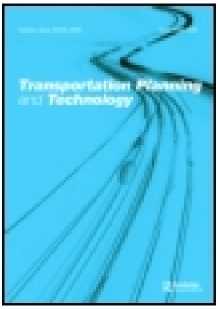

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The optimal location of airport fire stations: a fuzzy multi-objective programming and revised genetic algorithm approach

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THE OPTIMAL LOCATION OF AIRPORT FIRE STATIONS: A FUZZY MULTI-OBJECTIVE PROGRAMMING AND REVISED GENETIC ALGORITHM APPROACH

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As the global aviation business expands rapidly, issues of aviation safety become correspondingly important. In turn, aviation safety should be more emphasized. The crashes of China Airlines planes at Nagoya (Japan) international airport in 1994, and near Taipei's international airport in 1998, caused airport authorities around the world to pay closer attention to rescue and fire-protection plans at their airports. Our research reveals that the location and number of fire stations at an international airport is an important factor in its fire protection capability. However, if the sites of the fire stations are not appropriately planned and located, fire engines and crews cannot arrive at the accident area in a timely manner. Similarly, if the number of fire stations at an airport is not sufficient, fires caused by aircraft accidents may take longer to be extinguished, resulting in more injuries and fatalities. Therefore, a location model based on a fuzzy multi-objective approach is proposed in this paper. This model can help in determining the optimal number and sites of fire stations at an international airport, and can also assist the relevant authorities in drawing up optimal locations for fire stations. Finally, because of the combinatorial complexity of our model, a genetic algorithm (GA) is employed and compared with the enumeration method. The study results show that our revised GA is comparatively effective in resolution and that our model can be applied to the optimal location of other emergency facilities.

Keywords: Fuzzy; Multi-objective; Aircraft accidents; Airport; Fire station; Location; Combinatorial optimization; Genetic algorithm

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1. INTRODUCTION

In many countries, the number of aircraft taking off and landing has increased proportionally to their gross domestic product (GDP). For example, the traffic at Taipei's international airport in Taiwan has increased greatly since 1988, and in 1998 exceeded 80,000 aircraft movements. Thus, in the event of an accident, if an airport authority's response is not instantaneous, injuries and deaths may be greatly increased. Emergency action includes mainly the fire protection and rescue plans, both of which are executed in a timely manner by fire-fighters based at fire stations at an airport. Thus, the relevant authorities have the duty not only to provide adequate resources for fire fighting and rescue but also must have the capacity to direct these resources instantaneously to the accident area.

To assist the relevant authorities in such a timely fire protection and rescue response, the well-considered location of fire stations at an airport is needed. An appropriate fire station location can bring the following benefits: (a) it can shorten the distance between fire stations and the high-risk areas so as to improve reaction time efficiency; (b) fire stations can be located by considering the interaction between all fire stations – this can minimize overlap of fire station services, so as to utilize efficiently fire station resources; and (c) it can help determine the reasonable number of fire stations at an airport by considering an economical trade-off between accident-loss cost and total setup cost of fire stations. Using the above criteria, this study constructs a location model to promote the reaction efficiency of fire stations.

Previous research has included determining ambulance–hospital locations (Berlin *et al.*, 1976), locating facilities by fuzzy multi-criteria (Bhattacharya *et al.*, 1992), achieving maximal covering for locations (Church *et al.*, 1991), analyzing the trade-off between cost and accessibility (Current *et al.*, 1987), studying the US essential air service program (Flynn and Ratick, 1988), locating new facilities in a competitive environment (Hakimi, 1983), expanding facilities with multiple fuzzy goals (Hannan, 1981), finding the location for emergency facilities (Toregas, 1971), locating the treatment sites of hazardous wastes using multi-criteria methods (Giannikos, 1998), and discussing efficiency in a constrained continuous location problem (Ndiaye and Michelot, 1998). On the basis of this review, the location model of fire stations proposed in this study is implemented using a fuzzy multi-objective approach in which we simultaneously integrate the optimal number and sites of fire stations at Taipei's international airport. To solve our model with combinatorial complexity, a genetic algorithm (GA) is also used because it has proved to be suitable for solving combinatorial optimization problems (Sakawa, 1993; Sakawa *et al.*, 1997), and is effective for solving a large-scale location problem of the type considered here (Goldberg, 1989; Michalewicz, 1996). Our GA is similar in spirit to that of Sakawa's work (1997), but is revised to fit our location model.

