Eidgenössische Technische Hochschule Zürich
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Lecture with Computer Exercises:
Modelling and Simulating Social Systems

Project Report

Simulation of Escape Panic: Bottleneck Effect

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Contents

1 Abstract

Rapid evacuation of buildings and other locations, where large numbers of people come together, pose a huge challenge for architects, event organizers and other authorities. In the last years advances in modelling of crowed behaviour has helped to better understand evacuation scenarios and prevent casualties. In our project we model the behavior of up to 60 people in different closed rooms. They have different arrangements of additional walls, which act as barriers. Our goal is to find out to what extent additional barriers are responsible for casualties in an evacuation scenario.

2 Individual contributions

Since all team member helped each other out, it is not possible to make a clear distinction for individual contributions. Nevertheless each member of the group worked on certain parts of the code harder than the others did.
Pedro Rosso put a lot of work into finding a good integration method and implementing it. He also wrote the code for the Euler-Cluster. Edoardo Berardo made it possible to have walls inside the room, such that the agents are able to walk around them. Mathias Gassner was mainly responsible for the implementation of the differential equation and the computation of the forces. Felix Schur put a lot of effort into the visual representation of the results and made sure that the code fragments worked together.

3 Introduction and Motivations

Of paramount importance to architects and civil engineers is how to prepare for emergency situations (e.g., fire, bomb threat or toxic gas release) in a building (e.g., a theatre, a stadium, a shopping mall or an air terminal). If the crowd fails to escape from a building in time, due to failure of obstacles avoidance or wrong exit selection, people may be injured and killed (by fire, bomb or toxic gas). Also, the crowds behavior (e.g., simultaneously rushing towards the exits, shuffling, pushing, crushing, and trampling) itself may result in injuries and death. In these scenarios it is essential that the evacuation is realized in a small amount of time, but also that none of the involved people gets harmed.
Unfortunately, there are several examples for tragedies caused by escape panics. 21 people died and 541 were heavily injured at the most noted tragedy, the love parade in Duisburg in the year of 2010. Another adversity happened in 2012, where five girls died in a human stampede at a Halloween party in Madrid Arena. The most

recent incident happened in Italy on the eight of December 2018, where six people, five of them between an age of 14 and 16, died in the evacuation of a rap concert. This shows, that this topic is still of substantial relevance, and that it is important to analyze emergency situations in the planning of such a building.
This led to the goal of this project: the implementation of a force model - close to reality - of evacuation situations of many people for arbitrary rooms. Furthermore, different rooms should be tested in order to get an idea how to increase the speed of an evacuation and how to decrease the interacting forces during the evacuation, respectively, by adapting room (e.g adding walls). Additionally a corridor, where people are trying to escape in opposite directions, should be analyzed, since a similarly situation led to deaths and most of the injuries at the disaster in Madrid, 2012.

4 Description of the Model

There were several approaches to simulate crowd evacuations. The first proposed model was the cellular automata model by Von Neumann in 1970 [1]. Later in the 1980s lattice gas models were popularized by Fredkin and Toffoli [2] - and Wolfram [3, 4]. A social force model for pedestrian flows was proposed by Helbing and Molnar in 1995 [5]. Another approach to describe pedestrian flows was used by Henderson. He has conjectured that pedestrian crowds behave similarly to gases or fluids [6]. Bradley has hypothesized that the Navier-Stokes equations governing fluid motion could be used to describe motion in crowds at very high densities [7]. Helbing et al. have summarized that at medium and high densities, the motion of pedestrian crowds shows some striking analogies with the motion of fluids [8]. Some other approaches, which aren't reviewed more closely, are agent based models, game theoretical models and models based on experiments with animals. [9]
The model in this project is based on the previously mentioned social force model by Helbing and Molnar. They described the motion of pedestrians regarding to the following effects: (1) each person wants to reach a certain destination; (2) they want to keep distance between each other; (3) they also want to keep distance from obstacles such as walls; and (4) one is sometimes attracted by another person or an object [9].
In 2000, Helbing published a paper about escape panic [10]. The basic model in this paper was reduced to effects (1), (2) and (3), which were mentioned before. They modelled the collective phenomenon of escape panic in a framework of self-driven many-particle systems. Their resulting force model can be described as follows: Each of N agents i of mass m_i likes to move with a certain desired speed v_i^0 in a certain direction $\boldsymbol{e}_i^0$, and therefore tends to correspondingly adapt his or her actual

