Airport risk assessment: a probabilistic approach

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Abstract: Risk reduction is one of the key objectives pursued by transport safety policies. Particularly, the formulation and implementation of transport safety policies need the systematic assessment of the risks, the specification of residual risk targets and the monitoring of progresses towards those ones. Risk and safety have always been considered critical in civil aviation. The purpose of this paper is to describe and analyse safety aspects in civil airports. An increase in airport capacity usually involves changes to runways layout, route structures and traffic distribution, which in turn effect the risk level around the airport. For these reasons third party risk becomes an important issue in airports development. To avoid subjective interpretations and to increase model accuracy, risk information are collected and evaluated in a rational and mathematical manner. The method may be used to draw risk contour maps so to provide a guide to local and national authorities, to population who live around the airport, and to airports operators.

Key-Words: Risk Management, Risk assessment methodology, Safety Civil aviation.

1 Introduction
Risk reduction is one of the key objectives pursued by transport safety policies. Particularly, the formulation and implementation of transport safety policies need the systematic assessment of the risks, the specification of residual risk targets and the monitoring of progresses towards those ones. Furthermore, targeting phase needs a deep analysis to balance efforts, achievability, public and political acceptability of the policies to be implemented [24].

Risk assessment ranges from the interpretation of the available data concerning frequent threats or the estimation of very rare events likelihood: combining these information with the expected loss would result in quantifying the risk exposure index. Risk assessment is an essential process in making policy decisions for risk management. By identifying the nature and scale of the potential impact on consumers or employees, risk assessment can assist regulatory authorities and business organizations to determine what type of action is needed [13].

Risk and safety have always been considered critical in civil aviation [26].

An airport is a multifunction distributed system that is part of a much larger system. You can think of it as being at the centre of a dynamic network made up of all the sources of cargo, passengers and the other people who travel to and from the airport; visitors, cleaners, et alia. But that is just the ground system; a large number of these networks are interconnected to form a huge communications network; the nodes are the airports with their hinterlands, and the dialogues are made up of aircraft [23].

Airports presence causes a convergence of air traffic over the surrounding area so, people who lives in that area are unconsciously exposed to aircraft accidents risk. Actually, local risk levels are higher than might be expected. In fact, even if it is true that the accident per flight index is very low (typically 1 per 106), statistics demonstrate that accidents mostly happen during take-off and landing phases and hence, close to the airport. Moreover, the low probability of an accident per movement if combined with the high number of flight operations (typically several hundreds of thousands) may suggest the probability of one accident to be higher than we could expect. Risk level around large airports are, in effect, of the same order as those associated with participation in road traffic.

An increase in airport capacity usually involves changes to runways layout, route structures and traffic distribution, which in turn effect the risk level around the airport. For these reasons third party risk becomes an important issue in airports development.

In the late 1990s the world’s airline fleet consists of more than 15.000 aircraft flying a network of approximately 15 million km and serving nearly 10.000 airports. The sector directly employs more than 3.3 million people, with over 1.4 million in USA [5]. Some 12 billion people and 23 million tonnes of freight are being moved annually. The freight figure represents approximately one third of value of the world’s manufactured exports. A variety of international institutions, organisations and agencies deal with forecasting future trends, including International Civil Aviation Organization (ICAO) and International Air Transport Association (IATA). The airspace manufacturers such as Airbus Industry, Boeing and Rolls Royce also make
projections. Historically, when there has been relatively rapid growth in air transport, it has often been followed by a series of accidents. The occurrence of such events has stimulated the introduction of technical and operational measures. As a result, overall safety has improved over time.

So, there is a current move to widen the adoption of Safety Management Systems (SMS) within the air transport industry which carries with it a need to undertake risk assessments, either qualitative or quantitative.

As an example in the UK, the CAA describes the means of implementation of SMS by an aircraft operator [7]. Risk assessment is an essential part of such a system, and CAP712 therefore includes a risk tolerability matrix for use when quantifying risk.

The discipline of risk assessment has been applied in the aircraft systems, as required for aircraft certification under FAR23, FAR25 in U.S.A and under EASA Certification Specification (CS)-23/25 in Europe. Techniques for accomplishing the assessment of safety are quoted by the SAE in their Aerospace Recommended Practice (ARP)-4761.

**Flight Operations Risk Assessment System**, known as FORAS [14], is a risk management tool to “encode” human knowledge about a type of risk. The FORAS methodology employs a fuzzy expert system to identify the factors which have the greatest impact on overall risk.

A different approach has been adopted by [19] who has developed the **Aviation Safety Risk Model (ASRM)**. This makes use of the **Human Factors Analysis & Classification System (HFACS)** proposed by [27]. HFACS is a classification scheme which has been developed to capture and analyze the different types of human error that may occur. The framework draws on [21], in which was developed the so-called “Swiss-cheese” model of accident causation. ASRM was originally developed for use by US Naval Aviation, but has since been used more widely within the aviation industry. The ASRM uses Bayesian Belief Networks to model the uncertainty within the model, using either data or the opinion of “experts”.

