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Aircraft runway excursion features: a multiple correspondence analysis

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Abstract

Purpose – The risk of aircraft runway excursion, dependent on multiple factors, is related to operating conditions. The purpose of this paper is to identify the correspondence between features belonging to different aspects that occur in runway excursion events, distinguishing between take-off and landing phases.

Design/methodology/approach – To define the correspondence between the characteristic features of runway excursions, this study has applied multiple correspondence analysis (MCA). MCA is used to represent and model data sets as "clouds" of points in a multi-dimensional Euclidean space. There are five variables used in MCA: geographical region, potential cause, aircraft class, flight nature and aircraft damages. For the purpose of this research, the database contains only runway excursion accidents that took place between 2006 and 2016 among all categories of aircraft in all world regions. The events contained in the database were analyzed by separating those that occurred during take-off and those that occurred during landing.

Findings – With this method, this study identified a few particularly interesting variable combinations. Generally, the consequence of an aircraft runway excursion is substantial aircraft damage. Also, the most common cause of runway excursion during take-off is aircraft system faults, while during landing, it is weather conditions. Furthermore, the destruction of an aircraft is a result of a runway excursion due to bad weather conditions, both during take-off and landing.

Practical implications – The results of this study can be used by a broad range of civil aviation organizations for runway risk assessment and to select the most effective safety countermeasures for runway excursions.

Originality/value – The authors believe this study is original, especially for the statistical analysis method used.

Keywords Risk assessment, Overrun, Aircraft accidents, Airport safety, Potential causes, Veer-off

Paper type Research paper

Introduction

A large number of aircraft accidents occur during the take-off and landing phases. Most occur beyond the designated safety and protection areas, around the runway, when an aircraft overruns the runway-end during take-off or landing or when it undershoots the runway, with regard to the threshold, during landing.

Safety statistics show that runway excursions are the most common type of accident reported annually in the European region and worldwide.

Runway excursions during take-off and landing continue to be the highest category of aircraft accidents and often exceed 25 per cent of all annual commercial air transport accidents (IATA, 2015).

Runway excursions can result in loss of life and/or injury to persons either on board the aircraft or on the ground. The effect of runway excursions can result in damage to aircraft, airfield or off-airfield installations, including other aircraft, buildings or other items struck by the aircraft.

The most common and most survivable accident category is runway/taxiway excursions, with 98 per cent survivability; runway/taxi excursions represented 7 per cent of total fatalities over the five years from 2010 to 2014 (174 out of 2,541).

A runway excursion accident is defined as an accident in which an aircraft on the runway surface departs the end or side of the runway surface during take-off or landing (IATA, 2015).

It consists of two types of events:

1. *Veer off*: This is a runway excursion in which an aircraft departs the side of a runway.
2. *Overrun*: This is a runway excursion in which an aircraft departs the end of a runway.

It excludes accidents in which the aircraft did not initially land on a runway surface and take-off excursions that did not start on a runway (e.g. inadvertent take-offs from taxiways).

The current definitions of runway overrun do not specify any distance for arrivals and departures where an incident cannot be considered to be an overrun or undershoot, because it is too far out from the runway. For example, the current definitions used by Eurocontrol are as follows:

- *Overrun on take-off*: This is a condition where a departing aircraft fails to become airborne or successfully reject the take-off before reaching the end of the runway.

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- *Overrun on landing*: This is a condition where a landing aircraft is unable to stop before the end of the runway is reached.

The common taxonomy group of the ICAO commercial aviation safety team refers to runway excursion as a veer-off or an overrun off the runway surface. This definition is only applicable during either the take-off or landing phases. The excursion may be intentional or unintentional (for example, a deliberate veer-off to avoid a collision, brought about by a runway incursion). This classification applies to all cases where the aircraft leaves the runway, regardless of the excursion being the consequence of another event.

Within the context of aviation, safety is:

> [...] the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management (ICAO, 2013).

