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EVALUATION OF AIRCRAFT EVACUATION STRATEGIES USING A VIRTUAL SIMULATION

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ABSTRACT

A simulation model of evacuation strategies in aircraft accidents is proposed as an aid to improve policy planning. In the simulation passengers select their exit route to minimize escape time. Finding the best way to support evacuations, within the minimum required time in such chaotic situations, is difficult to solve optimally using analytical methods. To address this problem, virtual simulations were repeated under conditions of changing exit location and social choice mechanism to select a route to an exit until the best evacuation strategy was found. The efficiency for each exit was evaluated by using the cumulative number of evacuating agents. Using the B777-300 airframe as a case study, the location of an emergency exit was determined by an agent attempting to exit. Using our approach, the total evacuation time was reduced from 119.39 seconds to 83.27seconds, less than the 90 seconds requirement. The social choice mechanism used smoothed out imbalances in exit capacity, improving passenger strategies during emergency aircraft evacuations.

KEYWORDS

Policy Planning, Evacuation Strategies, Aircraft Accident, Virtual Simulations.

1. INTRODUCTION

It is critical for aircraft safety that both the skill of a flight crew and the internal cabin arrangement must be optimized to save human lives, by developing effective evacuation systems for use in case of an emergency. From this point of view, Federal Aviation Administration (FAA) regulates that a new aircraft must satisfy Federal Aviation Regulation (FAR) Part 25.803 (National Transportation Safety Board, 2000) which includes the “90 seconds rule.” This rule states that for the maximum seating capacity of an aircraft all passengers and crew members must be evacuated from the airplane to the ground within 90 seconds. However, this can be difficult because the egress time necessary for evacuation is influenced by many factors such as airframe (number, size and location of emergency exits, seat and aisle arrangement), passengers (age, health, gender, interrelationship and degree of panic) and flight crew (skill and training level).

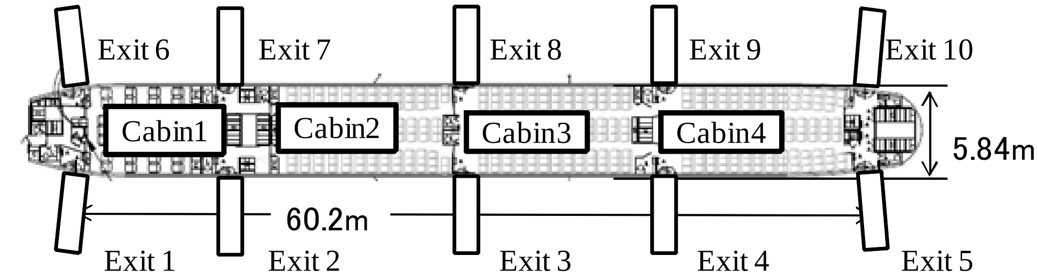
The traditional approach for doing evacuation experiments, with participants, is performed by airplane manufacturers (A380 Emergency Evacuation Test). However, these experiments are dangerous, expensive, and not easily repeatable. On the other hand, simulation models have been developed for evacuating civil structures and transfer vehicles (National Transportation Safety Board, 2000; Santos, S. G. and Aguirre, B.E., 2004; Galea, E.R. et al., 2007; Ceruti, A. and Manzini, R., 2003). In most previous work, a simulation tool used in manufacturing planning and industrial optimization has been applied to evacuation problems. In these approaches, the interactions between people queuing and operational time are addressed in industrial applications. However, it is difficult to determine how to best guide passengers in exiting an airplane, having the assistance of flight crews and a given internal cabin arrangement, within the required evacuation time in the chaos following an aircraft accident. In other words, it is difficult to optimize for an exact minimum evacuation time as these problems are not only difficult to formulate analytically but also difficult due to the chaotic uncertainty of incomplete or dynamic stages of passenger evacuation in an aircraft cabin having limited space.

In this study we used a dynamic model of an aircraft evacuation system by Miyoshi et al. (2009) as a visual interactive simulation tool to develop and evaluate several evacuation techniques. We provide a new optimization method for flight crews and cabin attendants that minimizes evacuation time for passengers by using an autonomous multi-agent simulation with a recursive procedure. The purpose of this study is to clarify the strategies for supporting and recognizing the behavior of passengers who must quickly evacuate in an aircraft accident within a limited time frame. A multi-agent simulation model is proposed, in which passengers select the best route to an exit. The evacuation behavior is formulated as an autonomous multi-agent system model evolving over a two-dimensional grid that represents the aircraft cabin and passengers. In this model, the autonomous agents are initially placed in seat squares and move toward an emergency exit when the aircraft accident occurs. The evacuation simulations are repeated using a social choice mechanism to improve the location of an exit until the best strategy is found for the evacuating passengers. In this case, the exit with the lowest performance was moved to the center of a neighboring exit in the first stage. The lowest performing exit was always targeted to be moved by applying the same strategic reasoning sequentially. Finally, the evacuation simulation was executed with the re-allocated exits. Using these exit re-allocations, agents are sent toward their best (optimized) exit as determined by this virtual method of optimizing exit location.

