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Abstract
Purpose – Bird strike risk (BSR) evaluation is a significant part of the avian radar system worldwide installed and operated at airports. The paper aims to discuss these issues.
Design/methodology/approach – This paper proposed a method using the real-time avian radar data to evaluate BSR with the estimations of bird strike probability and severity. The probability estimation model considered the attributes of the relative positions of the flock and the runway, the altitude of the flock and the aircraft, the flight path of the aircraft, and the ability of the bird species to avoid collision. The severity was estimated by the combination of the Delphi method and the analytic hierarchy process (AHP), called DAHP, which took full advantage of the expert knowledge and quantitative calculation.
Findings – The model was tested successfully on the simulated data at Beijing Capital International Airport (BCIA) with three runways and real data at Beihai Fucheng Airport (BFA) with one runway.
Practical implications – The BSR evaluation model was specifically designed for the airports with avian radars. It enabled the airport managers to objectively evaluate the risk in real time and to take effective measures.
Originality/value – The proposed BSR evaluation model was constructed with the real-time features of birds and aircraft based on the DAHP framework, providing scientific guidance for aviation safety and environmental management at the airport.

Keywords Evaluation, Probability, Analytic hierarchy process, Bird strike risk, Severity

Paper type Research paper

Introduction

With the development of civil aviation and the growth of bird population, bird strikes have been a major problem to aviation safety during the past several decades (Klope *et al.*, 2009). Up to 2012, birds are known to have caused at least 55 fatal accidents, 276 deaths and the destruction of 108 civil aircrafts (Thorpe, 2012). And these numbers are still increasing. It is reported that bird strikes cause annual economic cost of $1.2 billion to commercial aircraft worldwide (Allan and Alex, 2001). In China, the reported number of bird strikes incidents increases rapidly from 46 in 2008 to 127 in 2011 (Zhang, 2012). More than 90 per cent of the bird strikes happen in and around the airports, and 50 per cent of the damaging and hazardous accidents occur below 30 m during the periods of takeoffs and landings (Nohara, 2009). Therefore, it is necessary to evaluate the bird strike risk (BSR) in and around the airport to provide a scientific guidance for driving birds.

Different bird species pose different risks to aircraft due to their mass and size. For a long time, general BSR evaluation model used the historical recordings of bird strike events to estimate the strike probabilities of different bird species. Allan (2006) created a simple probability-times-severity matrix to evaluate risk based on both national and airport-specific data. The strike probability was measured by the frequency of strikes reported for different bird species at a given airport, while the likely severity was measured by the proportion of strikes with each species that result in damage to aircraft in the national bird-strike database. With reference to the protocol proposed by Allan, a tool is developed to provide decision-making support on the risk evaluation process, using a comprehensive database of Athens International Airport (Anagnostopoulos, 2003). Shaw studied methods for evaluation of aircraft susceptibility to strike and bird species susceptibility to strike. The methods were successfully used at nine Australian airports (Shaw and McKee, 2008). The United States Bird Avoidance Model (USBAM) has been established based on the historical data accumulated in the database recording bird activities and bird strikes, and combined with real-time information (Ruhe, 2005). The USBAM is based on approximate 30 years of historical bird observation data which are transformed into average bird mass values and interpolated spatially in a geographical information system environment with a resolution of 1 km^2. The BSR value is divided into nine levels according to the bird distribution density per km^2.

Clearly, the above approaches always evaluate the BSR values of certain species of birds based on the long-term stored reports of bird strikes. However, the bird strike reports are sometimes incomplete and inaccurate due to artificial influences, leading to unreliable evaluation results. In the last decade, radar has been a useful tool for bird observation. Several avian radar systems were developed to support the real-time BSR evaluation at airport, and the species of birds

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could be identified by a high-definition camera, which is usually the supplementary part of the radar system (Ning *et al.*, 2010; Nohara *et al.*, 2007). So, it seems feasible to give the BSR values with the current states of flying birds and aircrafts at airport. Wang and Herricks (2010) used radar to collect bird activity data to evaluate the bird strike threats to aircraft operations at an airport in Washington. Analytic hierarchy process (AHP), which is a structured technique developed by T.L. Saaty in the 1970s (Saaty, 1980) for organizing and analyzing complex decisions, has been introduced to access the BSR values with the consideration of the parameters of birds and aircraft. In our preliminary work, the parameters of birds and aircraft are both arranged on the same level of the AHP model, leading to the problem of consistency of the comparison matrix (Ning *et al.*, 2012; Chen *et al.*, 2012). In this paper, we propose a real-time BSR evaluation method based on the bird information collected by the airport-based avian radar system and the flight phase of the aircraft provided by the air-traffic control system. Our method comprehensively considers the bird strike probability and severity. The strike probability is estimated by a formula with the consideration of the current positions of the flock, the altitude of the flock and the aircraft, the flight path of the aircraft, and the ability of the bird species to avoid collision. The strike severity is estimated by the combination of the Delphi method (Linstone and Turoff, 1975) and the AHP, called DAHP, which can take full advantage of the expert knowledge and quantitative calculation, and overcome the poor authority in the simple use of AHP. To reduce the number of parameters on the same level, a two-level model is established with the DAHP method. The two-level DAHP model, as well as the introduction of probability estimation, could avoid the problem of consistency of the comparison matrix due to the high number of parameters on the same level.

