Validation and Verification of CA-Based Pedestrian Dynamics Models

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Validation and verification of CA-based pedestrian dynamics models

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Verification and validation (V&V) of pedestrian dynamics models have become a subject of extensive discussions over the last few years. While some requirements and tests are proper for all models, simultaneously each type of model requires also its own set of specific tests. In models based on Cellular Automata (CA) discretization of space and time is the main source of possible errors. This paper addresses some issues, that should be carefully investigated in order to obtain a final, reliable model.

The negative effects of discretization are discussed, as well as, the problem of maintaining pedestrian speed in different grid configurations i.e. movement isotropy. In parallel we show that wall penetration can occur in CA models and that input geometry has to be validated. The issue of automatic detection of collective effects in CA-based models is mentioned. Finally, the necessity of fundamental diagram application in validation is broadly discussed.

The aim of this paper is to bring the CA-based pedestrian dynamics models into current general discussion about V&V and to indicate specific issues of CA-based models.

Key words: validation and verification, CA-based crowd dynamics models, V&V process, fundamental diagram, discretization errors, wall penetration, collective effects

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1 INTRODUCTION

CA-based models constitute an important group within crowd dynamics models. However, currently the most popular models of all are those based on molecular dynamics. On the basis of the original Social Force model [12] new models have been developed over recent years, for instance: a model with waiting pedestrians [18], a model with signalized crosswalks [39] and a model which takes into account flow during escalator transfers [23]. Focusing on continuous models means that, in general, the emphasis in discussion about the models' validation and verification is put mainly on continuous, force-based models [29, 32, 41, 3, 1]. It should be stressed that discrete crowd dynamics models, especially those based on the Cellular Automata approach [2, 19], are becoming more and more popular due to their effectiveness and reliability. Different aspects of CA-based models have been discussed in recent publications, for instance: an analysis of pedestrian velocities and an extension of floor field model is proposed in [10], the idea of a proxemics floor field is presented in [8], queuing issue are considered in [21], group categorization and guidance attributes in the context of CA are introduced in [35], whilst "follow the leader" behavior is shown in [37].

One should also note the growing popularity of hybrid approaches in crowd modeling (taking into account both discrete and continuous approaches). Such approaches can be applied by different mechanisms: spatial fragmentation including continuous and discrete parts [4] or by using discretization in continuous models or some continuous mechanisms in discrete models [7].

Taking into account the growing interest in CA-based models - we believe that issues related to those models should be included in mainstream discussions about verification and validation (V&V) methodology in crowd dynamics modeling. The first commonly accepted validation and verification guidelines are the International Maritime Organization (IMO) notes 1033 [13] and 1238 [14], which contain detailed requirements for ship evacuation models and a set of basic verification tests. Over recent years several documents have built general purpose V&V guidelines on the base of the IMO notes, for instance [28] RiMEA project⋆ or [29] note released by the National Institute of Standards and Technology. General views on validation and verification from a fire safety engineering perspective is presented in different technical reports like: ISO/TR 16738:2009 - evaluation and management of occupant behavior [17], ISO/TR 13387-8:1999 - discussion about engineering methods to evaluate the location and conditions of occupants [15], DG 516 - guidance

⋆ Text available only in German.

on the use of numerical models to predict human behavior during emergency building evacuation [9], issues of assessment, verification and validation of calculation methods [16], design of facilities in the context of fire safety [36] and assessing of safety at sport grounds [6].

The main aim of this article is to discuss issues with the validation and verification of CA-based pedestrian dynamics models. The article is a continuation of our previous articles. In [24] we proposed the idea of dividing the main set of verification tests into basic and extended subsets, in order to include tests for different kind of models, whilst in [27] we discussed applying NIST Technical Note 1822 to CA-based crowd models. In the article we would like to take into account some essential issues related to V&V of CA-based models.

