

Towards Adaptive Aircraft Landing Order with Aircraft Routes Partially Fixed by Air Traffic Controllers as Human Intervention

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Abstract. This paper focuses on how cognitive loads of air traffic controllers can be reduced when optimizing both aircraft route and landing order in the airport landing problem (ALP), and proposes its method which can adaptively change the optimized aircraft landing order according to the aircraft routes partially fixed by air traffic controllers as human intervention. Though the intensive simulation on Haneda Airport in ALP, the following implications have been revealed: (1) our proposed optimization method succeeded to mostly maintain the same level of the results without fixing some of aircraft routes (i.e., the mostly same total distance of all aircrafts from the start position to the destination airport) even if air traffic controllers fixed some of aircraft routes; and (2) this result indicates that our proposed method has a great potential of reducing the cognitive loads of air traffic controllers by reducing the number of aircrafts that should be watched with fixing some of aircraft routes.

1 Introduction

For safe aircraft control, air traffic controllers give appropriate directions to aircrafts because they cruise at high velocity and it is difficult for pilots to independently operate aircrafts without aircraft collision. Since environment has occasionally changed by (e.g., sudden turbulence or a congestion of aircrafts), air traffic controllers consider safety for aircraft as a primary option. When the number of aircrafts in the airspace increase, cognitive loads of air traffic controllers extremely increase, which may prevent from keeping their concentration. Furthermore, air traffic increases every year, which demands more liability of air traffic controllers. For this issue, it is needed to reduce their cognitive load while optimizing both aircraft routes and their landing order [1]. Regarding the landing order optimization problem for aircrafts, Xiao proposed the binary-representation-based genetic algorithm method that can evolve the landing orders of the aircraft by evolutionary computation as the aircraft arrival order and scheduling problem [4].

2 Current Air Traffic Management

A method of air traffic control is different from Regarding to a method of air traffic control, it differs according to countries. Airspace is divided into some segments called sector and aircrafts are managed every sector. The air traffic controllers instruct appearance of aircrafts in this sector to change directions and velocity adjustment. In an airport, air traffic controllers consider a relation between aircrafts and should determine landing routes and an order for aircrafts. For this reason, air traffic controllers have a great work load of air traffic control in the airport. They determine the order for aircrafts based on FCFS(First Come First Serve). FCFS is a rule to determine order of arrival aircrafts based on estimated arrival time. If the aircraft's landing interval to the airport is short, air traffic controller gets the aircraft to take a detour route in order to change the arrival time. This is the rule to reduce the cognitive loads of air traffic controllers but this rule has a problem in a point of efficiency of a runway capacity. In rush hour of arrival and departure aircrafts on an airport, ATFM (Air Traffic Flow Management center) command to delay aircrafts in Japan to avoid being crowded aircrafts in the particular area. However this system does not deal with increasing the demand for aircrafts for these reason, Air traffic controllers hope the system which is less cognitive loads of air traffic controllers and the landing order optimization method to reduce the occupancy time of an arrival airport. From an interview with air traffic controller, the main three factor effect on their workload are the number of tasks at the same time, constraint on time and duration of time. There is a high relation between the number of aircrafts and the mental workload [3].

3 Conventional Method

L. Bianco proposed a scheduling model for aircraft which simulates a real environment to generate landing order [2]. H. Xiao proposed an optimization method which is based on Genetic Algorithm (GA) using Bianco's model. His optimization method successfully produced a landing order to minimize the occupancy time of a destination airport because this method takes into consideration a size of aircraft [4]. The Size is a significant impact on landing time interval (LTI), also different interval by the leading and follower of the aircraft. For example, LTI of 228s is needed for a category 1 to follow a category 4. This asymmetric relation is a key factor in this optimization. To solve ALP, the total airborne delay has to be minimized. The following formula represents the total airborne delay.

$$A_{Q(n)} = \begin{cases} P_{Q(n)} & n = 1 \\ \max(P_{Q(n)}, A_{Q(n-1)} + S(C_{Q(n-1)}, C_{Q(n)})) & n > 1 \end{cases} \quad (1)$$

$$D_i = A_i - P_i, \quad i = 1, 2, \dots, N_{AC} \quad (2)$$

$$\min_{Q(1), \dots, Q(N_{AC})} J_1 = \min_{Q(1), \dots, Q(N_{AC})} \sum_{i=1}^{N_{AC}} D_i \quad (3)$$