This paper is organized as follows: the introduction has briefly presented the problem background, the study's purpose, a review of the relevant literature and selection of methods for solving our location model. In Section 2, the International Civil Aviation Organization (ICAO) standards of fire protection are discussed. In Section 3, the mathematical model is constructed and a revised GA is proposed. In Section 4, our revised GA is employed and Taipei's international airport is used to illustrate the practicability and efficiency of our model. A comparison of resolution efficiencies between the enumeration method and our revised GA is also performed. Finally, some conclusions are presented in Section 5.

2. FIRE-PROTECTION STANDARDS SUGGESTED BY ICAO

Today's wide-bodied jets carry hundreds of passengers on each flight. If such an aircraft crashes at or near an airport, inappropriate or inadequate strategies in fire fighting and rescue could have disastrous consequences. Since fire station staff at airports are responsible for putting out fires and rescuing lives, a well-performed fire-protection strategy and well-considered location of fire stations can significantly help the relevant authorities improve this reaction efficiency. First, a well-performed fire-protection strategy has to be implemented based on the standards suggested by ICAO. The ICAO concept classifies airports into specified levels according to the number of aircraft movements. Each level, in turn, corresponds to a level of necessary fire-protection resources (e.g., number of fire engines, amount of fire extinguishers, etc.).

Briefly, the ICAO standards are as follows:

(*a*) *Categories of fire protection*

The categories are classified into 10 levels, depending on the number of aircraft movements, and the length and width of the aircraft body – these categories are shown in Table I.

It is obvious that a larger aircraft will be categorized at a higher fire-protection level. This also implies that we need more fire-protection resources for rescuing passengers in a larger aircraft body.

(*b*) *Extinguishers to be equipped*

Table II gives the minimum number of extinguishers needed in an airport at each fire-protection level (from 1 to 10). Level A contains the strictest standard for fire-protection levels.

TABLE I Airport category of fire-protection ability

Airport category	*Length of aircraft* (m)	*Width of aircraft* (m)
1	0–9	2
2	9–12	2
3	12–18	3
4	18–24	4
5	24–28	4
6	28–39	5
7	39–49	5
8	49–61	7
9	61–76	7
10	76–90	8

Source: ICAO, 1995.

TABLE II Airport category of necessary extinguishers

Airport category	*A level*		*B level*		*Complementary agents*		
	Water (l)	*Discharging rate* (l/min)	*Water* (l)	*Discharging rate* (l/min)	*Chemical powder* (kg)	*Halons* (kg)	*Carbon dioxide* (kg)
1	350	350	230	230	45	45	90
2	1 000	800	670	550	90	90	180
3	1 800	1 300	1 200	900	135	135	270
4	3 600	2 600	2 400	1 800	135	135	270
5	8 100	4 500	5 400	3 000	180	180	360
6	11 800	6 000	7 900	4 000	225	225	450
7	18 200	7 900	12 100	5 300	225	225	450
8	27 300	10 800	18 200	7 200	450	450	900
9	36 400	13 500	24 300	9 000	450	450	900
10	48 200	16 600	32 300	11 200	450	450	900

Source: ICAO, 1995.

(*c*) *Reaction time*
The acceptable reaction time for any aircraft accident should be no longer than 3 min. This reaction time is the time necessary for 50% of available fire engines to arrive at the accident area and implement fire fighting and rescue plans.

According to our survey, the current reaction time at Taipei's international airport (see Fig. 5) meets these criteria.

(*d*) *Fire stations*
The number of fire stations should be adequately established. Furthermore, the siting of fire stations should allow fire engines access to the accident area in minimum time.

To sum up, the ICAO standards provide guidelines for promoting the reaction efficiency of fire fighting and rescue plans but ICAO do not instruct the relevant authorities how to decide on the optimal number and siting of fire stations at an airport. Thus, the problem we try to solve in this study is to find the optimal number and sites of fire stations at an airport so as to meet ICAO standards. This problem will be formulated mathematically in next section.

3. MODEL CONSTRUCTION AND RESOLUTION

To integrate the optimal number and sites of fire stations, many objectives need to be considered. The concept and formulation of our location model is illustrated as follows:

3.1. Model Construction

A location model is established for optimizing the number and sites of fire stations. Decision variables for this model are of the binary (0–1) type – a fire station will be set up at the corresponding coordinate if this variable equals 1. Objectives and constraints of our model are as follows:

(*a*) *Minimizing the total setup cost of fire stations and total loss cost of an accident*
An insufficient number of fire stations will lead to inefficient reaction times – the loss caused by reacting inefficiently is defined as the total

loss cost (TLC) in this study. If no fire station is set up at an airport, the total loss cost will be equal to TLC; on the contrary, the TLC can be reduced when more fire stations are set up. Meanwhile, too many fire stations will result in wasting fire-protection resources. Therefore, there will be an optimal number of fire stations after the trade-off between total setup cost (TSC) of fire stations and total loss cost (TLC), weighted by some negative exponential form. The conceptual cost resulting from the TSC of fire station plus the weighted TLC should be minimized. This formulation is expressed in Eq. (1).