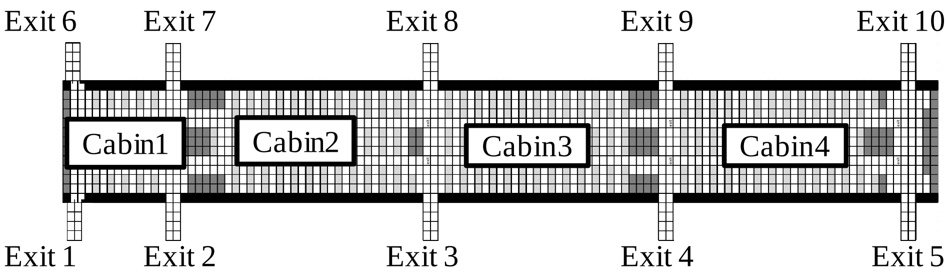
2. SIMULATION MODEL FOR EVACUATION IN AIRCRAFT ACCIDENT

2.1 Model Analogies of Passengers and Equipment

In this paper, simulation models by Miyoshi et al. (2009) and Ueno et al.(2010) are applied to a method of recursively searching for an optimum evacuation strategy by use of a social choice mechanism. In the model, the equipment and allocation of facilities in the aircraft cabins were formulated using a two-dimensional grid cell representation. The cabin interiors and cell models of several types of aircraft (DC10, B777 and B737) were modeled. Figure 1(b) represents a two-dimensional grid cell model of the actual dimensions and cabin interior of the B777-300, as shown in Figure 1(a). In the model, the flow of passengers is represented by movement of autonomous multi-agents attempting to exit the aircraft. The cell is used to represent the space around an economy class seat in the cabin, a seat whose actual size is approximately 0.43m square. Equipment and features, such as exit and emergency doors, emergency exit signs, lavatories, galleries, counters, aisles and seats are also approximated by analogies in the two-dimension model as to their location and the dimensions of the aircraft. Since slides can be deployed from an exit door to the ground in emergencies, slides were also incorporated into the simulation (Figure 1). Passenger evacuation delays would arise at an exit door if it could not accommodate the number of evacuating passengers at any point in time. The efficiency of an exit door was considered to be an inherent attribute of an aircraft, pre-determined based on the size of door and the available escape slide. The efficiency of an exit door, *Td*, was the time delay around an emergency exit, a pre-determined value found by using the performance of emergency evacuations as found in aircraft accident reports (Aircraft and railway accidents investigation commission, 1997, 2008). Generic passenger movement speeds during an evacuation were investigated by Galea et al. (2007), and computerized evacuation simulations were performed using the evacuation speeds from Ceruti [5]. The time step of the simulation was based on their evacuation speed determination (0.98m/s), i.e., the step interval was set to 0.43sec/step. A time variable, *T*, is set to 0 and incremented by 1 every 0.43s. It was assumed in the previously specified rules that the multi-agents move towards an exit to evacuate from an aircraft. It was noted that though the individual behaviors of the multi-agents were controlled by the local and autonomous algorithm, the final results of the movements by the individual agents were seen to yield a macro behavior controlled by group dynamics, such as social choice, in the evacuation flow of the aircraft cabin.



(a) Actual aircraft interior.



(b) Two-dimensional cell model.

Figure 1. Aircraft interior and cell model for B777-300.

2.2 Rules for the Movement of an Autonomous Agent

The rules for the movement of an agent, as summarized in Figures 2 and 3, consisted of the following steps:

Step 1: Each agent is instructed to move towards the nearest emergency exit. They gather information on the location, and direction, of available emergency exits or exit signs (Figure 2).

Step 2: The location and direction of emergency exits or emergency exit signs are stored in agent memory. If the location of an emergency exit or exit sign is recognized, the agent then moves to that location, otherwise the direction to the nearest exit route must be estimated from information an agent has. In this step, the location and direction of emergency exits or exit signs were determined

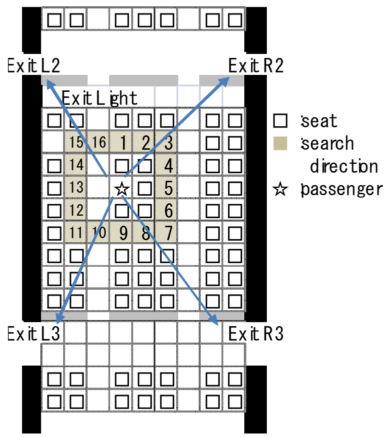


Figure 2. Local rules for agent.

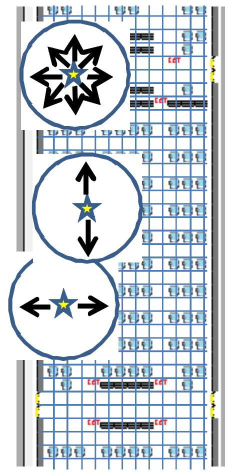


Figure 3. Rules for movement.

from among 16 directions as shown in Figure 2. For example, Exits 1, 2, 3, and Exit Sign 1, would be stored in agent (☆) memories as the 10th, 4th, 7th and 16th directions, respectively.

Step 3: The nearest neighborhood cell is selected as the new destination since it is on a critical path, that is, taking this route gives the shortest time to an exit, subject to physical limitations such as intervening seats and equipment allocation. These destinations are defined by a Moore neighborhood (i.e., the 8 surrounding cells) as shown in Figure 3.

Step 4: Agent makes a judgment as to whether the destination cell is occupied or not. An agent can move to the destination cell if it is not occupied by another agent. Otherwise, an agent must wait until the destination cell is empty.

3. RECURSIVE SEARCH METHOD FOR FINDING AN OPTIMUM EVACUATION STRATEGY INCORPORATING A SOCIAL CHOICE MECHANISM

3.1 Sequential Modification of the Emergency Exit Location

The goal of the evacuation simulation is to better understand and recognize the characteristics of emergency aircraft evacuations by considering conditions such as allocation of passengers within a cabin, efficiency of exits, and passenger instructions. In this paper the goal of mimicking an evacuation was developed to meet the "90 seconds rule" as found in FAR Part 25.803 (Federal Aviation Regulation, 1990). This states that the maximum seating capacity, including crew members, must be evacuated from the airplane to the ground under simulated