An additional technique has been adopted by Bazargan and Ross [6], who used the proportionate occurrence of causal factors obtained from accident reports, where fatalities or serious injuries were reported. This information is then combined with expert judgments on the relative importance of the flight attributes using **Analytical Hierarchy Process** (AHP).

The purpose of this paper is to describe and analyze the problem of safety aspects in airports paying attention to the following aspects:

- a strategic approach to improve airport safety, which includes the use of failure and hazard analysis techniques and fast time simulation modelling;
- safety of land side operations;
- certification aspects.

To avoid subjective interpretations and to increase model accuracy, risk information are collected and evaluated in a rational and mathematical manner. The method may be used to draw risk contour maps so to provide a guide to local and national authorities, to population who live around the airport, and to airports operators.

## 2 Definitions

A risk is “the combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence” [7]. The “combination” of these parameters determines a two dimensional quantity.

So, if the risk is to be reduced, it can be either be done in the severity axis, or in the likelihood axis, or both. To effect a decrease on both axes may be considered the best approach to risk reduction.

For natural hazards such as an earthquake, typically we cannot do anything to reduce the likelihood, but there is much that can be done to reduce the consequences: special building regulations can be put in place and “earthquake kits” can be pre-distributed to inhabitants. Alternatively, there is much that can be done to reduce the chances of happening of a mid–air collision of two aircraft: the air traffic control system and on–board radars are in place to monitor and maintain both vertical and horizontal separation.

Generally speaking, risk assessment procedure aims [23]:

- to derive the likelihood and the severity of consequence values for each hazard;
- to use obtained information as a means of prioritizing actions;
- to specify mitigating features as appropriate to each hazard;
- to predict the effectiveness of those features in reducing the risk.

A first, intuitive definition of the term “risk”, comes from the fact that there is risk if there exists a potential source of damage, or hazard. When an hazard exists (e.g. a system which in certain conditions may cause undesired consequences), safeguards are typically devised to prevent the occurrence of such hazardous conditions and its associated undesired consequences. However, the presence of an hazard does not suffice itself to define a condition of risk. Indeed, there is the uncertainty that the hazard translates from potential to actual damage. Thus, the notion of risk involves some kind of loss or damage that might be received and the uncertainty of its transformation in an actual loss or damage so, risk = damage + uncertainty.

This qualitative analysis is reflected in the various Dictionary-definitions of risk, such as “possibility of loss or injury and the degree of probability of such loss”.

Let \( x \) and \( p \) respectively refer as a given damage and the probability of receiving such damage. From a quantitative point of view, a measure of the associated risk \( R \) is:

\[
R = x \cdot p
\]  
(1)
In practice, the perception of risk is such that the relevance given to the damaging consequences x is far greater than that given to its probability of occurrence p so that eq. (1) is slightly modified to:

\[ R = p \cdot x^k, \quad k > 1 \]  

(2)

By so doing, numerically larger values of risk are associated to larger consequences. When considering complex systems, the above quantitative definitions must be extended to account for the fact that typically more than one undesirable events exist. With n undesirable events associated with the operation of a given system (composite risk), equation (1) changes in:

\[
R = \sum_{i=1}^{n} x_i \cdot p_i
\]  

(3)

and similarly it is done for eq. (2).

These quantitative definitions of risk are easily shown to be little informative for the purposes of risk analysis, management and regulation. Suppose you were considering two different systems A and B of equal risk \( R_A = R_B \) as defined (1). Let the risk of A be due to a potentially large consequence \( x_A \) occurring with small probability \( p_A \) and vice versa for the risk of B. Then, if we wish to act on the design, operation and regulation of the two systems in order to reduce the associated risks, we will act differently knowing the different natures of the risk in the two cases. To reduce \( R_A \) we would implement prevention and protection, on the contrary, if we were to reduce \( R_B \) we would do some mitigation. Thus, if we simply know the value of R, we may not be effective in reducing it by limiting its probability part or by mitigating its consequences; hence, the importance of keeping separate the constituents of risk, p and x. The situation is, naturally, worse in the case of the composite risk. Note also that, generally speaking, a good approach to risk reduction is: prevention, mitigation, protection, residual risk management. So, an informative and operative definition of risk should allow answering the following questions:

- Which sequences of undesirable events transform the hazard into an actual damage?
- What is the probability of each of these sequences?
- What are the consequences of each of these sequences?

The risk is, then, defined in terms of a set of triplets:

\[
R = \{ (s_i, p_i, x_i) \}
\]

where \( s_i \) is the sequence of undesirable events leading to damage, \( p_i \) is the associated probability and \( x_i \) the consequence.

