A Revised Particle Swarm Optimization Model of Airplane Evacuations

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Abstract. Aircraft accidents such as the Sukhoi Superjet 100 aircraft crash on May 5, 2019 at Sheremetyevo airport recently have drawn the public attention, requiring a safer evacuation plan and aircraft designs. In this paper, we conduct an evacuation model based on Particle Swarm Optimization (PSO) algorithm. Also, we learn from the PSO with emotion factor algorithm which shows that increasing the emotion raises the average velocity and decreases the repulsion force exerted by neighbour passengers. Our simulations also suggest that adding reaction time and blocking the exits increase the evacuation time significantly. In addition, we conduct simulations that incorporate passengers carrying luggage, according to the real-life scenarios, which has longer evacuation time.

1. Introduction
On May 5, 2019, the Sukhoi Superjet 100 aircraft was struck by lighting crashed while landing at Sheremetyevo airport. 41 out of 73 passengers and five crew died. Some passengers failed to escape because people in the front blocked aisle to save their luggage. According to Flight Safety, by June 27, 79 accidents have occurred in the database in 2019. This paper investigates in some factors that affect evacuation, which helps to improve passengers’ safety.

“The Federal Aviation Administration (FAA) published a 90-second evacuation regulation that aimed to set the evacuation safety criteria and to reduce the number of disasters”[1]. This regulation ruled that in specific conditions, aircraft must be totally evacuated in less than 90 seconds[2]. 20 full-scale evacuation demonstrations have been conducted since 1969, however, it is reported that 6% of the participants on average receive injuries, such as scrapes, bruises and broken bones[2]. In addition, over 7000 volunteers have been put into the investigation not to say real air-crafts, which use up a large number of resources. Fortunately, as the development of technology, computer simulation thrives and can be used to model real situations, which gives a more accurate and reliable result. Moreover, computing can model with consideration of various factors in real situations that may affect evacuation. This provides a better solution to improve safety.

Currently, there are two main types of evacuation models: macroscopic approach and microscopic approach. “Macroscopic approach focuses on the general behaviour of a large population of passengers and treat them as a fluid.”[3] Multi-agent continuous evacuation modelling based on large-scale evacuation by Enrich Ronchi et al. can be one example, identifying the main factors that will affect the evacuation as a whole. While microscopic approach tracks the movement of each passenger.
In this paper, we care only about the microscopic approach. Although indeed macroscopic approach can provide better results when the population is large, microscopic approach can involve various factors that may affect the evacuation time and this gives a more reliable prediction. For example, Yuan Cheng et al. developed a cellular automata model, investigated the connection between inspiration levels, as well as learning rate, and the frequency of cooperation[4]. Shaobo, Liu et al. also used this model but simulated different factors. They focused on the effect of occupant density on evacuation[5]. Cirillo, Emilioet al. proposed a lattice model considering evacuation in an invisible situation and giving the limitation of buddyng threshold[6]. Unlike the cellular automata or other nodes models, PSO allows passengers to infringe others’ spaces, which helps stimulate more accurate and gives a better consideration of reality. Particle Swarm Optimization algorithm (PSO) is based on the observation of the social behaviour of animals, considering the random behaviour of every individual and the effects of the companions, which is a microscopic approach. Junyuan, Lin et al. first applied the emotion factor in the PSO and investigated with the comparison of simulation with emotion and without emotion, this tells that emotion plays an important role in evacuation model[3]. Besides, Xuan Ta et al. investigated emotion in the evacuation process, analysing fear-related emotion and its positive effect by simulations[7]. Bangquan, Liu et al. used a combination of two models (geodesic path model and hydrodynamic emotional model) incorporate the influence of emotion (including positive and negative emotion) and situations in different scenarios[8].

There are some modifications, in this paper, we consider the reaction time and simulate evacuation with barriers in different parts of aisles, which gives the consideration of the situation that passengers block the way for their luggage. In total, modifications can be concluded as:
1) Considering reaction time
2) When simulating, consider barriers in different parts

When simulating, we assume that all the passengers are on their seats as they are asked to when there is an emergency, so pre-movement time is not taken into account. In addition, passengers with different genders and ages will have different behaviours in the evacuation, but it is nearly impossible to compute the model with consideration of these factors, this paper will only focus on the general behaviour of individuals. Our goal is to study how factors mentioned above will affect the evacuation path of individuals and evacuation time as a whole. We hope our model can offer a better understanding of passengers’ behaviour so that leads to safer design of the aircraft.