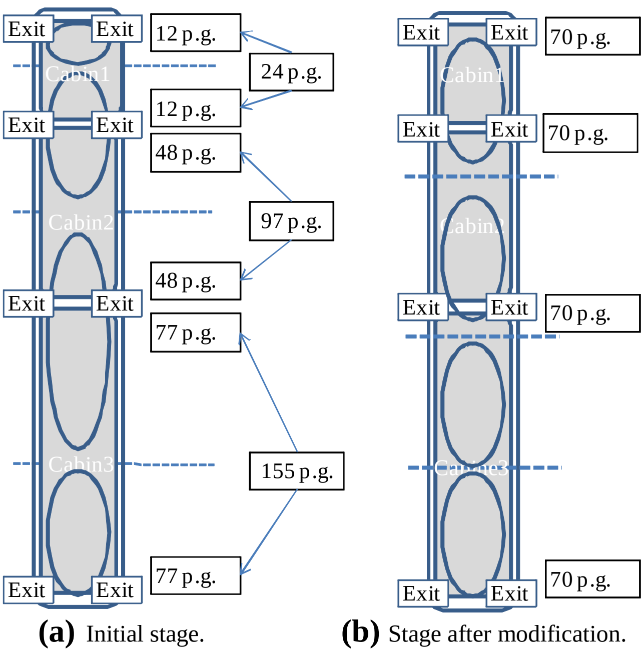


Figure 4. The area to reach an exit. (p.g. = passengers)

emergency conditions within 90 seconds. Guidance to passengers by crew members is necessary to achieve this goal must be planned to minimize the total egress time of all passengers and crew members. Subject to the agent movement rules, the queue of passengers towards some exits is larger as passengers tend to move towards the nearest emergency exit and so concentrate on getting to a specific exit. Based on the above considerations, the simulation's goal was to optimize the allocation of passengers towards the emergency exits such that the number of passengers passing through each emergency exit could be modified to smooth out any imbalance.

If the cabin seating capacities are different from each other, the numbers of passengers moving to the emergency exits would not be balanced. Figure 4 shows the numbers of passengers moving to the exits specified previously. It is seen that a larger number of passengers move towards the exit near the larger cabin (cabin 3). In Figure 4(a) the ellipses illustrate the area through which the passenger would travel to reach the corresponding exit. The number of passengers who chose each exit is also represented in the figure, before optimization, when the passenger is able to view a wide area of the cabin from a distance. The waiting queues of passenger to emergency exit3 and exit7 grow with an increasing egress time. Figure 4 (a) shows 125 passengers concentrated at emergency exit3 and exit7, with many queuing passengers. If the passengers moving to each exit can be better balanced, such as queuing passengers to a specified emergency exit as shown in Figure 4(b), total egress time would be reduced. To induce an optimum solution, the allocation of passengers to each exit was determined by considering distance to an exit. However, it can be difficult for a passenger to evaluate this distance because of the complex arrangement of cabin equipment. Thus, it is impossible to obtain the optimum allocation of passengers to the emergency exits using analytical methods. Instead of analytical optimization, we used a sequential modification method to obtain a satisfactory allocation of emergency exits by using social choice behaviors to prevent passenger concentration at an exit, while also considering the movement speed of passengers and queuing length at an emergency exit.

3.2 Initial Allocation of passenger to the exits

The number of passengers who leave through an exit should correspond to the evacuation efficiency of that exit in minimizing the egress time. If the capacity of the emergency exit is so large that the more passengers could get out from it in a unit time, the goal of the passengers should be to move toward such an exit. Figure 4(b) shows the initial setting of the capacity of passengers to leave through each emergency exit when the capacity of the emergency exits are equal; that is, exit1 and exit5, exit2 and exit6, exit3 and exit7, exit4 and exit8 are each set to accommodate 70 passengers. If passengers using the same emergency exit are initially located on opposite sides of the cabin, the passenger evacuation flow to the exits will cross and so create a traffic jam. This disrupts passenger flow, increasing egress time. To avoid these situations, passenger goals must be organized in an order that corresponds to the location of the emergency exit previously allocated. The goals of passengers in the front of the aircraft are set to use exit1 or exit5 up to the predetermined limit. After that, passenger goals are determined continuously as information becomes available.

The total number of passengers in the aircraft is denoted by N, with the passenger IDs arranged sequentially starting from the passengers in the front seats. The number of emergency exits is denoted by D and the IDs of the left-side emergency exits are designated

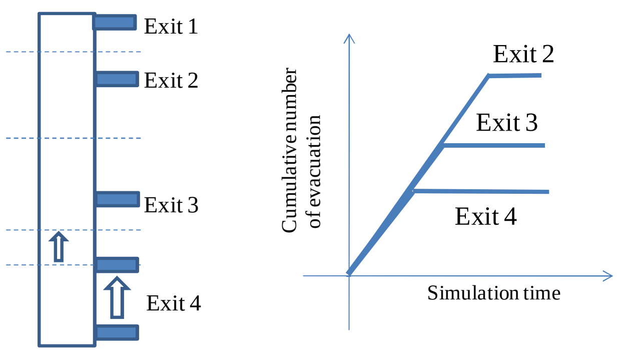
1,2,3,4 with the IDs of right-side exits as 5,6,7,8. The capacity of the *i* -th exit is denoted by e_i, where the capacity of emergency exit is the rate of out-going passengers per unit time. The number of passengers, p_i, whose goals are set up from the *i*-th exit, must be modified to re-allocate passengers to accomplish an equally-divided capacity.

$$p_i = N \frac{e_i}{\sum e_i}$$

If an emergency exit is closed by a circumstance such as a fire or other trouble, e_i is set to 0. Then, in the configuration where the four emergency exits are closed and the capacity of the four exits is equally divided, the number of passengers moving to each exit is set to $N/4$.

3.3 Searching for a strategic evacuation plan using a social choice mechanism to virtually move the location of an exit

The evacuation simulation showed that long queue lines and traffic jams occurred around the neighborhood of the nearest exit because of the concentration of agents. The frequency of these problems of evacuation flow, based on social selection, depended on the relation between the efficiency of an exit and capacity of that cabin. A strategic evacuation plan was developed by using a virtual simulation to move the location of an emergency exit to match the capacity of a cabin and its interior layout in a sequential fashion by using a social choice mechanism. That is, the evacuation simulations are repeated incorporating a changing of exit locations as shown in Figure 5(a) in which the social choice mechanisms of the agents were used until the best evacuation strategy was found by smoothing out the unbalanced performance at the emergency exits. In this case, the efficiency of exiting can be represented by the cumulative numbers of evacuated passengers for each exit. This is illustrated in Figure 5(b) where the horizontal axis indicates the elapsed simulation time.