Table 1. Minimum LTI

(seconds) Category of following aircraft

	1	2	3	4
1	96	200	181	228
2	72	80	70	110
3	72	100	70	130
4	72	80	70	90

Category of leading aircraft

1;B747 2;B727 3;B707 4;DC9

N_{AC} aircrafts are planning to land an destination airport during operation day, and C_i , P_i and A_i are the category of aircraft size, the predicted landing time and the ALT of the i th aircraft in the first predicted arrival order. $Q(n)$ is the n th aircraft in the optimized landing order. $S(i, j)$ is the LTI for an aircraft of category j to follow an aircraft of carefory i to land. D_i is a difference of i th aircraft optimization time and the original prediction arrival time. The initial landing time is setting on by the principle of FCFS. Note that this method does not consider the landing route of aircraft. This means, it can produce an adequate landing order so that reducing the occupancy time, and so it is still unclear how a landing route should be designed to follow the decided the landing order (Table 1).

4 Proposed Method

4.1 Aircraft Routes as Path Planning

As shown in Fig. 1, This figure shows the overview of the previous method, which consists of landing route and the landing order unit as a hierarchical structure. First, Landing route unit generates candidates of each aircraft landing route, for example, X candidates represented by blue, red and green line routes are generated as shown in this figure. After such a generation, the unit selects the top some amount of candidates, for example, the top Y amount of X candidates are selected as shown in this figure. Finally, the selected main route as appropriate landing order is added sub-routes. Then the candidates are evaluated in terms of two aspects; (1) the total distance of main route from the current position to the destination airport and (2) the diversity of the routes can be quantified based on novelty search [5]. Thus, this unit eventually produces the landing routes which indicates small distance to the destination airport and can be customized for adapting as many situations as possible. Note that the routes that pass on the prohibit area is identified as infeasible solution. Each candidate of main landing route (i.e., the gene) is generated by NSGA-II [6]. Then, if the generated route is feasible solution, sub-routes are added to the generated main landing route (see Fig. 3) by the following steps; Sub-route algorithm (Fig. 2).

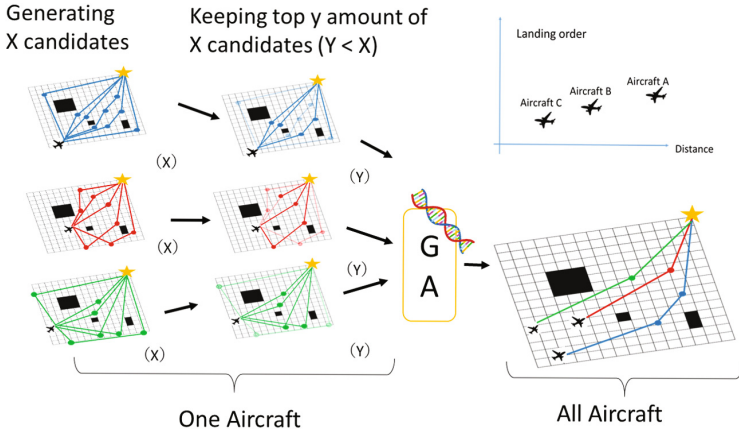


Fig. 1. Overview (Color figure online)

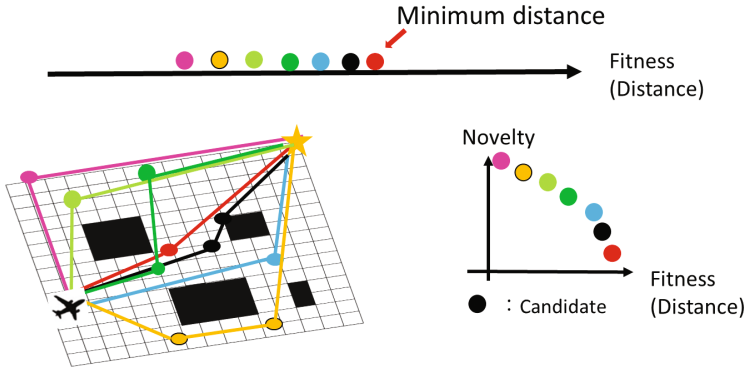


Fig. 2. Evaluating candidates of route

- Step 1: For one of main route, calculating each the distance between the way points.
- Step 2: Creating a square of distance r that center is a midpoint between the way points and a point on the vertical bisector randomly is determined. This point becomes new way point.
- Step 3: New route that the new way point created in Step 2 is added is calculated the evaluation value.
- Step 4: This route is saved as one of sub-route if the limitations of this route are met.
- Step 5: Repeating from Step 2 to Step 4 until the termination condition is satisfied.