The remaining of this paper is organized as follows. In the second section, the BSR evaluation method based on the evaluations of bird strike probability and severity is introduced. Then, the methods for the evaluations of bird strike probability and severity are discussed, respectively, in the third and fourth sections. Two examples are provided with the simulated and real data in the fifth section to test the proposed method. Some conclusions close the paper in the sixth section.

BSR evaluation

The risk level of the bird strike (R) is a function of the probability (P) and the severity (S) as shown in equation (1). P represents the probability of certain birds fly into the runway and S represents the severity of collision between birds and aircraft. Both the values of P and S could be classified into five categories of very high (VH), high (H), moderate (M), low (L) and very low (VL):

$$R = F(P, S) \tag{1}$$

The 5×5 risk evaluation matrix combining the probability and severity of bird strike is shown in Table I (Allan, 2006), which establishes a functional relationship between R and (P, S). The risk values are divided into three levels requiring different responses from the airport managers. Some suggestions for the responses at airport are listed in Table II (Allan, 2006).

Table I Risk evaluation matrix combining the probability and severity

			P		
S	**VH**	**H**	**M**	**L**	**VL**
VH	3	3	3	2	2
H	3	3	3	2	2
M	3	3	2	1	1
L	2	2	1	1	1
VL	1	1	1	1	1

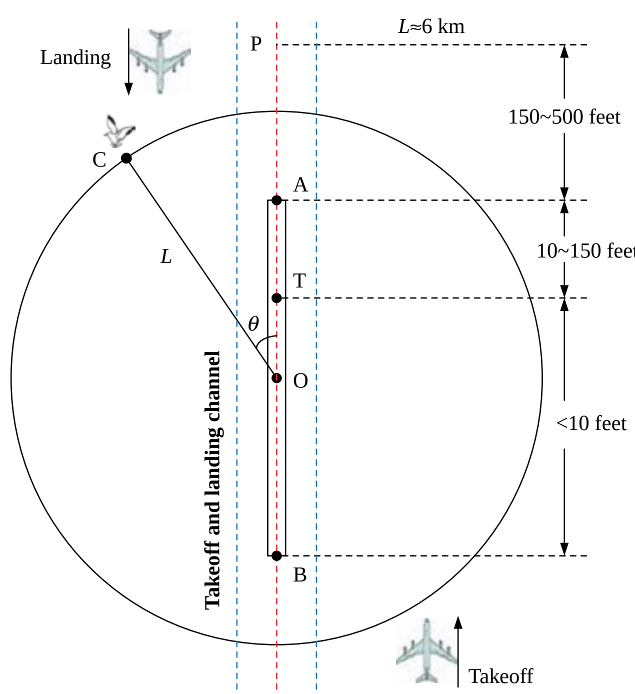
Table II Suggestions for the responses of the airport managers

Risk level	Responses
1	Attention to birds or flocks, and careful observation of the avian radar display
2	Close attention to birds or flocks and driving measurements taken if necessary (e.g. bird-repellent vehicle, gas cannon, laser and ultrasonic bird-repellent devices)
3	High attention to birds or flocks, driving measurements taken as soon as possible (e.g. as mentioned above) and close the runway if necessary

Probability estimation

In order to estimate the probability of a bird (or flock) flies into a certain runway, a probability estimation model is proposed with the first consideration of the relative positions of the bird (or flock) and the runway, which is shown in Figure 1. Points A and B represent the two ends of the runway. The distance between the position of the bird (C) and the middle point of the runway (O) is L. The angle between OC and the runway is θ ($0° \leq \theta \leq 90°$). In addition, the ability of the bird species to

Figure 1 Simulated positions of the bird (or flock) and the runway



avoid collision is also considered as a key attribute in the probability estimation model (Montemaggiori *et al.*, 2012; Morbach, 2003).