(a) Movement of exit. (b)Performance for each exit.

Figure 5. Virtual method of moving the location of exit.

The procedures for determining the best strategy are summarized in the following steps:

Step 1: The evacuation simulation is executed under initial conditions in which the exit locations for each passenger are specified.

Step 2: To determine the efficiency of each emergency exit, the cumulative number of evacuated passengers are evaluated.

Step 3: The total duration for evacuation is checked. If the total duration is the smallest among all results, complete the simulation. When the simulation is completed, the exit allocated is the recommended exit location using the virtual method of moving the location of an exit; go to step 5. Otherwise, go to Step 4.

Step 4: Change the location of the emergency exit having the lowest performance; go to Step 1. In this case, the exit with the lowest performance is moved to the center of a neighboring exit from the first stage; at any point in time the exit with the lower performance is moved sequentially using the same strategic reasoning.

Step 5: The evacuation simulation is executed again with the initial location of the exit in the recommended location as determined in Step 3. This is called the "re-allocation simulation."

As shown in Figure 5(a), the operation of moving the location of exit, along with the algorithm mentioned in Step 4, allocates the agents to smooth out unbalanced exit performance due to crowding and long waiting queues.

The simulation is repeated as above until the best evacuation strategy is found. The performance for each exit is evaluated by the cumulative number of evacuation passengers at each emergency exit as shown in Figure 5 (b).

4. NUMERICAL EXAMPLES

4.1 Case Study A: B777-300 using half of available exits and a 100% Passenger Load Factor

As a numerical example, the B777-300 configuration was examined to verify the proposed method of searching for the best strategic plan for evacuation in an aircraft accident by using a social choice mechanism. The cell model used is shown in Figure 1, with the aircraft specifications presented in Table 1. The purpose of this case study is to clarify how to best assist an evacuation from the aircraft to the ground under specified conditions in an accident situation. In this case study, only the half the exits on left side were available to use. In addition, the load factor was 100%, meaning the seats were full of passengers at the locations shown in Figure 1(a). In other words, the gray cells illustrated in Figure 1 (b) were fully filled with agents such that the aircraft was overcrowded when the accident happened. This condition is similar to that for the "90 seconds rule", with the goal to evacuate all agents within 90 seconds.

Table 1. Specifications of B777-300ER. [1]

	B777-300ER
Num. of seats	378
Num. of Business seats	28
Num. of Economy seats	350
Num. of cabins	4
Length of all cabin [m]	60.2
Width of interior cabin [m]	5.84
Length between forward and rear exits [m]	54.0
Num. of cells between forward and rear exits [m]	115
Num. of cells(right-left)	11
Length per cell [m]	0.470
Width per cell [m]	0.529
Num. of Exits	10
Width of Exit doors[m]	1.07

4.1.1 Initial setting for Sequential Simulation

As the first step in our search method for developing a strategic evaluation plan, an initial setting for the sequential simulations was prepared. The initial simulation, with the exit locations is illustrated in Figure 1, was executed using a 100% load factor. The results obtained are shown in Figures. 6 and 7. The performance capacity of each emergency exit using the initial setting is illustrated in Figure 6 with the cumulative number of evacuation (CNE) on the vertical axis. The relationship between the remaining passenger rate and the duration time from the beginning of the evacuation to its end under these initial conditions is illustrated in Figure 7. It is seen that the time required for total duration for evacuation (TDE), the time from the start of the evacuation to its completion, was 119.39 seconds.

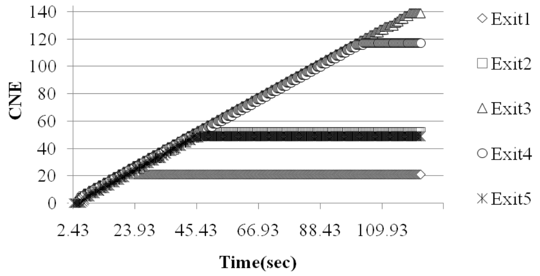


Figure 6. Cumulative number of evacuation passengers from each exit door.

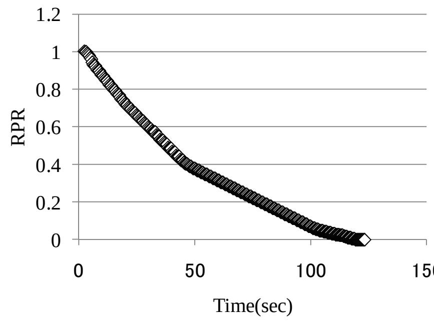


Figure 7. Remaining Passengers Rate of ordinary aircraft.

4.1.2 Searching for an evacuation strategy using a social choice mechanism by recursive simulation

To reduce the TDE from the 119.39 seconds obtained using the initial settings, the evacuation strategic plan was rerun using the procedure outlined in section 3. Based on the knowledge of social choice for the agent in Figure 6, note that Exit3 has the best performance while Exit1 had the lowest performance. Utilizing this knowledge, the procedures from 3.3 were used to search for an improved strategic plan by using the social choice mechanism- the virtual method of moving the location of an exit. As the process

(a) (b) (c) (d) (e) (f) (g)