After adding the sub-routes to each landing route, they are evaluated with the fitness function and applied to genetic operators (i.e., the crossover and

mutation) to find better solutions with a high fitness which have small distances to the destination and many sub-routes. Overall procedure can be described as follows; Calculating fitness of each route in terms of the distance to the destination airport and the number of sub-routes. Selecting routes as parents and copying them as the offspring. Then, the crossover and the mutation are applied to generated offspring. Producing a next generation population by the non-dominant sorting and degree of congestion tournament selection. Evaluation function Each route is evaluated based on two factor. One is a distance to the destination airport. The other is a robustness for changing environment. An evaluation function for the distance is as following equation.

$$\text{Distance evaluation} = \frac{1}{\text{distance}} \quad (4)$$

Where distance indicates total length of the route. From the equation, the shortest distance to the destination airport is the maximum evaluation value of the candidates. Next, an evaluation function of the diversity is calculating as follow.

$$\rho(x) = \frac{1}{K} \sum_{n=1}^k \text{dist}(x, \mu) \alpha \quad (5)$$

$$\alpha = a \left(\frac{\text{distance}}{d_{\text{min}}} - 1 \right) \quad (6)$$

Novelty-search is the radical evaluation method for individual solutions corresponding to landing routes. Novelty-search measures how solution is unique in all of them and novelty metric for solution Where ρ is calculated as shown in this equation, μ_i indicates the individual which is i th-nearest neighbor in the population and x means the evaluated individual. The “dist” function is used *Euclid*($\|x - \mu_i\|$) as usual. For scoring novelty, a target group as the neighbor is used an archive or the population which is current generation. The number of K is vary from the population and problems, and algorithms. K value is most used 15 [7].

4.2 Arrival Sequence Optimization

Figure 4 shows the overview of the arrival sequence optimization unit. This unit execute GA to search appropriate combination of routes for aircrafts. The arrival sequence optimization unit picks out the top N candidates by the non-dominant sorting and degree of congestion tournament selection and searches the best combination of landing routes for some aircrafts by GA [8]. Each solution is represented in the integer type of gene and each locus indicates the selected route with each aircraft. This unit takes the following steps;

Step 1: Selecting one route for each aircraft.

Step 2: Checking on interval of aircraft whether meet constraint condition or not.

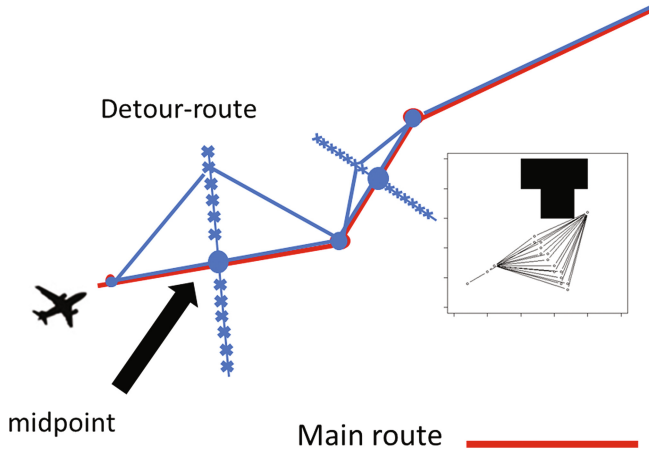


Fig. 3. Detour routes

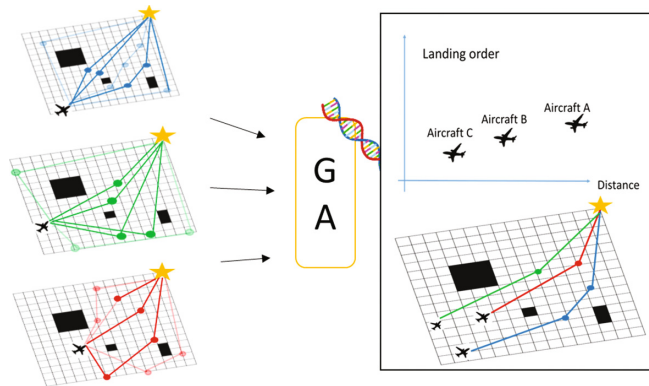


Fig. 4. Select arrival order

- Step 3: Calculating evaluation value that meets limitation.
- Step 4: Selecting parents from among solutions that meet limitation by using tournament selection.
- Step 5: Crossing between parents and mutation.
- Step 6: Repeating from Step 2 to Step 5 until the termination condition is satisfied.