As indicated in the following equation, the bird strike probability could be determined by three parameters: the probability caused by the distance ($0 < P_L \leq 1$), that caused by the angle ($0 < P_A \leq 1$), and that caused by the bird species ($0 < P_B \leq 1$):

$$P = \begin{cases} \eta \cdot P_L \cdot P_A \cdot P_B & P_L \cdot P_A \cdot P_B < 1 \\ 1 & \text{else} \end{cases} \tag{2}$$

where η is the impact factor, considering the situations when the birds flying into the takeoff and landing route of the aircraft. The value of P is constrained to the range of (0,1].

The parameter P_L could be calculated using the equation:

$$P_L = \exp(1 - L/L_0) \tag{3}$$

It decreases with the increasing distance. The value of P_L is 100 per cent when the parameter is set to $L = L_0$. The parameter L_0 controls the descending rate of P_L with the increasing distance. Smaller values of L_0 make the P_L curve steep, while larger values make it flat.

It is assumed that the strike probability increases as the birds fly into or near the takeoff and landing channel of the aircraft, which is plotted with a dashed line in Figure 1. So, the parameter P_A could be calculated using the equation:

$$P_A = 1 - a \cdot \sin\theta \tag{4}$$

where the parameter α controls the boundary values of P_A. The angle θ is calculated with the cosine law as:

$$\theta = \arccos \frac{\mathbf{OC} \cdot \mathbf{OA}}{|\mathbf{OC}| \cdot |\mathbf{OA}|} \tag{5}$$

Not all bird species are equally capable of actively avoiding a collision with an oncoming aircraft or staying out of the way of aircraft movement areas altogether (Carter, 2001), so each species should have its own P_B. However, it is hard to give an accurate value of P_B. In this paper, some birds are classified into two groups and assigned with suggested values of P_B (Table III). The birds that adept at avoiding aircraft are assigned with lower P_B, while that unskilled at avoidance with higher P_B.

Furthermore, some more attributes should be considered to modify the estimation model by the impact factor η, including the altitude of the flock and the aircraft, and the flight path of the aircraft. Obviously, during the takeoff and landing period of the aircraft, the birds that appear in the takeoff and landing channel ($L \leq 6$ km and $\theta \leq 5°$) at the specific height is the most dangerous, as shown in Figure 1. As the aircraft is taking off from B to A, the takeoff channel is divided into three parts. In each part of the channel, the probability increases greatly as the birds flying at the specific height. The first part is from B to T (the takeoff point), before the aircraft takes off, the birds in the channel below 10 ft is the most dangerous. The second part is from T to A, as the aircraft just takes off, the birds in the channel at the height of 10-150 ft is the most dangerous. The third part is from A to P ($L \approx 3$ km), as the aircraft is leaving the airport, the birds in the channel at the height of 150-500 ft is the most dangerous. Therefore, during the takeoff and landing period, if one of the above conditions of position and altitude are satisfied, the impact factor is set to $\eta = 1.5$; if none of the above conditions are satisfied, the impact factor is set to $\eta = 1$; otherwise, when the aircraft is not in the preparation or in the process of takeoff or landing, the parameter should be set as low as $\eta = 0.3$. Similarly, as the aircraft is landing from A to B, the most dangerous height is almost the same, which is 150-500 ft from P to A as the aircraft is approaching, 10-150 ft from A to T (the landing point), and below 10 ft from T to B. The rules for setting the values of the parameter η are exactly the same.

Table III P_B suggestions for some bird species

P_B	Bird species
0.8	Crows, northern harriers, American kestrels, ravens, etc.
1.0	Storks, curlews, raptors, swallows, geese, etc.

Now, the probability values could be divided into five grades to give increasing danger: VL ($0 \leq P < 0.2$), L ($0.2 \leq P < 0.4$), M ($0.4 \leq P < 0.6$), H ($0.6 \leq P < 0.8$) and VH ($0.8 \leq P \leq 1$).

Severity estimation

In this section, the Delphi method is introduced at first, and then the two-level DAHP model is proposed to estimate the bird strike severity based on the support of expert knowledge. The AHP method is described in detail in the Appendix.

Delphi method

The Delphi method is a structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts (Linstone and Turoff, 1975). In the standard version, the experts answer questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. It is believed that during this process the range of the answers will decrease and the group will converge towards the "correct" answer. Finally, the process is stopped after a pre-defined stop criterion and the mean or median scores of the final rounds determine the results. Two key issues of the Delphi method in bird strike severity estimation are discussed in the following paragraphs, including the design of expert questionnaire and the selection of experts.

In the expert questionnaire of bird strike severity estimation, the background knowledge of BSR is introduced first and then the Delphi and AHP methods are illustrated briefly. Judgment matrix is the main content of the expert questionnaire. The matrices on different levels are consulted. Opening questions are also required to answer on whether the influencing factors should the added, deleted or combined.

