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Analysis of wind data for airport runway design

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Abstract

Purpose: To provide a methodology, and examples of application, for analyzing wind data for the correct orientation of airport runways.

Design/methodology: More than 90000 observed wind data have been analyzed for each one of the three airports used as case studies. Both observed and estimated gusts have been considered.

Findings: If only observed data are considered, each single runway of the three airports used as case studies is correctly oriented. When estimated gusts are considered, the FAA requirements are not satisfied by a single runway in some airports (which anyway satisfy such requirements by using more runways).

Practical implications: The correct orientation of runways minimizes the crosswind components, then increases the safety of the airports.

Originality/value: The paper provides a methodology to evaluate the orientation of existing runways and to design new runways. Such methodology is based on the analysis wind data, considering both observed values and estimated gusts.

Keywords: Wind analysis; wind rose; runway orientation; gusts; wind coverage

1. Introduction

The analysis of wind data is fundamental in many sectors, not only, as obvious, in meteorology and climate, but also in air quality evaluation, architecture, energy production, analysis of outdoor sport performances, agriculture and many others.

Wind is, of course, a possible threat if not adequately considered in some specific fields. One of such fields is the designing of airport runways. Wind perpendicular to the runway (crosswinds) may cause serious accidents, especially during landing and for small airplanes. The analysis of past accidents (van Es, van der Geest & Nieuwpoort, 2001) has demonstrated that the probability of occurrence of an accident increases with increasing crosswind conditions. Statistical evidence, based on historic accident data, shows that the accident risk increases exponentially when operating in conditions with crosswind exceeding 20 knots, including gusts. Tailwind conditions are also important because they are often related to accidents, mainly overrun type of events during landing (van Es & Karwal, 2001).

This manuscript presents a possible way to analyze wind data for application in airport runway design and to evaluate the orientation of existing runways. It is important to note that runway design is a complex task including many aspects, such as determining the best location, avoiding air navigation obstructions, considering environmental implications, avoiding hazards for wildlife, and others. The manuscript is focused on a single important aspect, which is the determination/evaluation of the correct orientation of a runway.

The first part of the paper introduces the theoretical aspects of the problem (methodology): how runway orientation is defined, the definition of the allowable crosswind component, the introduction of the gust factor, etc. Then the materials used for the analysis are presented: the runways of three airports, the wind data and the software tool used to analyze them. Finally the wind data analysis is applied to the three airports and the results are discussed.

2. Methodology

As described by the Federal Aviation Administration (FAA), wind analysis is of fundamental importance for determining runway orientation (FAA, 2012). Ideally a runway should be aligned with the prevailing wind in order to minimize the crosswind components. Adverse wind conditions (i.e., strong crosswinds, tailwinds and wind shear) are involved in a considerable percentage of landing accidents.

2.1 Runway orientations

The runway orientation is indicated by a number between 01 and 36, indicating its heading with respect to the North in sectors of 10 degrees. For example, when landing or taking off on a runway labeled as 09 an aircraft points to East, while on runway 18 it points to South. This definition of the orientation is opposite to the one of wind direction, since a wind direction of 180 degrees indicates a wind blowing from South. If a runway is used in the opposite direction, it is named by adding or subtracting 18 (180 degrees). For example runway 09 becomes runway 27 when used in the opposite direction. Then the runway orientations are often indicated as XX/YY, where the absolute difference between XX and YY is 18 (for example 09/27). From the point of view of the following analysis a runway direction or its opposite do not change the results, the only difference is that headwinds become tailwinds, and crosswinds from left become crosswinds from right (and vice versa). Since only the absolute values of the crosswind is of interest, the runway can be considered with its orientation or with the opposite one. For this reason in the rest of the document headwind and tailwind may be considered interchangeable.

2.2 Allowable Crosswind Component

Each aircraft has a maximum crosswind component derived from flight test experiments. The crosswind component increases with the size of the aircraft, for example it is 33 knots for an Airbus A320 and 17 knots for a Cessna 172.

The FAA (2012) has established an allowable crosswind component (ACC) depending on the Runway Design Code (RDC). The RDC is a string composed by a letter and a Roman numeral; the letter, from A to E, is related to the aircraft approach speed (A low speed, E high speed), while the Roman numeral, from I to VI, is related to the wingspan or tail height (I small size, VI great size). Actually the RDC includes also a third information which is related to visibility, but it is not considered in determining the ACC. The ACC as function of RDC is reported in Table 1. Both the International Civil Aviation Organization (ICAO) and the European Aviation Safety Agency (EASA) establish the ACC as a function of the minimum required take off field length: 10 knots (5.1 m/s) for lengths smaller than 1200 m, 13 knots (6.7 m/s) for lengths smaller than 1500 m, and 20 knots (10.3 m/s) for lengths greater than 1500 m. Both the FAA, EASA and ICAO allowable crosswind component refer to a dry runway surface. When the runway surface is wet with risk of hydroplaning, or covered with slush or snow, the ACC decreases (e.g. ICAO, 2012; EASA, 2011). For example the ICAO and EASA ACC of 20 knots reduces to 13 knots when the runway is characterized by poor braking conditions (EASA, 2011).