A major contributor to the improved safety record can be traced back to the careful investigation of past accidents to determine what led to the accidents and what needs to be done to prevent such events from occurring again. This reactive approach to improving aviation safety has been enhanced by the thorough analysis of data from numerous accidents, which has aided in the identification of recurring patterns or risk factors that are not always apparent when individual accidents are investigated (Distefano and Leonardi, 2017). Shao *et al.* (2013) examine factors that have influenced the average accident rate per million departures in Taiwan from 1985 to 2011, involving turbojet aircraft hull loss. The subcategory runway excursion was the most significant effect for serious incidents. More recently, proactive approaches to determining ways to improve safety have become increasingly popular. An example of such a proactive approach is the analysis of incident data to identify areas of increased risk that may lead to an accident (Oster *et al.*, 2013). This study says there is still a role for careful accident investigation and there are still lessons to be learned from the few accidents that carriers have been in. But with improvements in safety and major reductions in accidents, airline safety analysis will have to shift toward analysis of incident and operational data with the intent of identifying safety risks before accidents occur. There are two potential benefits from looking at these types of data. One is to address the question of why some sequences of events result in accidents while other sequences do not. A better understanding of how potential accidents were avoided in some situations may lead to more such avoidances in the future. A second potential benefit is to identify trends in or the emergence of potentially hazardous sequences of events before they result in an accident. Here again, by identifying such trends, it may be possible to take corrective action before an accident occurs.

Oriola and Adekunle (2015) propose a study that models the probabilistic risk assessment of runway accident hazards in the Nigerian aviation sector. Six categories of runway accident hazards with their corresponding basic events were identified and modeled using fault tree analysis method of probabilistic risk assessment. The fault tree developed is a system of OR-gates, and the weights for each hazard were derived through a domain/expert opinion. The results of the analysis show a close relationship between runway accidents in the Nigerian aviation sector and aircraft system failure, approach/take-off procedures, human factor, weather conditions and collision risk.

Wagner and Barkerb (2014) focused on predicting if excursions will generate fatalities. Human errors are the strongest feature associated with fatal excursions. Another feature strongly associated with fatal excursions is adverse weather conditions. Also, fatal excursions occur more frequently on commercial flights than other categories of aircraft operation, and overruns are the most fatal category of runway excursions.

Moretti *et al.* (2017) propose an analysis that permits to compute the probability of veer-offs at any airport, after considering its specific conditions (e.g. number and type of plane, kind of movement and bearing capacity of the subgrade). The results of this study show that the average frequency of a veer-off accident is 1.44 in ten million movements for commercial flights over 30 Mg (ton), and that veer-offs are more frequent during landing than take-off.

The risk of runway excursion, dependent on multiple factors, is related to operating conditions. The goal of this paper is to identify the correspondence between features belonging to different aspects that occur in runway excursion events distinguishing between take-off and landing phases.

Identifying accident factors and their combinations by analyzing a large data set is not a trivial task. The commonly used statistical inferential method, ANOVA, and safety performance models cannot identify the combination of factors simultaneously.

In recent years, a few studies have been conducted relating to the analysis of historical data on aircraft accidents. Čokorilo *et al.* (2014) compares aircraft accidents in relation to the characteristics of the aircraft, environmental conditions, route and traffic type. The study was conducted using a database of over 1,500 aircraft accidents worldwide that occurred between 1985 and 2010. The data were processed and aggregated into groups, using cluster analysis based on an algorithm of partition binary, "Hard c means." For each cluster, the "cluster representative" accident was identified as the average of all the different characteristics of the accident. Moreover, a "hazard index" was defined for each cluster (according to annual movements). Using this index, it was possible to establish the dangerousness of each "cluster" in terms of aviation accidents. The obtained results allowed the construction of an easy-to-use predictive model for accidents, using multi-variate analysis.

Dambier and Hinkelbein (2006) have performed an analysis with the HFACS model and on the basis of the regularly published reports of the German state department for aircraft accident analysis (BFU), including accidents (but not incidents) of GA aircraft flown by German pilots in Germany and in other countries. The underlying reasons were classified as follows: pilot errors, organizational factors, ergonomic factors, aeromedical problems and crew resource management.

To define the correspondence between the characteristic features of the runway excursions, this study has applied the multiple correspondence analysis (MCA). MCA is an extension of correspondence analysis for more than two variables and is widely used in categorical data analyses, especially in social sciences and marketing research. By using this technique, the patterns of combined accident contributing factors can be visualized. MCA helps researchers discover the structure of categorical data by presenting complicated relationships in a simple chart that demonstrates a combination of significant variables through the reduced data dimension analysis. This method presents the correlation between the variables and their relationship with the interested resultant variable by creating combination clouds.

Fontaine (1995) was the first to use MCA for a typological analysis of vehicle-pedestrian crashes. Das and Sun (2016) use MCA to analyze eight years (2004-2011) of fatal run off road crashes in Louisiana. Jalayer and Zhou (2016) use the latest available data set (2009-2013) from the Critical Analysis Reporting Environment database to study motorcycle crashes in the state of Alabama.