$$\text{Min}\, f_1 = \sum_i \sum_j S_{ij} \times \text{SC} + \text{TLC} \times e^{-\sum_i \sum_j S_{ij}} \qquad (1)$$

where S_{ij}: the decision variable, if a fire station is set up on a x–y coordinate (i,j), then $S_{ij}=1$, otherwise, $S_{ij}=0$; and $\sum_i \sum_j S_{ij} \geq 1$; SC: the setup cost for a single fire station; TLC: the total loss cost. Moreover, although Eq. (1) is subjectively established by assumption, Eq. (1) is theoretically reasonable because f_1 has a U-shaped curve – this represents a trade-off between the TSC and weighted TLC. A simple example in Fig. 1 indicates that the optimal number of fire stations is two when TLC = 7 and SC = 1.

(*b*) *Minimizing the longest distance from the fire station to any point at the airport*
This objective is designed to increase the accessibility from any fire station to any point at or near the airport. This objective is shown

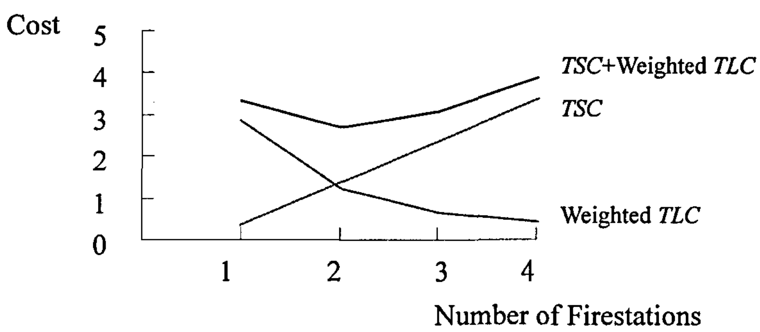

FIGURE 1 The trade-off between TSC and Weighted TLC.

in Eq. (2).

$$\text{Min } f_2 = \sum_{\{(i,j)|S_{ij}=1,\forall i,j\}} \left\{ \underset{x,y}{\text{Max}} |x-i| + |y-j| \right\} \tag{2}$$

where S_{ij}: the decision variable, if a fire station is set up on a x–y coordinate (i,j), then $S_{ij}=1$, otherwise, $S_{ij}=0$; x, y: if $S_{ij}=1$, then $x=i$ and $y=j$.

(c) Minimizing the longest distance from any fire station to the high-risk area

The distance from any fire station to the high-risk area should be minimized in order to increase reaction efficiency. This objective function is shown in Eq. (3).

$$\text{Min } f_3 = \underset{\{(i,j)|S_{ij}=1\}}{\text{Max}} \sum_i \sum_j r_{ij} \times \{|x-i| + |y-j|\} \tag{3}$$

where S_{ij}: the decision variable, if a fire station is set up on a x–y coordinate (i,j), then $S_{ij}=1$, otherwise, $S_{ij}=0$; x, y: if $S_{ij}=1$, then $x=i$ and $y=j$. r_{ij}: the risk rank for x–y coordinate (i,j). The risk rank r_{ij} is computed based on accident statistics for different areas at or near an airport – in this case, Taipei's international airport (this will be discussed in detail in Section 4).

In addition to the aforementioned three objectives, the first constraint in our model applies to the summation of S_{ij} being greater than or equal to 1. This implies that we should set up at least one fire station at the airport. This is shown in Eq. (4).

$$\sum_i \sum_j S_{ij} \geq 1 \tag{4}$$

where S_{ij}: the decision variable, if a fire station is set up on a x–y coordinate (i,j), then $S_{ij}=1$, otherwise, $S_{ij}=0$. Secondly, from a theoretical point of view, there should be a reasonable distance (d^r_{ab}) between any two fire stations; e.g., fire station a and fire station b. This distance should not only be not too long (d^l_{ab}) for fire stations to support each other but also should not be so short (d^s_{ab}) as to cause overlapping of fire station services. Expressions d^r_{ab}, d^l_{ab} and d^s_{ab} are utilized to construct