Runway Design Code (RDC)	Allowable Crosswind Component
A-I and B-I	10.5 (5.4)
A-II and B-II	13 (6.7)
A-III, B-III, C-I through D-III, D-I through D-III	16 (8.2)
A-IV and B-IV, C-IV through C-VI, D-IV through D-VI	20 (10.3)
E-I through E-VI	20 (10.3)

Table 1. Allowable crosswind component per Runway Design Code in knots (m/s in parenthesis). http://www.faa.gov/airports/engineering/design_standards/ - Accessed 18th January 2014

The ACC may be also defined starting from the analysis of past accidents. For example, one of the final recommendations of van Es et al. (2001), supported by statistical analysis of historical data, is that a crosswind limitation of 15 knots including gusts cannot be relaxed without compromising safety. This threshold of 15 knots (7.7 m/s) is considered as ACC in the following analysis.

2.3 Tailwind Component

Tailwinds increase the required takeoff and landing field lengths, therefore the needed takeoff and landing distances must be corrected for tailwinds. Aircraft flying at low approach speeds are relatively more sensitive to variations in tailwind with respect to landing distance than aircraft flying at high approach speeds. Often the same aircraft has equal tailwind limits for the takeoff and landing operations, but sometimes the limit is different for the two phases.

An analysis of accidents due to tailwinds (van Es & Karwal, 2001) shows that such component contributes mostly to overrun type of events during landing, and its effect is amplified when the runway surface is wet or contaminated. Moreover, many of the accidents happened for tailwinds greater than 10 knots.

2.4 Gusts

Gusts are due to the action of turbulence, they are shorter-acting winds of greater significance for causing damage (Harper, Kepert & Ginger, 2010).

According to the WMO a gust is a rapid fluctuation in wind speed, with "instantaneous" wind speed exceeding by 5 m/s (10 knots) the average wind speed over the period of observation.

The averaging time of wind speed is typically 10 minutes. Winds averaged over shorter periods (e.g. 1 minute) will have a greater variability, some of these short-averages will be smaller than the mean over the longer period, and some will be greater. The highest mean wind observed over each short period within a long period (e.g. 30 averages of 1 minute compared against a single average of 30 minutes) may be regarded as a gust. These gusts can be estimated using a gust factor applied to the mean wind speed (e.g. Davis & Newstein, 1968) as $v_{gust} = \beta * v$, where β is the gust factor and v the mean speed. The gust factor is a theoretical conversion between an estimate of the mean wind speed and the expected highest gust wind speed of a given duration within a stated observation period (Harper et al., 2010).

Therefore, even in hours where a gust has not been observed, a possible gust value can be estimated by means of the gust factor. The following analysis will consider both the actually measured average wind speeds and gusts, and the gusts estimated starting from the average wind speed applying a gust factor.

2.5 Wind rose

The first operation in deciding the orientation of a runway is the preparation of the wind rose. A wind rose is a chart which gives a view of how wind speed and wind direction are distributed at a particular location over a specific period of time. It is a very useful representation because a large quantity of data can be summarized in a single plot. The importance of the information given by wind roses in aircraft flight is known by more than half a century (e.g. Crutcher, 1954). Wind roses for designing runways are composed by 36 wind sectors, each one spanning 10 degrees. Typically each wind sector represents four to six wind speed classes, a higher number of classes is possible, but it might affect the readability of the plot. A possible variant of the wind rose consists in representing for each direction, the average and/or the maximum wind speed, or any percentile of the wind speed along such direction.

2.6 Crosswinds and tailwinds

The concepts of crosswinds and tailwinds are of particular importance in the correct design of runways. Generally a crosswind is any wind that is blowing perpendicular to a specific direction. In aviation a crosswind is the component of wind that is blowing across the runway making a landing more difficult than if the wind were blowing straight down the runway. If a crosswind is strong enough it may exceed an aircraft's crosswind limit and an attempt to land under such conditions could cause an accident. Crosswinds can also occur when travelling on roads, especially on large bridges and highways, which can be dangerous for motorists because of possible lift forces created as well as causing the vehicle to change direction of travel. Crosswinds and tailwinds, or headwinds, are also important during some outdoor sport activities, Pezzoli et al. (2013) for example describe the effects of crosswinds on the sport of rowing.

According to the Federal Aviation Administration (FAA, 2012) a runway orientation must satisfy 95% coverage considering yearly wind conditions. This means that for the 95% of the time, the crosswind component must be smaller than the allowable crosswind component (ACC). When the analysis of wind data shows that the 95% coverage is not satisfied for a runway, an additional runway with different orientation (e.g. perpendicular to the first one) may be present, in order to satisfy the 95% coverage as sum for the two runways. The same criteria is established by the European Aviation Safety Agency (EASA, 2011), which states that the number and orientation of runways should be such that the usability factor would be not less than 95% for the airplanes that the aerodrome is intended to serve. The terms coverage and usability factor must therefore be considered as synonymous.

For each wind speed v the crosswind (v_c) and tailwind (v_t) components are calculated as v_c=v sin(δ) and v_t=v cos(δ) respectively, where δ is the difference between the wind direction and the runway orientation. The signs of v_c and v_t are not considered in this study (i.e. their absolute value is used).

Once the ACC is known, the analysis of the wind data allows to determine the coverage for an existing runway, or to determine the best runway orientation for a given site during the design of an airport. In order to determine the best orientation of a future runway, the calculations must be carried out for "all" its possible directions (for example starting from 0 degrees – North – and increasing by steps of 10 degrees).

For airports working only in particular seasons or in particular hours of the day, only the wind data collected during such seasons or such hours must be considered during the analysis.