In relationship to the type of events, it is possible to define three typologies of risk:

- **Conventional risks**: they are relative to very frequent events and they interest one or two people;
- **Specific risks**: they are relative to continuous or frequent events with modest damages in brief times;
- **Great potential risks**: they are connected to very rare events with serious damages.

These last risks are the object of the proposed model and we will refer to them simply as risk of accident. In the case in which the risk of accident would be intolerable, some actions will be found to attenuate its intensity accordingly to the mentioned approach.

In this paper, events are classified according to the following definitions furnished by the National Transportation Safety Board (NTSB) and the International Civil Aviation Organization (ICAO):

- **Airplane accident**: An occurrence associated with the operation of an airplane that takes place between the time any person boards the airplane and the time all such persons have disembarked;
- **Hull loss** (Serious Incident): Airplane damage that is substantial and is beyond economic repair;
- **Substantial damage** (Incident): Damage or structural failure that adversely affects the structural strength, performance or flight characteristics of the airplane and would normally require major repair or replacement of the affected component;
- **Fatal accident**: An accident that results in fatal injury;
- **Fatal injury**: An injury that results in death within 30 days as a result of an accident;
- **Serious injury**: An injury sustained in an accident that:
  - Requires hospitalization for more than 48 hours that begins within 7 days of the date of injury;
  - Results in a fracture of any bone (except simple fractures of fingers, toes, or nose);
  - Produces lacerations that result in severe hemorrhages or nerve, muscle, or tendon damage;
  - Involves injury to any internal organ;
  - Involves second or third degree burns over 5% or more of the body;
  - Involves verified exposure to infectious substance or injurious radiation.

To stand any chance of achieving these goals we first need an hazard identification. When building a large system from a number of smaller ones we find that many of the hazards arise from the intra-system interfaces [23]. When performing a risk assessment, then, we can start off by identifying those interfaces and the hazards arising from them. Where a system is made up of subsystems from different suppliers their domains of influence also need to be considered. An airport has a lot of interfaces with outside world: air traffic control has radio and telephones, there are navigational aids that communicate with aircraft (instrumental landing systems), there are road/rail links, etc. We will consider only one airside interface, the runway: which is the interface between the air navigation system and
the ground handling area.

3 Safety Data Records
The airport risk assessment includes a series of connected activity:

- events historical analysis;
- accident frequencies determination;
- magnitude and the risk evaluation.

Information were acquired by:

- investigating aircraft accidents causes;
- accident location;
- accident consequences.

Accident data are obtained, when available, from government accident reports. Otherwise, information is solicited from operators, manufacturers, various government and private information services. Such information is inferred by a historical analysis of the events, making reference to:

1. local files (ANSV);
2. world files (AAIB, AAIU; ATSB; NTSB; TSB, etc.).

In order to determine a tool that allows a brief and exhaustive description of the analyzed aircraft accidents, as well as a support to record the first news of an investigation, a report has been compiled (Fig. 1).

![Fig. 1 - A synthetic scheme to collect a principal factors concerning aircraft accident](image)

In this report the ID_NUMBER is the code of the analyzed report whereas the field DATE AND HOUR indicates the date and the time when the accident has happened (in conformity with the prescriptions of the ICAO Annex 13, it is express in local or coordinated universal schedule UTC, Universal Time Coordinated). LOCATION is the place in which the accident is occurred and AIRCRAFT_ID is the typology of aircraft interested by the accident (in our case commercial airplanes). The field CLASS indicates the class of the aircraft defined in relationship to its maximum takeoff weight (MTOW), identified with the following letters:

- A: aircrafts with MTOW < 6.750 Kg with an only motor;
- B: aircrafts with MTOW < 6.750 Kg and two motors;
- C: aircrafts with 6.750 kg < MTOW < 136.000 Kg;
- D: aircrafts with MTOW > 136000 Kg and more than two motors.

FLIGHT_CONDITIONS are the flight meteorological conditions before and during the accident event distinguished in:

- VFR (Visual Flight Rules): it deals with a flight performed with the visual references aid. Naturally the possibility to effect visual flights is tied up to the existence of an enough visibility (VMC, Visual Meteorological Condition). In the checked aerial spaces the “least” VMC are: flight visibility in 8 Km, distance from the clouds 1,5 Km in horizontal direction and 300 m in vertical direction. In Italy the visual flight rules are forbidden in the night time hours and the flight have to sustain under the 600 ms of height, cannot be landed in VFR with visibility to the ground lesser than 8 Km and with ceiling lesser than 450m;
- IFR (Instrument Flight Rules): when the flight is performed using radiofrequency aids (VOR, NDB, DME, TACAN, etc.).