2 CA SPECIFIC ASPECTS OF VERIFICATION AND VALIDATION OF CROWD DYNAMICS MODELS

2.1 Discretization effects

One of the most significant sources of errors in numerical simulations is discretization of space and time variables. This is due to the interpretation of a single cell in CA-based crowd dynamics model - one cell corresponds with one pedestrian and a typical cell size for the a square grid is 0.4 m. Such a coarse grained discretization has several dramatic implications on the results of a CA-based crowd simulation.

First of all, relations like a fundamental diagram will never be as smooth as diagrams acquired in experiments or ones produced through continuous models, because precise values of speed and density are not achievable within a discretized model. In addition, such granularity results in frequent problems with space representation, as not all physical dimensions are consistent with the cell size. The problem becomes more significant if the geometry represented in the model requires non straight angles or curved lines.

The second aspect of space discretization is an emerging loss of isotropy in models with a finite grid. This issue has been addressed in several ways: by counting diagonal steps [31], by calculating the real distance covered by agents [20] or with the use of a borrowed time concept [25]. In order to check how a model is affected by space anisotropy, it should be verified with test cases where movement of the pedestrians is not parallel to the main axis of the lattice. This issue has been broadly discussed in section 2.4.

A simple test to evaluate how discretization errors affect pedestrian flow was proposed in [24]. A room with 50 pedestrians should be evacuated using a 10 meter length corridor. Details of test geometry are shown in Fig.1. In consecutive runs corridor width should increase by 10 cm from 50 cm to 150 cm. According to experimental data, pedestrian flow in the measurement area should increase linearly [33]. A discretization error can affect this regularity, therefore a linear correlation between pedestrian flow in consecutive runs is proposed to be a simple measurement of any errors introduced.

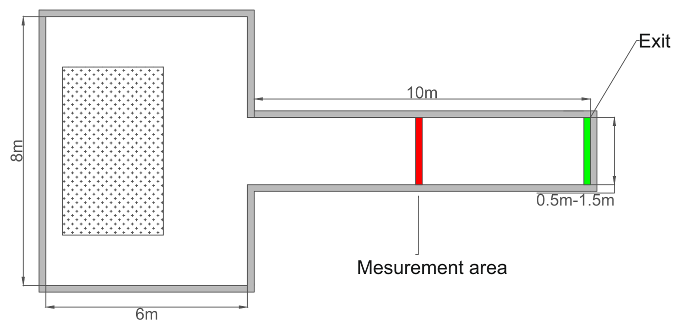

Figure 1
Geometry of test to verify the influenceof discretization errors on pedestrian movement. Corridor width changes from 0.5 m to 1.5 m.

2.2 Wall penetration

Wall penetration is a well known issue in force-based models. Seemingly, this problem does not occurs in CA-based models - it is enough to declare the set of wall/obstacle cells as unavailable. However, trajectories are considered, rather than positions, wall penetration in CA-based models becomes possible and significantly interferes with simulation results.

In models with an applied Moore neighborhood, when a simulated pedestrian moves around the corner he/she does not move into an unavailable cell, but penetrates the wall/obstacle cell during the movement. The discussed scenario is presented in Fig. 2. In most cases such a problem will result in unrealistic trajectories at corners, but in some situations, eg. in a corridor oriented at 45 degree to the underlying lattice, it can significantly increase corridors throughput.

Another situation that can be interpreted as *wall penetration* in CA crowd dynamics models occurs when a real obstacle is too thin to be represented as an entire unavailable cell. Some models can discretize a thin wall as a free

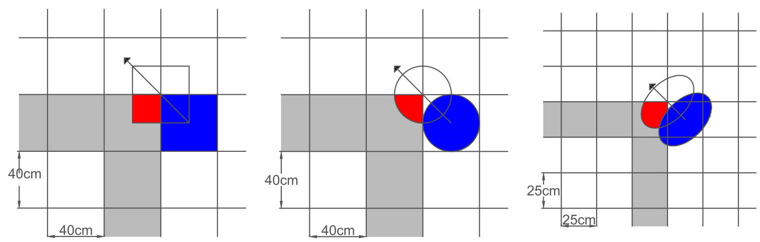

Figure 2
An agent penetrating a wall/obstacle in models with a finite square grid.

cell or take such obstacles into consideration only during the calculation of values of a floor field. In such cases a pedestrian can, in fact, move through obstacles. Such a scenario is presented at Fig. 3 and 4 A and D.