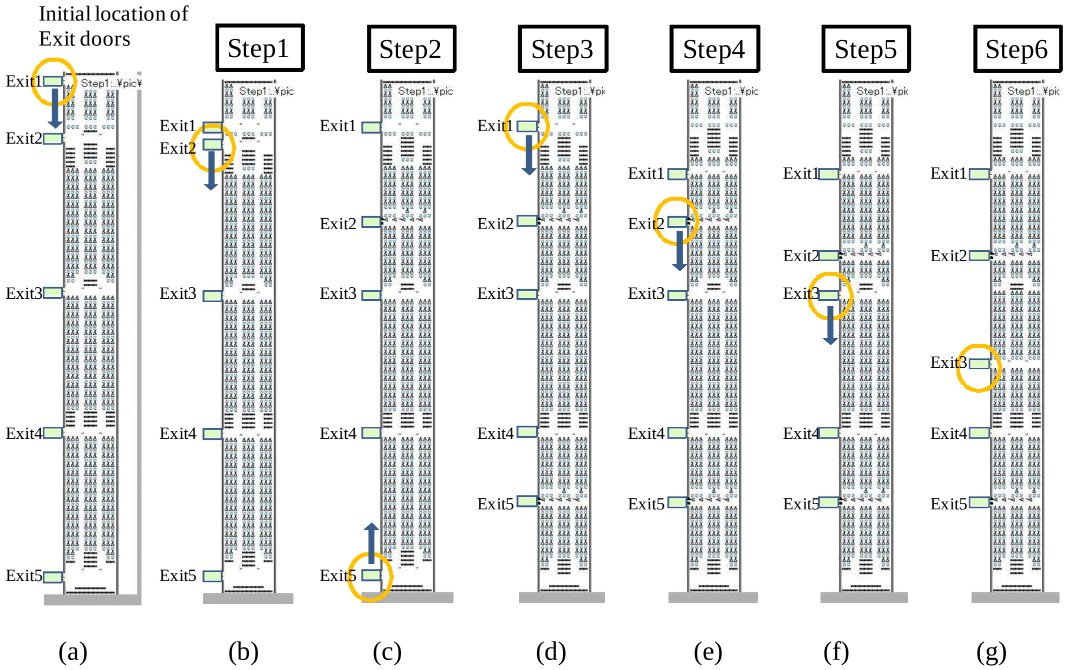
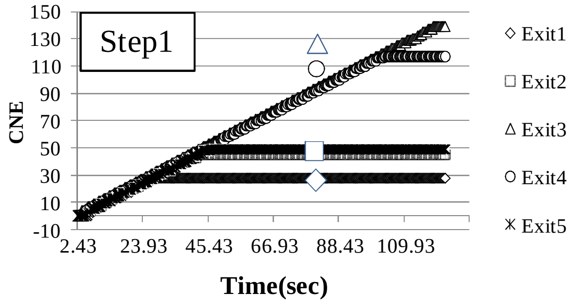
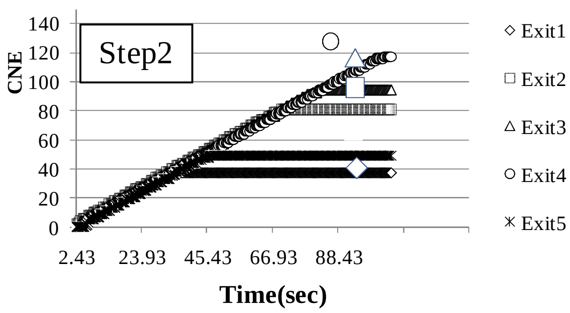


Figure 8. Virtual movement of exit door location at each improvement step. (Circles indicate that the door location was changed.)

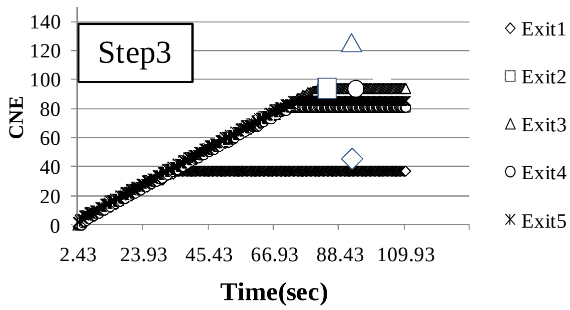
transitions (steps) from the initial stage to the final stage, the results of the process change based on the virtual movement of the door locationas illustrated in Figure 8. On the other hand, the performances of each exit door at each step are illustrated in Figure 9. The sequential simulation process has been repeated until the best evacuation strategy was found. The final results of the search for a best evacuation strategy, the complete evacuation time of each stage, are summarized in Table 2. The initial value of TDE 119.39 seconds was improved to 78.17 seconds at step 6 and 83.27 seconds during a re-allocation simulation. Finally, the evacuation simulation was executed using the initial location of the exits under the condition that the exit locations for all agents are determined by using the virtual method of moving the location of exits. The results of this simulation are compared to the performance strategy of re-allocating the emergency exits (Figure 10). The differences in evacuation flows are illustrated in Figure 11, where it is shown that the unbalanced allocation of exit performance has been smoothed out by the social choice mechanism that virtually moved the location of an exit.



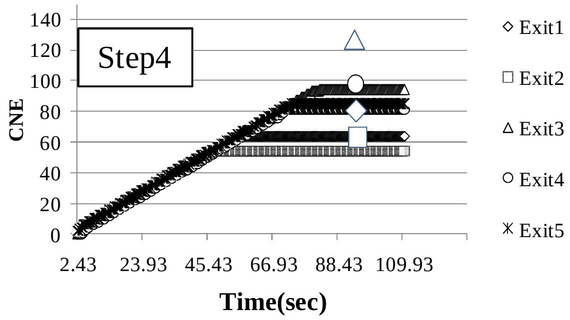
(a) Step1: allocation of No1 Exit.



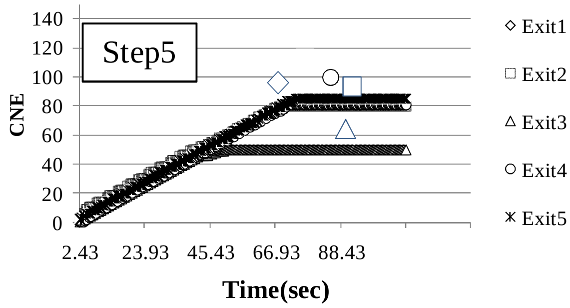
(b) Step2: allocation of No1 Exit.



