Three Different Approaches in Pedestrian Dynamics Modeling – A Case Study

Robert Lubaś, Janusz Miller, Marcin Mycek, Jakub Porzycki, and Jarosław Wąs

AGH University of Science and Technology,
Institute of Applied Computer Science,
al. Mickiewicza 30, 30-059 Kraków
{rlubas,miller,mycek,porzycki,jarek}@agh.edu.pl

Abstract. In this work different approaches to crowd dynamics modeling are compared in terms of efficiency and accuracy. The authors analyze and test applicability of some characteristic microscopic models including: Generalized Centrifugal Force Model, Social Distances, as well as macroscopic model represented by hydrodynamic approach. Models were compared on a real life test case, for which precise empirical results were obtained, to find sufficient balance between dependability of results and computational effort.

1 Introduction

As the global population grows, capacity of buildings, size of public events and gatherings grows as well. Furthermore rapid development of means of interpersonal communication in the last century [1], especially boom of so-called social networks in the last decade such as most known Facebook, dramatically changed dynamics of public gatherings life cycle. Because of that reaction time available to public services in case of emergency is decreasing. Such situation brings necessity of developing models for crowd safety analysis that are both fast and accurate.

Despite rapid development in this field of knowledge, predictive capability is still too low. On the one hand low fidelity models are fast to compute, but fail to capture small scale events which can be critical to predict in time emergency situations. On the other hand, more complex, high fidelity models manage to capture such phenomena, but are very time-consuming to compute. Hence, choice of most appropriate model is crucial to obtain dependable results in reasonable time.

We can ask the following question: is it possible to create an fast simulation with sufficient fidelity and accuracy?

Three various models characterized by different level of fidelity were chosen for further analysis.

One macroscopic model:

Hydrodynamic Approach – continuous model based on observation that crowd in high densities behaves like a fluid [2],

W. Zamojski et al. (Eds.): *New Results in Dependability & Comput. Syst.*, AISC 224, pp. 285–294.
DOI: 10.1007/978-3-319-00945-2_25

Two microscopic models:

Generalized Centrifugal Force Model – continuous self-driven multi particle system based on psychological field theory [3].

Social Distances Model – based on non-homogeneous cellular automata approach to pedestrian dynamics making use of proxemics rules [4, 5].

For a test case free evacuation of lecture hall was chosen. During experiment average outflow and evacuation time was measured. Geometry and initial number of people in room were shared as parameters between models, as well as mean free velocity of pedestrians.

2 Proposed Models of Pedestrian Dynamics

2.1 Macroscopic Approach

Macroscopic models of pedestrian movement take inspiration from hydrodynamics or gas-kinetic theory. The state is described by locally averaged quantities - density $\rho = \rho\ (t, x, y)$, and mean velocity $v = v\ (t, x, y)$ - regarded as dependent variables of time and space. The density has to satisfy a hyperbolic partial differential equation invoking the mass conservation law. Interactions between pedestrians are represented either by a system of partial differential equations (e.g. Helbing [6] or Bellomo and Dogbé [7]) or by closure relations for the average velocity of individuals in terms of the density and its gradient (e.g. Hughes [8] or Coscia and Canavesio [2]).

The model described in this work is similar to the one presented by Coscia and Canavesio [2]. It is a macroscopic, first-order model of crowd dynamics in bounded domain for two-dimensional flow-problem. It takes into account two fundamental aspects of pedestrian movement. On the one hand, pedestrians aim toward specific target, which determines the main direction of motion v_0 but on the other, they tend to avoid crowding (this deviation is represented by a vector v_1). The primary direction of motion is determined by the shortest way to the target. A pedestrian tends to maintain a preferential direction of motion toward target he wants to reach, but at the same time he is disposed to slightly deviate from it in order to avoid crowding. Coscia and Canavesio [4] take this into account including a minimum directional derivative in the visual range of the pedestrian. In contrast to this approach we suggest representing a circumvent of crowding by a vector

$$v_1 = (\overline{\rho} - 1)\nabla\overline{\rho}\,, \tag{1}$$

where $\overline{\rho}$ is a nondimensionalized ρ with respect to $\rho_{\max}$. To sum up, the preferred direction of motion of the individuals **u** is specified by the weighted sum

$$u = v_0 + \alpha v_1\,, \tag{2}$$

where α is a parameter of the model (we assume $\alpha = 0.8$ [m^2/s]).