In the field MANOUVRE_CONDITIONS the maneuvers that the aircraft was performing during the accident are reported (landing and takeoff in IFR or VFR conditions, etc.). The EVENT_TYPE is the typology of aircraft accident:

- run off: it is frequent in the case of long landing or aborted take-off;
- veer off: it is relative to an aircraft side off and can happen both in take-off phase and landing; it can be due to an elevated value of the wind transverse component, to a mechanical breakdown, etc;
- short landing: it is relative to a touchdown happened before the runway threshold. It is due, mainly, to bad meteorological conditions;
- run incursion: it occurs both in take-off phase and landing and can concern both aircrafts and other vehicles.

In the field FLIGHT_PLAN there’s a synthetic description of the flight plan performed by the plane. Particularly it records the departure airport and his id code, intermediary airports, the destination airport and the flight typology. METEOROLOGICAL_CONDITIONS are the conditions recorded in the place of the accident during the event. Particularly, they regards the presence and height of the clouds, visibility, wind direction and intensity, precipitation, temperature and dewy point. In the field SYNTETIC EVENT DESCRIPTION there’s a brief but exhaustive description of the accident dynamics. In such description are underlined:

- in landing phase, the touchdown point in which the accident is verified and the stop point in which the
In this report the PROBABLE CAUSES are that brought to the accident are reported too. Essentially we refer to human factors, mechanical factors or environmental factors. Even if these factors are not interdependent, they can interact. Mechanical and environmental factors are obviously unchangeable in the brief period: there’s only the possibility to act on human errors applying preventive measures that aim to reduce the accident. As concern human errors typology, the following classifications can be made:

- **active failures** (errors or active drawbacks): errors or drawbacks that have an immediate negative effect;
- **latent failures**: failures existing before the event.

A description of the features interested by the accident is reported in the field AIRPORT FEATURES INTERESTED: RWY, TWY, Apron or also the zone where the accident is occurred, as well as the state in which was found during the accident. Some interesting airport features about runways are:

- a synthetic description of the geometric characteristics: length, width, longitudinal and transversal inclination, presence of stop way and his dimensions, TORA (Take Off Run Available), TODA (Take Off Distance Available), ASDA (Accelerate and Stop Distance Available), LDA (Landing Distance Available), runway instrumentations, ILS system for landing. Particularly, in relationship to the runway visual range and to the decision height, the ILS is divided in ILS of CAT I, it allows an approach of precision until to a height of decision of 60 mt and a RVR of the 800m, ILS of CAT II, it actually allows an approach of precision to a decision height of 30 mt and a RVR of the of 400 ms, ILS of CAT III, it allows an approach of precision without some decision height and a RVR between the 200 and 50 mt;
- the pavement conditions during the accident. To define aforesaid conditions is made reference to the ICAO terminology. The followings terms we have been used:
  - damp, to point out that the surface shows changes of color because of the damp;
  - wet, to point out that the surface is full water, but there is no puddles;
  - water patches, to point out that on the surface they are visible puddles;
  - flooded, to point out that on the surface they are visible ample zones covered of water.

If there’s some ice on the runway the terms used are: rime or frost covered normally to the millimeter, dry snow, wet snow, slush, ice, compacted or ruled snow, frozen ruts or ridges.

The EVENT SCHECTH is a graphic accident representation in which the points in the synthetic description of the accident and a possible photographic documentation are underlined.

### 3.1 Experimental analysis: acquisition and elaboration data

For each accidental event, relieved trough the government or others operators accident reports, proposed report has been compiled. Acquired data allowed to establish that the 46,4% of the 1.174 commercial airplanes accidents concerned the airport (58,5% concerning the RWY, 33,6% concerning the apron and 7,9% concerning the TWY) and the 18,1% the approach paths. As concern risk events typology: 40,1% are accident, 54,7% are incident and 5,2% are serious incident.

From these results emerges that during the taxing maneuvers, from and for the runway, and those of standstill in the terminal area, there aren’t human damages if we except fear or light injuries. On the other hand, the accidents during the take-off or landing phases are characterized by an high percentage of injuries and deaths. Indeed, in this paper “apron maneuvers” have not been considered. Investigating causes of those fatal aircraft accidents is difficult because they generally stem from a complex system of mutually dependent, sequential factors. These factors can be classified in several ways. At first, according to the current state-of-knowledge, they can be categorized into known and avoidable and unknown and unavoidable causes. The former should be considered conditionally in the sense that immediately after an accident the real causes are seldom fully known but as the investigation progresses they become known and avoidable. Then, with respect to accident type, the main causes can conditionally be classified into human errors, mechanical failures, hazardous weather, sabotages or military operations.

As concern data about the accidents happened on the runway, a 75% of these ones happen in the landing phase and the remaining 25% in the take-off maneuver. Considering the single maneuvers:

- in the landing phase, the 66% of the accidents are due to human errors, 20% to mechanical failures and 14% to meteorological conditions;
- in the take-off phase, the 45,5% of the accidents are due to human error, 45,5% to mechanical failures and 9% to meteorological conditions.

