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Cell-based evacuation simulation considering human behavior in a passenger ship

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ABSTRACT

Advanced evacuation analysis of passenger ships is a stochastic method in which the total evacuation time is calculated via computer-based simulations, by considering each passenger's characteristics (e.g., age, gender, etc.) and the detailed layout of the ship. This study presents simulations of advanced evacuation analysis using a cell-based simulation model for human behavior in a passenger ship. The cell-based simulation model divides the space in a uniform grid called *cell*. Each passenger is located in a cell and moves to another cell according to a set of local rules that are assumed to be associated with the individual, crowd, and counterflow-avoiding behaviors of the passengers. Individual behavior is described with the basic walking direction that a passenger will take during the evacuation. The change in the direction and speed of a passenger based on his/her interaction with the other passengers is expressed via the crowd behavior, which has three basic rules: separation, alignment, and cohesion. The passenger's behavior to avoid other passengers moving in the opposite direction is referred to as "counterflow-avoiding behavior" because such counterflow is included in the evacuation scenario. These behavior patterns are implemented as the local rules and are assigned to each cell. To verify the usefulness of the proposed simulation model, 11 tests specified in International Maritime Organization Maritime Safety Committee/Circulation 1238 (IMO/MSC Circ. 1238) were conducted, and it was confirmed that all the requirements of such tests had been met.

1. Introduction

In accordance with Circulation 1238 (Circ. 1238) of the International Maritime Organization (IMO) Maritime Safety Committee (MSC), entitled *Guidelines for Evacuation Analysis for New and Existing Passenger Ships*, a mandatory regulation issued by IMO, evacuation analysis should be performed for all passenger ships (IMO, 2007). The purpose of this regulation is to determine if the total evacuation time for a vessel is less than the allowable time according to the regulation. The maximum allowable time is 60 min for RORO (roll-on/roll-off) passenger ships and 80 min for regular passenger ships.

The guidelines offer the possibility of using two distinct methods for evacuation analysis: simplified evacuation analysis and advanced evacuation analysis. Simplified evacuation analysis is a deterministic method in which the total evacuation time is calculated using a simple hydraulic scheme, by considering that all passengers have identical characteristics. The total evacuation time can be calculated using a simple formula provided by the IMO, and the results should be submitted to the ship owner and the classification society. On the other hand, advanced evacuation analysis is a stochastic method in which the total evacuation time is estimated using a microscopic approach, by considering each characteristic of each passenger. In this analysis method, the total evacuation time is estimated via computer-based simulations that represent each passenger and the detailed layout of the vessel. Advanced evacuation analysis is currently not mandatory but is expected to be required in the future. Thus, a study on an advanced evacuation analysis was carried out in this paper.

The rest of this paper is as follows. Section 2 presents related studies on evacuation analysis and cell-based simulation techniques. Section 3 presents cell-based rules for human behavior in a passenger ship. Section 4 shows how to model passenger behavior based on the Cell–DEVS formalism, which is presented as a combination of discrete event system specifications (DEVS) and cellular automata. In Section 5, the results of 11 tests in IMO/MSC Circ.1238 and advanced evacuation analysis for a RORO passenger ship are explained to verify the passenger behavior model, and the aforementioned analysis method is compared

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with the commercial evacuation analysis program Evi. Finally, Section 6 presents the conclusions and future directions.

2. Related works

In recent years, researchers applied various approaches to study crowd evacuation under various situations, sometimes using such approaches separately or combining them. In Section 2.1, cellular automata models for evacuation analysis are reviewed. Sections 2.2 and 2.3 review the concepts of DEVS and Cell–DEVS, respectively.

2.1. Cellular automata models for evacuation analysis

Emergent evacuation is a system composed of many pedestrians characterized by strong interactions and environments. People want to move faster than usual in an emergent-evacuation scenario. The local interactions among pedestrians and those between pedestrians and the environment (e.g., a wall or a door) determine the global behavior of pedestrians. Various simulation models have been proposed to study the dynamics of evacuation. To simulate evacuation situations, it is important to comprehend the factors that affect passenger behavior, and to create a passenger behavior model that considers such factors.

Helbing and Molnar (1995) and Helbing et al. (2000) proposed a social-force model for pedestrians' continuous motion. In this model, pedestrians are treated as particles subject to long-range forces induced by the social behavior of individuals. The movement of pedestrians can be described with a main function, which determines the physical and social forces, and the induced velocity changes. The social-force model is determined by the acceleration equation. In recent years, social-force models were further developed to study crowd evacuation (Zheng et al., 2002; Seyfried et al., 2006). Referring to these social forces, Cho et al. (2010) and Cho (2011) modeled passenger behavior as velocity-based, taking into account different aspects of human behavior in an evacuation. They suggested that passenger behavior consists of individual, crowd, and counterflow-avoiding behaviors. Using this model, they developed an advanced evacuation analysis program for passenger ships. This program was verified with the 11 tests specified in IMO/MSC Circ.1238 and was applied to a RORO passenger ship.