The following is described the limitation condition that a solution meet, how to calculate evaluation value of the solution (Step 2 and Step 3) and how to mutate and crossover (Step 5) in detail. Constraints and evaluation value after generating of the combination of routes for some aircrafts, the arrival sequence optimization unit determines the landing order of aircrafts. Here, when the landing order indicates that the interval between each aircraft's landing is small,

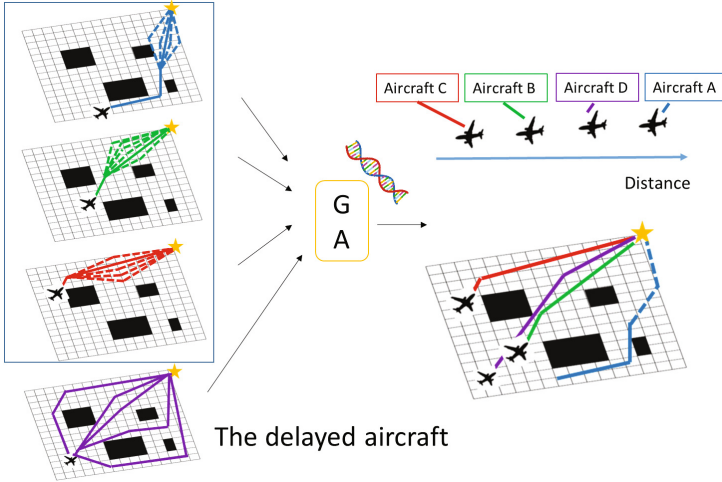


Fig. 5. Select detour route (Color figure online)

its landing order can be identified as infeasible since for safe landing, an enough interval is required. Thus, to identify the generated landing order either one of feasible solution or infeasible one, we add the following constraint condition for landing order;

$$r > distance_p - distance_n \tag{7}$$

Symbol $distance_n$ and $distance_p$ represent the distances to the destination of two aircrafts n and p; thus $distance_p - distance_n$ represents the interval between the two aircrafts. Then, if the interval is larger than a threshold r for all possible route combination of two aircrafts, its landing order is identified as a feasible solution. Additionally, to evaluate the generated landing order we introduce the following equation as calculation of fitness;

$$Fitness = \sum_{n=1}^m distance_n \tag{8}$$

The fitness of landing order is simply calculated as the summation of distance of each aircraft. It is the distance of main route. Thus, the small value of fitness means that its landing order can reduce the occupancy time of the destination airport. Crossover and mutation This employ the uniform crossover and the mutation changes each gene locus to a random value with a certain probability. After this step, main route of each aircraft is determined and these aircrafts are cruising on landing route. If it occurs unexpected situations such as appearance of new aircrafts, the aircraft which determined main route takes an opportunity to select sub-route. In case of this, arrival order generating unit replace sub-routes for main routes and research the best combination of landing routes by GA (See Fig. 5). The landing order optimization unit recalculates the landing

order applying detour routes. In this figure, three, blue, green and red aircrafts select their own detour routes and the other delayed purple aircraft selects a landing route. Such an appropriate combination of all routes is searched by GA. Then the landing order is determined.

5 Experiment

5.1 Experiment Setting

We conduct experiments on the grid map as introduced in [9]. As shown in Fig. 6 is a grid-map where the aircraft was flying. Noted that the black squares represent obstacles which indicate a prohibit area. Around Haneda airport, are set up outbound aircraft from this airport and for military purpose. Two dimensions map and this map we use here is a $250 \text{ km} \times 250 \text{ km}$. In this experiment, we use Haneda airport as a reference. This airport is highest air traffic in Japan. Aircrafts which arrives at Haneda airport come from east or west. There are four runways so from east and west side aircraft can own runway separately. Given this situation, we take scheduling only west side.