Therefore, this study is based on a large database of relevant accident cases. The results of the current study can be used by a broad range of civil aviation organizations for risk assessment and to select the most effective safety countermeasures.

Method and data

Runway excursions data were processed using MCA by SPSS statistical analysis software.

Multiple correspondence analysis

Summarily, MCA is part of a family of descriptive methods (e.g. clustering, factor analysis and principal component analysis) that reveal patterning in complex data sets. However, specifically, MCA is used to represent and model data sets as "clouds" of points in a multi-dimensional Euclidean space, which means that it is distinctive in describing the patterns geometrically by locating each variable/unit of analysis as a point in a low-dimensional space. The results are interpreted on the basis of the relative positions of the points and their distribution along the dimensions. As categories become more similar in distribution, the closer (distance between points) they are represented in space. Although it is mainly used as an exploratory technique, it can be a particularly powerful one as it "uncovers" groupings of variable categories in the dimensional spaces, providing key insights on relationships between categories (i.e. multi-variate treatment of the data through simultaneous consideration of multiple categorical variables), without needing to meet assumptions requirements, such as those required in other techniques widely used to analyze categorical data (e.g. chi-square analysis, Fischer's exact test, G-statistics and ratio test). The use of MCA is, thus, particularly relevant in studies where a large amount of qualitative data are collected, often along with quantitative data, and where qualitative variables can become sub-optimized in the data analysis. MCA plots are a better way of presenting information graphically and one can interpret them by examining the distribution of variable groupings in space. Points (categories) that are close to the mean are plotted near the MCA plot's origin and those that are distant are plotted farther away. Categories with a similar distribution are near one another in the map as groups, while those with different distributions stay farther apart. In a two-dimensional graphical display of the data, categories sharing similar characteristics are located close together, forming point clouds.

MCA is performed on an I × Q indicator matrix in which I is the set of individual records and runway excursion accidents and Q is the set of categories of all variables and characteristic features. Given this, the component in the cell (i, q) consists of the individual record i and category j. Associated categories in MCA are placed close together in a Euclidean space, leading clouds or a combination of points that have similar distributions. Notably, MCA produces point clouds that are usually defined by two-dimensional graphs.

Suppose the number of individual records associated with category k is denoted by n_k (with $n_k > 0$), where $f_k = n_k/n$ is the relative frequency of individuals who are associated with category k. The values of f_k will generate a row profile. The distance between two individual records is created by the variables for which both have different categories. Suppose for variable q, individual record i contains category k and individual record i′ contains category k′, which is different from k. The squared distance between individual records i and i′ for variable q is defined by equation (1):

$$d_q^2(i,i') = \frac{1}{f_k} + \frac{1}{f_k'} \tag{1}$$

Denoting Q as the number of variables, the overall squared distance between i and i′ is defined by equation (2):

$$d^2(i,i') = \frac{1}{Q}\sum\nolimits_{q\in Q} d_q^2(i,i') \tag{2}$$

The cloud of categories is a weighted cloud of K points (by category k, a point denoted by M^k with weight n_k is represented). For each variable, the sum of the weights of category points is n, hence for the whole set K, the sum is nQ.

If $n_{kk'}$ indicates the number of individual records having both categories (k and k′), then the squared distance between M^k and $M^{k'}$ is defined by equation (3):

$$(M^k M^{k'})^2 = \frac{n_k + n_k' - 2n_{kk}'}{{n_k n_{k'}}/{n}} \tag{3}$$

The numerator is the number of individual records associated with either k or k′.

In this study, MCA was determined to be the better choice for data processing. MCA was chosen because it is better for interpreting large data sets than conventional log-linear models.

Moreover, in MCA there is no need to consider any underlying distribution and no relationship has to be hypothesized. Moreover, rules with a large number of item sets are difficult to interpret in association rules mining. MCA overcomes these difficulties by performing efficient dimensionality reductions and compiling results into easy-to-read plots.

The research team used statistical software SPSS version 24.0 to perform the MCA technique.

Data

The primary data source used in this work is a database created by Aviation Safety Network (ASN).

ASN is a private, independent initiative founded in 1996. Online since January 1996, ASN covers accidents and safety issues with regard to airliners, military transport planes and corporate jets.

