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A generalized validation procedure for pedestrian models

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A B S T R A C T

Pedestrian models need to be validated before being applied to real-life planning. Thus, the validation of these models is worthy of special investigation. In this work, we perform two validation exercises with the pedestrian models named FDS+Evac and JuPedSim based on a well-controlled pedestrian experiment. A comprehensive combination of multiple characteristics is used to enhance the reliability of validation results, including model stability, pedestrian flow, time series of density and velocity, spatiotemporal profiles and pedestrian trajectories. The results show that both FDS+Evac and JuPedSim have weaknesses in reproducing full pedestrian characteristics realistically. Our validation exercises illustrate that single characteristic is not enough to guarantee a reliable validation result and a comprehensive combination of multiple characteristics is necessary. This work demonstrates the defects in most of existing validation of pedestrian models and presents a general validation procedure for pedestrian models in future research.

1. Introduction

In recent years, a large number of pedestrian models have been developed to investigate pedestrian dynamics [1]. These models provide useful insights into crowd movements and improve our knowledge on pedestrian characteristics. Besides, they also help reproduce evacuation process and predict critical situations. One should note that the correctness of these models need to be checked before applying the simulation results into practice [2]. Thus, the validation of pedestrian models is worthy of special investigation.

Some researchers conducted the validations by comparing their models against already validated models [3, 4]. However, validation results are non-effective if the correctness of the compared models is not guaranteed. Other researchers found that reliable validations are preferentially based on empirical data. Field data [5] exist extensively but are hard to be controlled, i.e., unwished influencing factors in the field. To solve this problem, pedestrian experiments under well-controlled laboratory conditions [6-9] were designed and performed to keep focus on influencing factors of interest.

Pedestrian characteristics of interest in the validation of pedestrian models are various. Microscopic ones include pedestrian trajectories [8] and self-organised behaviours, such as arching [10], clogging [11] and herding [12]. Macroscopic ones cover egress time [13], pedestrian flow (specific flow) [9], density [14], velocity [15], exit usage [16], and so on. In most validations only one pedestrian characteristic was considered [16–18], which is however insufficient to guarantee the correctness [19]. Therefore, the combination of different characteristics was proposed. The fundamental diagram [20–22] was the most

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frequently used combination, which checks three characteristics (density, velocity and specific flow) simultaneously. Egress time and pedestrian flow (specific flow) [6] were also commonly combined to enhance the reliability of validations. It is true that the combination of more characteristics gives more reliable validation results [19]. However, to our best knowledge, no special investigation has been done regarding the comprehensive combination of multiple characteristics in the validation of pedestrian models.

Our work addresses this issue by performing two validation exercises. One is with the well-developed pedestrian model FDS+Evac, which has been widely validated by pedestrian experiments [8], handbooks [3,4] and other pedestrian models [23]. The other one is with the pedestrian model JuPedSim [24,25] appeared in recent years. We use two validation exercises to demonstrate that our method can be applied to different pedestrian models in a consistent way. The validation of the two models are performed separately by using the data from a well-controlled bottleneck experiment. In contrast to previous work, we use a comprehensive combination of multiple characteristics, including model stability, pedestrian flow, time series of density and velocity, spatiotemporal profiles and pedestrian trajectories. We extensively test if the two models are able to reproduce realistic pedestrian dynamics in bottlenecks to make the validation results more accurate and reliable.

The remainder of the paper is organised as follows. Section 2 illustrates the validation of the pedestrian model FDS+Evac, including model description, validation setup, simulation procedure and validation result. Section 3 describes the corresponding validation of the pedestrian model JuPedSim. Section 4 gives a discussion based on the above two validation exercises. Finally, Section 5 makes the conclusion.

2. Validation of pedestrian model FDS+Evac

2.1. Model description

The pedestrian model FDS+Evac is an embedded module working on the platform of Fire Dynamic Simulator [26]. There are two parts in FDS+Evac: an evacuation part Evac and a fire part FDS. The versions of these two parts used in this work are FDS 6.0.1 and Evac 2.4.1, respectively. The Evac is an agent-based model, which treats each evacuee as an individual agent and gives her own properties and evacuation strategy. The fire part FDS is a computational fluid dynamics model, which creates fire-driven fluid flow. These two parts can be used independently or combined together [27]. For example, FDS+Evac can be used to predict pedestrian dynamics in a subway station under normal circumstances or an emergency evacuation in a fire accident.