A magnitude of the pedestrians' velocity is a scalar function of density. To describe this dependency we assume the Kladek function [9]

$$\varphi(\rho) = v_{des} \cdot \left[1 - \exp\left(-\gamma \left(\frac{1}{\rho} - \frac{1}{\rho_{\max}} \right) \right) \right], \tag{3}$$

where v_{des} is the free (desired) speed of a pedestrian and γ denotes a parameter of the model. Like in [9] we assume $\gamma = 1.913$ [m^{-2}].

Finally the motion of pedestrians in presented model is described by two equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0, \tag{4}$$

which expresses the principle of conservation of mass (pedestrian), and

$$v = \frac{\varphi(\rho)}{\|u\|} u, \tag{5}$$

which links the velocity to the local density conditions.

Partial differential equation (4) is supplemented by boundary conditions of Dirichlet type for exit gate and Neumann type in case of walls or another obstacles (in presence of obstacles, they are understood as internal boundaries to the walking area).

2.2 Centrifugal Force Model

Social Force Models. Social Force models of pedestrian movement, first introduced by Helbing et al [10] are based on simple analogy to Newton's laws of motion. First law states that when an object experiences no *net force*, then it is either at rest or it moves in a straight line with constant speed. By this analogy, if pedestrian changes his velocity in the presence of other pedestrians, one can model this interaction as a social interaction force. In mathematical terms, the change of velocity v_i in time t is given by the acceleration equation:

$$m_i \frac{dv_i}{dt} = F_i^D + \sum_{j \neq i} F_{ij}^I + \sum_W F_{iW}^I, \tag{6}$$

where m_i denotes mass of a pedestrian, $F_i^D = m \frac{v_i^0 - v_i}{\tau_i}$ is a driving term responsible for keeping desired velocity $\mathbf{v_i^0}$ with some time constant $\boldsymbol{\tau_i}$. $\mathbf{F^I_{ij}}$ is an interaction term induced by other pedestrian and finally $\mathbf{F^I_{iW}}$ describing interaction between pedestrian and surrounding walls **W**.

Centrifugal Force Model. Original Social Force model [10] assumed exponential with regard to relative distance interaction term. Yu, Chen, Dong and Dai [11] proposed different interaction term based on the fact that with dimension analysis only one dimensionless quantity can be constructed for acceleration, speed and relative distance:

$$F_{ij}^{I} = -m_i K_{ij} \frac{V_{ij}^2}{\left\| R_{ij} \right\|}, \tag{7}$$

where $\mathbf{V_{ij}}^2$ is relative velocity of pedestrians, $\|R_{ij}\|$ is distance between pedestrians and K_{ij} is a coefficient which takes into account field of vision of pedestrians:

$$K_{ij} = \frac{1}{2}\left[\frac{V_i \cdot e_{ij} + \left\| V_i \cdot e_{ij} \right\|}{\left\| V_i \right\|}\right], \tag{8}$$

where $\mathbf{e_{ij}}$ is a versor pointing from one pedestrian to another:

$$e_{ij} = \frac{R_{ij}}{\left\| R_{ij} \right\|}, \tag{9}$$

Name of the model comes from familiarity of this interaction term to centrifugal force known from classical physics. This approach was adopted and developed by Chraibi et al. [3] in Generalized Centrifugal Force Model which is used in this work, where in addition pedestrian shape depends on their velocity.

2.3 Social Distances Model

In the models based on cellular automata, space is divided into square cells and one cell can be occupied by only one pedestrian [12]. Pedestrian movement is mainly determined by the current configuration of the neighborhood. Thanks to that, this model is extremely efficient. Most of cellular automata models are based on square lattice based on 40 cm cells. Fidelity of the classical model is higher than in macroscopic models, but space representation is relatively coarse.

To improve fidelity of classical CA models, Social Distances model was proposed [4]. In the model each pedestrian is represented as ellipse placed in square lattice. The model was then adapted for modeling the evacuation of large objects [12, 13].

In the presented model pedestrians are represented as a part of multi-agent systems using some rules of asynchronous and non-homogeneous cellular automaton. Each pedestrian (agent) has its own independent attributes: speed, direction, destination, distance traveled, and evacuation time. The model described in this section is: *discrete, microscopic, numerical* and *stochastic*.

Due to the fact that the model uses the theory of cellular automata is unavoidable discretization of space. It is impossible to accurately represent real world on a two-dimensional discrete square grid of size 25 cm.

Because of potential gradient layer, is possible to choose the next cell and pedestrian can make a move. Each cell, on which the pedestrian can move, has a value increasing proportionally to the distance from the exit.