The ASN Safety Database contains detailed descriptions of some 17,600 incidents, hijackings and accidents to airliner, military transport category aircraft and corporate jet aircraft safety occurrences since 1921. Most of the information are from official sources (civil aviation authorities and safety boards), including aircraft production lists, ICAO ADREPs and countries' accident investigation boards.

For the purpose of this research, the database contains only runway excursion accidents that took place between 2006 and 2016 among all categories of aircraft in all world regions. This period was considered to be sufficient to obtain statistically relevant results.

To make statistically significant data to be analyzed fields suitable to regroup together the elements of some records of the database have been created. These fields constitute the variables used in MCA. Table I shows the five variables individuated and all the categories defined for each variable.

The countries' airports that had runway excursions were grouped as recited in the IATA classification of the geographic regions (IATA, 2015). NASIA does not appear in the categories of variable 1 because, in the analysis period, only two events were recorded.

The aircraft operation classes are defined as:

1. *General aviation aircraft (GA)*: Typically, these aircraft can have one (single) or two (twin) engines. Their maximum gross weight is usually below 14,000 lb.
2. *Corporate aircraft (CA)*: Typically, these aircraft can have one or two (sometimes three) turboprop-driven or jet engines. Their maximum gross mass is 90,000 lb.
3. *Commuter aircraft (Com A)*: Usually, these are twin-engine aircraft, with a few exceptions such as the De Havilland DHC-/ that has four engines. Their maximum gross mass is below 70,000 lb.
4. *Transport aircraft (TA)*:
   - *Short-range (S-R)*: Their maximum gross mass is usually below 150,000 lb.
   - *Medium-range (M-R)*: These are transport aircraft used to fly routes of less than 3,000 nm (typical). Their maximum gross mass is usually below 350,000 lb.
   - *Long-range (L-R)*: These are transport aircraft used to fly routes of more than 3,000 nm (typical). Their maximum gross mass is usually above 350,000 lb.

Scheduled services are flights scheduled and performed for remuneration according to a published timetable, or so regular or frequent as to constitute a recognizably systematic series, which are open to direct booking by the public. A non-scheduled air service is a commercial air transport service performed as other than a scheduled air service. A charter flight is a non-scheduled operation using a chartered aircraft. Military flights were not taken into account in this study.

The database created for this analysis includes all 406 runway excursions that occurred in the 11-year period from 2006 to 2016. Runway excursions occurred most often during the landing phase (355 events), with a slightly lower division for landing overruns (145 events) respect to veer-offs (190 events). Take-off runway excursions (71 events) present a more or less equal division between overruns (40) and veer-offs (31).

Table I Variables and related categories

Variable 1 – Geographical region	
R1	*NAM*: North American
R2	*EUR*: Europe
R3	*LATAM*: Latin America and the Caribbean
R4	*AFI*: Africa
R5	*ASPAC*: Asia Pacific
R6	*CIS*: Commonwealth of Independent States
R7	*MENA*: Middle East and North Africa
Variable 2 – Potential cause	
C1	*Aircraft system faults*: engines, brake (wheel brakes, spoilers or reversers), hydraulic, electric, main gear, tire, other
C2	*Human errors*: incorrect flight planning, communication/coordination, pilot error, visual illusion, excessive speed, loss of control, other
C3	*Weather conditions*: Low visibility, rain, wind shear, tailwind, ice, crosswind, low ceiling, strong wind, turbulence, freezing rain, other
C4	*Runway conditions*: Wet, contaminated (standing water, rubber, oil, ice, slush, snow), FOD, wildlife hazards, down slope
C5	*Unknown*
Variable 3 – Aircraft class	
A1	*GA*
A2	*CA*
A3	*Com A*
A4	*S-R*
A5	*M-R*
A6	*L-R*
Variable 4 – Flight nature	
F1	*Cargo*
F2	*Domestic non-scheduled passenger*
F3	*Domestic scheduled passenger*
F4	*Executive*
F5	*International scheduled passenger*
F6	*Private*
F7	*Unknown*
F8	*Other (ambulance, agricultural, training, ferry/positioning, parachuting)*
Variable 5 – Aircraft damages	
D1	*Minor*
D2	*Substantial*
D3	*Destroyed*

Table II shows the distribution of these events for the various variables analyzed for this study, separate for flight phase.

Results and discussions

MCA was applied to the data collected. The events contained in the database were analyzed by separating those that occurred during take-off and those that occurred during landing. To define the correspondence between the categories of each variable defined for the analysis of the runway excursion events, the statistical software SPSS version 24 was used. Output of MCA is a two-dimensional graph. The MCA graphical representations help simplify the process of interpreting the relationships among variables.