Therefore, while in landing phase the predominant cause is represented by the human error, in the take-off there’s no difference between mechanical failures and human errors.

### 4 A risk assessment methodology

Basic element to conduct a statistical analysis of an event is the sample data description and determination. In this study
the sample elements are the commercial aircrafts involved in runway accidents in take-off and in landing phases. Specifically we have not considered:

- the missed collisions in the runway among two aircrafts or among these and any other vehicle;
- the damages of the aircrafts in take-off phase that has not brought any harmful effect;
- the aircrafts that, during the landing phase has suffered failures and went out the runway without further problems.

The our model calculating airport risk accidents is composed by three main elements: the probability model of an occurrence of aircraft accident and the accident location probability model to determine the frequency of an occurrence p in (1); the accident consequence model in order to determine the x variable in (1).

4.1 The aircraft accident probability model

Of this study phase has been the subdivision of the surrounding area runway in isofrequency lines or rather zones characterized by the same commercial aircraft accident probability (as shown in figure 2).

The model as a result was born from a careful analysis of the incidental phenomenon, particularly of the various phases that have brought to the aircraft arrest outside runway, both in take-off and in landing phases. It has emerged that the interested events (the touchdown point or take-off interruption phase; the accident causes; the aircraft or debris stop point) may be considered. Such event can occur randomly any time and in any point in space. Past aircraft accidents had these features. They occurred in a random manner in different parts of the world. Therefore it is possible to determine the frequency of an occurrence through a partial shares model.

Particularly fixing a Cartesian reference (x, y) with axis x coincident with the runway, and we have subdivided the area of study through squared or rectangular grid. It will be possible to calculate the probability that the airplane or debris, involved in a generic accident, belonging to i class, stops in a determined point (B) center of the generic unit grid. This probability is related to the probability that define touchdown or aborted take-off point (A). Then we have the following relationship:

$$Pr_i^I\{B\} = \frac{\sum n_i}{\sum n_i} \cdot Pr^I\{I\} \cdot Pr_i^I\{A\} \cdot Pr_i^I\{B/A\}$$  \hspace{1cm} (4)

where:

- $\sum \frac{n_i}{\sum n_i}$ is the percentage of airplanes related to i weight class that landing or take off from the airport object of this study;
- $\frac{n_i}{\sum n_i} \cdot Pr^I\{I\}$ represents the proportion of aircraft within the airport vicinity that have an incident that causes it to crash, or run – off the runway, etc. The $I$ variable represents the type of accident the aircraft will have (i.e. crash short of runway on approach, or run off the side of the runway, etc.);
- $Pr_i^I\{A\}$ is the probability that the airplane of i class touches in the landing phase or aborts the take-off in the determined point A;
- $Pr_i^I\{B/A\}$ is the probability that the airplane of i class, departing from the point A comes to stop itself in point B.

Adding, for every point B, the probabilities determined (4), relatively for every category in which the sample will be divided, total probabilities are calculated. Enveloping the points characterized by the same total probability the above mentioned areas we are obtained.

Since the examined accidents interested different measures of runway, to give a correct interpretation of the statistic data related to the distances has been necessary to make adimensional the distances information. To such purpose we have introduced "standard runway" that has a length equal to 10.000 ft and a width equal to 150 ft. Dividing these dimensions for the real ones of the runways interested by the relieved accidents, the values of two homogenized coefficients ($C_x$ and $C_y$) have been obtained. Multiplying dictates values for the real length and width, may be possible to define the accidents schemes of the "standard runway", on the base of which the study has been conducted.

For example the 11/07/2001 in Fiumicino Rome Airport accident has interested a type MD-11 airplane. In such case the runway 16C dimensions are 9.850 ft, of length and 150 ft, of width. Dividing these measures of the "standard runway" to these the following values of the $C_x$ and $C_y$ coefficients are obtained:

- $C_x= 1,015$
- $C_y= 1,000$.

Multiplying these distances according to the x and y axis, and the above mentioned coefficients we are obtained some homogenized values bases of our study has been conducted. In detail results that the aircraft MD-11 has touched the
runway to a distance of 914 ft and it is arrested to 3665 ft from this. We have proceeded in analogous way for all relieved accidents and for every maneuvers (landing and take-off).

The model provides equations in order to determine either the impact or wreckage location of an aircraft following an accident. Several equations are described for all permutations of:

- Aircraft operation (approach and departure);
- Crash from flight, or runway run off;
- Crash location (before or after the prepared runway surface).

These equations form a set of probability distribution functions of a crash occurring per unit area.