2. Particle Swarm Optimization

Particle Swarm Optimization is motivated by the regularity of the bird’s cluster activity. When birds flock, they get food information from their partners who are the nearest to the object and the whole bird-group moves towards that direction with the influence of group emotion and the individual will until food is found. PSO is based on this kind of activity, which starts from a random set of particles, finding an optimum solution by iteration. This algorithm was introduced by Kennedy and Eberhart in 1995 and it was a new Evolutionary Algorithm[9]. Since it was introduced, PSO has been applied to various fields. For example, in 2005, Bo, Liu improved this algorithm and used it to model chaos[10]. In 2003, Gaing used PSO to solve the economic dispatch problem in power system.[11]

The current position of particles is updated by their velocities and is affected by social behaviour. After the initial position and velocities are specified, the position $x_i^k$and velocities $v_i^k$are updated at each particle, where $k$ is the number of iterations and $i$ is the index of the particle[3].

There are three factors that affect a particle’s velocity: inertia movement, particle self-search and group influence. The inertia term which shows the tendency that each particle would consist its original speed and direction. The self-search part describes personal best position observed by each particle, which they tend to move towards. Group influence term is based on the best position observed by the whole group, which is compared at each iteration. This is described as the global best position. All the particles share information about this point and are attracted to it. These three terms update the velocity and the equation is shown below.
Here, \( n \) is the inertia factor which is normally smaller than 1; \( s_1 \) and \( s_2 \) are the strengths of self-confidence and swarm-confidence; \( b_i^p \) is the personal best position of particle \( i \) at current move \( k \); \( b_i^g \) is the position of particle with best global fitness at current move \( k \); uniform random variables on (0,1) are \( R_i^k \) and \( R_i^s \) [3].

3. Modified PSO Model

Particle Swarm Optimization (PSO) as mentioned above is particles finding an optimum solution by iteration based on best position observed by individual and the group. Here, we modified the formula to make it better fit our plane evacuation situation. Differences are mainly in these three parts: particle self-search, group influence and collision part.

Particles search for the best place which is the exit near them in this evacuation situation. In the modified model, each particle is led by a fitness function which describes the current environment and the environment is modelled by a potential function that describes the overall structure of the plane (includes seats and exits). The local self-search of the particle is calculated by finding the gradient of the potential function at its position[3] which is calculated by the hill function as shown below. The gradient of each particle is shown in figure 1 below and it is based on the real situation.

\[
\nabla h(\nabla f) = \frac{\nabla f}{h_0 + |\nabla f|}
\]

\( \nabla h(\nabla f) \) is (1) \( x_{k+1}^i = x_k^i + v_k^i + \Delta t \)
\( v_{k+1}^i = v_k^i + s_1 R_k^1 (b_i^p - x_k^i) + s_2 R_k^2 (b_i^g - x_k^i) \).

\[
(1)
\]

Figure 1. Gradient field corresponding to the potential function shown in Figure 2

The seating is designed down towards the aisle which shows the natural tendency of passengers moving towards the aisle. The aisle is inclined towards the nearest exit and this represents the emergency lights that lead passengers towards the exits. Here in our model, considering the exits and
the number of rows, we divide the plane into two parts and set the aisle slope towards the front exits and back exits respectively. Also, the row of the exits is designed incline towards the exits. These base the gradient of each particle. The potential function of Sukhoi Superjet 100-95B is shown in figure 2.

The swarm influence term is also different from the previous one. In the previous PSO, particles look for the best position based on global best fitness and share the information of best position with the whole group. In our model, passengers will move towards the nearest exit instead of searching for the global best position themselves and this avoids particles move towards exits far away from them. Emergency exits locations are clear to passengers as they are marked on the plane and noticed on the information card. To consider extreme situations, we reduce the information of the exits by reducing the effect of the global fitness term. Here, we use the hill function to reach the purpose.

$$h = \frac{x}{\text{const}+|x|}$$  \hspace{1cm} (3)

The collision term is added as considering the repel force between individuals. In previous PSO, particles move quickly and can squeeze together. However, in our plane model, passengers tend to avoid staying too close to each other and will not take the place of others’. Here, we calculate the effect of repelling force by the formula below.

$$\sum_{j \neq i}^{N} \text{Repel}(|x_j - x_i|)$$  \hspace{1cm} (4)