3. Material

3.1 Wind data

Three airports have been considered for exemplifying the analysis of wind data. The first airport is the Catania Fontanarossa international airport (Sicily, Italy – ICAO code LICC), with a runway oriented 08/26, and a length of about 2.4 km (Wikipedia, 2014a). The airport is located at latitude 37.47N and longitude 15.07E, to the West of the sea, which is very close (less than 1 km).

The other two airports are both located in Spain, they are the Barcelona airport (ICAO code LEBL) and the Valencia airport (ICAO code LEVC). The Barcelona airport (41.33N, 2.06E), one of the most important airports in Spain, is located at about 10 km SW from the city, on the sea side. It has three runways, two of them are parallel and oriented 07/25, one has a length of about 3.7 km, and the other one has a length of about 2.7 km. The third runway is oriented 02/20 and has a length of about 2.5 km (Wikipedia, 2014b).

The Valencia airport (39.49N, 0.48W) is located at about 8 km NW from the city. It has two runways, the main one is oriented 12/30 and has a length of about 3.2 km, while the second one is oriented 04/22 and has a length of about 1.1 km (Wikipedia, 2014c).

An aerial view of the three airports, which shows the orientations of their runways, is shown in Figure 1.

Figure 1. Aerial view of the three airports: Catania (left), Barcelona (center) and Valencia (right). Google Earth

3.2 Meteorological data

The METAR (Meteorological Aerodrome Report) data of three airports for the period 2008-2012 (5 years) were collected with a half hour time resolution (i.e. more than 90000 records for each site). It is observed that this choice agrees with the EASA requirements (EASA, 2011), which states that a minimum of five years must be used with at least eight observations each day (while 48 daily observations were used in this study).

The METAR data contain information about average wind speed and direction, gusts, temperature, visibility, cloud cover and others.

The average wind speed in the METAR reports is measured over a ten-minute period. Gusts are determined using a 3 seconds moving average window, and are included in the reports when their value exceeds the 10-minutes average value by at least 10 knots, as described in paragraph 2.4.

Each alphanumeric string of the METAR data has been decoded and analyzed in order to extract the wind direction, wind speed and gust values.

3.3 The tool

The analysis of the wind data and the graphical representations have been obtained by means of the WindRose PRO3 software (Enviroware, 2013). The software allows to load wind data in many formats, among which notable meteorological formats (Typical Meteorological Year TMY2 and TMY3, compressed WBAN hourly surface observations TD-1440, NOAA Integrated Surface

Hourly files), air quality models formats (AERMOD, ISC3ST, CALMET 5.8 and CALMET 6), Microsoft Excel files or ASCII files with fields separated by specific delimiters. A time filter option allows to analyze the data and produce wind roses only for particular years, months, days of the week or hours. It is also possible to produce wind roses only for day or night hours, which are determined by the software itself starting from the geographical position and the time zone of the meteorological station. The numerical results of the data analysis can be exported in a Microsoft Excel file which contains a different number of worksheets depending on the types of analysis carried out. Some charts (typical day, data distribution, exceeding frequencies and others) are automatically created by the software within the Excel file.

4. Results

4.1 Analysis based on actual (observed) data

The wind roses of the three airports for the period 2008-2012 are illustrated in Figure 2. They include both measured average speeds and gusts.

The prevailing wind direction of the Catania airport (Figure 2, top) is 240 degree, followed by 250 degree, then the most frequent winds blow from WSW. Winds come almost always from the arcs SW-W and NE-E, therefore they are roughly aligned along an imaginary axis going from WSW to ENE, which is approximately the runway orientation.

The wind rose of the Barcelona airport (Figure 2, center) shows that winds are not aligned along a single axis. The prevailing directions are respectively 330 and 340 degrees (NNW). However, in some hours of the day also the winds from SW (220 degrees) are frequent. The temporal analysis of the data has shown, in fact, that winds from NNW are frequent during the night and the morning, while winds from SW are frequent during the afternoon. As an example, Figure 3 illustrates the average hourly wind direction distribution during the five years analyzed. The horizontal axis reports the hours of the day, while the vertical axis reports the percentage of occurrence of a specific direction. It is observed, for example, that the wind directions from 320, 330, 340 and 350 degrees are very frequent during the night and the morning.

The most frequent winds of the Valencia airport come from 270 degree (Figure 2, bottom). Winds blow essentially from two arcs: from WSW to NNW (about 48% of the data), and from NE to SE (about 31% of the data). Representations such as the one shown in Figure 3 for Barcelona, show that the winds of the first arc are very frequent during the night and the morning.