In the model agent is represented by an ellipse, whose center is situated in the middle of a single cell. Pedestrian may move to another cell in the Moore neighborhood of radius 1, taking into account the field of vision, which is wide at 180°, and is defined for different positions 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°.

The crucial issue is to establish the set of forbidden and allowed positions for all cells in Moore neighborhood of radius 1, each cell being occupied by one person [4]. The calculation of the allowed/forbidden positions is based upon simple geometrical dependencies [13]. It takes into account the following: the orientations of two ellipses occupying two adjacent cells and the size of their cross-section. It is assumed that the position is allowed if the ratio of the calculated cross-section (for this position) to the size of the ellipse is smaller than imposed tolerance $\varepsilon_N \in [0,1]$.

3 Experimental Data and Simulation Results

Models mentioned above were compared with a real life test case. In 240 seats lecture hall an experimental evacuation of approximately 210 students was conducted. Experiment was carried out under normal conditions as *announced drill* (according to [15]).

Fig. 1 shows simplified plan of the lecture hall used for the experiment. There are 15 rows, with 16 seats each. Grey areas indicate place unavailable for pedestrians. During the experiment only one half of the lower exit was opened, while upper doors were closed.

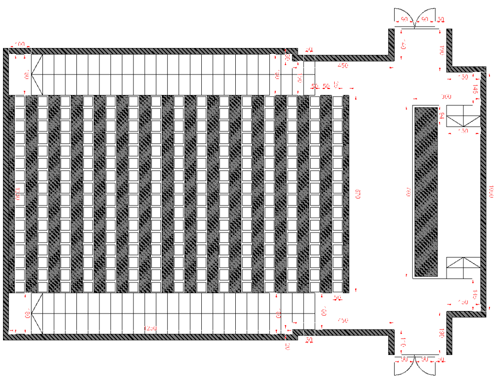

Fig. 1 Lecture hall plan with dimensions

Total evacuation time was 162 seconds. Fig. 2 represents observed outflow[1]. The highest observed peek slightly exceed 2.5 persons per second. However, on average it is approximately 1.35 persons. Trend line shows that at the beginning outflow reach average level of 1.7, but then as the crowd density increases, outflow decreased to approximately 1.2.

Another important observed feature are significant oscillations of outflow with average amplitude of ~1.3 and period of 8-10 sec. This phenomenon is caused by forming waves of denser and sparser crowd.

The outflow data from experiment was compared with analogical outflow data obtained from simulations of: macroscopic model Fig. 3, Centrifugal Model Fig. 4 and Social Distances Model Fig. 5. Highest similarity of the flow function to real data was observed in Social Distances Model and slightly lower similarity in Centrifugal Model. In macroscopic model similarity of flow function was lowest.

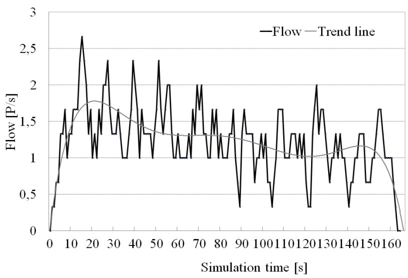

Fig. 2 Real data - statistics of pedestrians outflow measured in experiment

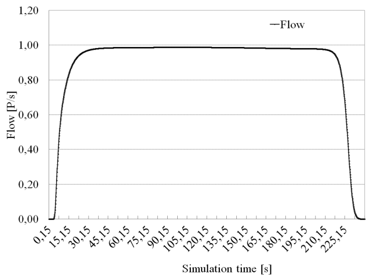

Fig. 3 Macroscopic model - statistics of pedestrians outflow

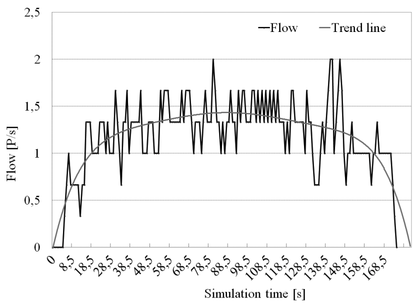

Fig. 4 Centrifugal model - statistics of pedestrians outflow

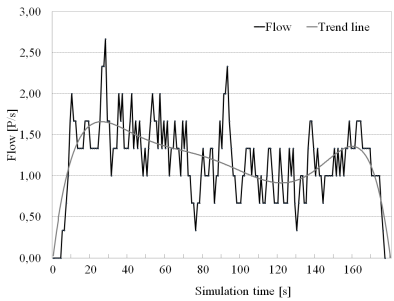

Fig. 5 Social Distance Model - statistics of pedestrians outflow

[1] To reduce high frequency noises, value for given second N is calculated as an average of data for seconds N-1, N and N+1.