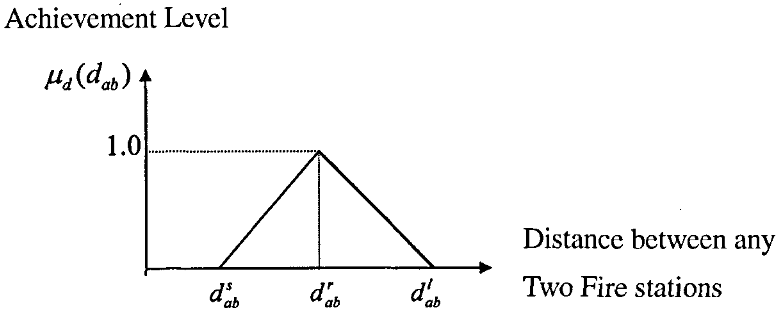

FIGURE 2 The achievement level of distance constraint between any two fire stations.

fuzzy constraints. The membership function $\mu_d(d_{ab})$ of distance between any two fire stations is shown in Eq. (5) and Fig. 2.

$$\begin{cases} \mu_d(d_{ab}) = 1, & \text{if } d_{ab} = d^r_{ab}, \\ \mu_d(d_{ab}) = (d^l_{ab} - d_{ab})/(d^l_{ab} - d^r_{ab}), & \text{if } d^l_{ab} \geq d_{ab} > d^r_{ab}, \\ \mu_d(d_{ab}) = (d_{ab} - d^s_{ab})/(d^r_{ab} - d^s_{ab}), & \text{if } d^s_{ab} \leq d_{ab} > d^r_{ab}, \\ \mu_d(d_{ab}) = 0, & \text{otherwise.} \end{cases} \tag{5}$$

Let $\{S_{ij}\}$ denote the set of $S_{ij} = 1$, let also a and b be any two different elements taken from $\{S_{ij}\}$, then the aforementioned constraint is shown in Eq. (6).

$$|x_a - x_b| + |y_a - y_b| \approx d^r_{ab} \tag{6}$$

where x_a: the i value of element a taken from $\{S_{ij}\}$; x_b: the i value of element b taken from $\{S_{ij}\}$; y_a: the j value of element a taken from $\{S_{ij}\}$; y_b: the j value of element b taken from $\{S_{ij}\}$; $\approx$: the symbol of fuzzy equality. Furthermore, the i and j values are expressed in x–y coordinate form. This presentation coincides with the grid map for rescuing people at an airport. In the next section, Taipei international airport is taken to represent a numerical example, which shows the establishment and working of our model.

3.2. Fuzzy Multi-objective Optimization Model

A fuzzy multi-objective approach is employed for the following reasons. First, the model should be simultaneously optimized for the number and siting of fire stations at an airport. Thus, techniques for optimizing only one single objective are not suitable for such a problem (Cohon, 1976; Fendel and Spronk, 1983; Yu, 1985; Zeleny, 1982). Second, the fuzzy multi-objective approach is quite simple when compared with traditional weighting methods for multi-objective optimization (Bellman and Zadeh, 1970; Fedrizzi *et al.*, 1991; Lai and Hwang, 1994; Sakawa, 1993; Sakawa *et al.*, 1997). Finally, the fuzzy multi-objective approach is more efficient when compared with traditional methods related to utility functions in multi-objective optimization (Chen and Hwang, 1992; Sakawa, 1993).

The basic concept of fuzzy multi-objective optimization is to find the maximal achievement level among constraints of conflicting objectives (Sakawa, 1993). Using Eqs. (1)–(3) as an example, and assuming that the optimistic value of the kth objective ($k = 1, 2, 3$) is f_k^+ while the pessimistic value is f_k^-, the achievement level can then be expressed as in Fig. 3 (Hannan, 1981).

Where $\mu_k(f_k)$ represents the fuzzy membership function of f_k, it also reveals the achievement level of f_k. By using the λ transformation (Sakawa, 1993; Sakawa *et al.*, 1997), and $\lambda = \underset{k}{\text{Min}}\, \lambda$, Eqs. (1)–(6) can be rewritten as in Eq. (7).

$$\begin{aligned} &\underset{S_{ij}}{\text{Maximise}}\ \lambda \\ &\text{subject to} \\ &\lambda \leq \frac{f_k - f_k^-}{f_k^+ - f_k^-}, \quad k = 1, 2, 3 \end{aligned} \tag{7}$$

and Eqs. (4)–(6).