Table 2. Parameter

Path Planning		Arrival Schedule Sequence	
parameter	value	parameter	value
populationsize	100	population size	100
generation	500	generation	1000
crossovertime	1	crossover rate	1
mutationrate	0.7	mutation rate	0.3
k	15	constraint	9.26
a	10		

We define forty aircrafts are staying at the starting area denoted by the blue-rectangle in the figure. To investigate whether our method successfully optimizes its order that reduces the occupancy time of the destination airport, we conduct the following one experimental case; This system optimizes each aircraft route and arrival order at five minutes intervals The maximum number of appearance aircrafts is three at one time. About thirty aircrafts land on Haneda airport per an hour, therefore average appearance aircraft is considered three. Each aircraft chooses an appropriate route which is considered interval of length of another aircrafts routes. Once aircraft routes had been determined, the aircraft must cruise along the course of chosen route. We conduct three steps per one seed and 10 trials. In comparison to proposed method, we conducted four methods. (1) the first method is the all fixed landing route method. Once the arrival optimization unit determine each landing route, Aircrafts does not select a detour route in this method. (2) this method is called the partially fixed landing route.

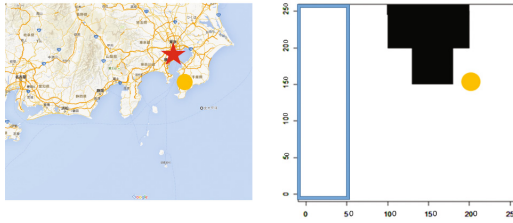


Fig. 6. Map (Color figure online)

This method is almost identical to the all fixed landing route method. This method is different in that some aircraft have a opportunity to select a detour route in comparison to that. In this experiment, the one aircraft selected randomly does not select at one step. (3) Third method is called No fixed landing route. This method selects a detour route of all aircrafts. (4) In this method, we change the evaluation which use only *Distance evaluation*.

We used the following parameter setting for NSGA-II and simple GA (Table 2).

6 Result

Table 3 indicates the value of the total distance every step for each method. Figure shows the experiment result. Figure 7 indicates the total distance for each

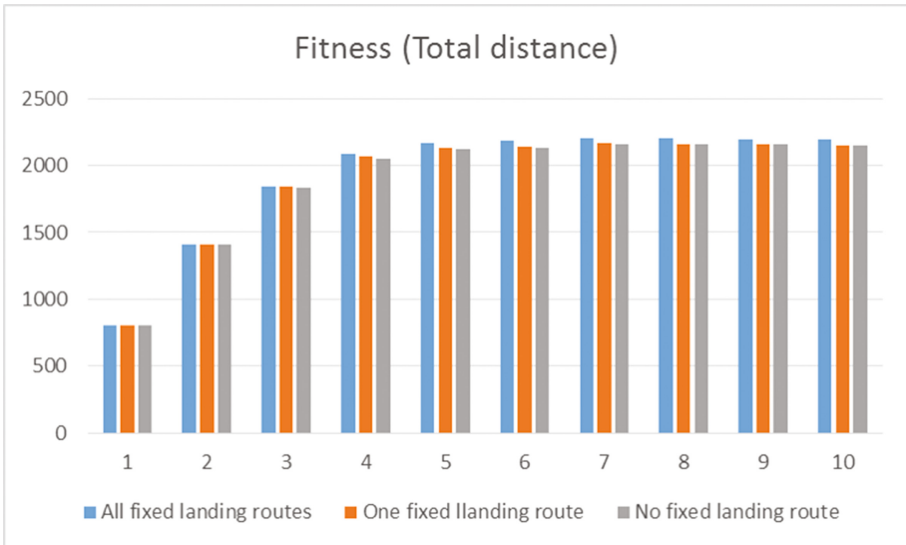


Fig. 7. Total distance (Color figure online)

Table 3. Total distance value

Step	All fixed landing route	One fixed landing route	No fixed landing route
1	799.886	799.886	799.886
2	1410.877	1410.877	1410.877
3	1843.04	1838.889	1832.655
4	2083.344	2066.65	2053.593
5	2166.057	2134.609	2127.239
6	2182.452	2144.567	2136.06
7	2200.697	2168.342	2156.187
8	2200.414	2162.278	2158.935
9	2196.006	2162.478	2159.398
10	2191.331	2152.006	2149.272

Table 4. The number of feasible solution (GA)

Step	The number of feasible solution (GA)
1	2
2	1
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0

step. The vertical axis means averages of total distance over 10 experiments and horizontal axis means each step. The blue bar shows the total distances by all fixed landing route (without employed detour routes), The orange bar shows the total distance by a part of fixed landing route and the black shows the total distance by applied detour routes. Table 4 indicates the number of feasible solution of the arrival order.