2.3 Verification of input geometry

Fine discretization in CA-based models leads to significant differences between real geometry and geometry used in simulation. Small changes in room or corridor dimensions usually do not have a strong effect on the simulation results. However some places, like doors, narrow corridors, thin walls, are especially susceptible to discretization errors. For example door width has big influence on pedestrian outflow, while incorrect discretization of thin walls, can lead to unrealistic evacuation paths (see Fig. 3 and 4).

Therefore, the input geometry should be carefully checked. One should confirm whether discretization errors change the overall structure. This process is especially crucial in the case of automatic or semi-automatic conversion from architectural plan to input geometries. Inappropriate size, position and orientation of the underlying grid can remove or create new passages or reduce the width of corridors.

2.4 Maintaining walking speed

In most documents one of the first tests is to verify whether a model is able to maintain designed pedestrian speed (eg. ISO 1033/1238: test 1, 2, 3; NIST Note 1822: test 2.1, 2.2). In the case of models with a fine grid (mostly CA-based models), results can be strongly affected by grid rotation. Only NIST Note 1822 mentions this problem. A simple example of differences in pedestrian trajectories caused only by changes in grid orientation is shown in Fig.: 5.

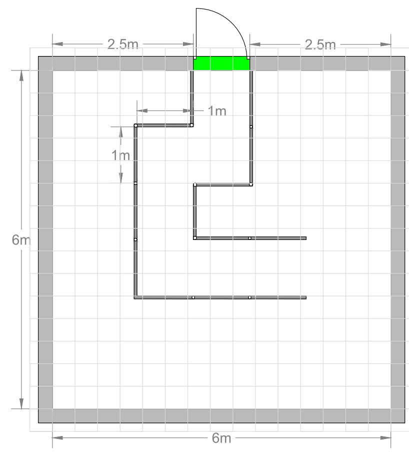

Figure 3
Simplified plan of room with thin obstacles - 5 cm wide barriers. Such solutions are often found at airports, railway stations, etc. The underlying simulation grid is shown.

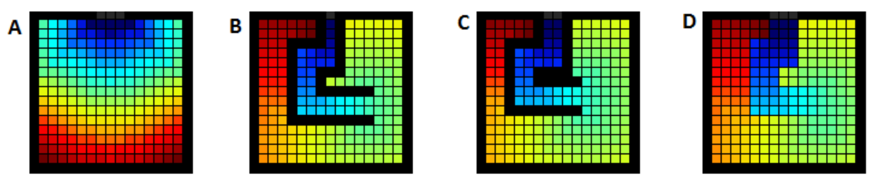

Figure 4
Four approaches to constructing input geometry and static floor field on the geometry base shown in Fig.: 3. A - cell is marked as obstacle only if more than 50% of its area on plan is covered by obstacles, B - cell is marked as obstacle if any of its area on the plan is covered by an obstacle, C - manually changed input geometry to obtain proper corridor width, D - thin obstacles affect only static floor field. This also requires additional rules/manual intervention to adjust proper corridor width.

Moreover due to fine space discretization in CA-based models, some values of speed, time and position are not available. Expected test results should be given as range of accepted values, rather than exact values.

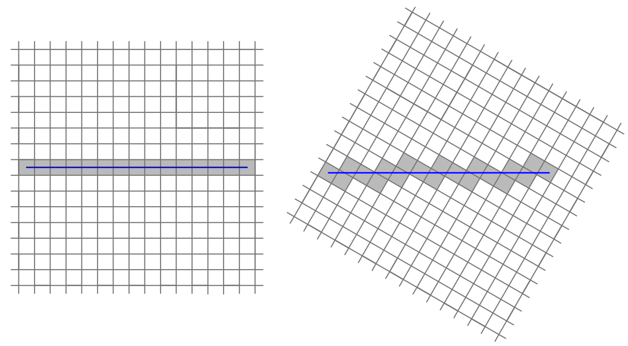

Figure 5
Influence of grid orientation on pedestrian path. An occupant is expected to have a similar travel time in different grid orientations, however fine grid discretization leads to significant distortions in movement isotropy.