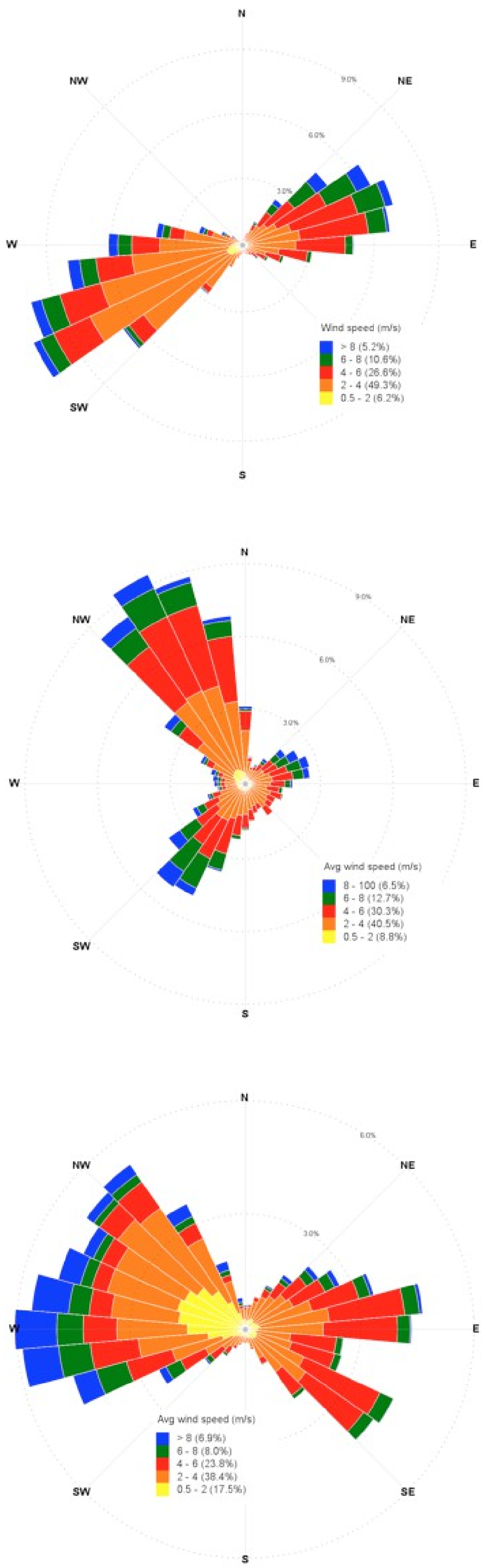

Figure 2. Wind roses 2008-2012 for the airports of Catania (top), Barcelona (center) and Valencia (bottom).

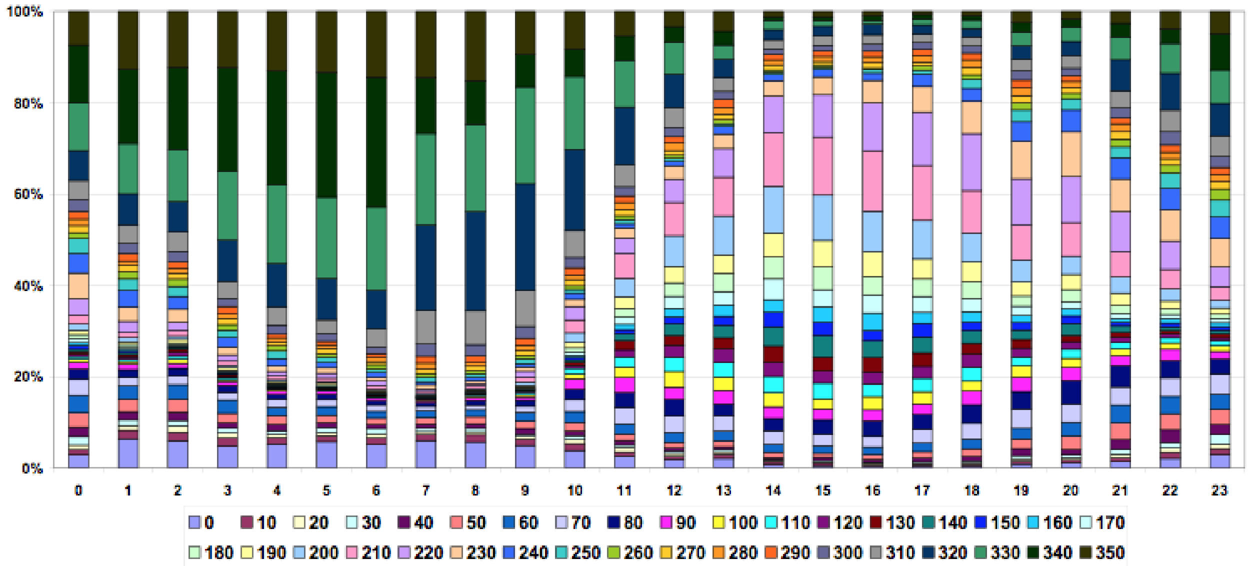

Figure 3. Average hourly wind direction distribution (2008-2012) for the Barcelona airport

The distribution of the absolute values of crosswind and tailwind are reported in Figure 4 (respectively top and bottom part of the figure). Absolute values means that crosswind from left and from right is considered in the same way, and the same is true for headwind and tailwind. The crosswind distribution plot helps to estimate graphically the wind coverage once the ACC of the runway has been defined. Similarly, the plot of tailwinds distributions allows to estimate how frequently the threshold of 10 knots (see paragraph 2.3), or 5.1 m/s, is exceeded. In this case study the wind coverage, crosswinds and tailwinds have been exactly calculated by the software using the observed average wind speeds and gusts, and considering an ACC of 7.7 m/s (15 knots). The calculated wind coverage values are reported in Table 2 for all the runways of the three airports. The highest wind coverage is obtained for the Catania airport (LICC), and this result was expected due to the shape of the wind rose, which does not show important wind components perpendicular to the runway. Also the runways of the Barcelona airport (LEBL) have a wind coverage higher than the 95% established by the FAA. Concerning the Valencia airport (LEVC), one of the two runways (12/20) has a wind coverage greater than 98%, while the other one has a wind coverage exactly equal to 96%.

