Orientations Optimization for two Runway Configurations

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Abstract: The runway orientation is the result of compromises between the airport usability and additional factors, such as available land, existing obstructions, topographic difficulties, flight path interference, noise pollution and other environmental impacts. Therefore, the solution of a combination of acceptable orientations, which avoids excessive crosswinds at least 95% of the time, as well as the optimal orientation, is essential to conduct those compromises in the runway orientation analysis. The objective of this paper is to develop a computer model which is capable of providing a combination of acceptable runway orientations, changing the allowable crosswind limit flexibly, and determining the optimal orientations of two runway configurations. Instead of visual estimation or geometric computation, this paper presents an analytical method for wind coverage analysis, which is running in spreadsheet and VBA. The numerical example and comparison show that the model is competitively accurate and improved convenient in comparison with previous ones.

Keywords: Airport Planning and Design; Wind Rose; Runway Orientation; Spreadsheet VBA; Environmental Impact; GIS Obstructions.

1. INTRODUCTION

The most basic and fundamental design features of an airport are its runway orientation and configuration. The runway orientation is the aircraft operating direction related to true north. The runway configuration is the length, width, number and layout of runways. The runway orientation and configuration must be suitable for the size and shape of available land, satisfying the capacity requirement, safely avoiding existing obstructions, and minimizing environmental impacts to residential areas. Most importantly, they must satisfy the operational requirements of aircraft for landing and takeoff. A major factor influencing the orientation, number, width and layout of runways is wind coverage (Airport Usability). The actual runway orientation is the result of compromises between the airport usability and additional factors, such as available land, existing obstructions, topographic difficulties, flight path interference among runways and airports, noise pollution and other environmental impacts. Therefore, the solution of a combination of acceptable runway orientations, which avoids excessive crosswinds at least 95% of the time, as well as the optimal orientation solution, is essential to conduct those compromises in the runway orientation analysis.

Due to the obvious advantages of landing and taking off into the wind, runways are oriented in the direction of prevailing winds. Aircraft may not maneuver safely on a runway when the crosswind speed (i.e. wind speed component perpendicular to the runway orientation) exceeds a specified allowable limit. The point at which this component (called the crosswind) becomes excessive depends upon the size and operating characteristics of the aircraft. Specific magnitudes of crosswinds may exist that could constrain aircraft takeoffs and landings. In the runway orientation analysis, determining allowable crosswind is critical, and is the basis of the airport reference code (ARC). In the FAA standards, the allowable crosswind is based on the operational and physical characteristics of the airplane types, and to a lesser extent on runway width. For the ICAO standards, the allowable crosswind is based entirely on the airport reference field length (Ashford *et al.*, 2011). The FAA and ICAO allowable crosswinds are compared in Table 1. In terms of flexibility of runway orientations analysis, the magnitude of allowable crosswind limit must be a changeable variable for all types of ARC.

Table 1. FAA and ICAO Allowable Crosswind Components

FAA		ICAO	
Airport reference code	Runway width (ft)	Allowable crosswind component (kt/Km/h)	Reference field length (Meter)
A-I and B-I	<75	10.5/19	<1200
A-II and B-II	75-100	13.0/24	1200-1499
A-III, B-III, &C-1 through D-III	100-150	16.0	
A-IV through D-VI	>150	20.0/37	1500 or more

Adapted and Combined from Ashford *et al.* (2011) and ICAO (2004)

Standards of the ICAO and the FAA agree that runways should be oriented so that the usability factor of the airport is not less than 95%. The usability factor is the percentage of time during which the use of the runway system is not restricted because of an excessive crosswind (ICAO, 2006). Where a single runway or set of parallel runways cannot be oriented to provide a usability factor of at least 95%, one or more crosswind runways is recommended (FAA, 2012). Consequently, a model which is capable of analyzing two runway orientations is needed.

Many methods and models have been studied or developed to facilitate the runway orientation analysis. Although some of them provide one or more functions as mentioned above, none of them is capable of fully analyzing the runway orientations, as indicated in Table 2. The objective of this paper is to develop a computer model which is capable of simultaneously providing a combination of acceptable runway orientations, changing the allowable crosswind limit flexibly, and determining the optimal orientations of two runway configurations in an airport.