Analysis of trend lines[2] shows overall tendencies of outflow changes. For experimental data it varies from 1.7 to 1.2 decreasing as crowd density increase. Similar phenomenon could be observed in Social Distance Model. Although in this method outflow is in range 2.05 - 1.6, one can observe outflow decreasing in time. Other methods, Centrifugal Force Model and macroscopic approach, don't show this phenomena.

Table 1 Total and partial evacuation times for all simulated models and real life experiment. Total evacuation time is measured from beginning of the experiment to the moment when there is nobody in the room. Partial evacuation times for stairs are defined similarly - it is time after which there is no one on the stairs. Model parameter V_{des} describes pedestrians desired velocity.

Model	V_{des}[m/s]	Total evacuation time	Left stars time	Right stairs time
Macroscopic Model	0.98	230	87	199
	1.11	198	73	172
	1.34	171	61	149
Social Distances	0.9	172	80	160
	1.11	131	66	120
	1.34	105	58	103
Centrifugal	0.9	173	108	164
	1.11	160	94	154
	1.34	158	98	146
Experimental		163	83	129

Total evacuation time for every used model is close to empirical data. Comparison of evacuation times in particular models with experimental data are presented in Table 1. Parameter V_{des} describes value of pedestrians desired velocity, total evacuation time is time measured from start of evacuation to the last person passing through the exit, and respectively left and right stairs time - flow time on stairs measured from the first person who appears on the stairs, to the last person who leaves the stairs.

One can notice that the different methods have different sensitivity to the change of the parameter of desired velocity V_{des}. Macroscopic model and Centrifugal model are less sensitive than Social Distances model.

Fig. 6 illustrates evacuation times gained from different models. Centrifugal and Social Distances Model have similar statistics, while macroscopic model has slightly different results.

[2] Trend line was calculated as 5th order polynomial approximation.

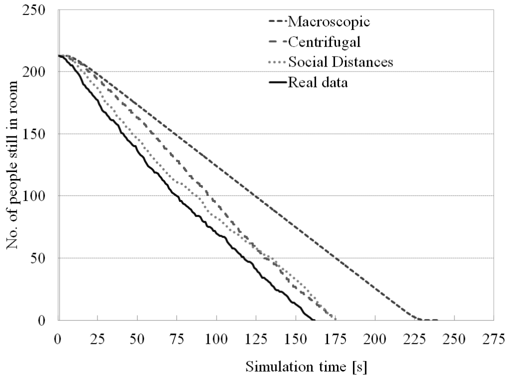

Fig. 6 Evacuation times - comparison of all models for V_{des} = 0.9 m/s and real data (experimental results)

Considering the performance of each method, it should be noted that the most effective is macroscopic model and its demand for computational power is constant during an executed simulation (Fig. 7).

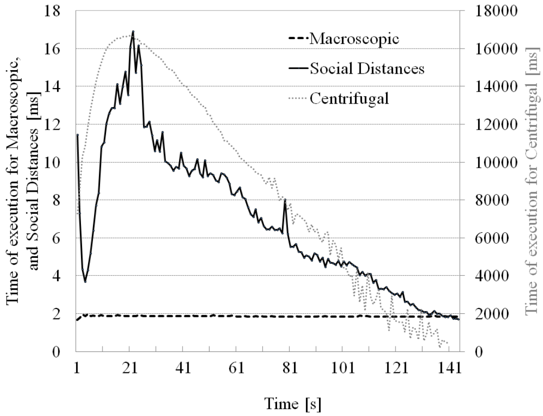

Fig. 7 Performance tests for all models. Plot shows execution time for every consecutive second of simulation. For macroscopic and Social Distances models axis of performance is placed on the left side of chart, while for Centrifugal model axis of performance is placed on the right side of the graph.

Although demand for computing power for Social Distances and Centrifugal differs significantly in scale, both of them have similar characteristic points Fig. 7. The maximum is associated with *the highest number of interactions and collisions among pedestrians* in both *microscopic models*, as the largest contribution to the computational complexity.

Centrifugal Force Model has lowest computational efficiency from all models as can be seen on Fig. 7 Social Distances and macroscopic models have similar efficiencies - two orders of magnitude lower.

4 Concluding Remarks

Three completely different approaches in modeling of evacuation are presented in the article. The first one; macroscopic approach based on hydrodynamics - crowd is represented as a fluid with its motion characterized by using differential equations. The second approach is Generalized Centrifugal Model based on microscopic Social Force Model, when all pedestrians are represented as moving, interacting particles. The third approach is Social Distances model based on non-homogeneous cellular automata where pedestrians are represented as ellipses placed on a square lattice.