Table II Distribution of runway excursions for the five variables and flight phase

Variables	Landing	Take-off
Geographical regions		
NAM	93	24
EUR	42	10
LATAM	61	15
AFI	36	9
ASPAC	70	9
CIS	15	9
MENA	37	4
Potential cause		
Aircraft system faults	85	19
Human errors	101	23
Weather conditions	57	10
Runway conditions	26	6
Unknown	87	22
Aircraft damage		
Minor	46	7
Substantial	284	59
Destroyed	26	14
Aircraft class		
GA	65	15
CA	83	29
Com A	88	16
S-R	85	13
M-R	25	3
L-R	10	4
Nature of flight		
Cargo	46	10
Domestic non-scheduled passenger	21	2
Domestic scheduled passenger	128	25
Executive	31	7
International scheduled passenger	33	2
Private	22	5
Unknown	15	5
Other	41	15

The model resulted in two dimensions with eigenvalues >1, both for take-off and landing, explaining 74.13 per cent of the variance for take-off and 73.42 per cent of the variance for landing (Table III).

Figure 1 illustrates the MCA plot for runway excursions in take-off and Figure 2 illustrates the MCA plot for runway excursions in landing.

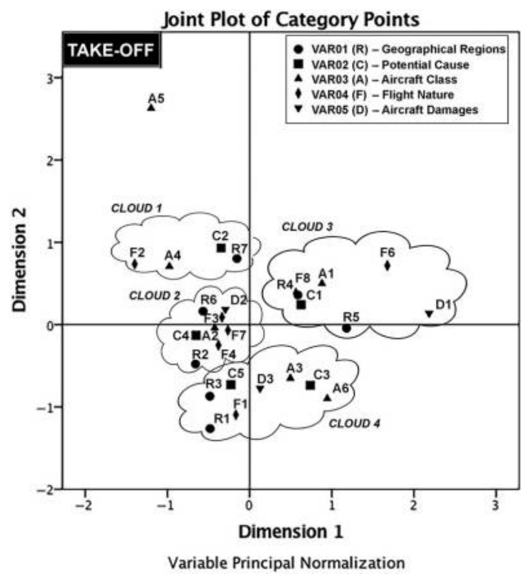
An MCA plot shows the distribution of the coordinates of all categories. This plot gives us an idea of the variable categories' positions on the two-dimensional space based on their eigenvalues. When the categories are relatively close, they form a combination cloud. In this study, four significant combination clouds from each MCA plot are chosen. The combination groups with redundant information, despite being relatively closer, were not considered.

Table III Model summary resulting from the MCA

Dimension	Cronbach's alpha	Variance accounted for total (Eigenvalue)	Inertia	% of variance
Model summary for take-off				
1	0.607	1.945	0.389	38.906
2	0.54	1.762	0.352	35.231
Total		3.707	0.741	74.137
Mean	0.576[a]	1.853	0.371	37.068
Model summary for landing				
1	0.671	2.16	0.432	43.192
2	0.423	1.512	0.302	30.234
Total		3.671	0.734	73.426
Mean	0.569[a]	1.836	0.367	36.713

Note: [a]Mean Cronbach's alpha is based on the mean Eigenvalue

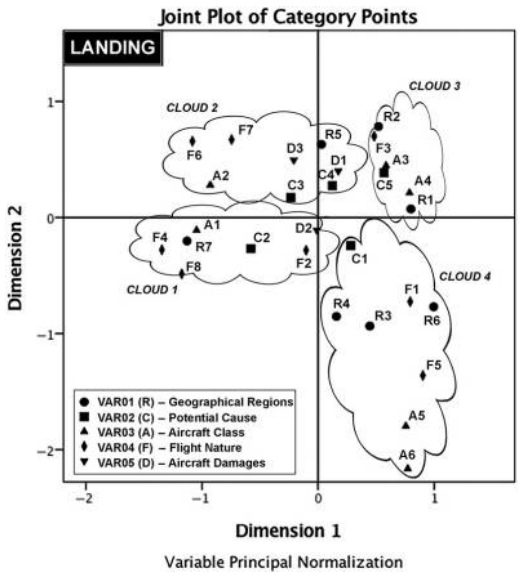
Figure 1 MCA plot for runway excursions on take-off



Each of the combination groups identified the categories of the five variables that are most likely to occur simultaneously in a runway excursion event.