2. LITERATURE REVIEW AND METHODOLOGY

Since aircraft operate safely in the direction of prevailing headwinds and limited by crosswind components, a method is required to determine the orientation of the proposed runway which will minimize the probability of certain critical crosswinds. Many methods have been developed over years. Conventionally, the orientation of the runway or runways at an airport was determined through graphical vector analysis, called the Wind Rose method. A standard wind rose consists of a series of concentric circles cut by radial lines using polar coordinate graph paper. The radial lines are drawn to the scale of the wind magnitude such that the sector between each pair of successive lines is centered on the wind direction. On a template, three equally spaced parallel lines have been plotted. The middle line represents the runway centerline, and the distance between the centerline and each outside line is, to scale, the allowable crosswind limit (in this case, 13 Knots/h). The template is placed over the wind rose in such a manner that the centerline on the template passes through the center of the wind rose (Figure 1). Optimum directions can be determined from this wind rose by rotating the template, trial and error, until the sum of the percentages included between the outer lines is a maximum (Horonjeff *et al.*, 2010). When one of the outer lines on the template divides a sector of wind direction and magnitude (like the shaded area between 35°-45° and 17-21 Knots in Figure 1), the partially covered sector is estimated visually. Some of very small percentages which are marked as a plus (+) symbols are also estimated manually. Through intensively manually repeating processes, the method is capable of determining a combination of acceptable runway orientations for single runway or two-runway configurations. The procedures of trial and error and visual estimation make the accuracy questionable.

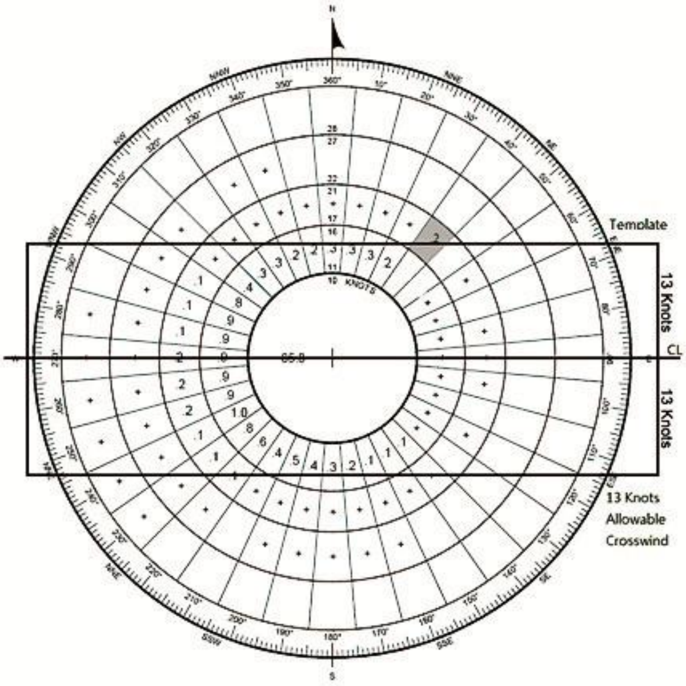


Figure 1. Wind Rose and Template (Edited from FAA, 2012)

Mousa *et al.* (2000) present a computer model, named WNDROS, for optimizing the runway orientation based on given wind data and allowable crosswind limit. The model is based on a mathematical formulation, which transfers circles and radial lines of the wind rose method into points with numeric coordinates. They develop the FORTRAN 77 programs to calculate the adjustment factor for the ratios between the full or partially covered sectors, which generate from wind rose and template intersecting. In their model, the geometrics computation of partially covered sectors provides accurate solutions rather than the visual estimation of the Wind Rose method. However, the method requires intensive geometric computations and is not flexible with respect to the standard wind data format in which FAA recommend 10 degrees increments in directions. The model is only able to solve the optimization of single runway orientation. Mousa (2001) presents an integrated computer model (WNDROS2) for optimizing runway orientation at airports having two-runway configurations. This research is also to develop a computer program with FORTRAN to upgrade the WINDROS Model. The model makes much improvement over the Wind Rose Model. In the model, the number of primary and crosswind runways is limited. The optimization is limited in only ten priority cases which are the combinations of the predefined primary and crosswind runways. As mentioned in his paper, the future efforts include conversion of the FORTRAN code into Visual Basic to enhance model capability. Mousa (2002) presents a VB-WNDROS model by converting WNDROS2 program code into Visual Basic language. The method is still based on the previous WNDROS2 model.