Cellular automata models have also been developed to study crowd evacuation under various situations. A cellular automata model quantifies the evacuation area in terms of discrete cells. Each cell can be empty or occupied by a pedestrian or an obstacle object. A pedestrian can move to an empty neighboring cell in each time step.

Cellular automata models can be classified into two categories. The first category is based on the interactions between environments and pedestrians. For example, Zhao et al. (2006) proposed a two-dimensional cellular automata random model to study the exit dynamics of an occupant evacuation. Song et al. (2006) and Yu and Song (2007) proposed a cellular automata model without a step back to simulate the pedestrian counterflow in a channel considering the surrounding environment. These models demonstrate that various environments, such as the exit width and obstacles, have an impact on the pedestrian movement. The second categroy is based on the interaction among pedestrians. Kirchner et al. (2003) proposed a cellular automata model for pedestrian dynamics with friction to simulate competitive egress behavior. Kirchner and Schadschneider (2002) proposed a bionics-inspired cellular automata model to describe the interaction among the pedestrians and to simulate evacuation from a large room with one or two doors. Additionally, Weng et al. (2006) proposed a cellular automata model without a swith different walking velocities.

As mentioned above, the observed phenomena that occur during evacuations have been reproduced by these models in the last few years. Due to the complex rules of the social-force model, it does not offer good calculation efficiency. On the other hand, cellular automata models are discrete in space, time, and state variables. This makes the models ideally suited for large-scale computer simulation. As the advanced evacuation analysis for passenger ships is intended for thousands of passengers, the cellular automata model was adopted in terms of its performance. Therefore, the three passenger behaviors proposed by Cho et al. (2010) and Cho (2011) were modeled as cellular automata in this study.

2.2. DEVS (discrete event system specifications) formalism

Praehofer and Zeigler proposed a modeling and simulation method that can handle simulation models of a discrete event and a discrete time (Praehofer, 1992; Zeigler et al., 2000). This method, called discrete event system specifications (DEVS) and discrete time system specifications (DTSS) formalism, is widely used as a standard for modeling and simulation.

DEVS formalism consists of two models: the atomic model and the coupled model. The atomic model shown in Fig. 1 is the basic model and has specifications for the dynamics of the model. The coupled model, on the other hand, provides the method of assembly for several atomic and/or coupled models to build a complex system hierarchy.

Bang and Cha developed a simulation framework based on the combined DEVS/DTSS concepts (Bang, 2006; Cha et al., 2009; Ha et al., 2009; Cha et al., 2010). To evaluate the efficiency and applicability of the simulation framework, Bang and Cha applied it to the block erection process in shipbuilding and underwater warfare simulation.

2.3. Cell–DEVS

In the studies of Wainer and Giambiasi (2002) and Wainer (2009), the Cell–DEVS formalism was presented as a combination of DEVS and cellular automata with explicit timing delays, which are discrete time steps for updating the state of each cell. DEVS formalism is one of the discrete-event modeling and simulation techniques that were based on systems theory concepts. Cell–DEVS formalism describes cell spaces as discrete event models, wherein each cell is seen as a DEVS atomic model that can be updated at each time step. This approach is still based on the formal specifications of DEVS, but it allows the user to focus on the problem to be solved using simple rules for modeling, as with CA. Wainer (2009) applied Cell–DEVS formalism to various fields, including biology, emergency planning, and chemistry. Ha et al. (2011) simulated the oil slick movement based on Cell–DEVS formalism.

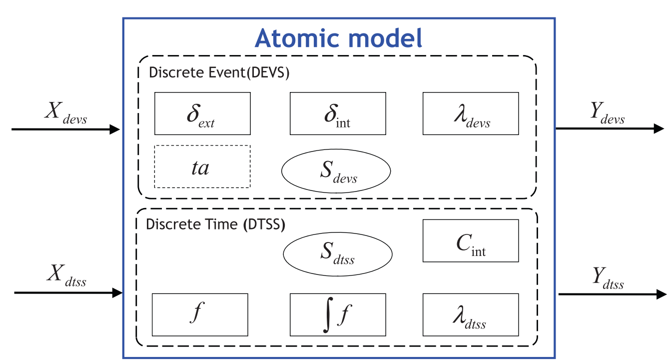

Fig. 1. Configuration of the combined DEVS/DTSS atomic model.