To solve the model in Eq. (7), a two-step optimization approach can reduce the resolution complexity. The first step is to compute the optimal number of fire stations in the first objective ($k = 1$); the second

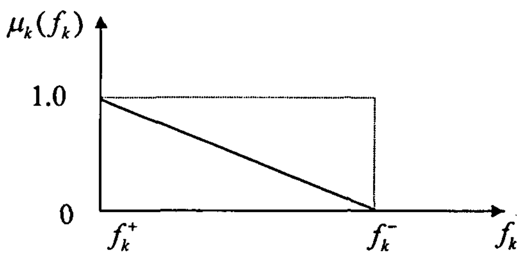

FIGURE 3 The achievement level for fuzzy objectives ($k = 1, 2, 3$).

step is to optimize Eq. (7) with the optimal number of fire stations from the first step. (In Section 4.2, our revised GA and enumeration method are both applied and compared for their resolution efficiency).

3.3. Model Resolution by Revised GA

To solve the mathematical model in Eq. (7), a two-step approach is necessary. The first step is to decide the optimal number of fire stations at the airport; the second step then uses the results from the first step to maximize the global λ under other constraints. For this study, a GA is also developed for the following reasons: (a) the concept of GA is comparatively easy to follow by those who lack a strong background in mathematics; (b) the GA is fully transferable – the other problems which are similar to our study can apply almost the same steps for resolution; and (c) our model is an NP-hard problem, and the GA has been proved to be effective in solving such combinatorial optimization problems (Sakawa *et al.*, 1997). The traditional and basic notion of gene type in GA, e.g., 0010 (Goldberg, 1989), is also applied to form our gene population. But considering the characteristics of our model, we omit the crossover in GA to prevent infeasible solutions and promote self-evolution efficiency – this revised approach is also called the *simple* GA (SGA). Thus, gene type, reproduction, mutation and performance evaluation are re-defined as follows:

(a) Gene type
From Fig. 4, we observe that the range of the x-axis is from 0 to 16, while the range of the y-axis is from 0 to 7; therefore there are 136 ($17 \times 8 = 136$) available sites to set up fire stations at the airport. A 0–1 string of 136 bits is proposed to indicate whether or not to set up a fire station at any specified location (i,j). All S_{ij} are listed from left to right, and the corresponding x–y coordinates (i,j) to S_{ij} are $(0,0), (1,1), (1,2), \ldots,$ $(16,7)$, respectively. Thus, if $S_{ij} = 0$, no fire station is located on the corresponding x–y coordinate (i,j); if $S_{ij} = 1$, a fire station is set up on the corresponding x–y coordinate (i,j). This gene notation is shown as follows:

Gene Type (136 *bit string*): 101 ... 1
Corresponding Coordinate (i,j): $(0,0), (1,1), (1,2), \ldots, (16,7)$.