2.5 People with movement disabilities

An important issue attracting growing interest is the representation of disabled people (wheelchairs) and their influence on overall simulation results. The most popular approach is that a disabled person should be slightly slower and occupy more space than a typical pedestrian [29].

Both of these requirements are hard to obtain in CA-based models. Especially problematic is the fact that disabled people in wheelchairs should occupy more than one cell. Simulations in which pedestrians have different sizes are impossible when using *pure* CA models (where a pedestrian is represented as a state of a single, 40 cm x 40 cm sized cell). However, CA models with finer representation of pedestrians [38] are able to represent disabled pedestrians. Such an agent is still assigned to single cell, but he/she modifies local rules for the neighborhood. In parallel it should be stressed that small differences in speed are hard to obtain in CA models.

2.6 Collective effects

A large variety of self-organization phenomena can be observed in real world. Any pedestrian dynamics model, including CA-based, ought to reproduce these effects. This fact can be the basis for a set of verification tests if these phenomena can be detected/measured in a robust and repetitive way.

- *Jamming* - usually occurs at high crowd density in places where capacity is reduced (bottlenecks). This phenomenon is a consequence of the fact that space can be occupied by one agent at a time. From real event observation the jamming in front of a bottleneck is drop or wedge-shaped. A second type of this effect appears in counter-flow situations, where pedestrian inflow from both directions causes blockage. In CA-based models such a situation can be detected by calculating the local percentage of pedestrians that do not change their current cell. The jamming should occur in a repetitive way under specific circumstances.

- *Lane formation* - in counter-flow, when two groups of pedestrians are moving in opposite directions, lanes are formed for those people who move in same direction. The number of lanes is not constant, changes over time and depends on the width of the flow. Some quantitative empirical data and experimental setup can be find in [22]. Lanes and groups of people moving in the same direction can be detected by clustering pedestrians based on their direction of movement. However, it should be noted that differentiating between lanes and mere groups would need to be very accurate for the test to be trustworthy. It is quite easy to reproduce lanes in CA-models, however it is important to keep in mind discretization issues.

- *Density waves* (stop-and-go waves) - these typically occur in a densely crowded corridor (close to the density that causes the total absence of movement). In [26] the authors quantitatively and qualitatively compared pedestrian trajectories from two empirical experiments with simulation data in the case of stop-and-go wave occurrence. Additionally we can use the *Verif.2.1. Speed in a corridor* test from [29] with slight modifications - uniformly distributed pedestrians with a high density up to $7\frac{P}{m^2}$ moving in the same direction. As noted in [26], when such a situation occurs speed distribution does not follow a uni-modal, but rather a bi-modal distribution, a fact that can be easily used as criterion for the verification test.

- *Oscillations* - in counter-flow at bottlenecks, e.g. doors, one can sometimes observe oscillatory changes in the direction of motion. This should be observed in e.g.: *Verif.2.8. Horizontal counter-flows (rooms)* test from [29]. Such an effect can be easily quantized by calculating the direction of motion and detecting stable changes between alternating phases.

- *Freezing-by-heating effect* - at sufficiently high crowd density and under extreme conditions (panics) pedestrian lanes are disturbed by increasing fluctuation. This leads to the formation of blockages which may have a regular structure [11]. The *Verif.2.8. Horizontal counter-flows (rooms)* test with modification, may be used to observe this effect, e.g. in a situation where there are 100 pedestrians in each room moving to the opposite room. In the case of a classical CA-based model completely blockage may occur and without changes in the transition function deadlock will be permanent.