Jia, *et al.* (2004) present a Geographic Information System (GIS) based system called Airport Runway Optimization (ARO) that determines the best runway orientation for the effective layout of airport facilities. The method uses customized GIS technology and spatial database management tools to optimize the runway orientation based on given wind data and allowable crosswinds. It considers a wind rose as a GIS database in which each cell is handled as an independent polygon. While rotating the runway template around the wind rose, the model extracts the sectors (cells) and calculates the total wind coverage. The ARO system significantly improves the previous model of using ''trial and error'' and computation intensive methods for the optimization of runway orientation. As indicated in the paper, the ARO system only provides the best and second best orientation options for single runway.

The FAA developed a wind analysis computer programs to help users determine the orientation of runways (FAA, 2000). The program provides a spreadsheet for the calculation of the percentage of wind coverage given inputs of wind data and runway direction specified by the user. The program is useful for automating the optimization process of runway orientation. The program is available on the FAA Airport Surveying-GIS Program website: https://airports-gis.faa.gov/public/index.html (FAA, 2012). This program is capable of calculating wind coverage precisely, optimizing the orientation of two-runway configurations and solving the VMC, IMC or All Weather wind coverage separately. When solving the wind coverage in this program, the runway directions have to be preset. After manually presetting and solving all the runway orientations one by one, the optimum orientation can be terminated. The same method may be repeated for each combination of the first and second runway until the combined wind coverage reaches the requirement of usability factor.

Table 2. Features comparison among the proposed model and previous works

	Solving Partially Covered Sectors	Standard wind data format	Combination of Acceptable Orientations	Two-runway Orientations
Wind Rose	Visual Estimation	Yes		Yes
Mouse 2000	Geometric Computation		Yes	
Mouse 2001	Geometric Computation		Yes	Yes
Mouse 2002	Geometric Computation		Yes	Yes
Jia 2004	GIS Functions	Yes	Yes	
FAA model	Geometric/Spreadsheet	Yes	Manual	Manual
Proposed Model	Analytical Method	Yes	Yes	Yes

The Wind Rose method, an approximate graphical tool, was developed in the early era of airport design, when the computer modeling was not available. It is not necessary to use today's computers with fast and precise calculation capability to solve the approximate geometrical problems of partially covered sections. Instead, this paper presents an analytical method for wind coverage analysis. The probability of coverage is presented as what-if equations with trigonometric functions and solved in a spreadsheet. With the input of standard wind data format and any allowable crosswind limit, the proposed model solves the optimal orientations and simultaneously provides a combination of acceptable runway orientations for two runway configurations. Table 2 shows the features comparison among the proposed model and previous works.

3. The DESIGN AND FEATURES OF THE MODEL

Runway Orientation Optimization: Wind Data Form

New Wind | Use | Upload Data File | Save Data File

File Name: Crosswind Component: 13 | Calculate

	Hourly Observations of Wind Speed (knots)								
Direction	0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>41	Total
10°	469	842	568	212						2091
20°	568	1263	820	169						2820
30°	294	775	519	73	9					1670
40°	317	872	509	62	11					1771
50°	268	861	437	106						1672
60°	357	534	151	42	8					1092
70°	369	403	273	84	36	10				1175
80°	158	261	138	69	73	52	41	22		814
90°	167	352	176	128	68	59	21			971
100°	119	303	127	180	98	41	9			877
110°	323	586	268	312	111	23	28			1651
120°	618	1397	624	779	271	69	21			3779
130°	472	1375	674	531	452	67				3571
140°	647	1377	574	281	129					3008
150°	338	1093	348	135	27					1941
160°	560	1399	523	121	19					2622
170°	587	883	469	128	12					2079
180°	1046	1984	1068	297	83	18				4496
190°	499	793	586	241	92					2211
200°	371	946	615	243	64					2239
210°	340	732	528	323	147	8				2078
220°	479	768	603	231	115	38	19			2253
230°	187	1008	915	413	192					2715
240°	458	943	800	453	96	11	18			2779
250°	351	899	752	297	102	21	9			2431
260°	368	731	379	208	53					1739
270°	411	748	469	232	118	19				1997
280°	191	554	276	287	118					1426
290°	271	642	548	479	143	17				2100
300°	379	873	526	543	208	34				2563
310°	299	643	597	618	222	19				2398
320°	397	852	521	559	158	23				2510
330°	236	721	324	238	48					1567
340°	280	916	845	307	24					2372
350°	252	931	918	487	23					2611
360°	501	1568	1381	569	27					4046
Calm	7729									7729
TOTAL	21676	31828	19849	10437	3357	529	166	22	0	87864