Expert selection is another significant issue in the Delphi method, which should follow the principles of authority and universality. The experts are selected from ornithologists in university, researchers of aviation safety in civil aviation academy and bird-driven staff at nationwide airports. The number of experts should also be properly set. A small number restricts the representativeness in subjects and area, while a large one results in management difficulties.

Generally, it is suitable to invite ten to 20 experts to answer the questionnaires (Saaty, 2008).

Two-level DAHP

The severity of bird strike is estimated with a two-level DAHP model. On the first level of the hierarchy, two elements of the aircraft and birds are considered, which are denoted as E_A and E_B, respectively, in equation (6). Furthermore, the element E_A governs the sub-elements of T_A and P_A on the second level, which represents the type and flight phase of the aircraft; while the element E_B governs the sub-elements of N_B and M_B on the second level, which represents the number and mass of the birds:

$$S = F_{\mathrm{AHP}}\{E_A; E_B\} = F_{\mathrm{AHP}}\{(T_A, P_A); (N_B, M_B)\} \tag{6}$$

Ten experts were invited to answer the questionnaires. Two experts are ornithologists from university, five are researchers of aviation safety from academy and three are bird-driven staff from different airports. Their answers of the comparison matrices on the two levels converged after three rounds.

On the first level, the comparison matrix of E_A and E_B is as follows:

$$\begin{array}{cc} & \begin{array}{cc} E_A & E_B \end{array} \\ \begin{array}{c} E_A \\ E_B \end{array} & \begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix} \end{array}.$$

So the weights of the two elements on the first level are:

$$W^1_{E_A} = 0.25, \quad W^1_{E_B} = 0.75.$$

On the second level, the comparison matrix of the sub-elements of T_A and P_A, which are governed by E_A on the first level, is as follows:

$$\begin{array}{cc} & \begin{array}{cc} T_A & P_A \end{array} \\ \begin{array}{c} T_A \\ P_A \end{array} & \begin{bmatrix} 1 & 1/4 \\ 4 & 1 \end{bmatrix} \end{array}.$$

So the weights of the two sub-elements on the second level are:

$$W^2_{T_A} = 0.2, \quad W^2_{P_A} = 0.8.$$

In addition, the comparison matrix and weights of the sub-elements of N_B and M_B on the second level are also obtained as follows:

$$\begin{array}{cc} & \begin{array}{cc} N_B & M_B \end{array} \\ \begin{array}{c} N_B \\ M_B \end{array} & \begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix} \end{array}.$$

$$W^2_{N_B} = 0.25, \quad W^2_{M_B} = 0.75.$$

Therefore, the final weight of each sub-element is calculated by the multiplication of its weight on the second level and the weight of its governing element on the first level, using the equation:

$$W^{1-2}_{E^2} = W^1_{E^1} \cdot W^2_{E^2} \tag{7}$$

Thus, the final weights of the four sub-elements are:

$$W^{1-2}_{T_A} = 0.05, \quad W^{1-2}_{P_A} = 0.2, \quad W^{1-2}_{N_B} = 0.1875,$$
$$W^{1-2}_{M_B} = 0.5625.$$

It is clear that the weight of the bird mass is the highest.

According to the specific situations on the runway, the scores of all the elements on the second level are divided into five grades (Table IV). As for the aircraft type, the small aircrafts (e.g. CRJ and EMB) get higher scores while the large ones (e.g. A380) get lower scores. As for the flight phase, it is assumed that the phases of takeoff and climbing is the most dangerous (score 5) and the phase of taxiing the least (score 1). During the phases of descending, approaching and landing, the higher the aircraft is, the higher the severity score is. As for the bird mass, since Part 25 of the Federal Aviation Regulations requires for the aircraft engine successful testing against birds of 2,500 g (FAA, 2010), we set the bird mass of 2,500-5,000 g with the score of 4, and that of $>$5,000 g with the score of 5.

Then, the severity value decided by the information of the aircraft and birds is calculated as:

$$S = \frac{1}{5} \sum_{i=T_A,P_A,N_B,M_B} G_i \cdot W^{1-2}_i \tag{8}$$

where G_i denotes the grade division for each element.

Obviously, the severity value is between 0 and 1, and can be divided into five grades to give increasing danger: VL ($0 \le S < 0.2$), L ($0.2 \le S < 0.4$), M ($0.4 \le S < 0.6$), H ($0.6 \le S < 0.8$) and VH ($0.8 \le S \le 1$).