3 FUNDAMENTAL DIAGRAM IN VALIDATION OF CA-BASED MODELS

The absence of a correct relationship between pedestrian flow and its density should be considered as a serious mistake in the modeling process. Therefore, the model validation cannot omit this important reliability assessment.

In order to assess the reliability of the pedestrian dynamics models in terms of safety analysis we require special design tests and empirical data to compare with gathered simulated data. A qualitative validation with the fundamental diagram is appropriate to verify whether a microscopic model based on Cellular Automata properly reproduces the relation between velocity and density. There are differences between the fundamental diagrams obtained so far, but nevertheless all of them show a monotonically decreasing velocity with increasing density.

The general idea is to store pedestrians' trajectories from simulation of a test case, and then to construct a fundamental diagram and compare the diagram with a diagram gained using empirical data. There are a variety of experiments performed to obtain the relation between velocity and density [30]. It is important to notice that different measurement methods can have a significant influence on investigating this relation [40]. Therefore, the measurement of density, velocity and flow should be performed with the same method as used in the corresponding experiment. Regardless of the fact that there is no consensus in the context of divergences in shapes of curves, we should investigate the reliability of models in this qualitative manner. A basic model based on CA has a symmetrical fundamental diagram around half of the density range, which is not close to reality. The more complicated rules of this model can lead to reproducing e.g. Weidmann's curve with high accuracy.

A proposal for qualitative evaluation of the model results was presented in [24]. The idea is based on an experiment described in [34]. In Fig. 6 the geometry of the test case is presented. To gain diverse densities, the scenarios with 15, 20, 25 and 34 uniformly distributed agents should be performed. Each scenario consisted of three laps whilst avoiding of passing other agents. The expected result is that individual velocity decreases with the increasing density.

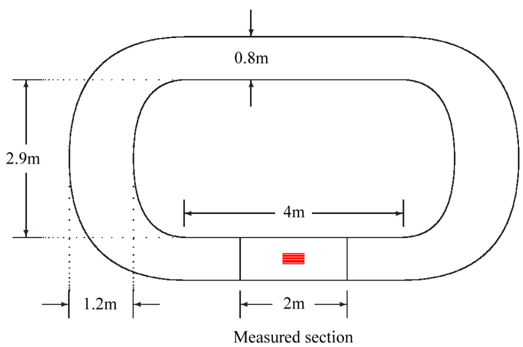

Figure 6
The geometry of a fundamental diagram testing scenario.

4 THIRD PARTY V&V OF CROWD DYNAMICS MODELS

A growing topic getting more and more traction is testing and certification of pedestrian dynamics models by a third party or a consortium of parties. Such an approach was proposed in [27] and during the *Workshop on Collecting and Analysing Experimental Data of Pedestrian Dynamics* [5] heeld in the JĂźlich Supercomputing Center.

In particular, the second voice in the discussion should be emphasized. The approach is to have a continuous integration server nightly building the newest version of the simulation model. It performs not only typical software tests, but also automated verification and validation tests. The test suite is based on tests from V&V documents and norms as well as based on other previous experiences such as for example that two pedestrians should not interact with each other when there is no line of sight between them. The result of this approach is that any person can see and compare the results of an always up to date model.

While this is currently a closed approach, one can imagine a more open one - where any one can upload their model and share publicly information about passing the V&V tests. Such a situation would allow for models to be tested and certified in a clear, transparent way by a third-party body. However, when preparing such an initiative great care should be taken not to discriminate CA models over continuous ones with the choice of tests, as outlined in the previous sections. In addition one approach is an analysis of the trajectories generated with the model. In most CA models time resolution is low compared to other models and needs to be accounted for when designing the system.

5 CONCLUSIONS

Confidence and reliability of a crowd dynamics model is the basis of its practical application.

In order to ensure a high level of the reliability, a careful and holistic V&V process is always required. In recent years significant improvements can be observed in defining V&V procedures. However, most published documents are general purpose guidelines, that do not take into consideration differences between model types. In order to address this issue we propose a division of verification tests into basic and advanced sets (see [24]). The basic test set should be applied to all types of models, while advanced sets should be designed for specific types, applications or features.

