities greatly the aircraft landing efforts therefore ILSs can reduce the probability of landing excursion events during IMC and intense weather conditions [12].

There is a difference of one order of magnitude between the extreme weather scenarios and normal (state of art) condition for landing-related events. Average probability of all types of the runway excursion events undergo significant alteration by moving from unfavorable to favorable meteorological conditions, except for TOVO. Meteorological conditions can have more critical impacts on the overruns and undershoots types of events rather than veer-off accidents, since the divergence of the veer-off probability values are less than the others. Meteorological parameters such as wind gusts (especially crosswinds), rain, ice and snow are the principal factors that cause unfavorable weather conditions. In other words, those factors can increase the chance of specific accident up to three orders of magnitude. Furthermore, wind element and specifically cross-wind turned out to be the most dominant influencing factor on runway excursion risks.

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