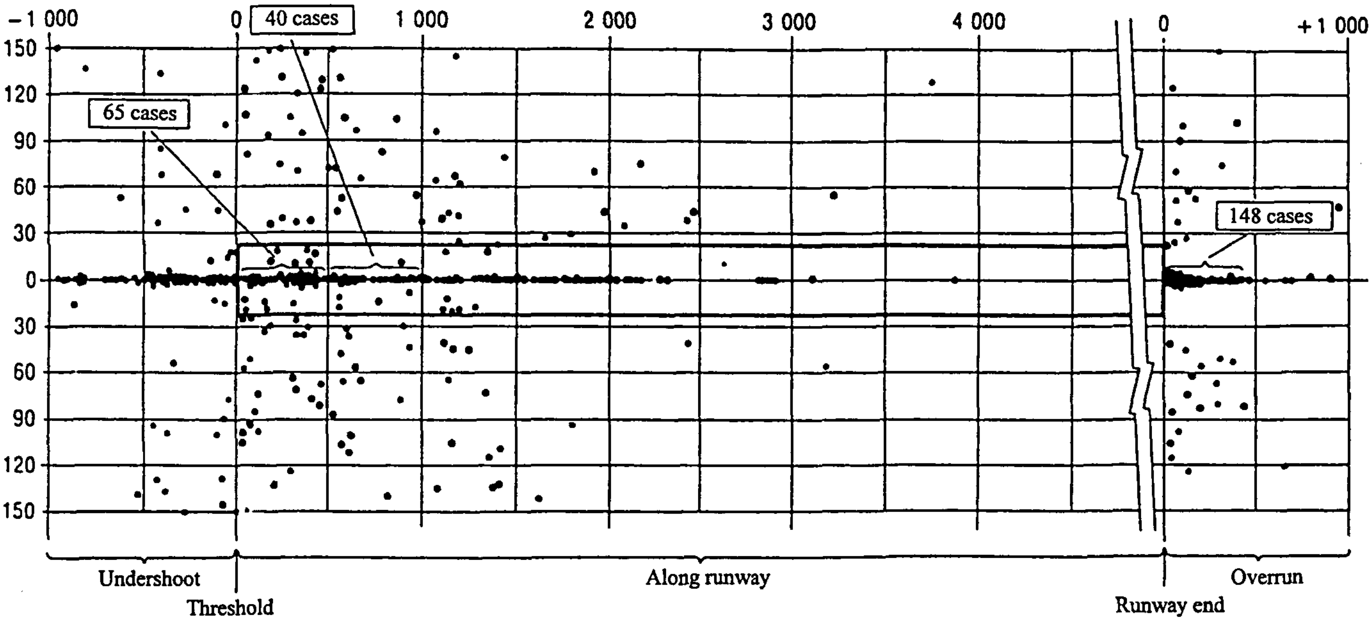

FIGURE 4 Statistical analysis of air crashes around the airport in the world (source: ICAO, 1995).

(b) Reproduction
The reproduction probability (RP) is designed to give a higher reproduction-chance to the gene, which will make λ have a larger value in a gene population. In view of any gene (g) in the gene population, this reproduction probability is shown in Eq. (8).

$$RP_g = \frac{\lambda_g}{\sum_g \lambda_g}, \quad \forall g. \tag{8}$$

(c) Mutation
The mutation is defined as the recombination for a randomly selected gene. First, two cut-points are randomly selected. Secondly, the content between two cut-points is preserved and shifted to the left-hand side. Finally, the gene is recombined from left to right. Mutation in this study is shown as follows:

Parent Gene: 1010010001...1 *Offspring Gene* 1: 1001010001...1

(d) Performance evaluation
The self-evolution mechanism in generations is the important characteristic in GA. A generation in this study is defined as a process to make the gene population undergo rank-selection once, reproduction once and mutation once (no crossover is applied). The rank selection applied in this study tries to find the optimal sets of x–y coordinates, which will finally make λ have the largest value among all possible values of λ in Eq. (7).

4. NUMERICAL EXAMPLE: CASE OF TAIPEI'S INTERNATIONAL AIRPORT

This section follows the procedural steps for a practical application of our location model to Taipei's international airport – this will validate the model's practical applicability and effectiveness.

4.1. Problem Description and Data Collecting

First, in order to compute the risk rank r_{ij} of Eq. (3), the accidents at or near Taipei's international airport from January 1, 1996 to December 31, 1997 are collected and analyzed statistically. Because different kinds of accident occur at the airport, the accident frequency by type is calculated and summarized in Table III.

Secondly, in Fig. 4, the areas where accidents occur are taken from ICAO is statistical and geographical analysis and combined with Table III. Thus, after a conditional probability and normalized computation, the accident frequency rate is obtained for different areas, and this risk-rank table for Taipei's international airport is established, as shown in Table IV.

Thirdly, r_{ij} is assigned to the corresponding area at or near the airport – this is shown in the grid map of Fig. 5. The lower value of

TABLE III Statistical analysis of accident at or near Taipei's international airport

Accident	*Frequency*	*Frequency rate %*	*Accident area*
1. Airplane mechanical failure	30	11.28	Runway/aprons
2. Airplane engine failure	36	13.53	Runway/aprons
3. Airplane landing failure	6	2.26	Runway/aprons
4. Airplane flap failure	8	3.01	Runway/aprons
5. Airplane tire failure	9	3.38	Runway/aprons
6. Airplane going off runway	2	0.75	Runway
7. Oil or fuel leakage	41	15.41	Aprons
8. Building fire	29	10.90	Building
9. Ground crew accident	12	4.51	Aprons
10. Passenger accident	40	15.04	Building/aprons
11. Runway poorly maintained	11	4.14	Runway
12. Hijack accident	2	0.75	Aprons/runway
13. Bomb threat	3	1.13	Building/aprons
14. Others	37	13.91	Building/aprons
Total	266	100	—

TABLE IV The risk rank of areas at the Taipei's international airport

Accident area	*Risk rank* $r_{ij} = 1/AFR$	*Accident frequency rate % AFR*
1. Runway end to nearby areas	1	1.00
2. Approach over 500 m to runway end	2	0.50
3. Approach less than 500 m	3	0.33
4. Building and aprons	4	0.25
5. Others	5	0.20