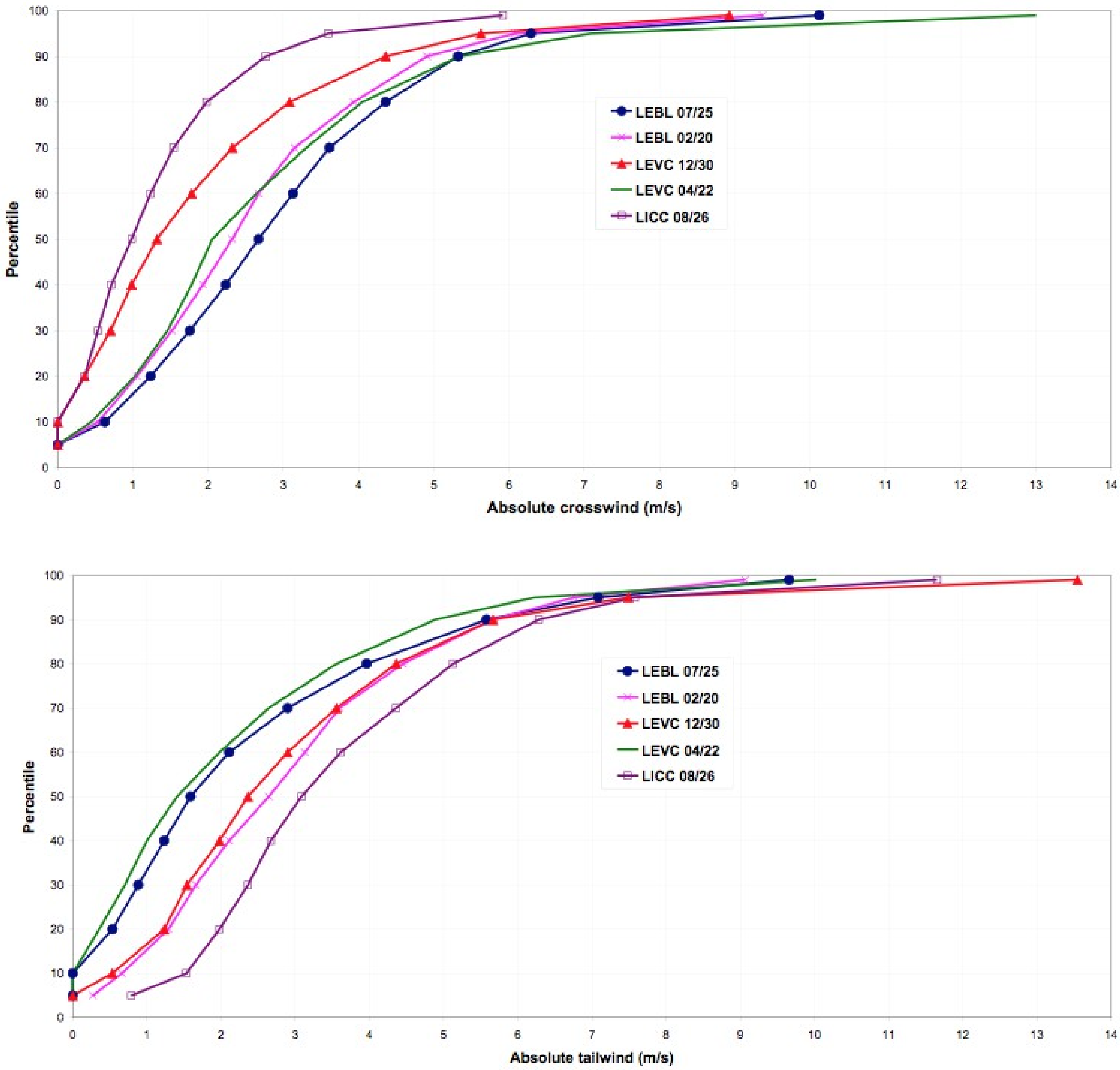

Figure 4. Distribution of the absolute values of crosswinds and tailwinds for the three airports during the period 2008-2012

Runway	Coverage
LICC 08/26	99.5
LEBL 07/25	97.6
LEBL 02/20	97.7
LEVC 12/30	98.3
LEVC 04/22	96.0

Table 2. Wind coverage for the runways of the three airports

So far the impact of wind on the existing runways has been analyzed. But during the design phase of an airport, when the runways are not yet present, it is necessary to determine the best runway orientation in order to get the maximum wind coverage. Therefore different hypothetical orientations of the runways have been investigated, starting from 0 degree with steps of 10 degrees. The results of the analysis are reported in Table 3, Table 4 and Table 5, respectively for the airports of Catania, Barcelona and Valencia. For each possible runway orientation the tables report wind coverage, average (AAC), median (MAC) and 99 percentile (P99AC) of the absolute values of crosswinds, and average (AAT), median (MAT) and 99 percentile (P99AT) of the absolute values of tailwind. The FAA states that in designing runway orientation, the most desirable runway is one that has the largest wind coverage and minimum crosswind components. Table 3 shows that the optimal runway directions for the Catania airport are respectively 07/25 and 08/26 (which is the actual runway direction). On the other hand such directions are characterized by tailwinds greater than 10 knots (5.1 m/s) for about 20% of the time (e.g. Figure 4 bottom for 08/26), therefore they may pose the risk of overrun accidents if not adequately faced.