Figure 2. The potential function for SSJ100-95B measured in inches
Here, $\text{Repel}(r) = \frac{1}{r^2}$ which is the repulsion force between the two agents. The whole equation we modified based on our model is shown below.

$$
\begin{align*}
    x_{k+1}^i &= x_k^i + v_{k+1}^i \Delta t \\
    v_{k+1}^i &= n v_k^i - \sum_{j \neq i}^N \text{Repel}(|x_j - x_i|) + s_i R_i (h(\nabla f(x_j^i))) + s_i R_i^2 h(b^i - x_j^i)
\end{align*}
$$

(5)

3.1. PSO simulations

The plane Sukhoi Superjet 100-95B has one business class with three rows and one economy class with 15 rows. Each row of the economy class has two seats on the left and three seats on the right, which is special. There are 12 seats in the business class and 75 seats in the economy one. We assume that all the seats are occupied and all the exits are available with $\Delta t = 0.05$ . Structure of the plane is shown in figure 3.

In our simulation, we delete the barrier in front of the business class of the first row on the right as there are few people choose to escape from the exit on the right in the front. Particles avoid the barriers and seats in the simulation, and they would not take the space of other particles because of the repel force between them. Figure 4 is the snapshot of the plane at different iterations.

![Figure 3. Seating arrangement for SSJ100-95B](image)

Within 80s, all of the passengers escape from the plane and 95% of them leave within 74s with 90% leave within 70s. The last 5% use more time to escape as the rest of them feels less attraction force because the data of the particles that have already escaped would be deleted. We also have observed that particles in row 9 and 10 search the front and the back to determine the best exit. Also when particles come to the middle of the exit row, they will also make a choice whether to go to the left or right exit. The last agents that escape the plane are particles in row 16, 17 and 18 especially
particles on the right (with three seats per row) as there is a repel force between each particle, as a result, they experience the repulsion from the particles that are already at the aisle. Besides, rows on the right have one more seat than that on the left so they have a lower row strength, which means it takes them a longer time for them to move to the aisle.

![Diagram of SSJ100-95B at different iterations](image)

**Figure 4.** Snapshot of SSJ100-95B with no emotion at t=1, 50 and 100 iterations

4. Revised PSO with emotion
In real situations, passengers tend to feel panic and their emotion raises when there is an aircraft accident. It is proposed by Tetsuya et al. in 2011 that this abnormal evacuation behavior of panic agents generates time delays in the evacuation flow towards the exits [12]. As a result, it is necessary to consider the emotion factor in the aircraft simulation. $e$ is the emotion factor we added and it ranges from 0 to 1 where 0 represents calm and 1 is extreme emotion. We assumed that when a passenger encounters an accident, the emotion level raises to 1. The emotion factor will update based on the surroundings. Particles adjust the emotion also under the influence of their neighbour and finally decays to zero gradually. In our model, we assume that the rise of emotion will increase the velocity of particles as well as the force exerted on other agents, but reducing the repulsion of barriers such as the seats.

$$e_{k+1}^i = -\alpha e_k^i + \frac{1}{N_e} \sum_{i=1}^{N_e} g(e_k^i - e_k^j)$$

(6)

Here, $\alpha$ represents the emotion decay. $e_k^i - e_k^j$ is the emotion difference between particles.

$$g(d) = \begin{cases} \lambda d & d > 0 \\ \frac{\lambda}{2} & d < 0 \end{cases}$$

(7)

This represents the agent to agent spread of emotion. $\beta$ is a constant that decides the pace of emotion spreads. The updated formula is shown below:

$$x_{k+1}^i = x_k^i + v_{k+1}^i \Delta t$$

$$v_{k+1}^i = v_k^i - \sum_{j\in N} \text{Repel} \left( \frac{|x_k^i - x_k^j|}{1 + (e_k^i - e_k^j)} ight) + s_R R_e^i (h(\nabla f(x_k^i))) + s_b R_b^i (h(x_k^i - x_k^j)(1 + e_k^j))$$

(8)