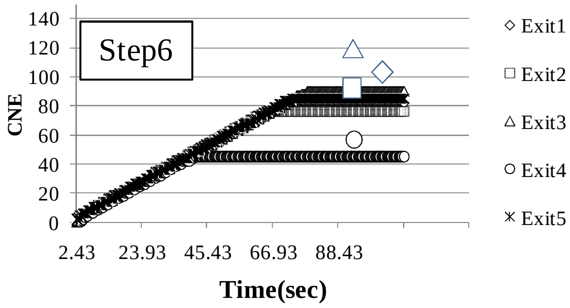
(c) Step3: allocation of No1 Exit.



(d) Step4: allocation of No1 Exit.



(e) Step5: allocation of No1 Exit.



(f) Step6: allocation of No1 Exit.

Figure 9. Evacuation performance of each exit door.

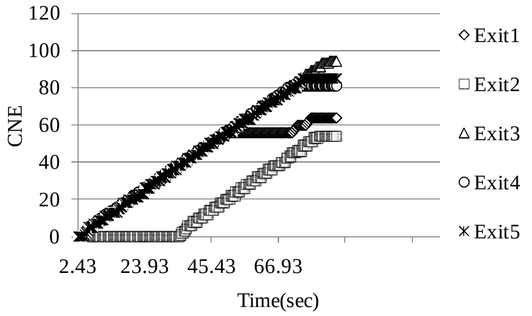
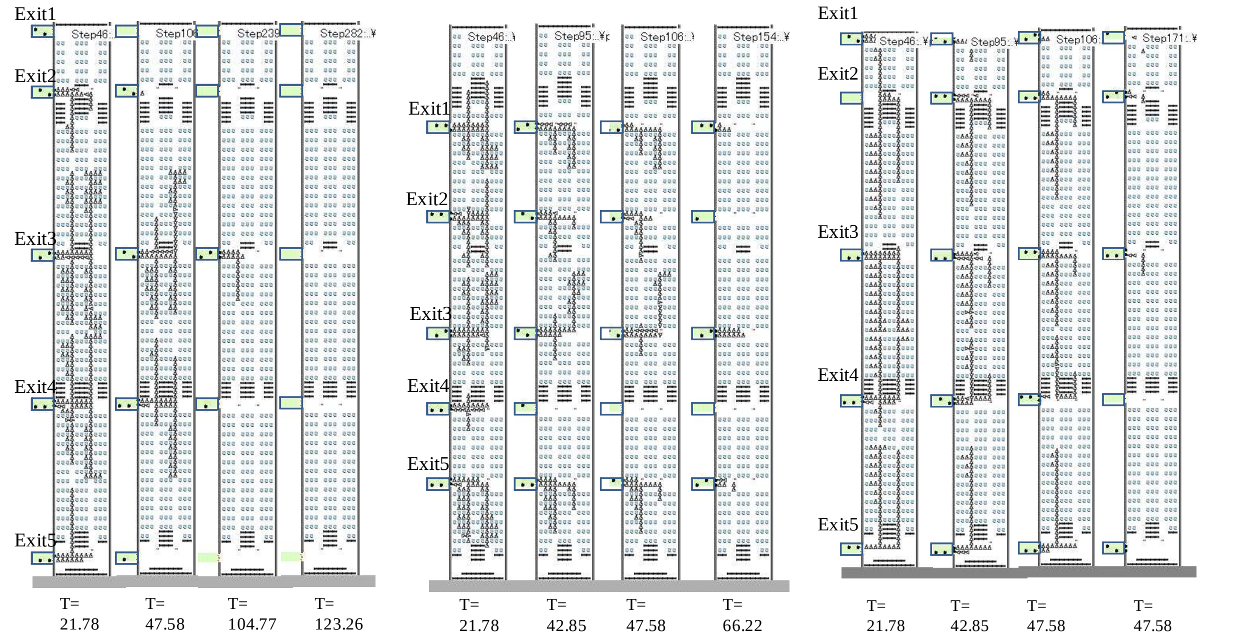


Figure 10. Determination of the exit door which each agent would go out in the evacuation simulation.

Table 2. Improvement of *TDE for* Case Study A.

Load Factor 100%

	TDE(sec)
normal evacuation	119.39
Calculating process	
step 1	119.39
step 2	103.48
step 3	81.55
step 4	82.41
step 5	73.38
step 6	78.11
re-allocation	83.27



(a) Initial location of exit without assist. (b) Virtual moving of exit at step6. (c) Initial location of exit with re-allocation.

Figure 11. Differences of evacuation flow around exits in Case Study A.

4.2 Case Study B: B777-300 using half of the exits with a 50% Passenger Load Factor

4.2.1 Initial Settings for the Sequential Simulation

In this case study, only the half of the exits on left side of the plane were available for use with a 50% load factor, indicating that half of the passengers were seated at the location (Figure 12). Evacuation flow is sensitive to the relationship between the location of available exits and initial position of passengers when the evacuation starts. The configuration of initial positions (Figure 12) seems to provide unfavorable conditions for allowing smooth evacuation flow. The required total duration for evacuation (TDE), using a set of initial conditions such as the location of an exit and so on, was 94.84 seconds.