Figure 2. Wind Data Form in the Model

A record which covers the latest 10 consecutive years of wind observations is recommended by FAA. The wind data for the airport site should be formatted with the standard 36 wind sectors (the National Climate Dada Center, NCDC, standard for noting wind directions) and usual speed groupings (FAA, 2012). Figure 2 shows the standard hourly wind observations input of the proposed model. Each sector is represented as a cell in spreadsheet, with directions in row and speed groupings in column. The functions of uploading, downloading, saving wind data are designed for user friendliness. The allowable crosswind limit is a changeable variable for meeting all types of ARC. With the powerful array calculation capability of the spreadsheet, the recorded directions and speed groupings of wind observations are converted to percentages of total observations.

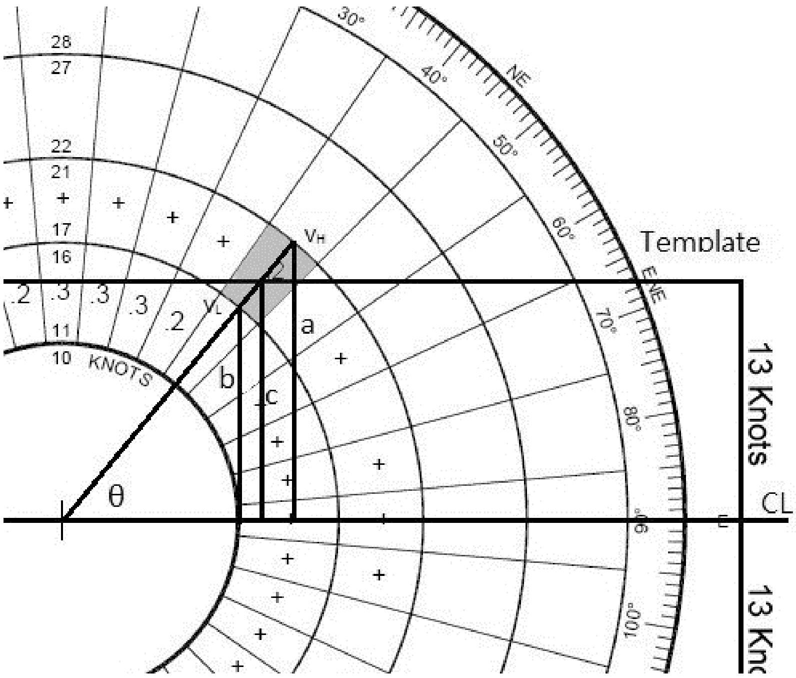


Figure 3. Improved Solution of Partially Covered Sectors

Instead of a geometrical method, this is paper proposes an analytical method for wind coverage analysis. The graphical wind rose in Figure 3 is helpful in explaining the proposed method. The shaded area in the wind rose represents a partially covered sector which represents 2% of the total time, wind direction angled at θ degrees to the predefined runway 09/27, and wind speeds between 17 and 21 knots. For analysis purposes, winds are assumed to be uniformly distributed throughout each of the individual sector. The adjustment factor, noted as f, is used to adjust the percentages of covered, uncovered and partially covered sectors. The adjustment factor for each sector can be solved as follows:

$$f = 1,\ if\ V_L \times |sin\theta| \geq V_c \quad (1)$$

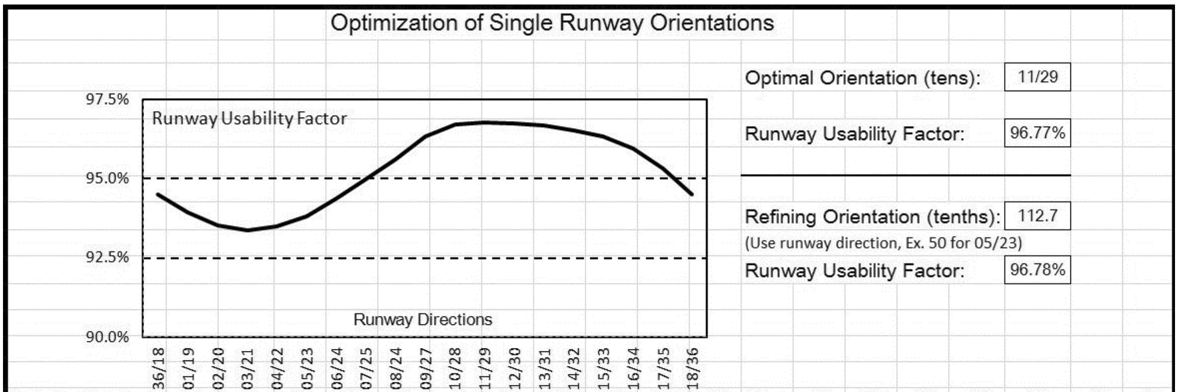
$$f = 0,\quad if\ V_H \times |sin\theta| < V_c \quad (2)$$

$$f = \frac{V_H \times |sin\theta| - V_c}{V_H \times |sin\theta| - V_L \times |sin\theta|},\ if\ V_L \times |sin\theta| < V_c \leq V_H \times |sin\theta| \quad (3)$$

where,

f = Adjustment factor for a sector
V_L = Lowest wind speed in a sector
V_H = Highest wind speed in a sector
V_c = Allowable crosswind speed limit
θ = Angle between wind direction and the predefined runway

These what-if equations are converted to spreadsheet formulas to adjust the percentage of total observations for each sector. The usability factor is obtained through the array calculations of the adjusted percentage for each cell. Initially, the calculation is limited to one predefined runway direction. A VBA algorithm is developed to activate the repeated calculations along the ten degrees incremental directions. In the proposed model of Figure 4, a combination of acceptable orientations is identified and marked as “OK” for those orientations in which the usability factors are not less than 95% and “Max” for the quasi-optimal orientation. Based on the solutions, a chart with runway orientations and usability factors is drawn automatically, as shown in the left of Figure 4. As one of its important features, the proposed model provides a combination of acceptable orientation options to be traded off with the additional factors. The optimal runway orientation can be obtained by further refining the runway orientation up to one decimal, as shown in the right of Figure 4.



Analyzing Result	X	X	X	X	X	X	X	X	OK	OK	OK	Max	OK	OK	OK	OK	OK	OK	X
Runway Direction	36/18	01/19	02/20	03/21	04/22	05/23	06/24	07/25	08/24	09/27	10/28	11/29	12/30	13/31	14/32	15/33	16/34	17/35	18/36
Usability Factor:	94.51%	93.93%	93.52%	93.36%	93.49%	93.82%	94.36%	94.98%	95.59%	96.32%	96.71%	96.77%	96.74%	96.67%	96.52%	96.33%	95.96%	95.33%	94.51%

Figure 4. Optimization of Single Runway Orientations

In the stage of airport design or runway planning, the runway orientation always has to be trade-off with additional factors, such as terrain obstructions, navigation difficulties or land use. If any of these factors limit the runway can only be oriented in specific directions with a usability factor below 95%, one or more crosswind runways may be needed to meet the requirement of the combined usability factor of at least 95%. For example, if the runway 04/22, which only provides a usability factor of 93.49% (See Figure 4), intentionally be designed as the first runway, one or more crosswind runway is needed. Therefore, another

VBA algorithm is designed to repeatedly calculate the second runway orientation options and their usability factors though the spreadsheet's array computation. The combined usability factor is determined by comparing and selecting the higher usability factors of the decided first runway and each second runway orientation options. As shown in Figure 5, after selecting the runway 04/22 as the first runway and activating the 2nd runway calculation, the combination of acceptable orientation options for the second runway is identified and marked as "OK" or "Max". The number of acceptable orientation options increases from 10 (Figure 4) to 14 (Figure 5). That means that selecting any one of these 14 orientation options can meet the requirement of combined usability factor, otherwise, the third crosswind runway is needed.