Examples at airports

To test the proposed BSR evaluation method, examples are conducted at Beijing Capital International Airport (BCIA)

Table IV Rating standard to elements of severity estimation

Elements	Grade division	Score
Aircraft type (T_A)	CRJ, EMB	5
	A320, B737	4
	A330	3
	A340, B747	2
	A380	1
Aircraft flight phase (P_A)	Takeoff and climbing	5
	Descending	4
	Approach	3
	Landing	2
	Taxiing	1
Bird number (N_B)	$>$15	5
	11-15	4
	6-10	3
	2-5	2
	1	1
Bird mass (M_B)	$>$5,000 g	5
	2,500-5,000 g	4
	1,000-2,500 g	3
	500-1,000 g	2
	0-500 g	1

with the simulated data and Beihai Fucheng Airport (BFA) with the real data, respectively.

Simulated data

Figure 2 shows the BCIA map with the simulated data. The lengths of the three runways of the airport are 3.2, 3.8 and 3.8 km, respectively. BSR of the simulated flying birds to different runways at BCIA are evaluated and analyzed. The information of the three runways and the aircrafts on them is described in Table V, including the coordinates of the two ends of the runways and the types and flight phases of the aircrafts. The three aircrafts are all in the phase of "Takeoff" (from the south to the north). The northern end of Runway 2 is set as the origin of coordinates. The positive y-axis directs to the north. The northern ends of the runways are denoted by "A" and the southern ones denoted by "B". The domain of the map is $[-8, 8] \times [-8, 8]$, which is the surveillance region of radar. Four flock targets are simulated and their trajectories are plotted on the map. The information of flock targets are given in Table VI, including the start and end points of the targets and their number, mass and altitude. As for the capability to avoid aircraft, it is assumed that Flocks 1-3 are skilled and Flock 4 is unskilled. The start points of the four targets are plotted with a circle in Figure 2. The simulated time for each target is 200 s with the step of 10 s. Here, the step is set longer to show the change of the bird positions more significantly.

Figure 2 BCIA map with the simulated data

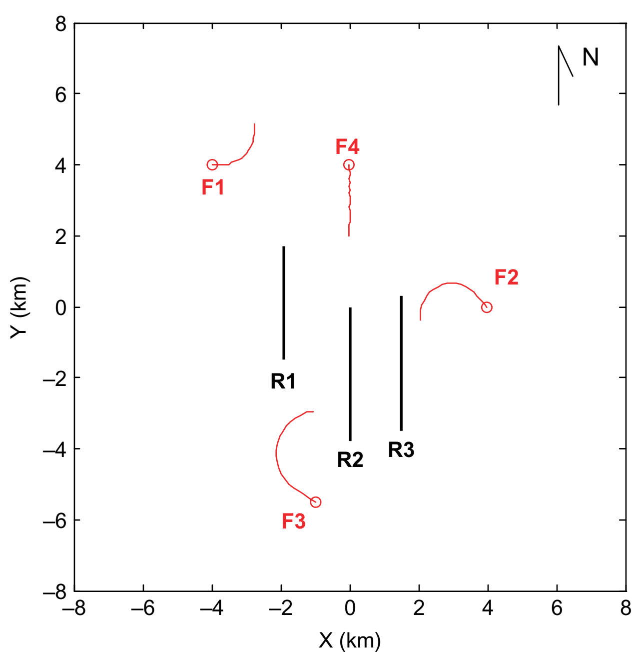


Table V Information of runways and aircrafts

Runway	A (km)	B (km)	T_A	P_A
1	(−1.9, 1.7)	(−1.9, −1.5)	B737	Takeoff
2	(0, 0)	(0, −3.8)	A340	Takeoff
3	(1.5, 0.3)	(1.5, −3.5)	A380	Takeoff

Table VI Information of flock targets

Flock target	Start (km)	End (km)	N_B	M_B (g)	Altitude (ft)
1	(−4, 4)	(−2.8, 5.2)	50	30	400
2	(4, 0)	(2.1, −0.4)	3	1,500	120
3	(−1, −5.5)	(−1, −3)	5	600	15
4	(0, 4)	(0, 2)	1	6,000	180

According to the above simulated data, the strike probability and severity of each target are estimated. Figure 3 shows the probability estimation of the four targets to the three runways. Since Flock 1 is far from the runways, its strike probability is the lowest, which is always lower than 0.4 to the three runways during the whole simulation. In Figure 3(a), the probability of Runway 1 is the highest due to the shortest distance between Flock 1 and Runway 1. Figure 3(b) shows that the probability of Flock 2 to Runway 3 is almost 80 per cent after 150 s because the flock is too close to the runway (about 0.6 km) in this period. Flock 3 moves in the region between Runways 1 and 2, so its strike probabilities to the two runways are relatively higher as shown in Figure 3(c). Note that Flock 4 is right in the takeoff channel of the aircraft on Runway 2 and its height is 180 ft, so the impact factor is set to $\eta = 1.5$ and the probability curve is obviously higher than the other two.