### 4.1.1 The proportion accident type model

This approach model involves the statistical modelling the occurrence of air accidents over time; a Poisson sequence or Poisson process is often deployed. Such a process is based on the following assumptions:

- an event can occur randomly and at any time and any point in space. Past aircraft accidents had these features. They occurred in a random manner in different parts of the world;
- the occurrence of an event in a given time or space interval or segment is independent on what happened in any other non-overlapping intervals or segments. Air accidents, except very rare mid-air collisions, have occurred as the series of independent events in time and space;
- the probability of an event occurring in a small interval $\Delta t$ is proportional to $\Delta t$ and can be calculated by $\lambda \cdot \Delta t$ where $\lambda$ is the mean rate of occurrence of the event. It is assumed constant and equal to $\lambda = \frac{1}{T_a}$, where $T_a$ is the average time interval between consecutive events. The probability of two or more occurrences in $\Delta t$ is negligible (of higher order of $\Delta t$).

From empirical evidence, $\Delta t$ is assumed to be a short period, the probability of an occurrence of more than one aircraft accident will normally be negligible.

In Poisson processes the time intervals between successive events is exponentially distributed, indicating no-memory property in the process. This means that future events do not depend on the number or time of previous events. This would logically seem to be the case with air accidents.

Mathematically, let $T$ be the random variable representing the time between any two consecutive events. This variable is exponentially distributed. The probability that no accident will occur in time period $t$ is:

$$P(T \leq t) = P(X_t = 0) = e^{-\lambda t}$$

where, $X_t$ is the number of air accidents in time $t$ and $\lambda$ is the average accident rate. Similarly, the probability of the occurrence of at least one event in time $t$ is:

$$P(T \leq t) = 1 - P(T \geq t) = P(X_t \neq 0) = 1 - e^{-\lambda t} \quad (6)$$

The probabilistic assessment of accidents uses a sample of 101 accidents over the period 1995 – 2003. The distribution of time intervals between these events is shown in Fig. 3. A simple calculation provides an estimate of the average accident rate: $\lambda \cong 7.851$ accidents per year or $\lambda \cong 0.0215$ accidents per day. An analysis of the time intervals between accidents, independent of aircraft type, indicates they have been independent and exponentially distributed (a $\chi^2$ test confirms the hypothesis matching the empirical and theoretical data:

$$\chi^2_{0.05} = 16.9191; \chi^2 = 15.706 \Rightarrow \chi^2 < \chi^2_{0.05}.$$  

This offers confirmation that the observed pattern of accidents can be treated as Poisson process. Using the exponential distribution shown in Fig. 3, it is possible to assess the probability of an air accident occurrence.

![Fig. 3 - Distribution of time intervals between consecutive air accidents (1995 – 2003)](image)

If there is unlikely to be any improvement in safety features then this distribution can be used for assessing the probability of future events. This probability rises over time until the occurred event.

### 4.1.2 Model formulation $Pr\{A\}$ to landing phase

Divided the point sample of touchdown in two subsets corresponding to the two C and D classes of aircraft. For each of these classes a fixed number of touchdown distance intervals has been defined. In order to avoid having empty intervals (condition that corresponds to a lower part number of intervals) or information loss around the form of the function distribution (condition that corresponds to an elevated interval numbers) the number of these intervals and their respective amplitudes has been defined through the relationships:

$$k = 1 + 3.3 \log_{10} n_i$$

$$Pr\{A\} = \frac{k}{\sum_{i=1}^{n} k} \quad (7)$$
\[ \Delta x = \frac{x_{\text{max}} - x_{\text{min}}}{k} \] (8)

with \( n_i \) total number of landings related to the above weight aircraft classes.

Bringing for the whole sample and for the single weight classes the distribution of the touchdown points and interpolating the obtained results, it is possible to verify, through the test of the hypotheses \( \rho^2 \), of which will be said subsequently, that these are distributed according to a Normal function of average and standard deviation varying according to the weight class aircraft:

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2}, \quad -\infty < \mu < +\infty; \sigma > 0 \] (9)

particularly, as shown in figure 4 and 5:

\[ \mu = 2.02, \quad \sigma = 1.79 \] for the C class aircrafts;

\[ \mu = 1.58, \quad \sigma = 1.16 \] for the D class aircrafts.

Therefore the probability that an aircraft touches the runway in the point A is obtained by the following integral:

\[ \Pr(A) = \Pr\left( \frac{x_{\text{d}} - \frac{\Delta x}{2} \leq x_{\text{d}} \leq x_{\text{d}} + \frac{\Delta x}{2}} \right) = \int_{x_{\text{d}} - \frac{\Delta x}{2}}^{x_{\text{d}} + \frac{\Delta x}{2}} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2} \] (10)

For example if we would determine the probability of touchdown for class C aircraft in the distance measuring interval 1.400 – 2.600 ft, uniforms such distances (dividing for 1.000), from the preceding figure are drawn that:

\[ \Pr[1.4 \leq x \leq 2.6] = \Pr[x \leq 2.6] - \Pr[x \geq 1.4] = 0.68 - 0.37 = 0.31. \]

### 4.1.3 Model formulation \( \Pr^{i}[B/A] \) to landing phase

Also in this case to define a statistic model that allows to determine the probability that an airplane of \( i \) class stops in point B, of coordinates \((x_b; y_b)\), after having touched in point A of the runway, for every class of aircraft and for the different touchdown zones, the stop distances were divided along the x and y axes in homogeneous intervals of amplesness equal to:

\[ \Delta x = \frac{x_{\text{max}} - x_{\text{min}}}{k} \quad \text{and} \quad \Delta y = \frac{y_{\text{max}} - y_{\text{min}}}{k} \] (11)

with \( k = 1 + 3.3 \log_{10} n_{ij} \), where \( n_{ij} \) is the sample numerousness related to the weight class \( i \) and to the touchdown interval \( j \).