4.1. PSO simulation with emotion

In order to model the real situation, we block the two exits at the back and also simulate a fire spreading towards the front. Particles change from color blue to dark pink and then light pink immediately as emotion factor increases from 0 to 1. Those that are far from the fire change color more slowly as their emotion is gradually increasing with the advance of the fire. Compared to the non-emotion simulation, the velocities of particles increase in general. Also, particles tend to squeeze together, which means the space between two particles decrease. This is shown in figure 5 at different iterations. All the particles evacuate within 71 seconds, 95% within 66 seconds and 90% within 63 seconds.
4.2. PSO simulation with emotion and reaction time
In reality, people have reaction time when they face an emergency. Different people will have different reaction times which depend on the emotion and their body functions. In evacuation, reaction time plays an important role as it is a delay of total evacuation time. Therefore, it is necessary to include this factor in our model. However, it is impossible to collect the reaction information from all the passengers. As a result, we choose to use the average reaction time which is 0.28 seconds[13]. We randomly choose 10% of all to have a longer reaction time than others by reducing their velocity in
response to the average reaction time. In simulation, all of the passengers evacuate within 77 seconds which is slower compared to the previous situation.

4.3. PSO simulation with emotion in real situation

According to the report of the Sukhoi Superjet 100 aircraft accident on May 5, 2019, some passengers delayed the evacuation process as they attempted to carry their luggage overhead, stopping passengers at the end of the plane from evacuating. This action increases the evacuation time. To model this situation, we randomly reduce the velocity of some passengers in the range of 0 to 70% compared to others. We test passengers in business and economy cabin separately in order to explore the extent of delay in different cabins. All the passengers escape within 81 seconds under the delay in business cabin while escape within 83 seconds in the economy cabin. Compared to the simulation without emotion escaping within 80 seconds, both situations take longer time.

5. Simulation with blocked exits

In reality, exits may be blocked for various reasons, such as blocked by obstacles. It is necessary to model different situations where not all the exits are available. We simulate the situation with one or both exits are blocked with and without emotion factor.

Table 1 and 2 are the average evacuation times of passengers with various configurations of blocked exits both with and without emotion. The one with emotion displays much faster evacuations with average time decreases approximately 1.4 seconds and the maximum velocity increases by nearly 14 percent. As SSJ100-95B is almost symmetric, blocking a single front or rear exit takes similar average evacuation time both with and without emotion. Blocking the right rear exit requires slightly more time to escape as the right side has more passengers. This suggests that the right rear exit has a larger effect on the evacuation.

Table 1: Average evacuation times for SSJ100-95B without emotion

| Exits Blocked       | Evacuation Time (s) | Maximum Velocity (ft/s) |
|---------------------|---------------------|-------------------------|
|                     | 90% | 95% | 100% |                     |
| None                | 66  | 71  | 80   | 8.2                  |
| Single Front Exit   | 66  | 72  | 81   | 8.3                  |
| Single Rear Exit (left) | 68 | 73  | 82   | 8.4                  |
| Single Rear Exit (right) | 69 | 75  | 84   | 8.6                  |
| Both Front Exits    | 92  | 103 | 118  | 8.5                  |
| Both Rear Exits     | 91  | 99  | 116  | 8.3                  |

Table 2: Average evacuation times for SSJ100-95B with emotion

| Exits Blocked       | Evacuation Time (s) | Maximum Velocity (ft/s) |
|---------------------|---------------------|-------------------------|
|                     | 90% | 95% | 100% |                     |
| Single Front Exit   | 28  | 32  | 39   | 9.7                  |
| Single Rear Exit (left) | 30 | 33  | 40   | 9.8                  |
| Single Rear Exit (right) | 31 | 36  | 43   | 9.9                  |
| Both Front Exits    | 64  | 68  | 75   | 9.7                  |
| Both Rear Exits     | 63  | 66  | 71   | 9.8                  |

6. Conclusion

In conclusion, we have a modified PSO algorithm to model aircraft evacuation both with and without emotion. Compared to both stimulation, the one with emotion increases the average velocity of passengers and shortened the average evacuation times. We considered the reaction time and found
that reaction time slowed down average times in high-dense evacuation. We also considered various blocked exits and discovered that blocking exits has a large effect on evacuation. To make our model fit the real situation, we simulated a situation that passengers attempted to carry their luggage overhead. The result suggests that carrying luggage slows down the evacuation times considerably. Our simulations suggest that future aircraft designs should consider the arrangement of exits and passengers should not take their luggage during evacuating, which is also the responsibility of the aircraft companies. In the future, we would like to consider the density of passengers when evacuating as passengers may make a response to the high-density exits and change their direction. Also, we could consider the radius of passengers in response to the emotional stimulation. All of the modifications to our PSO model would be helpful in modeling a more realistic situation so that could help design the the aircraft and the evacuation paths.

7. References
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