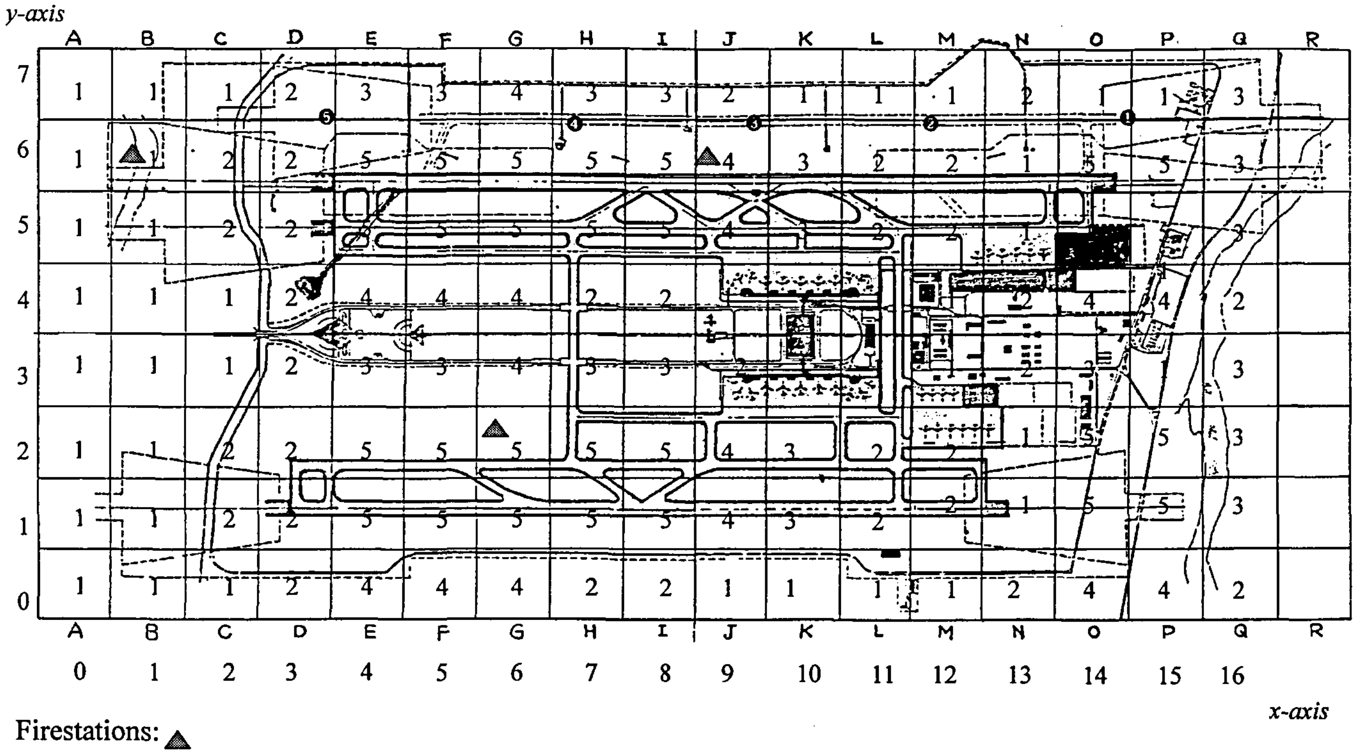

FIGURE 5 The risk rank cubic map of Taipei's international airport.

r_{ij} indicates that there is more chance for accidents to occur in the area of the x–y coordinate (i,j).

Finally, the TLC and SC are computed as follows:

(a) Computing TLC

If there is only one fire station at the airport, the passengers in an air crash have a significantly lower chance of survival due to lack of sufficient rescue and fire-fighting resources. We compute the cost by estimating the number of deaths multiplied by the insurance payment for each. Assuming that there are 250 deaths in an air accident, and life insurance will pay NT$ 13.5 million dollars for each death, the TLC is computed to be about NT$ 3.4 billion dollars (the exchange rate in 1997 was one US$ equals 32 NT$ dollars).

(b) Computing SC

If we try to set up one fire station at the airport, the capital equipment costs (e.g., fire engines, buildings, extinguishers, etc.) and operating costs (e.g., salary and life insurance of fire-fighters, training costs, etc.) are estimated by the relevant authorities at Taipei's international airport to be NT$ 165 million dollars; therefore the SC is estimated to be NT$ 165 million dollars.

Since TLC equals NT$ 3.4 billion dollars and SC equals NT$ 165 million dollars, the optimal number of fire stations at Taipei's international airport would be three by optimizing the first objective ($k = 1$). Moreover, after consulting fire-fighters at the airport, the distances are set to $d^r_{ab} = 8$, $d^l_{ab} = 15$ and $d^s_{ab} = 1$, respectively. Nevertheless, the risk-weighted grid map of Taipei's international airport will be our initial input for optimizing Eq. (7). Moreover, the GA and enumeration method are implemented for comparison.