The strike severities of the four flocks to the three runways are given in Table VII. Note that Flock 4 poses much higher severity level (VH) than that of Flock 1 (M), so it could be inferred that a single 6,000 g bird will present a much greater threat than 50, 30 g birds which have a combined mass of 1,500 g.

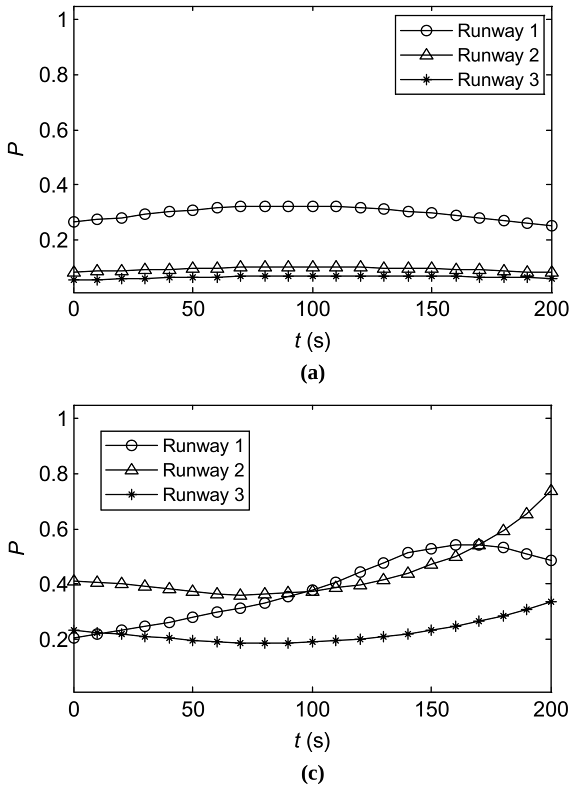
Based on the estimations of strike probability and severity, the risk levels are evaluated with the rules in Table I and the results are shown in Figure 4. As shown in Figure 4(a), since Flock 1 is relatively far from the three runways, is risk level is always "1". It is shown in Figure 4(b) that the risk level of Flock 2 to Runway 3 is much higher than that to the other two runways, because it is more close to Runway 3. In Figure 4(c), the risk level of Flock 3 to Runway 3 is the lowest due to the low strike probability. In Figure 4(d), since Flock 4 is moving toward Runway 2 along the takeoff channel of the aircraft at the specific height, which is the most dangerous situation, so the risk level is always "3".

We also design an experiment to test the influence of flight phases on the risk evaluation. The flight phase of the aircraft B737 on Runway 1 is altered to "Landing" (from the south to the north) and "Taxiing". The risk levels of Flock 3 to Runway 1 are analyzed with different flight phases. It is shown in Figure 2 that Flock 3 is right in the landing channel, but its altitude is 15 ft, so it poses limited threat to the landing aircraft in this position. Note that the severity values for the three phases are 0.4273, 0.3073 and 0.2673, so the severity levels of "Taxiing" and "Landing" are both "M" and their risk levels are the same (Figure 5).

Real data

Some real data were obtained by the avian radar experimental system developed by Beihang University and China Academy of Civil Aviation Science and Technology (Ning *et al.*, 2010) at BFA in May 2012. Figure 6 shows the BFA map with the plotted flock trajectory. The length of the runway is 3.2 km with the ends of (0, −0.3) and (0.8, 2.8).