Table 4 shows that for the Barcelona airport the highest wind coverage (98.0%) corresponds to a runway direction 09/27, however the average and median crosswind components for this direction are a bit higher than those calculated for the actual runway orientations of the airport (02/20 and 07/25), which are also characterized by a high wind coverage.

Table 5 shows that for the Valencia airport the best runway orientation would be 10/28, which is characterized by a 98.9% wind coverage and by small values of crosswind. It is observed that the shorter runway, oriented 04/22, has a wind coverage equal to 96%, but such runway might be used by small aircrafts with a smaller ACC value (therefore the actual coverage might be lower than 96%). Runway orientations 00/18, 01/19, 02/20 and 17/35 must be avoided, or not used alone, since they have a wind coverage lower than 95%.

All the analysis have been carried out under the hypothesis that the airports work during the whole year and for all the hours of the day. For airports operating only in particular hours of the day, or months of the year, the wind data must be filtered according to date and time.

Orientation	Wind Cov. (%)	AAC (m/s)	MAC (m/s)	P99AC (m/s)	AAT (m/s)	MAT (m/s)	P99AT (m/s)
00/18	96.2	3.5	3.0	11.6	1.5	1.2	6.7
01/19	97.0	3.3	2.8	11.1	1.9	1.6	7.6
02/20	97.6	2.9	2.5	10.6	2.3	2.0	8.5
03/21	98.1	2.5	2.1	9.6	2.7	2.3	9.6
04/22	98.6	2.1	1.8	8.6	3.1	2.6	10.3
05/23	99.0	1.6	1.3	7.6	3.4	2.9	11.1
06/24	99.4	1.3	1.0	6.7	3.6	3.0	11.6
07/25	99.5	1.2	0.9	5.9	3.6	3.1	11.7
08/26	99.5	1.3	1.0	5.9	3.6	3.1	11.7
09/27	99.4	1.5	1.2	6.7	3.5	3.0	11.6
10/28	99.1	1.9	1.6	7.6	3.3	2.8	11.1
11/29	98.5	2.3	2.0	8.5	2.9	2.5	10.6
12/30	97.7	2.7	2.3	9.6	2.5	2.1	9.6
13/31	96.7	3.1	2.6	10.3	2.1	1.8	8.6
14/32	95.9	3.4	2.9	11.1	1.6	1.3	7.6
15/33	95.3	3.6	3.0	11.6	1.3	1.0	6.7
16/34	95.2	3.6	3.1	11.7	1.2	0.9	5.9
17/35	95.5	3.6	3.1	11.7	1.3	1.0	5.9

Table 3. Catania airport. Statistics calculated for each possible runway direction

Orientation	Wind Cov. (%)	AAC (m/s)	MAC (m/s)	P99AC (m/s)	AAT (m/s)	MAT (m/s)	P99AT (m/s)
00/18	97.6	2.5	2.0	9.2	3.0	2.8	9.1
01/19	97.6	2.6	2.1	9.1	3.0	2.8	8.7
02/20	97.7	2.6	2.3	9.4	2.9	2.6	9.1
03/21	97.6	2.6	2.3	9.8	2.8	2.4	9.3
04/22	97.5	2.7	2.4	10.2	2.7	2.1	9.6
05/23	97.5	2.8	2.4	10.3	2.5	1.8	9.8
06/24	97.4	2.8	2.6	10.3	2.4	1.6	9.8
07/25	97.6	2.9	2.7	10.1	2.3	1.6	9.7
08/26	97.9	3.0	2.8	9.6	2.4	1.8	9.6
09/27	98.0	3.0	2.8	9.1	2.5	2.0	9.2
10/28	97.8	3.0	2.8	8.7	2.6	2.1	9.1
11/29	97.3	2.9	2.6	9.1	2.6	2.3	9.4
12/30	96.7	2.8	2.4	9.3	2.6	2.3	9.8
13/31	96.3	2.7	2.1	9.6	2.7	2.4	10.2
14/32	96.2	2.5	1.8	9.8	2.8	2.4	10.3
15/33	96.3	2.4	1.6	9.8	2.8	2.6	10.3
16/34	96.7	2.3	1.6	9.7	2.9	2.7	10.1
17/35	97.2	2.4	1.8	9.6	3.0	2.8	9.6

Table 4. Barcelona airport. Statistics calculated for each possible runway direction

Orientation	Wind Cov. (%)	AAC (m/s)	MAC (m/s)	P99AC (m/s)	AAT (m/s)	MAT (m/s)	P99AT (m/s)
00/18	94.4	3.1	2.5	14.3	1.6	1.3	8.2
01/19	94.5	3.2	2.5	14.4	1.6	1.3	7.9
02/20	94.9	3.1	2.5	14.0	1.7	1.3	8.1
03/21	95.4	3.0	2.4	13.5	1.9	1.3	8.9
04/22	96.0	2.8	2.1	13.0	2.1	1.4	10.0
05/23	96.7	2.5	2.0	12.0	2.3	1.6	11.4
06/24	97.4	2.2	1.6	10.8	2.6	1.9	12.6
07/25	98.0	1.9	1.5	9.8	2.8	2.1	13.4
08/26	98.5	1.7	1.3	8.9	3.0	2.4	14.0
09/27	98.8	1.6	1.3	8.2	3.1	2.5	14.3
10/28	98.9	1.6	1.3	7.9	3.2	2.5	14.4
11/29	98.8	1.7	1.3	8.1	3.1	2.5	14.0
12/30	98.3	1.9	1.3	8.9	3.0	2.4	13.5
13/31	97.5	2.1	1.4	10.0	2.8	2.1	13.0
14/32	96.6	2.3	1.6	11.4	2.5	2.0	12.0
15/33	95.7	2.6	1.9	12.6	2.2	1.6	10.8
16/34	95.0	2.8	2.1	13.4	1.9	1.5	9.8
17/35	94.5	3.0	2.4	14.0	1.7	1.3	8.9