Optimization of Two Runway Orientations

1st Runway Options: 40 (Use runway direction, Ex. 50 for 05/23) Add 2nd (crosswind) R/W

2nd Runway	36/18	01/19	02/20	03/21	04/22	05/23	06/24	07/25	08/24	09/27	10/28	11/29	12/30	13/31	14/32	15/33	16/34	17/35	18/36
2 R/W Usability Factor:	96.26%	95.28%	94.47%	93.95%	93.49%	94.31%	95.41%	96.60%	97.71%	98.86%	99.49%	99.73%	99.67%	99.56%	99.29%	99.02%	98.42%	97.52%	96.26%
Analyzing Result	OK	OK	X	X	X	X	OK	OK	OK	OK	OK	Max	OK	OK	OK	OK	OK	OK	OK

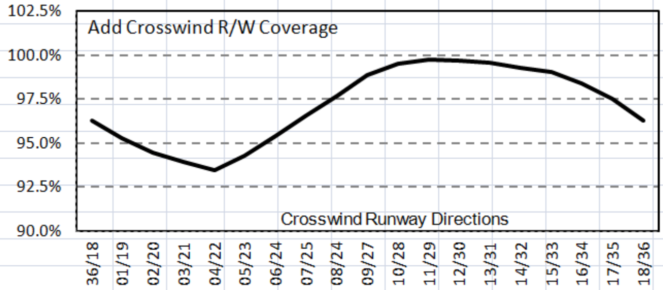


Figure 5. Orientations Optimization of Two Runway Configurations

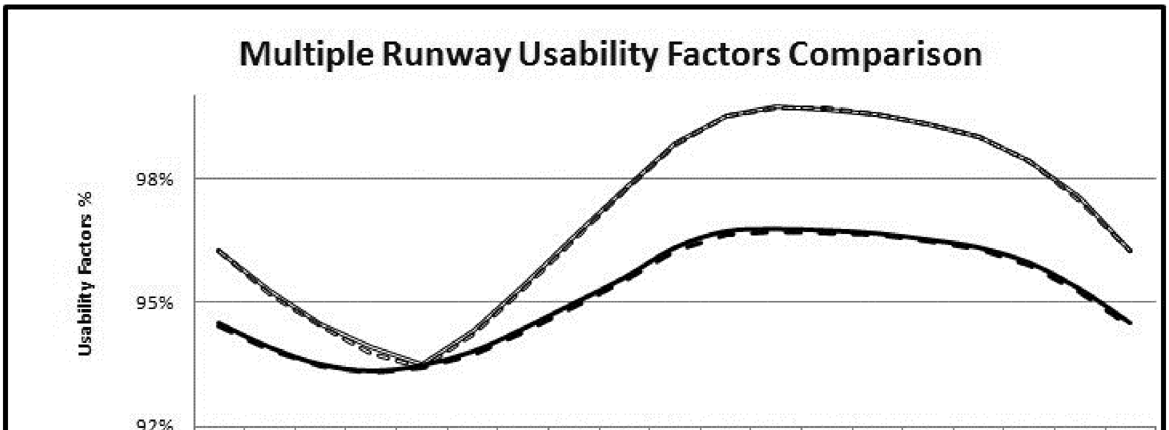
4. NUMERICAL EXAMPLE AND COMPARISON

To verify the proposed Model, a numerical example, in which FAA (2000) wind data and allowable crosswind limit are adopted, is conducted to compare their results. The data has a standard format of wind observations for ten consecutive years. After uploading the wind data, selecting a crosswind limit 13 knots, and running the calculation in the model (Figure 2), a combination of acceptable orientation options is identified as from 08/24 to 17/35, in which 11/29 has the highest usability factor (quasi-optimal), as shown in the Figure 4. When refining the orientation to 112.7°, the maximal usability factor of 96.78% is obtained. Refining the runway orientation up to one decimal place is one of the important features that the model provides. As another example, after refining the orientation of runway 07/23 (the original usability factor is lower than 95%) to 70.4°, the usability factor of the runway becomes acceptable. These features provide the users complete information and flexibility in runway orientation analysis.