In particular, on take-off, combination cloud 1 combines four categories (Middle East and North Africa, aircraft for S-R, domestic non-scheduled passenger and human error), combination cloud 2 combines eight categories (Europe, Commonwealth of Independent States, corporate aircraft, domestic scheduled passenger, executive, unknown flight nature, runway conditions and substantial aircraft damages), combination cloud 3 combines seven categories (Africa, Asia Pacific, general aviation aircraft, private or other flight nature, aircraft system faults and minor aircraft damages) and combination cloud 4 combines eight categories (North America, Latin America and Caribbean, cargo, commuter

Figure 2 MCA plot for runway excursions on landing



aircraft, aircraft for L-R, weather conditions, unknown potential cause and destroyed aircraft).

The MCA of runway excursion accidents on take-off allows us to state that accidents with total loss of the aircraft occur for large aircraft, caused by bad weather conditions. This result is consistent with the study by Mazon *et al.* (2018). On the other hand, accidents that have caused substantial damage to the aircraft are caused by poor runway conditions (wet, contaminated, FOD, etc.) as demonstrated by De Luca *et al.* (2016).

On landing, combination cloud 1 combines seven categories (Middle East and North Africa, general aviation aircraft, domestic non-scheduled passenger, executive or other flight nature, human error and substantial aircraft damages), combination cloud 2 combines eight categories (Asia Pacific, corporate aircraft, unknown or other flight nature, weather conditions, runway conditions, minor aircraft damages and destroyed aircraft), combination cloud 3 combines six categories (North America, Europe, commuter aircraft, aircraft for S-R, domestic scheduled passenger and unknown potential cause) and combination cloud 4 combines eight categories (Africa, Latin America and Caribbean, Commonwealth of Independent States, aircraft for L-R and M-R, cargo, international scheduled passenger and aircraft system faults).

The MCA of runway excursions on landing allows us to state that accidents with total loss of the aircraft occur for small aircraft, caused by bad weather conditions and poor runway conditions.

The results of this study offer important points of discussion regarding the characterization of runway excursion accidents. Simultaneously analyzing the two MCA plots – one relating to take-off and the other to landing – it is possible to conclude the following:

- Generally, the consequences of a runway excursion accident are substantial aircraft damage (D2) and, only rarely, the total destruction of it (D3).
- The most common cause of runway excursion during take-off is aircraft system faults (C1), *which only cause minor damage to the aircraft*; while on landing, it is weather conditions (C3), *which cause greater damage to the aircraft*.
- Human error (C2) is the most common cause of runway excursions in Middle East and North Africa (R7), both during take-off and landing.
- For larger aircraft (A6), the most common cause of runway excursions is weather conditions (C3) during take-off and aircraft system faults (C1) while landing.
- Runway condition (C4) is the most common cause of a runway excursion for corporate aircraft (A2) during both flight phases considered.
- Destruction of the aircraft (D3) is a result of a runway excursion because of bad weather conditions (C3), both during take-off and landing.

Conclusions

Runway excursion accidents constitute a significant percentage of aviation accidents across all aircraft classes and operations and result from a large number of causal and contributing factors that occur individually or (more often) in combination.

In this study, the authors have identified the correspondence between features belonging to different aspects that occur in runway excursion events, distinguishing between take-off and landing phases. The variables taken into consideration are geographical region, potential cause, aircraft class, flight nature and aircraft damages.

The main results of this study show that the consequences of a runway excursion accident are substantial aircraft damage; the potential causes vary according to the class of the aircraft and the geographical region. Runway excursions with total loss of the aircraft are caused by bad weather conditions and poor runway conditions, both during take-off and landing.

The results presented in this paper demonstrate that MCA would be a good option to extract significant knowledge from runway excursion accidents data. The findings of this research will be helpful to aviation safety professionals in determining the hidden risk association group of variables in runway excursion accidents.

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Further reading

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About the authors

Dr Natalia Distefano was born in Catania on October 21,1974. In April 2001, she graduated in Civil Engineering (transportation address) from the Faculty of Engineering of Catania University. In 2006, she received PhD in "Engineering of the Road infrastructures." She won the scholarship for the deepening of the scientific research "Design criteria and safety performance of the urban and road infrastructures" at the Department of Civil and Environmental Engineering of Catania University (June 2006-May 2007). Since February 2008, she is a Research Assistant in the field of "Safety of road, rail, airport, port and intermodal infrastructures." Natalia Distefano is the corresponding author and can be contacted at: ndistefa@dica.unict.it

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