In this paper we focus on several issues related to verification and validation of CA-based models. This paper is not intended to be definitive guidance, our intention is rather to extend discussion about V&V procedures in order to include CA-based models.

We propose two new validation tests, namely: fundamental diagram testing and measurement of the influence of discretization errors on pedestrian flow. Regarding discretization, we also analyze some practical problems connected with the introduction of geometry. We take into consideration a case study with barriers and the consequences of using different variants of representation of such a scenario.

We address also the issue of wall penetration, which is noticeable, when we use a Moore neighborhood. In this case it is important to take into account partial „fuzzification" of states of borderline (wall) cells, and finally, to include this element into estimations of discretization error.

In opposition to some recent suggestions, we believe that using fundamental diagrams (the relationship between flow and density) is absolutely necessary in the V&V process.

It should be noted that collective dynamics of moving pedestrians is a very complex problem and in fact even a very extensive test does not cover all possible situations. There are unexpected scenarios and different types of situations, where even a well validated model can produce wrong results. The aim of the verification and validation process is to check whether a model correctly implements basic functionality and how results produced by the model compare with experimental data in chosen simple scenarios. The V&V process is the basis for confirming the suitability of model to simulate a given class of situation, e.g.: stadium evacuation, crowd management during mass gatherings, modeling behavior during concerts, etc.

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REFERENCES

[1] J.L. Berrou, J. Beecham, P. Quaglia, M.A. Kagarlis, and A. Gerodimos. (2007). Calibration and validation of the legion simulation model using empirical data. In Nathalie Waldau, Peter Gattermann, Hermann Knoflacher, and Michael Schreckenberg, editors, *Pedestrian and Evacuation Dynamics 2005*, pages 167–181. Springer Berlin Heidelberg.

[2] Carsten Burstedde, Kai Klauck, Andreas Schadschneider, and Johannes Zittartz. (2001). Simulation of pedestrian dynamics using a two-dimensional cellular automaton. *Physica A: Statistical Mechanics and its Applications*, 295(3 - 4):507 – 525.

[3] C.J.E. Castle, N.P. Waterson, E. Pellissier, and S. Le Bail. (2011). A comparison of grid-based and continuous space pedestrian modelling software: Analysis of two uk train stations. In Richard D. Peacock, Erica D. Kuligowski, and Jason D. Averill, editors, *Pedestrian and Evacuation Dynamics*, pages 433–446. Springer US.

[4] Nitish Chooramun, Peter J. Lawrence, and Edwin R. Galea. (2012). An agent based evacuation model utilising hybrid space discretisation. *Safety Science*, 50(8):1685 – 1694. Evacuation and Pedestrian Dynamics.

[5] Mohcine Chraibi, (2014). Verification and validation of models for pedestrian dynamics. http://ped.fz-juelich.de/workshopSlides. Workshop on Collecting and Analysing Experimental Data of Pedestrian Dynamics.

[6] Media Department for Culture and Sport. (2008). *Guide to Safety at Sports Grounds*. TSO.

[7] Felix Dietrich, Gerta Koester, Michael Seitz, and Isabella von Sivers. (2014). Bridging the gap: From cellular automata to differential equation models for pedestrian dynamics. *Journal of Computational Science*, 5(5):841 – 846.

[8] Takahiro Ezaki, Daichi Yanagisawa, Kazumichi Ohtsuka, and Katsuhiro Nishinari. (2012). Simulation of space acquisition process of pedestrians using Proxemic Floor Field Model. *Physica A: Statistical Mechanics and its Applications*, 391(1 - 2):291 – 299.

[9] Jeremy Fraser-Mitchell and David Charters. (2010). Dg 516 evacuation modelling and human behaviour in fire. Technical report, Digest.

[10] Zhijian Fu, Xiaodong Zhou, Kongjin Zhu, Yanqiu Chen, Yifan Zhuang, Yuqi Hu, Lizhong Yang, Changkun Chen, and Jian Li. (2015). A floor field cellular automaton for crowd evacuation considering different walking abilities. *Physica A: Statistical Mechanics and its Applications*, 420(0):294 – 303.