As you can see this Fig. 7, the result of No fixed landing route is the best performance in all step of all and it found that detour routes contributed to reduce the occupancy time of the arrival airport. The result of all fixed landing routes was worst performance of the three, but this method could generate feasible solution of the arrival order in all steps. Because, Each aircraft generated a variety of landing routes of distance. The less aircrafts employed the detour route, the less air traffic controllers have cognitive loads. That is, to employ

much detour routes cause increasing the directions. On the other hand, The GA hardly generated a feasible solution because this method could find the shortest route from to the destination airport and this had not mechanism to search a variety of candidates of distance. For this reason the evaluation based on novelty search had a good effect on generating diversity of distance and it is useful to reduce the cognitive loads of air traffic controllers.

7 Conclusion

This paper focused on how cognitive loads of air traffic controllers can be reduced when optimizing both aircraft route and landing order in the airport landing problem (ALP), and proposes its method which can adaptively change the optimized aircraft landing order according to the aircraft routes partially fixed by air traffic controllers as human intervention. Concretely, our proposed method consists of the aircraft route and the landing optimization units as a hierarchical structure. In this method, some aircrafts select detour routes, while the other aircrafts do not select detour routes. To investigate effectiveness of the proposed method, we tested it on the grid map of Haneda Airport in ALP. The experimental results revealed the following implications: (1) our proposed method could optimize the aircraft routes and their landing order even if the aircraft routes are fixed by the air traffic controllers. In detail, our proposed optimization method succeeded to mostly maintain the same level of the results without fixing some of aircraft routes, i.e., the total distance of all aircrafts (from the start position to the destination airport) with fixing some of aircraft routes is a little bit worse than without fixing some of aircraft routes. which some aircrafts are fixed landing route is as short as that one which all aircraft can select the detour route. (i.e., the mostly same total distance of all aircrafts even if air traffic controllers fixed some of aircraft routes; and (2) this result indicates that our proposed method has a great potential of reducing the cognitive loads of air traffic controllers by reducing the number of aircrafts that should be watched with fixing some of aircraft routes. What should be noticed here is that the result has only been obtained from the specific case, i.e., the Haneda Airport. Therefore, further careful qualifications and justifications, such as an investigation to the other airports, are needed to generalize our results. For an actual application, the advices or comments from air traffic controllers are needed.

References

1. Bennell, J.A., Mesgarpour, M., Potts, C.N.: Airport runway scheduling. *Ann. Oper. Res.* **204**(1), 249–270 (2013)
2. Bianco, L., Dell’Olmo, P., Giordani, S.: Scheduling models and algorithms for TMA traffic management. In: Bianco, L., Dell’Olmo, P., Odoni, A.R. (eds.) *Modelling and Simulation in Air Traffic Management*. Transportation Analysis, pp. 139–167. Springer, Heidelberg (1997)

3. Aoyama, H., Shiomi, K., Iida, H.: Study on Cognitive Process of Air Traffic Controller in En-route Control, Technical report of IEICE. SANE, vol. 107(67), pp. 7–12 (2007)
4. Hu, X.-B., Chen, W.-H.: Genetic algorithm based on receding horizon control for arrival sequencing and scheduling. *Eng. Appl. Artif. Intell.* **18**(5), 633–642 (2005)
5. Lehman, J.: *Evolution Through the Search for Novelty*. University of Central Florida Orlando, Florida, Diss (2012)
6. Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.: A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **6**(2), 182–197 (2002)
7. Cuccu, G., Faustino, G.: *When Novelty Is Not Enough*. Springer, Heidelberg (2011)
8. Golberg, D.E.: *Genetic Algorithms in Search, Optimization, and Machine Learning*, p. 102. Addison-Wesley, Reading (1989)
9. Tajima, T., Nakano, K., Ichikawa, M.: A real-time path planning using genetic algorithms. *J. Jpn. Soc. Artif. Intell.* **10**(14) (1995)