In the model analysis of Figure 5, the runway 04/22 with the lower usability factor is selected to be the first runway. This is intended to simulate the worst case of compromising with the additional factors, such as terrain obstructions, navigation difficulties or land use. As the result, the number of acceptable runway orientation options for the second runway increases from 10 (Figure 4) to 14 (Figure 5). Clearly, any selection of these 14 neighboring directions as the second runway can reach the combined usability factor of 95%. As we can further analyze, even the selections of the worse case of pair parallel runway 04/22, the requirement of usability factor still can be met by adding any of these 14 runway directions.

All of these are attributed to the complete information and flexibility that the model can provides for runway orientations analysis.

As mentioned, FAA developed wind analysis computer programs to improve the accuracy and convenience of analyzing runway orientations. This research tried to input the same wind data and allowable crosswind limit into FAA computer model for comparison. After manually calculating for every 10° increments in orientation, the sets of runway options with usability factors for a single runway and for the second runway are obtained. By comparison, it is found the average difference of usability factors between FAA Model and proposed model is lower than 0.07%, as shown in Figure 6. While the FAA computer needs few hours, the propose model takes few seconds to get the result of Figure 6. The proposed model is competitively accuracy and improved convenience over previous methods.



	36/18	01/19	02/20	03/21	04/22	05/23	06/24	07/25	08/24	09/27	10/28	11/29	12/30	13/31	14/32	15/33	16/34	17/35	36/18
OMRO 1R/W	94.51	93.93	93.52	93.36	93.49	93.82	94.36	94.98	95.59	96.32	96.71	96.77	96.74	96.67	96.52	96.33	95.96	95.33	94.51
FAA 1R/W	94.44	93.86	93.46	93.31	93.43	93.74	94.27	94.89	95.53	96.25	96.65	96.72	96.68	96.62	96.47	96.28	95.90	95.26	94.44
OMRO 2R/W	96.26	95.28	94.47	93.95	93.49	94.31	95.41	96.60	97.71	98.86	99.49	99.73	99.67	99.56	99.29	99.02	98.42	97.52	96.26
FAA 2R/W	96.24	95.21	94.44	93.78	93.43	94.24	95.34	96.52	97.67	98.80	99.49	99.70	99.69	99.55	99.33	98.99	98.41	97.45	96.24

Figure 6 Comparisons Between Proposed and FAA Models

5. CONCLUSIONS AND FUTURE EFFORTS

This paper proposes an analytical method for successfully solving the runway wind coverage problems which are critical in runway orientation analysis. This overcomes the deficiency of the geometrical method and allows the proposed model to apply the array calculation feature of a spreadsheet to determine a combination of acceptable orientations, which avoids excessive crosswinds at least 95% of the time. This allows the runway orientations to be traded off with additional factors, such as available land, existing obstructions, topographic difficulties, flight path interference among runways and airports, noise pollution and other environmental impacts, while satisfying the operational requirements of aircraft for landing and takeoff. The special features of the proposed model include the flexible crosswind limit setting, refining for the optimal orientation, and solving two runway orientations. The numerical example and comparison show that the proposed model is competitively accurate and convenient in comparison with previous studies. This paper presents an up-to-date model for the orientations optimization of two runway configurations in an airport. The proposed model is currently stored and published in the website of Chinese University of Science and Technology (http://cc.hc.cust.edu.tw/~swaychang/). It may be downloaded and used for the purpose of paper review. More computer coding effort is needed to convert it into a web based model for public use. The proposed model must be expanded to multiple runway orientation optimizations for modern airports. With more detailed and categorized wind data, the model also can solve the VMC, IMC or all weather wind analysis problems separately. A combined airport cost minimization model, which combines airfield land use, multiple runway orientation optimization, GIS obstruction model, and cost estimation modules, will be a long-term goal. Unfortunately, the current development of GIS does not support dynamic volumetric solving of earthwork. A GIS obstruction model has been submitted to the journal and is currently under review. The proposed optimization model for runway orientations is the essential module of the future combined model. It has been proposed earlier as a useful tool for airport design, transportation infrastructure planning, and airfield safety management.

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