[11] Dirk Helbing, Illés J. Farkas, and Tamás Vicsek. (Feb 2000). Freezing by heating in a driven mesoscopic system. *Phys. Rev. Lett.*, 84:1240–1243.

[12] Dirk Helbing and Péter Molnár. (1995). Social force model for pedestrian dynamics. *Physical Review E*, pages 4282–4286.

[13] IMO. (2002). Interim guidelines for evacuation analyses for new and existing passenger ships. msc.1/circ.1033. Technical report, International Maritime Organization.

[14] IMO. (2007). Guidelines for evacuation analysis for new and existing passenger ships. msc.1/circ.1238. Technical report, International Maritime Organization.

[15] ISO. (1999). Iso/tr13387-8 fire safety engineering - part 8 life safety - occupant behaviour, location and condition. Technical report, ISO.

[16] ISO. (2008). Iso 16730 fire safety engineering - assesment, verification and validation of calculation methods. Technical report, ISO.

[17] ISO. (2009). Iso/tr16738 fire-safety engineering - technical information on methods for evaluating behaviour and movement of people. Technical report, ISO.

[18] Fredrik Johansson, Anders Peterson, and Andreas Tapani. (2015). Waiting pedestrians in the social force model. *Physica A: Statistical Mechanics and its Applications*, 419(0):95 – 107.

[19] Ansgar Kirchner, Katsuhiro Nishinari, and Andreas Schadschneider. (2003). Friction effects and clogging in a cellular automaton model for pedestrian dynamics. *Phys. Rev. E*, 67:056122.

[20] Hubert Klupfel. (2003). *A Cellular Automaton Model for Crowd Movement and Egress Simulation*. PhD thesis, Universitat Duisburg-Essen.

[21] Gerta Koester and Benedikt Zoennchen. (2014). Queuing at bottlenecks using a dynamic floor field for navigation. *Transportation Research Procedia*, 2(0):344 – 352. The Conference on Pedestrian and Evacuation Dynamics 2014 (PED 2014), 22-24 October 2014, Delft, The Netherlands.

[22] Tobias Kretz, Anna Grünebohm, Maike Kaufman, Florian Mazur, and Michael Schreckenberg. (2006). Experimental study of pedestrian counterflow in a corridor. *Journal of Statistical Mechanics: Theory and Experiment*, 2006(10):P10001.

[23] Wenhang Li, Jianhua Gong, Ping Yu, Shen Shen, Rong Li, and Qishen Duan. (2015). Simulation and analysis of congestion risk during escalator transfers using a modified social force model. *Physica A: Statistical Mechanics and its Applications*, 420(0):28 – 40.

[24] Robert Lubas, Marcin Mycek, Jakub Porzycki, and Jaroslaw Was. (2014). Verification and validation of evacuation models - methodology expansion proposition. *Transportation Research Procedia*, 2(0):715 – 723. The Conference on Pedestrian and Evacuation Dynamics 2014 (PED 2014), 22-24 October 2014, Delft, The Netherlands.

[25] Marcin Mycek, Robert Lubaś, Jakub Porzycki, and Jarosław Wąs. (2015). An expanded concept of the ”borrowed time” in pedestrian dynamics simulations. In Mohcine Chraibi, Maik Boltes, Andreas Schadschneider, and Armin Seyfried, editors, *Traffic and Granular Flow ’13*, pages 257–263. Springer International Publishing.

[26] Andrea Portz and Armin Seyfried. (2011). Analyzing stop-and-go waves by experiment and modeling. In *Pedestrian and Evacuation Dynamics*, pages 577–586. Springer.

[27] Jakub Porzycki, Robert Lubas, Marcin Mycek, and Jaroslaw Was. (2014). Application of nist technical note 1822 to ca crowd dynamics models verification and validation. In Jaroslaw Was, GeorgiosCh. Sirakoulis, and Stefania Bandini, editors, *Cellular Automata*, volume 8751 of *Lecture Notes in Computer Science*, pages 447–452. Springer International Publishing.