Table 5. Valencia airport. Statistics calculated for each possible runway direction

4.2 Analysis based on estimated gusts

The analysis of wind data for runway orientation must include both average speeds and gusts, but gusts are not always available in observed data. However, as described in paragraph 2.4, gusts can be estimated by multiplying the average wind speed and a "gust factor" coefficient. The value of such coefficient depends from many factors, for example the land cover and the time duration of the gust itself. Harper et al. (2010) propose some values for the gust factor coefficients in different situations, but such values are applicable during tropical cyclone conditions, and cannot be used in this study. Van Es et al. (2001) state that for an airport the gust factor is typically about 1.3-1.6 at a height of 10 meters, and as a rule-of-thumb a gust factor of 1.5 can be used.

Since a relatively long period of data is available in this study, a suitable value for the gust factor can be estimated by analyzing the gusts and the associated average wind speeds measured at the three airports during the period 2008-2012. Some statistics for the ratios between gusts and associated average wind speeds are reported in Table 6. It is observed that the maximum value of the ratios is very high, particularly for the Catania airport, however the 99th percentiles of the distributions show that such high values are outliers which can be neglected (and the graphical observation of the data supports such conclusion). Theoretically a different gust factor should be applied to each site, but since the average value of the ratios is very similar in the three airports (approximately between 1.8 and 2.1), a unique value of 1.9, which falls within such interval, is used. It is observed that such value belongs also to the interval defined by the minimum and maximum values of the median (50^{th} percentile). Table 6 indicates that for sure the gust factor cannot be smaller than 1.3.

Therefore, considering only the measured average wind speed (without the measured gusts), the potential values of the gusts have been estimated applying a gust factor. The values of the crosswinds have been calculated by using the estimated gusts in order to evaluate a more restrictive scenario with respect to the one presented in the previous paragraph.

Statistics	**LICC**	**LEBL**	**LEVC**
Number of data	940	1873	1887
Minimum	1.30	1.31	1.31
Average	1.81	2.14	1.84
Standard deviation	0.94	0.59	0.70
Median	1.66	2.09	1.63
Percentile 99	3.8	3.8	5.3
Maximum	25.4	16.5	10.7

Table 6. Statistics of the ratios between gusts and corresponding average wind speeds for the three airports

It is observed that the potential gust values could be also estimated by means of other approaches. For example, by assuming a linear relation between gusts and average wind speeds (i.e. y = a*x + b, where y = gust, x = average wind speed, and a and b are the coefficients), the analysis of the data of the three airports gives the results shown in Table 7. Then, for all the three airports, the slope (a) of the equation is a bit greater than 1, while the intercept (b) is greater than 5.

However, the results shown in the rest of the paragraph have been obtained by means of a gust factor β equal to 1.5 (the "rule of thumb" value suggested by van Es et al., 2001) and also with a gust factor equal to 1.9, as obtained from the analysis of wind data.

	LICC	**LEBL**	**LEVC**
a	1.087	1.031	1.071
b	5.213	5.584	5.261
R2	0.898	0.901	0.934

Table 7. Coefficients estimated for the linear relation between gusts and mean speed for the three airports

The impact of possible (estimated) gusts on the existing runways has been summarized in Table 8 by means of the wind coverage values. In this situation only the runway of the Catania airport has a wind coverage higher than 95%, both with a gust factor equal 1.5 and 1.9. The directions of wind data measured at such airport are often aligned along the runway, and the wind speeds are rarely high, this explains why the wind coverage remains high also estimating possible gust values. On the contrary the wind roses of the Barcelona and Valencia airports (Figure 2) show directions which are strongly variable during the day. For this reason the effect of possible gusts is more drastic and results in a sensible reduction of the wind coverage. In any case, the two Spanish airports considered in the case study have two runways (actually Barcelona has three runways, but two have the same orientation), and they are such that the sum of their wind coverage satisfies the 95% criteria established by the FAA.

	β = 1.5	**β = 1.9**
Runway	**Coverage (%)**	**Coverage (%)**
LICC 08/26	98.9	97.1
LEBL 07/25	90.0	78.2
LEBL 02/20	93.0	85.0
LEVC 12/30	88.6	79.3
LEVC 04/22	87.4	76.0

Table 8. Wind coverage for the runways of the three airports using estimated gust values

A final analysis has been carried out with the estimated gusts to evaluate if a better runway orientation is possible for the three airports. The results of such analysis in terms of wind coverage are reported in Table 9 (values greater than 95% are in bold). For the Catania airport the wind coverage of the actual runway orientation (08/26) is exceeded only by orientation 07/25, anyway the differences between the wind coverage values are small. The results for the Barcelona airport show that a single runway with a wind coverage greater than 95% does not exist. Anyway one of the two existing runway directions (02/20) is characterized by the highest coverage value when β=1.5, and by the second highest when β=1.9. Together with the other existing runway direction (07/25) the 95% criteria is satisfied. Concerning the Valencia airport, when β=1.5 all the directions from 07/25 to 12/30 are characterized by a coverage greater than 95% (and 12/30 is the direction of one of the airport's runways). When gusts are estimated using β=1.9, the only single direction with a coverage greater than 95% is 09/27.