Bringing the distribution of the stop points along the axe x, relatively to the sample, to the single classes of aircraft and the touchdown single distance intervals defined above, the results obtained are shown in Fig. 6.

![Fig. 6 - Example of stop points distribution related to the distances of touched by the runway threshold lesser or equal than the 800 ft and class C of aircraft](image)

From an analysis of the obtained results it is deduced that the probabilistic distribution function of the stop points along the axis x is a Gamma function:

\[ f(x; \alpha) = \frac{e^{-x/x^\alpha-1}}{\Gamma(\alpha)} \] (12)

with parameter:

- \( \alpha = 6 \) for the class C of aircrafts and for all the distances of touchdown point A on the runway;

- \( \alpha = 8 \) for the class D of aircrafts and distances from A point lesser or equal to the 2.000 ft;

For the stop points far to touchdown more than 2.000 ft it is possible to approximate, for class D of aircrafts, the empirical data with a Normal function of average \( \mu = 8.05 \) and standard deviation \( \sigma = 1.46 \)

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x - \mu)^2}{2\sigma^2}} \] (13)

Therefore the probability that an aircraft stopped in the point with coordinates \((x_b; 0)\) once touched in A is given from:
for the class C of aircrafts apart from the touchdown point, and the class D aircraft and touched distances by the threshold runway lesser or equal to 2.000 ft. While for the class D aircraft and touched distances by the runway threshold more than 2.000 ft, this is given:

\[
\Pr\{\gamma_x/A\} = \int_{\gamma_x/2}^{\gamma_x} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy
\]

(14)

for the class C of airplane.

\[
\int_{\gamma_x/2}^{\gamma_x} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy
\]

(15)

for take-off phase

\[
\Pr\{\gamma_x/A\} = \int_{\gamma_x/2}^{\gamma_x} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy
\]

In equivalent way, the probabilities can be calculated through the following figures as difference of the ordinates corresponding to the points:

\[
x_A - \frac{\Delta x}{2} \quad \text{and} \quad x_A + \frac{\Delta x}{2}
\]

(16)

Likewise in y direction we have determined the stop points distribution, expressed by a normal function:

\[
f_y(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(y-\mu)^2}
\]

(17)

with:

- \(\mu = 0.856; \sigma = 1.439\) for C class airplanes and touchdown distances lesser or equal to the 800ft;
- \(\mu = 0.380; \sigma = 1.434\) for C class airplanes and touchdowns among to the 800 ft and the 2.000 ft;
- \(\mu = -0.309; \sigma = 2.408\) for C class airplanes and touchdown distances more than 2.000ft;
- \(\mu = -0.248; \sigma = 2.321\) for D class airplanes and touchdown distances lesser or equal to 2.000 ft;
- \(\mu = -0.44; \sigma = 0.983\) for D class airplanes and touchdown distances more than 2.000ft;

Therefore the probability that the aircraft stops in point (0, yB) once touched A is given by:

\[
\Pr\{\gamma_y/B\} = \int_{\gamma_y/2}^{\gamma_y} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy
\]

(18)

Finally the probability that the C class aircraft stopped in the B point, after touching in A point is given from:

\[
\Pr\{\gamma_y/B\} = \int_{\gamma_y/2}^{\gamma_y} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy \cdot \int_{\gamma_y/2}^{\gamma_y} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(y-\mu)^2} dy
\]

(19)

instead, for the D class of aircraft the above probability is changed in:

\[
\Pr\{\gamma_y/B\} = \int_{\gamma_y/2}^{\gamma_y} \frac{e^{-\frac{1}{2}(y-\mu)^2}}{\sigma\sqrt{2\pi}} dy \cdot \int_{\gamma_y/2}^{\gamma_y} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(y-\mu)^2} dy
\]

(20)

4.1.3 Model formulation \(\Pr\{A\}\) and \(\Pr\{B/A\}\) for take–off phase

Following an analogous procedure to the landing case, it has been possible to verify that the distances in which the take-off was aborted are distributed according to a normal function:

\[
f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(x-\mu)^2}, \quad -\infty < \mu < +\infty; \sigma > 0
\]

(21)

with:

- \(\mu = 5.09\) and \(\sigma = 2.72\) for the C weight class of airplane;
- \(\mu = 5.16\) and \(\sigma = 3.17\) for the D weight class of airplane.