velocity $\boldsymbol{v}_i$ with a certain characteristic time τ_i. Simultaneously, he or she tries to keep a velocity-dependent distance from other pedestrians j and walls W, which can be modelled by 'interaction forces' $\boldsymbol{f}_{ij}$ and $\boldsymbol{f}_{iW}$, respectively. All together, this leads to a N-dimensional equation of motion:

$$m_i \frac{d\boldsymbol{v_i}}{dt} = m_i \frac{v_i^0(t)\boldsymbol{e}_i^0 - \boldsymbol{v}_i}{\tau_i} + \sum_{j \neq i} \boldsymbol{f}_{ij} + \sum_{W} \boldsymbol{f}_{iW}. \tag{1}$$

The forces $\boldsymbol{f}_{ij}$ and $\boldsymbol{f}_{iW}$ can be determined with:

$$\boldsymbol{f}_{ij} = \Big(A_i \exp\big((r_{ij} - d_{ij})/B_i\big) + k\, g(r_{ij} - d_{ij}) \Big) \vec{n}_{ij} + \kappa\, g(r_{ij} - d_{ij}) \Delta v_{ij}^t \vec{t}_{ij} \tag{2}$$

and

$$\boldsymbol{f}_{iW} = \Big(A_i \exp\big((r_i - d_{iW})/B_i\big) + k\, g(r_i - d_{iW}) \Big) \vec{n}_{ij} + \kappa\, g(r_{iW} - d_{iW})(\vec{v}_i \cdot \vec{t}_{iW}) \vec{t}_{iW}. \tag{3}$$

Here A_i and B_i are constants, which were taken from the paper with
$A_i = 2\ 10^3$ N and $B_i = 0.08$ m for all agents i. The distance between two agents i,j is defined as d_{ij}, where r_{ij} is the sum of their radii (for the sake of simplicity, we assume the agents to be cylindrical). In the equation (3) d_{iW} is the shortest distance from agent i to wall W and r_i is the radii of agent i. The constants k and κ are also took over as $k = 1.2\ 10^5\ \mathrm{kg\,s^{-2}}$ and $\kappa = 2.4\ 10^5\ \mathrm{kg\,m^{-1}s^{-1}}$. The normalized direction vectors between agent j and i, respectively, wall W and agent i are used as $\vec{n}_{ij}$ and $\vec{n}_{iW}$. The vectors $\vec{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ and $\vec{t}_{iW} = (-n_{iW}^2, m_{iW}^1)$ are the normalized tangential direction vectors. The function $g(x)$ is zero if $x > 0$ and else the value of x, so that this additional term is from importance only if an agent is touching a wall or another agent. The tangential velocity difference is defined as $\Delta v_{ij}^t = (\vec{v}_j - \vec{v}_i) \cdot \vec{t}_{ij}$. This force model was used in this project to implement the escape simulations.

5 Implementation

5.1 Physical Model

5.1.1 Acting Forces

As discussed in detail in section 4, the forces acting on people are based on three fundamental pedestrian concepts: reach a certain destination; keep distance between each other; keep distance from obstacles. In order to do this, we have implemented a system of functions returning all the various parameters present in equation (1). In this way we were able - in parallel with the integration method - to reproduce the desired physical system, calculating the respective acceleration of pedestrian for each step.

5.1.2 Pedestrian Direction

In order to perform - in the most efficient way - the shortest path for each pedestrian, our direction model is based on the intersection between the agent-destination and the wall lines. In this way people can recognize which are the walls placed between them and their destination and, consequently, "choose" which is the most appropriate way. In particular, we have created functions to deal with two possible situations: the case of a "free corners" wall and that one of a "close corner" wall. In the first situation - as long as the intersection is on the wall - the function returns the person-corner direction for which the person takes the shorter total path. In the second - and most complicated - case, the function works on more levels: as first step, the function recognizes whether the wall has zero, two or only one "close corner" point. In the first of these cases, the function discussed above is called, while, in the last case, the direction of the "free corner" is chosen. Finally, when the intersection point is no more on the wall, people simple take the destination direction.