[28] Rimea. (2009). Rimea, richtlinie für mikroskopische entfluchtungsanalysen, ver: 2.2.1, (2009). Technical report, Rimea.

[29] Enrico Ronchi, Erica D. Kuligowski, Paul A. Reneke, Richard D Peacock, and Daniel Nilsson. (2013). Nist technical note 1822, the process of verification and validation of building fire evacuation models. Technical report, NIST.

[30] Andreas Schadschneider, Wolfram Klingsch, Hubert Klüpfel, Tobias Kretz, Christian Rogsch, and Armin Seyfried. (2009). Evacuation dynamics: Empirical results, modeling and applications. In Robert A. Meyers, editor, *Encyclopedia of Complexity and Systems Science*, pages 3142–3176. Springer New York.

[31] M. Schultz, S. Lehmann, and H. Fricke. (2007). A discrete microscopic model for pedestrian dynamics to manage emergency situations in airport terminals. In Nathalie Waldau, Peter Gattermann, Hermann Knoflacher, and Michael Schreckenberg, editors, *Pedestrian and Evacuation Dynamics 2005*, pages 369–375. Springer Berlin Heidelberg.

[32] Stefan Seer, Christian Rudloff, Thomas Matyus, and Norbert Brandle. (2014). Validating social force based models with comprehensive real world motion data. *Transportation Research Procedia*, 2(0):724 – 732. The Conference on Pedestrian and Evacuation Dynamics 2014 (PED 2014), 22-24 October 2014, Delft, The Netherlands.

[33] Armin Seyfried, Oliver Passon, Bernhard Steffen, Maik Boltes, Tobias Rupprecht, and Wolfram Klingsch. (August 2009). New insights into pedestrian flow through bottlenecks. *Transportation Science*, 43(3):395–406.

[34] Armin Seyfried, Bernhard Steffen, Wolfram Klingsch, Thomas Lippert, and Maik Boltes. (2007). The fundamental diagram of pedestrian movement revisited - empirical results and modelling. pages 305–314.

[35] Eleftherios Spartalis, IoakeimG. Georgoudas, and GeorgiosCh. Sirakoulis. (2014). Ca crowd modeling for a retirement house evacuation with guidance. In Jaroslaw Was, GeorgiosCh. Sirakoulis, and Stefania Bandini, editors, *Cellular Automata*, volume 8751 of *Lecture Notes in Computer Science*, pages 481–491. Springer International Publishing.

[36] British Standards. (2008). Bs 9999:2008 code of practice for fire safety in the design, management and use of buildings. Technical report, BSI.

[37] Christos Vihas, Ioakeim G. Georgoudas, and Georgios Ch. Sirakoulis. (2013). Cellular automata incorporating follow-the-leader principles to model crowd dynamics. *J. Cellular Automata*, 8(5-6):333–346.

[38] Jarosław Wąs and Robert Lubaś. (2013). Adapting Social Distances model for mass evacuation simulation. *Journal of Cellular Automata*, 8:395 – 405.

[39] Weiliang Zeng, Hideki Nakamura, and Peng Chen. (2014). A modified social force model for pedestrian behavior simulation at signalized crosswalks. *Procedia - Social and Behavioral Sciences*, 138(0):521 – 530. The 9th International Conference on Traffic and Transportation Studies (ICTTS 2014).

[40] J. Zhang, W. Klingsch, A. Schadschneider, and A. Seyfried. (2011). Transitions in pedestrian fundamental diagrams of straight corridors and t-junctions. *Journal of Statistical Mechanics: Theory and Experiment*, 2011(6).

[41] Jinghui Zhong, Nan Hu, Wentong Cai, Michael Lees, and Linbo Luo. (2015). Density-based evolutionary framework for crowd model calibration. *Journal of Computational Science*, 6(0):11 – 22.