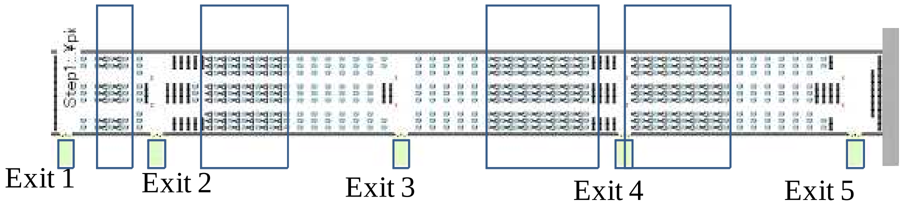
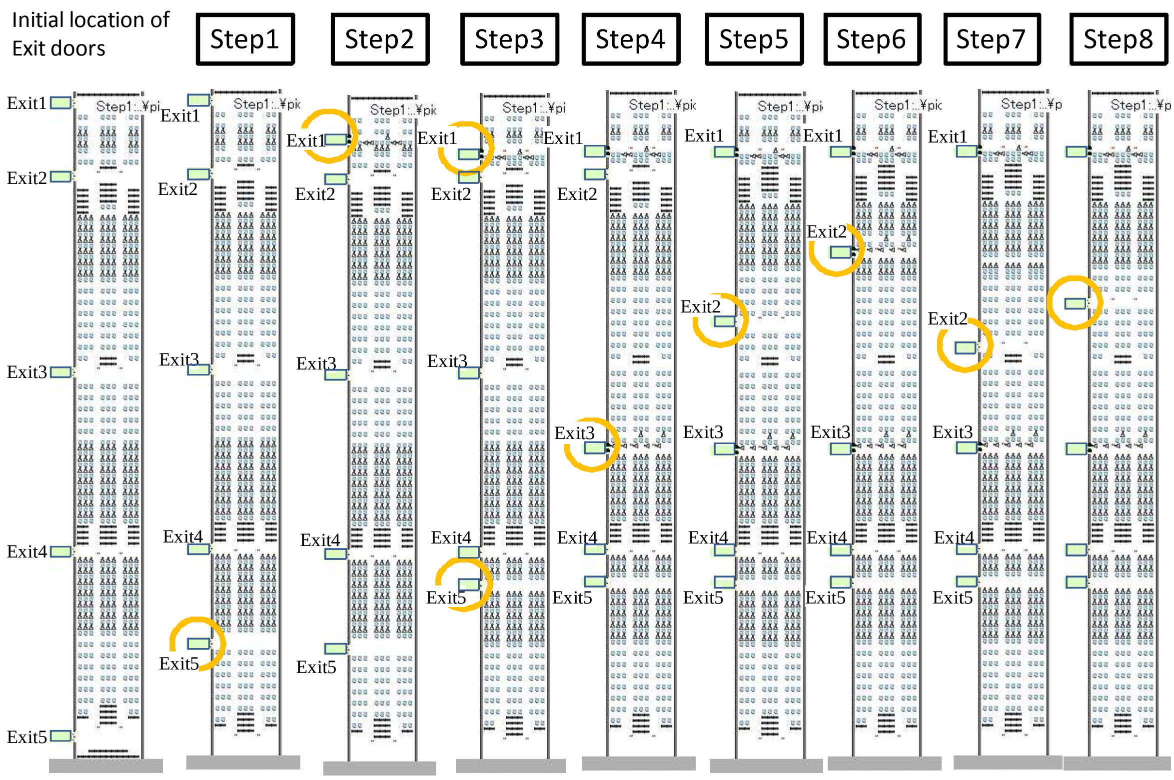


Figure 12. Initial condition of position seated previously for Case Study B

4.2.2 Searching for an Evacuation Strategy using a Social Choice Mechanism by Recursive Simulation

To reduce the TDE from 94.88 seconds at the initial conditions, the evacuation strategic plan was improved by using the procedure of section 3. By considering social choice of an agent as seen in case study A, the sensitivities of performance are taken into account from the view



※Gray circles means that the door location was changed.

Figure 13. Virtual movement of exit door location at each improvement step for Case Study B.

points of evacuation flow efficiency and the effect of smoothing any unbalance performance for each exit. Utilizing this knowledge, the procedures from 3.3 were used to search for a better strategic plan using the social choice mechanism. The results of virtual movement of the exit door location are illustrated in Figure 13 with the performance of each exit door illustrated in Figure 14, as the process transitioned from the initial stage to the final stage. It is noted from Figure 14 in case study B that the unbalanced performance at each exit has been improved in the final stage at step 8. The final results of the search for a best evacuation strategy and the complete evacuation time for each stage, is summarized in Table 3 where it is seen that the initial vale of TDE 94.39 seconds was improved to 38.12 seconds at step 8 and 44.57seconds at re-allocation.

Table 3. Improvement of *TDE* for Case Study B.

Load Factor 50%

	TDE(sec)
normal evacuation	94.88
Calculating process	
step 1	91.98
step 2	83.70
step 3	59.62
step 4	50.16
step 5	38.12
step 6	47.58
step 7	43.28
step 8	38.12
re-allocation	44.57

Finally, the evacuation simulation was executed using the initial location of the exit with the final location of an exit obtained by the virtual method of moving the location of exit. The results of this simulation compare the performances of re-allocating emergency exits (Figure 15). The differences in evacuation flows are illustrated in Figure 15 where it is confirmed that the unbalanced allocation of exit performance was markedly improved as compared to case study A by using the social choice mechanism which virtually moved the location of an exit.

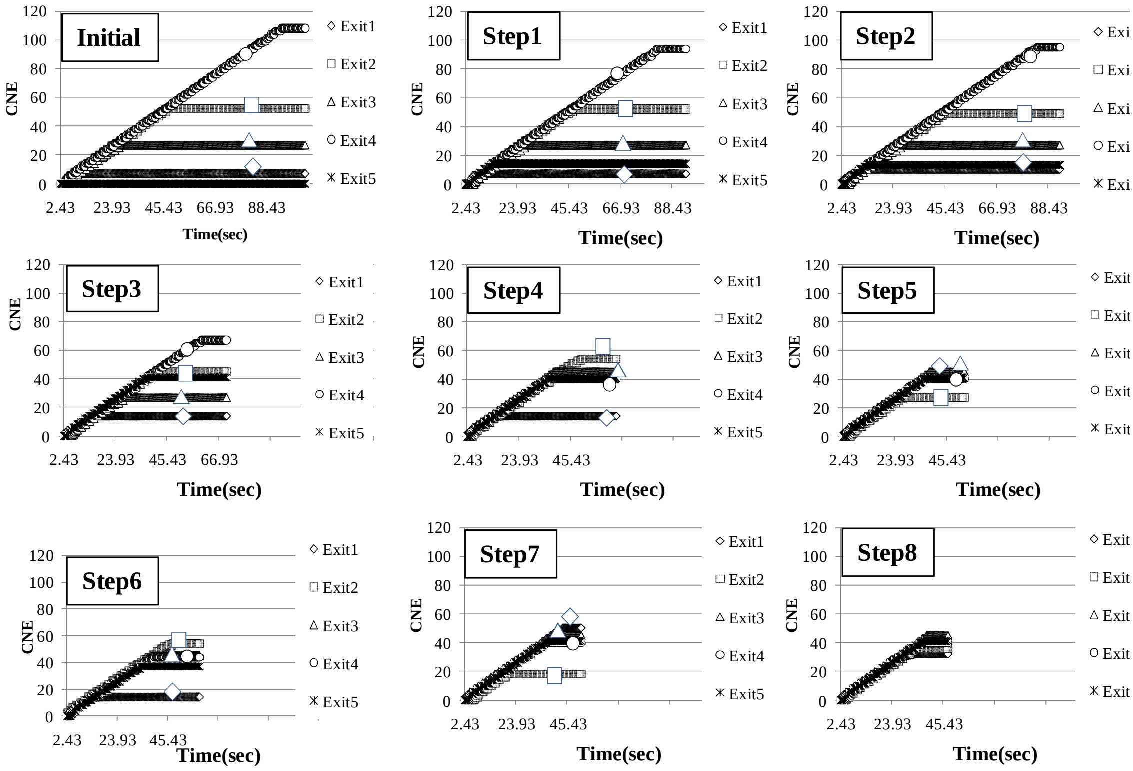
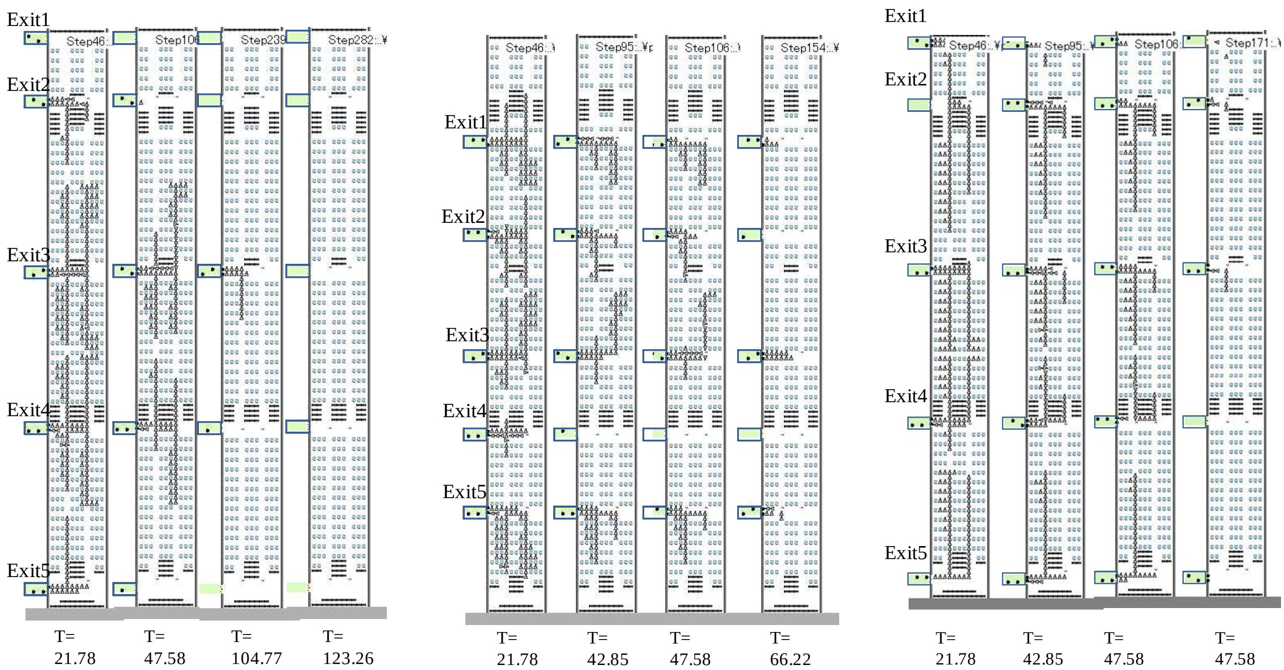


Figure 14. vacuation performance of each exit door for case study B.



(a) Initial location of exit without assist. (b) Virtual moving of exit at step6. (c) Initial location of exit with re-allocation.

Figure15.Differences in evacuation flow around exits in Case Study B.

5. CONCLUDING REMARKS

Based on the proposed procedures, evacuation simulations were conducted in which a social choice mechanism of evacuating passengers was utilized to move the virtual location of emergency exits until the best evacuation strategy was found. As the numerical examples for the B777-300 demonstrated, the location of an emergency exit can be determined by simulation. In this case study, the total evacuation time was reduced from 119.39 seconds to 85.42 seconds, a time less than the required 90 seconds. This indicates that a good evacuation strategy was obtained by the proposed procedure which used a social choice mechanism representing passengers in a multi-agent simulation and then mining the best strategic plan for a given set of circumstances.

The effectiveness of the proposed method was demonstrated as the total time required for complete evacuation was reduced with the unbalance performance of an exit smoothed out in both case studies. Comparing the different case studies, the factors affecting evacuation such as available exits, load factor of passengers and seat position, and so on, allowed for the prevention of traffic jams and the concentration of passengers moving toward one location by the proposed method. These results will be useful for the improvement of passenger evacuation instructions and the training of flight attendants.

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