5.2 Integrators

The problem presented is analogous to a n-body simulation in physics. Each agent has a position given by a x_1 and a x_2-coordinate, and a velocity vector (v_1, v_2). In a system with n agents, their position is implemented as a $2n$-dimensional vector, same case for the velocity. Given that for $n \geq 3$ there is no general analytic solution, it is necessary to make use of numerical integration methods. Several approaches were tried to implement a stable integration method. Two methods were chosen:

5.2.1 Leap Frog

The leap-frog method is a simple yet efficient method for computing time evolution for differential equations. This is ideal for when the function evaluation has a high algorithmic cost, which is the case of equation (1): if only the interpersonal forces are considered, a system with n agents requires n forces to be calculated for n agents, which yields a algorithmic cost of $\mathcal{O}(n^2)$ operations. It may yield some inaccurate results, however, as the methods used consist basically of using first order approximations.

5.2.2 Dormand-Prince's ode45

Dormand-Prince's ode45 [11] is a highly complex differential equation solver. It uses 4th and 5th order polynomials to yield the most accurate results. It's main characteristic which makes it to be used in any standard library is the adaptivity: in each iteration it calculates the time evolution using the 4th and 5th polynomials separately. At the end, the norm of the difference of the results is calculated. If it lies within a tolerance value, the method saves the current value and continues the process. If the difference is greater than the tolerance, the step distance is reduced. This means that in stiff differential equations, this methods does several iterations per step, in order to lead more accurate results. The price to pay is the algorithmic cost of the function evaluation: each iteration evaluates the function more than 7 times.

5.3 Graphical Implementation

In order to graphically present our result, we decided to use the standard package "matplotlib" for the graphs and the package "pygame" for the simulation itself. Given the position of the walls and the position of the agents a room is drawn for each time step. To make sure that the representations of the rooms have the same size regardless of the actual size of the rooms, we created a normilzer variable. The normilizer is equal to the quotient of the desired representation size and the actual size of the room. By multiplying each coordinate with the normilizer, the goal is achieved without changing the relative position of the objects. The speed of the simulation is controlled by choosing the time which passes before a new image is drawn.

6 Simulation Results and Discussion

6.1 Square Room

The first room we want to discuss, is a simple square room with one exit and no extra walls. The results show, that indeed some deaths are caused by the bottleneck effect at the final exit. Since they are not relevant to the research question, but are present in any simulation, it is important to get an estimate in order to evaluate the data more carefully. Of utter importance is to notice that if an agent experiences a force over the agreed value of 700 N, it is still simulated as being alive. This means that the graph with number of deaths are actually number of agents who experience life-threatening forces. The third graph shows the force magnitude acting on a randomly selected agent at a given time step. The simulations with leap frog methods were are not accurate enough for more than 7 agents involved, thus their results must be ignored. The first results are shown in figure 1. The bottleneck effect is clearly recognizable. The code also outputs the forces in Newton and the amount of agents escaped, with the results of the first two runs shown in figure 2. The initial peaks in the number of dead people is due to the initialization process and shall be not considered. The deaths in the undisturbed scenario range from three to five in

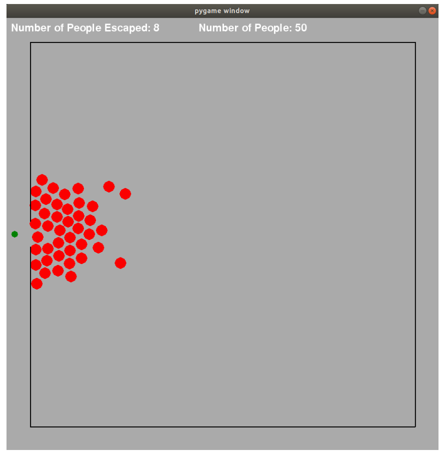

Figure 1: Simulation with 50 agents and no obstacles (integrator: ode45)