In FDS+Evac, a preferred walking direction vector field $\mathbf{v}_i^0$ which guides agents to exit doors is calculated as an approximation to potential flow problem of 2D incompressible fluid in a given boundary conditions by the flow solver of FDS, where exit doors act as fans. Agents are classified into five types: *ADULT, MALE, FEMALE, CHILD* and *ELDERLY*. Each type has different default values of their properties, such as radius and preferred walking direction vector field (see Table 1 of [28]).

The motion of agents is controlled by a movement algorithm based on a human movement model [29,30]. The model tracks the trajectories of agents in continuous time and space, while the geometry is limited to underlying rectilinear mesh. In more detail, the equation of motion for an agent i at time t is described as [28]:

$$m_i \frac{\mathrm{d}^2 \mathbf{x}_i(t)}{\mathrm{d}t^2} = \mathbf{f}_i(t) + \xi_i(t), \tag{1}$$

where m_i is the mass of agent i, $\mathbf{x}_i(t)$ is the position of agent i, $\mathbf{f}_i(t)$ is the total force on agent i, and $\boldsymbol{\xi}_i(t)$ is a random fluctuation force. The total force $\mathbf{f}_i(t)$ is made up of four components: a motive force $\mathbf{f}_i^{\text{mot}}$, an agent-agent interaction $\mathbf{f}_{ij}$, an agent-wall interaction $\mathbf{f}_{iw}$ and an agent-environment interaction $\mathbf{f}_{ie}$. The motive force works as:

$$\mathbf{f}_i^{\text{mot}} = \frac{m_i}{\tau_i}\left(\mathbf{v}_i^0 - \mathbf{v}_i\right), \tag{2}$$

where τ_i is the relaxation time setting the strength of the motive force and $\mathbf{v}_i$ is the walking direction vector field. The agent-agent interaction includes a social force $\mathbf{f}_{ij}^{\text{soc}}$, a contact force $\mathbf{f}_{ij}^{\text{con}}$ and an attraction force $\mathbf{f}_{ij}^{\text{att}}$. The social force between agents $\mathbf{f}_{ij}^{\text{soc}}$ works as [31]:

$$\mathbf{f}_{ij}^{\text{soc}} = A_i e^{\frac{-\left(d_{ij}-r_{ij}\right)}{B_i}} \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\varphi_{ij}}{2}\right)\mathbf{n}_{ij}, \tag{3}$$

where d_{ij} is the distance between the centres of agent i and agent j, r_{ij} is the sum of the radii of agent i and agent j, $\mathbf{n}_{ij}$ is the unit vector pointing from agent j to agent i, A_i is the strength extent of the social force, B_i is the spatial extent of the social force, and λ_i is the anisotropy of the social force. The contact force between agents $\mathbf{f}_{ij}^{\text{con}}$ works as:

$$\mathbf{f}_{ij}^{\text{con}} = \left(k_{ij}\left(r_{ij} - d_{ij}\right) + c_d \Delta v_{ij}^n\right)\mathbf{n}_{ij} + \kappa_{ij}\left(r_{ij} - d_{ij}\right)\Delta v_{ij}^t \mathbf{t}_{ij}, \tag{4}$$

where k_{ij} is the strength of the radial elastic force, κ_{ij} is the strength of the frictional force, Δv_{ij}^n is the diference of normal velocities between agent i and agent j, Δv_{ij}^t is the difference of tangential velocities between agent i and agent j, $\mathbf{t}_{ij}$ is the unit tangential vector pointing from agent j to agent i, and c_d is the damping force [30]. Similar to the agent-agent interaction $\mathbf{f}_{ij}$, the agent-wall interaction $\mathbf{f}_{iw}$ and the agent-environment interaction $\mathbf{f}_{ie}$ can be deduced. Further description and explanation of the movement algorithm see [28].