4.2. Model Resolution by Revised GA and Enumeration Method

To solve the mathematical model in Eq. (7), we first apply GA to solve this location problem. Because the traditional and basic notion of gene type in GA is binary, e.g., 0–1 type, and the decision variable S_{ij} is also 0–1 type, Goldberg's encoding can be applied in a direct sense. After computing the optimal value of f_1, and the ceiling and bottom values for f_2 and f_3, Eq. (7) can be rewritten as in Eq. (9)

by the λ transformation

$$
\begin{aligned}
&\underset{S_{ij}}{\text{Maximise}}\ \lambda \\
&\text{subject to} \\
&\lambda \leq 1, \\
&\lambda \leq \frac{51 - f_2}{51 - 30}, \\
&\lambda \leq \frac{3481 - f_3}{3481 - 1427}, \\
&\lambda \leq \mu_d(d_{12}), \\
&\lambda \leq \mu_d(d_{13}), \\
&\lambda \leq \mu_d(d_{23}), \\
&\sum_i \sum_j S_{ij} = 3.
\end{aligned}
\tag{9}
$$

The rank selection applied in this study tries to find three sets of x–y coordinates: namely, the ones which make λ have the largest value among all possible values of λ. Thus, λ is our performance index used to evaluate any solution (gene) in the GA. The gene population is sorted by the λ value of each gene in descending order. Twenty runs of this GA derived a satisfactory solution after 30 generations. The final result is shown in Table V. In computing terms, it took 20.33 min to find the above results using a Pentium PC computer.

Since the enumeration method can find exactly the optimal location of fire stations at the international airport, this method is used for

TABLE V Fire station sites proposed by GA and corresponding λ value

Fire station sites proposed by GA			*λ value*
Fire station 1	*Fire station 2*	*Fire station 3*	
(1, 6)	(9, 6)	(6, 2)	0.75
(6, 1)	(9, 3)	(0, 3)	0.71
(1, 1)	(6, 5)	(7, 0)	0.71
(9, 4)	(1, 6)	(5, 0)	0.71
(5, 6)	(13, 6)	(9, 4)	0.70
(12, 0)	(5, 3)	(11, 6)	0.70
(5, 0)	(9, 4)	(2, 6)	0.70
(5, 1)	(4, 7)	(0, 3)	0.68
(7, 1)	(4, 4)	(11, 7)	0.60
(11, 6)	(11, 0)	(5, 3)	0.60

comparison with the GA. This enumeration method proceeds by examining all possible combinations of available setup sites for three fire stations so as to achieve the maximal λ value. It took 73.57 minutes to find an optimal λ of 0.78.

4.3. Results and Discussion

From the GA, three sets of fire-station site are obtained, whose x–y coordinates are $(1,6)$, $(9,6)$ and $(6,2)$. The final achievement level is 0.75. These three fire stations can be identified in Fig. 5 by the triangular symbols. Comparing the GA and enumeration methods, GA used less computing time than the enumeration method (20.33 min vs. 73.57 min), yet still yielded a satisfactory achievement level between conflicting objectives ($\lambda = 0.75$ vs. $\lambda = 0.78$). Therefore, the GA demonstrated its feasibility and effectiveness in this study. Furthermore, the GA should be able to solve efficiently larger-scale location problems of other emergency facilities. This means that many optimal sites (e.g., three or many more than three sites) for any emergency facility can be easily derived from our model, which is very easy to operate and can be a powerful decision support when deciding location problems.

5. CONCLUSIONS

The tragic crash of the China Airlines aircraft near Taipei's international airport in February 1998 stimulated relevant authorities around the world to study more advanced topics for promoting the reaction efficiency of fire protection and rescue at airports. The siting and number of fire stations are factors heavily affecting reaction efficiency. The location model developed in this paper, using a fuzzy multi-objective approach in order to decide the optimal number and sites of fire stations, has shown that it can be applied successfully at Taipei's international airport. Furthermore, because of the combinatorial complexity in resolution, the GA was employed and proved to be effective when compared with the enumeration method. In addition, our model has the potential to be expanded to devise solutions for the optimal location of other emergency facilities.

Secondly, this study still leaves much room for modification and further development. For example, re-formulating and validating the risk-cost, constructing fuzzy risk-weights to reflect the uncertainty of accidents, dynamically updating the parameters in the model for sensitivity analysis, and expanding the scale of this model so as to optimize any similar location model for other facilities.

Finally, this study can be regarded as providing a basis for the development of a decision support system (DSS) which, combined with a geographic information system (GIS), could assist decision making for emergency location problems or rescue problems in real situations.

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