The probability function is:

\[
\Pr\{x/A\} = \int_{x-\Delta x/2}^{x+\Delta x/2} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(x-\mu)^2} dx
\]

(22)

For the probability function that determine the aircraft or debris stop points distribution we have determined that they change in accord with Gamma function:

\[
f_x(x) = \frac{e^{-x/x^\alpha-1}}{\Gamma(\alpha)}
\]

(23)

with:

- \(\alpha = 5\) for the C weight class of airplane;
- \(\alpha = 4\) for the D weight class of airplane.

The probability function is:

\[
\Pr\{x_B/A\} = \int_{x_B-\Delta x/2}^{x_B+\Delta x/2} \frac{e^{-x/x^\alpha-1}}{\Gamma(\alpha)}
\]

(24)

In y direction we have noticed a normal distribution to determine the stop point in the \((y_B,0)\) coordinates related to the aborted take–off in B points:

\[
f_y(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(y-\mu)^2}, \quad -\infty < \mu < +\infty; \sigma > 0
\]

(25)

with:

- \(\mu = 0.050, \sigma = 1.464\) for the C weight class of airplane and stop distances lesser or equal to 4.500 ft;
- \(\mu = -0.428, \sigma = 0.920\) for the C weight class of airplane and stop distances more than 4.500 ft;
• \( \mu = 1,563 \), \( \sigma = 3,898 \) for the D weight class of airplane and stop distances lesser or equal to 4.500 ft;
• \( \mu = 0,167 \), \( \sigma = 0,518 \) the D weight class of airplane and stop distances more than 4.500 ft

and the probability function is:

\[
\Pr\{y_B / A\} = \int_{y_B - \frac{\Delta y}{2}}^{y_B + \frac{\Delta y}{2}} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(y_B - \mu)^2}{2\sigma^2}} dy
\]

The probability that the aircraft stopped in the B point, after aborted the take-off manoeuvre in A point is given as:

\[
\Pr\{B / A\} = \int_{x_A - \frac{\Delta x}{2}}^{x_A + \frac{\Delta x}{2}} \int_{y_A - \frac{\Delta y}{2}}^{y_A + \frac{\Delta y}{2}} e^{-\frac{(y_B - \mu)^2}{2\sigma^2}} dy \int_{x_B - \frac{\Delta x}{2}}^{x_B + \frac{\Delta x}{2}} e^{-\frac{(y_B - \mu)^2}{2\sigma^2}} dx
\]

4.2 Results analysis
The model result give us the isoprobabilistic points in which we determine aircraft or debris related to accident. If we join such points we determine the crash location areas around the airport, as shown in the following figure 7. Particularly in this research we have considered Naples International Airport with mix index traffic:

- 68% aircrafts belonging to C weight class;
- 32% aircrafts belonging to D weight class.

If the above repartition change the boundaries may be change. In fact in the probability determined with the model implemented in the previous paragraph it is hypothesized a relation between the probability of the accident location \( P(B) \) and the mix index traffic \( \left( \frac{n_i}{\sum n_i} \right) \):

\[
\Pr\{B\} = \frac{n_i}{\sum n_i} \cdot \Pr\{I\} \cdot \Pr\{A\} \cdot \Pr\{B / A\}
\]

4.3 Evaluation of accidents consequences
In order to assess the consequences of an accident is, for different reasons, rather difficult. In the present study we have proposed as magnitude scale that founded on the number of people in the object study area, in relationship to their permanence time. Particularly we have determined the number of people inside every accident location, above schematized, through the product of the housing density, (data ISTAT sources) for the extended area. Such value with permanence coefficient we have multiplied. This coefficient will be given by the relationship of the permanence time, in hour, for the fixed people category, inside the interested area, and the total hours in the day, multiplied for 1000; therefore in the resident case this will be equal to 1000, for the students it will be equal to 660; for the employees 330 (in fact we have hypothesized that they remains for the job time alone), for the people on the board in the aircraft we have hypothesized a value equal to 1.

Multiplying dictates values for the respective accident probability, discussed in the previous paragraphs, the risk is obtained.

4 Conclusion
This paper has considered risk assessment applied to airport runways. Some new – computer based tools have been described in order to support the assessment by helping in the specification and evaluation of mitigating features. With this model we determine the region around airport that will be interested by the incident. In other words we determine the area affected by different probability occurrence of incident (frequency of occurrence of a defined hazard). In order to determine the risk the magnitude function and the probability model (frequency of accident referred to accident and the operation of aircraft types) are multiplied.

This model is a quantitative tool that can be utilized both in airport design and in the operations management, assessing in the first case an useful tool to the infrastructure realization of a given capacity in the other case a “limit” to the airport capacity.

References:


