



A new simulation model for assessing aircraft emergency evacuation considering passenger physical characteristics



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ARTICLE INFO

Article history:

Received 8 February 2013

Received in revised form

20 August 2013

Accepted 1 September 2013

Available online 8 September 2013

Keywords:

Aircraft emergency evacuation

Physical characteristics

Evacuation route

Fine network simulation model

ABSTRACT

Conducting a real aircraft evacuation trial is oftentimes unaffordable as it is extremely expensive and may cause severe injury to participants. Simulation models as an alternative have been used to overcome the aforementioned issues in recent years. This paper proposes a new simulation model for emergency evacuation of civil aircraft. Its unique features and advantages over the existing models are twofold: (1) passengers' critical physical characteristics, e.g. waist size, gender, age, and disabilities, which impact the movement and egress time of individual evacuee from a statistical viewpoint, are taken into account in the new model. (2) Improvements are made to enhance the accuracy of the simulation model from three aspects. First, the staggered mesh discretization method together with the agent-based approach is utilized to simulate movements of individual passengers in an emergency evacuation process. Second, each node discretized to represent cabin space in the new model can contain more than one passenger if they are moving in the same direction. Finally, each individual passenger is able to change his/her evacuation route in a real-time manner based upon the distance from the current position to the target exit and the queue length. The effectiveness of the proposed simulation model is demonstrated on Boeing 767–300 aircraft.

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1. Introduction

As investigated by the National Transportation Safety Board (NTSB), 78% of all fatalities occurred post-impact, of 95.4% were resulted from smoke inhalation and burns due to slow and inefficient evacuations [1]. If post-impact crash survivors can be evacuated promptly, the survival rate would be increased by 98.3% as claimed by NTSB [1]. As reported by the NTSB, the inefficient evacuation in the Asiana Airlines Boeing 777 crash caused injuries on July 6, 2013. On the other hand, Boeing company forecasts that global airlines will require 33,500 new aircraft worth 4 trillion US dollars from 2011–2030, a 60% increase compared to the past decade. Along with bringing new technologies and concepts into aircraft design and manufacturing, the safety of newly designed aircraft also greatly concerns both manufacturers and passengers [2].

In the case of an emergency, to ensure the safe and rapid evacuation of passengers from aircraft is of paramount importance. In order to meet domestic and international regulations and obtain the service permission, a suite of tests must be conducted to ensure that emergency evacuation requirements are fully complied by any newly designed civil aircraft. The International Civil Aviation

Organization (ICAO) requires that the aircraft shall be equipped with sufficient emergency exits to allow maximum opportunity for cabin evacuation within an appropriate time period [3]. More specifically, FAA certification criteria and test methods are integral to evaluating the evacuation capability of new aircraft, and it requires a full-scale evacuation demonstration that all passengers and crew must be evacuated from the cabin of an aircraft to the ground under simulated emergency conditions within 90 s, with only a half of emergency exits available [4]. The commonly accepted way of demonstrating this capability is to perform a series of full-scale trials using an appropriate mix of passengers [5]. However, in most cases, these results are kept confidential due to commercial reasons. On the other hand, the extremely expensive cost and the potential threat of injury to the participants forbid the use of the real evacuation trials. For instance, it costs around two million US dollars to conduct a single evacuation trial for a wide-body aircraft [6]. Additionally, during seven full-scale demonstrations conducted by aircraft manufacturers between 1972 and 1980, 166 of 2571 total participants (around 6.5%) got injuries, such as broken bones and paralysis [6]. As both Airbus and Boeing companies are planning to launch a new generation of aircraft, also called Very Large Transport Aircraft (VLTA), carrying up as many as 1000 passengers [7,8], emergency evacuation of VLTA in the event of survivable crash, therefore, poses a challenge for aircraft manufacturers and certification authorities [9,10].

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To overcome all of the aforementioned shortfalls in real evacuation trials, computer models have been developed recently to simulate the evacuation process instead of executing real evacuation trials. The simulation models can not only greatly reduce expenditure and void potential risks in real evacuation trials, but also provide insights on the evacuation performance of a new aircraft to manufacturers before the aircraft is physically built and/or put into service. In general, existing evacuation models can be categorized into network flow models and network node models. The former treats evacuees of a simulator as if they are fluid in a pipeline, but they cannot characterize movements of evacuees separately and differentiate behaviors of each individual passenger. This type of models is usually used to simulate building evacuation with a huge population. Exit 89 [11], GPSS [12], and EVACNET [13] are representative simulators using network flow models. The network node models, on the other hand, represent the entire simulation environment via a network of nodes. Evacuees pass from one node to another until they completely evacuate. Based upon the size of the nodes in the model, network node models can be further classified into the coarse network approach and the fine network approach, offering different extents of accuracy. As the network node models are capable of characterizing the respective behaviors of each individual evacuee, it can therefore provide details of an evacuation process and more accurate results. For example, EXODUS [14], ARCEVAC [15], and airEXODUS [16] are those which are capable of characterizing the behaviors of evacuees individually and tracking every evacuee throughout a simulation process. Each individual in the evacuee population could be assigned a set of properties that would determine evacuees' behaviors.

Most of the existing evacuation models were developed for building industry, and over 30 different evacuation models are used for building design and certification [17–19]. For aircraft evacuation, airEXODUS is one of the most extensively used aircraft evacuation software and still under development [16,20,21]. In recent years, several simulation models were developed for aircraft evacuation. For example, Galea et al. [22] considered the impact of aircraft post-crash fire in evacuation simulation. Kirchner et al. [23] took into account the competitive behaviors of individual evacuees in the aircraft emergency evacuation. Miyoshi and Nakayasu [24] developed an evacuation model considering the influence of passengers' emotion. Xue and Bloebaum [25] investigated the individual and interactive effects of cabin configuration (e.g. fuselage width, aisle width, exit aperture width, etc.) on aircraft evacuation efficiency. Most recently, with development of artificial intelligence techniques, artificial passengers in simulation models are designed to mimic human intelligence with respect to their surrounding environment to more accurately represent decision-making process of evacuees in aircraft evacuation [26–29], and it is called agent-based approach.

It is noteworthy that there is still a need for improving the accuracy and credibility of aircraft evacuation models to better reflect the real evacuation processes in emergency conditions. For example, as observed in real evacuation trials [30], the physical characteristics of evacuees, like waist size, gender, age, and disability, have critical impact on the egress time in aircraft emergency evacuation. Koo and Kim [31] assessed the impact of disabled residents on the evacuation in high-rise building. Their work indicated that the disabled population could lead to a significant increase of the egress time in emergency evacuation. These physical characteristics of passengers, however, have been rarely taken into account in existing aircraft evacuation simulation models. Moreover, in the most reported works, the cabin space are divided into a set of equal-size nodes [23,24,26], e.g. $0.5\text{ m} \times 0.5\text{ m}$ square nodes are used by EXODUS and $0.2\text{ m} \times 0.2\text{ m}$ square are adopted by SIMULEX. Also, the limitation that each node can be

occupied by only one passenger in these models would result inaccurate representation of evacuation processes as in emergency conditions evacuees stay next to each other very closely. Last but not least, artificial passengers models in existing models will choose the nearest available exit as the target exit and never change their target exit throughout the entire evacuation process (as seen in Refs. [23,24,26,32]). However, in reality, the flow rate of exits varies from one type of exits to another. The exit with a higher flow rate will be less crowded and has a shorter queue length. This may affect the passengers' choice of the target exit and evacuation route.

With the aim of addressing the aforementioned issues, an agent-based approach in conjunction with a multi-level fine network representation is proposed in this work to emulate the aircraft evacuation process. The contribution of this work lies in taking account of the influences of passengers' physical characteristics on the evacuation time, and introduction of several improvements to make simulation closer to reality.

The rest of this paper is organized as follows: Section 2 describes the proposed model for simulator. Section 3 introduces a new model for characterizing passengers' evacuation behavior with respect to their physical characteristics, along with the proposed evacuation route selection strategy. A case study together with the comparative and sensitivity analysis is detailed in Section 4, and it is followed by a brief closure in Section 5.

2. The proposed model for simulator

2.1. Discretization of cabin space

Compared to other simulation environments, like buildings, parks, and public squares etc., the aircraft has several unique features, such as complex structure, numerous obstructions on evacuation paths, and narrow legroom, etc. In most reported aircraft evacuation simulation models, the internal structure of an aircraft can be represented by a set of interconnected two-dimensional "nodes", each of which can be either empty or occupied by a passenger.

To facilitate and simplify simulation program, traditional network node models discretize cabin space of an aircraft into small equal-size square nodes, say $0.4\text{ m} \times 0.4\text{ m}$, in most studies [23,24,26]. However, it appears that the width of legroom is much smaller than the seat size as observed from the cabin layout of Airbus A320 as shown in Fig. 1. Actually, in the economy class of a commercial civil aircraft, the width of legroom is around 0.3 m , whereas the seat is around 0.5 m .

Even though extreme fine network nodes can be used to improve the accuracy of representing cabin space in a simulation model, it requires that the sizes of legroom, seat, and toilets must be integral multiples of the finer nodes. The number of nodes will be increased exponentially and consequently lead to a tremendous computational burden and time. To achieve a good trade-off between the accuracy of layout representation and computational burden, instead of using equal-size nodes as many reported works [23,24,26], a cabin space in our work is subdivided into multiple levels of fine nodes with different sizes. The seat pitch (the space between each seat anchor) of economy class of both Boeing and Airbus aircraft fall in the range of $[0.787\text{ m}, 0.863\text{ m}]$ whereas the width of seat in the range of $[0.45\text{ m}, 0.53\text{ m}]$. In addition, referring to the latest report of human physical dimensions [33], the width between elbows of the 95th percentile of males is less than 0.5 m ; whereas the depth of chest is less than 0.28 m . The seat pitch ($0.8\text{ m} \times 0.5\text{ m}$) of our simulation model of a Boeing 767-300 is thereby divided into seat nodes and legroom nodes with different sizes, say $0.5\text{ m} \times 0.5\text{ m}$ and $0.3\text{ m} \times 0.5\text{ m}$ for the seat node and

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