The most accurate representation of space is achieved in Generalized Centrifugal Model, next in Social Distances model and the least accurate is macroscopic model. This means that fidelity of the models is changing from highest level in Molecular Dynamics based Centrifugal Model, through middle level - Cellular Automata model, to macroscopic level. It should be stressed, that presented case study it is not optimal size of the simulation environment because macroscopic model is more often used for vast environments.

In terms of performance, the most efficient method is macroscopic model - based on the principles of hydrodynamics, whilst somewhat lower performance presents Social Distances model (but it is the same order of magnitude as macroscopic model). Among the models tested, the least efficient model is Centrifugal Force Model and it is a cost of the most precise representation of pedestrians positions and velocities.

Thus, it should be noted, that the accuracy/fidelity of a model is closely related to its performance. The more accurate is the model; the lower is its performance. Comparisons of models plays important role in choosing best one that guarantee highest dependability of produced crowds simulation systems both in terms of efficiency and fidelity.

Important issue is to clarify the difference in the results of evacuation times received using various methods, as well as potential sources of errors. An important role is played by parameterization of each model, obtained as a result of the calibration process. Each model obviously requires further, more precise calibration to adapt to the specific conditions.

Acknowledgement. This work is partially supported under the FP7 ICT program of the European Commission under grant agreement No 231288 (SOCIONICAL).

References

[1] Gwizdalla, T.: International Journal of Modern Physics C 17(12), 1791-1799 (2006)
[2] Coscia, V., Canavesio, C.: First order macroscopic modeling of human crowd dynamics. Math. Models Methods Appl. Sci. 18, 1217–1247 (2008)
[3] Chraibi, M., Seyfried, A., Schadschneider, A.: Generalized centrifugal-force model for pedestrian dynamics. Phys. Rev. E. 82, 046111 (2010)
[4] Wąs, J., Gudowski, B., Matuszyk, P.J.: Social distances model of pedestrian dynamics. In: El Yacoubi, S., Chopard, B., Bandini, S. (eds.) ACRI 2006. LNCS, vol. 4173, pp. 492–501. Springer, Heidelberg (2006)
[5] Wąs, J., Lubaś, R., Myśliwiec, W.: Proxemics in discrete simulation of evacuation. In: Sirakoulis, G.C., Bandini, S. (eds.) ACRI 2012. LNCS, vol. 7495, pp. 768–775. Springer, Heidelberg (2012)
[6] Helbing, D.: A fluid-dynamic model for the movement of pedestrians. Complex Systems 6, 931–415 (1992)
[7] Bellomo, N.: On the modeling crowd dynamics from scaling to hyperbolic macroscopic models. Math. Models Methods Appl. Sci. 18(suppl.), 1317–1345 (2008)
[8] Hughes, R.L.: The flow of large crowds of pedestrians. Mathematics and Computer in Simulations 53, 367–370 (2000)
[9] Weidmann, U.: Transporttechnik der Fussgänger Transporttechnische Eigenschaften des Fussgängerverkehrs, Literaturauswertung, Schriftenreihe des IVT. Technical Report 90, Institut für Verkehrsplanung und Transportsysteme, Zürich (1992)
[10] Helbing, D., Farkas, I., Vicsek, T.: Simulationg dynamical features of escape panic. Nature 407, 487 (2000)
[11] Yu, W.J., Chen, R., Dong, L.Y., Dai, S.Q.: Centrifugal force model for pedestrian dynamics. Phys Rev. E. 72, 026112 (2005)
[12] Schadschneider, A., Klingsch, W., Kluepfel, H., Kretz, T., Rogsch, C., Seyfried, A.: Evacuation Dynamics: Empirical Results, Modeling and Applications. In: Encyclopedia of Complexity and Systems Science. Springer Science+Business Media, New York (2009)
[13] Wąs, J., Lubaś, R., Myśliwiec, W.: Towards realistic modeling of crowd compressibility. In: Peacock, R.D., Kuligowski, E.D., Averill, J.D. (eds.) Pedestrian ad Evacuation Dynamics. Springer US (2011)
[14] Burstedde, C., Klauch, K., Schadschneider, A., Zittartz, J.: Simulation of pedestrian dynamics using a two-dimensional cellular automaton. Physica A: Statistical Mechanics and its Applications 295(3-4), 507–525 (2001)
[15] SFPE, SFPE handbook of fire protection engineering. The Society of Fire Protection Engineers (2008)