Figure 3 Probability estimation of four groups of birds



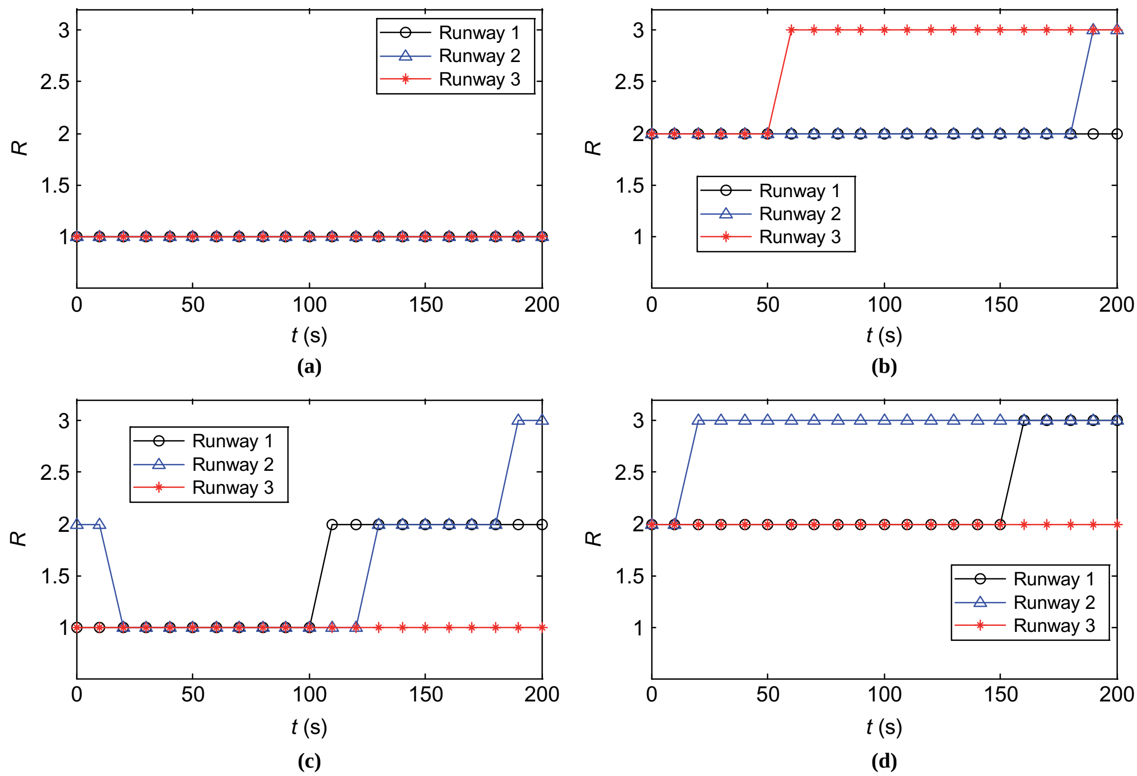
Notes: (a) Flock 1; (b) Flock 2; (c) Flock 3; (d) Flock 4

Table VII Severity estimations

Flock target	Runway	*S* value	*S* level
1	1	0.54	M
	2	0.52	M
	3	0.51	M
2	1	0.6265	H
	2	0.6325	H
	3	0.6225	H
3	1	0.54	M
	2	0.52	M
	3	0.51	M
4	1	0.84	VH
	2	0.82	VH
	3	0.81	VH

The system was located at the southern end of the runway, which is (0, 0) on the map. One scanning period of the antenna was 2.5 s and 24 frames of radar images were collected in 1 min and processed by the in-house data processing scheme (Chen *et al.*, 2012). The measurements of birds in 1 min were extracted and plotted on the map. The target measurements were indicated by a square symbol at the current position with a line emanating from the square pointed to the direction the target is heading. During the observation period of 1 min, three small resident birds (0-50 g) skilled at avoiding strikes were flying across the southern end of the runway, when a B737 was taxiing to the northern end of the runway after landing from the southern end. Since there was no aircraft in the preparation or in the process of takeoff and landing, the impact factor was set to $\eta = 0.3$ and the probability level was assumed to be "L" (Figure 7) and the severity level was "L" ($S = 0.2675$) as well, so the risk level was "1" when continuous attention should be paid to the birds.

Figure 4 Risk evaluation of the flock targets



Notes: (a) Flock 1; (b) Flock 2; (c) Flock 3; (d) Flock 4

Figure 5 Risk evaluation of Flock 3 to Runway 1 with different flight phases

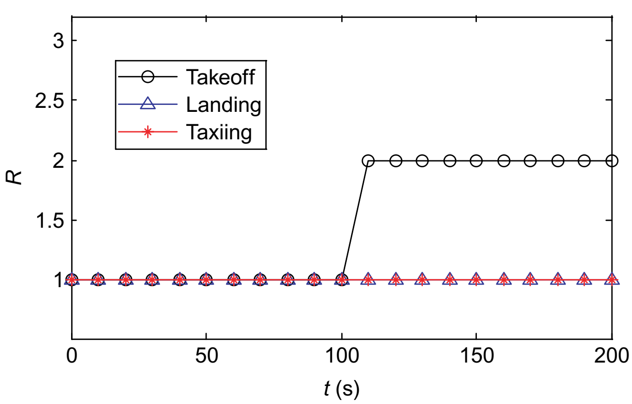
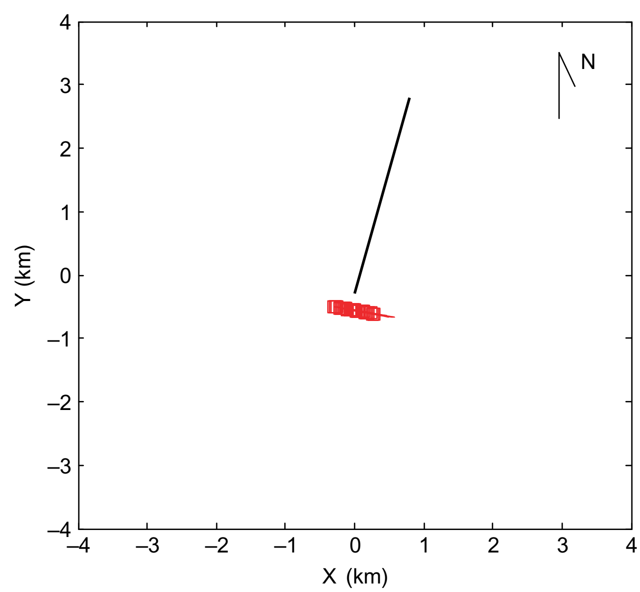