Orientation	LICC β=1.5	LICC β=1.9	LEBL β=1.5	LEBL β=1.9	LEVC β=1.5	LEVC β=1.9
00/18	83.1	69.9	91.3	84.5	86.6	76.2
01/19	86.6	73.7	92.5	85.1	86.7	76.1
02/20	90.5	79.5	93.0	85.0	87.4	77.2
03/21	93.9	86.0	92.6	84.1	88.6	79.3
04/22	**96.2**	91.3	91.9	83.0	90.5	82.1
05/23	**97.7**	94.8	91.0	81.7	92.2	85.4
06/24	**98.5**	**96.9**	90.6	80.4	94.2	88.7
07/25	**99.0**	**97.6**	90.0	78.2	**96.0**	91.7
08/26	**98.9**	**97.1**	89.1	76.4	**97.3**	94.3
09/27	**98.1**	**95.2**	88.5	75.9	**97.8**	**95.6**
10/28	**96.4**	91.9	88.1	76.7	**97.7**	94.9
11/29	93.8	87.7	87.8	78.2	**96.8**	93.0
12/30	90.6	82.8	87.5	79.5	**95.2**	90.3
13/31	87.2	77.7	87.0	80.4	93.0	87.4
14/32	84.2	73.4	86.7	80.6	91.0	84.1
15/33	81.9	70.0	87.2	81.0	89.0	81.4
16/34	80.7	68.2	88.2	81.9	87.6	79.2
17/35	81.1	68.1	89.7	83.2	86.9	77.3

Table 9. Wind coverage estimated for each possible runway direction at the three airports

5. Conclusions

The analysis of wind data is of fundamental importance to design new runways and to evaluate the orientation of existing runways. As demonstrated by the analysis of past accidents, both crosswinds and tailwinds have adverse effects during landing and takeoff operations. These two wind components (crosswinds and tailwinds) must be determined considering both mean wind speed and gusts.

Indeed gusty wind is the most important contributing factor in crosswind-related accidents. The strength of the gustiness depends mainly on the total wind, and this can also be evinced from the linear relation coefficients reported in Table 7.

The Federal Aviation Administration and the European Aviation Safety Agency have established that a runway orientation must satisfy 95% wind coverage (or usability factor) considering yearly wind conditions. This means that for the 95% of the time, the crosswind component must be smaller than the allowable crosswind component. When the analysis of wind data shows that the 95% coverage is not satisfied for a runway, an additional runway with different orientation may be present, in order to satisfy the 95% coverage as sum for the two runways. The allowable crosswind component depends on the runway features, including of course the aircraft operating on it. Anyway, the statistical analysis of historical data has shown that a crosswind limitation of 15 knots (7.7 m/s) including gusts cannot be relaxed without compromising safety. Considering dry runway conditions, this value has been used for the analysis of wind data of three airports used as case studies. The probability of a crosswind related accident during landing or takeoff on a wet or contaminated runway is higher than on a dry runway.

Two different analysis have been carried out. The first one considering only measured wind data, including average wind speeds and gusts. In the second one possible peak gusts have been estimated from mean wind speed data by applying the gust factor approach, using a "typical" gust factor equal to 1.5, and a gust factor estimated from the wind data used in the study, equal to 1.9.

Five years of METAR data from the Catania airport (Italy) and the Barcelona and Valencia airports (Spain) have been analyzed. Crosswinds and tailwinds have been calculated for each measured data and their maximum values have been determined, together with their statistical distributions.

The results of the analysis show that the unique runway of the Catania airport is correctly oriented, since its coverage exceeds the 95% threshold value even under the most conservative conditions considered in the study. The wind coverage of each runway of the Barcelona and Valencia airports are greater than 95% when the analysis is carried out using the observed mean wind speeds and gusts. On the contrary, when the analysis is carried out under the most conservative conditions by estimating the gust values, no one of these runways presents a coverage greater than 95%. However, as established by the FAA, the wind coverage criteria of the two Spanish airports considered in this study is satisfied by considering the sum of the coverage of each runway.

This study has shown a possible methodology to evaluate the orientation of existing runways and to establish the correct orientation of new runways during the design phase. The proposed methodology differs from the existing ones in many aspects. For example the FAA methodology is mainly graphical and uses wind direction and wind speed data organized in tables (i.e. number of events for each range of wind speed and wind direction) not in hourly or sub-hourly records. Also the FAA computerized wind analysis (FAA, 2014) is based on joint frequency tables of wind speed and wind direction.

The methodology proposed in this paper uses both average wind data and gusts measured with arbitrary time resolution (30 minutes in the examples discussed above). At each measuring time crosswind and tailwind are calculated, therefore at the end of the procedure a distribution of these variables is available and many statistics can be extracted (e.g. mode, median, percentiles, etc.). Moreover, the proposed methodology allows to estimate possible gusts when they are not measured, making the calculations more conservative. Finally, for future airport locations, the proposed methodology automates the calculations for all the possible runway orientations. The output tables allow to select the orientation characterized by the greatest coverage and the minimum crosswind component. The correct application of the results of the wind data analysis will add safety and utility to the airports.

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