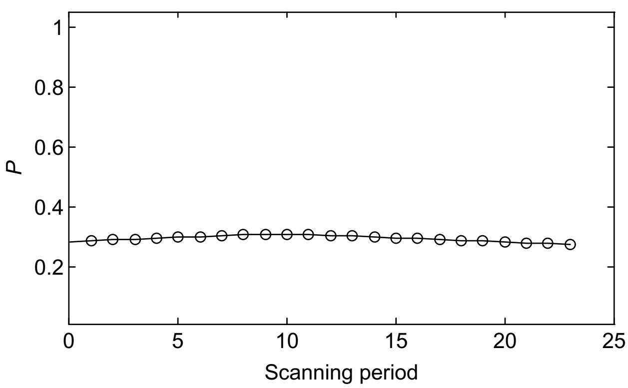
Figure 6 BFA map with the real data



Conclusion

This BSR evaluation method is specifically designed for the airports with avian radar. It enables the airport managers to objectively evaluate the risk at their airport in real time and to take effective measures. This method considers two factors: the probability estimation and severity estimation. The probability estimation incorporates the parameters of bird positions while the severity estimation incorporates the parameters of bird mass, bird number, aircraft flight phase and type. In the probability estimation, the velocity and heading direction of birds are not considered. These factors ultimately influence the positions of birds. Since the bird positions could be updated in very short period, the factors of velocity and heading direction could be ignored. In the severity estimation, the influencing factors are arranged in a two-level model based on the DAHP method, which could avoid the problem of consistency of the comparison matrix due to the high number of parameters on the same level.

Figure 7 Probability estimation of the flock at BFA



The BSR evaluation method described in this paper adopts real-time bird information while many existing methods use the historical reports on bird strikes. It could calculate the specific risk level of a certain flock target to a certain runway, which is very useful to the airport with multiple runways. Since the method is based on the real-time bird information, the success of this technique depends on the good reporting of bird information by the airport-based avian radar system. Failure to report bird intrusion leads to an underestimation of the true risk, while the false alarms may lead to blindfold management efforts. It may prove possible to modify the real-time BSR evaluation method with the historical experience of bird strike incidents, and further investigation is needed in this field.

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Appendix

Analytic hierarchy process

The method of AHP is based on the idea that a complex problem can be effectively examined if it is hierarchically decomposed into its components. Thus, AHP provides a holistic view of the problem. AHP begins with the top level in the hierarchy that reflects the main objective. An element at a higher level of the hierarchy is said to be the governing element for those elements at the lower level. Elements at a certain level are compared against each other with reference to their effect on the governing element. Let us consider the elements $E_1, E_2, \ldots, E_n$ of some level in a hierarchy and denote their normalized weights by $W_1, W_2, \ldots, W_n$, respectively. The value of W_i reflects the degree of importance of the E_i element. The first step in the calculation of W_i is to derive pairwise comparisons between the n elements. These pairwise comparisons are structured into an $n \times n$ matrix called a comparison matrix:

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$$
\mathbf{A} = \begin{array}{c c}
 & \begin{array}{cccc} E_1 & E_2 & \ldots & E_n \end{array} \\
\begin{array}{c} E_1 \\ E_2 \\ \vdots \\ E_n \end{array} & \begin{bmatrix} a(1,1) & a(1,2) & \ldots & a(1,n) \\ a(2,1) & a(2,2) & \ldots & a(2,n) \\ \vdots & \vdots & & \vdots \\ a(n,1) & a(n,2) & \ldots & a(n,n) \end{bmatrix}
\end{array}.
$$

Elements of the matrix **A** can be derived using a nine-scale approach. The values of $a(i, j)$ represent the importance comparison between the elements of E_i and E_j. More specifically, the value of $a(i, j)$ is set to 1, 2, 3, …, 9. Also, $a(j, i) = 1/a(i, j)$ for all $j = 1, 2, \ldots, n$. The weight of E_i is the averaged and normalized value of all the elements in its row of the matrix **A**.

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