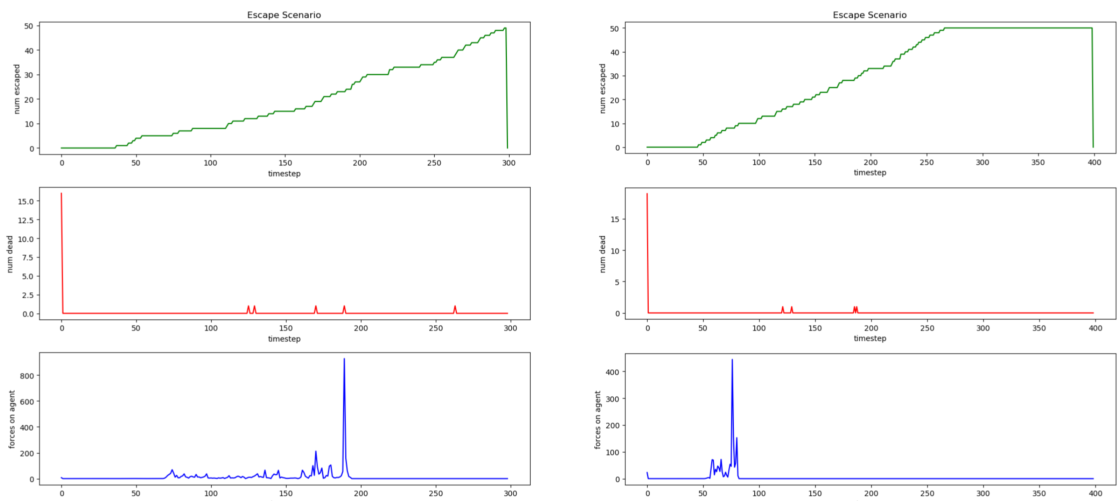

Figure 2: Simulation results for the first two runs (50 agents, no obstacles, integrator: ode45)

a situation with 50 agents.
Of further interest are two special evacuations rooms: one with a wall in the middle preventing the straight route and another in which barriers are added to narrow the the stream of people. The first variant is shown in figure 3. The results of the simulations are shown in figure 4. The graphs show more deaths compared to the simulations in rooms without obstacles, and a overall greater force acting on agents. Interestingly enough, some of these deaths happen before the first agent has even

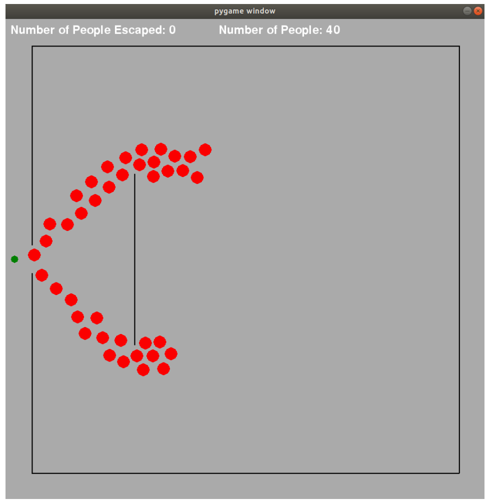

Figure 3: Simulation with 40 agents and a great wall in the middle

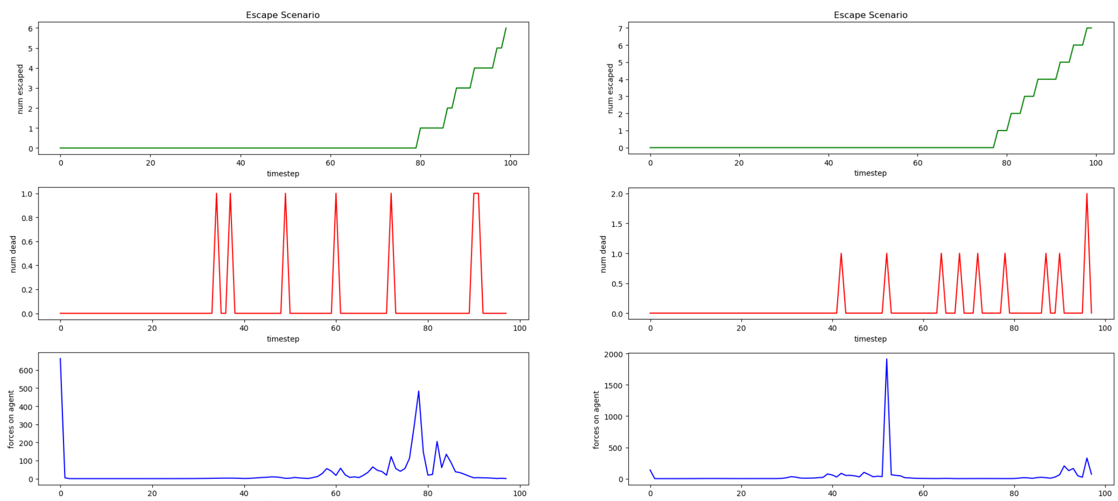

Figure 4: Simulation results for two runs (40 agents, one wall in the middle, integrator: ode45)

reached the door. The stress is mostly at the tips of the barrier, where usually one or two agents are pushed towards the center and collide with the wall. As they try to join the current and escape, they are pushed further back, and can only escape at the end; this could also imply death in a situation where escape time is a factor of survival, e.g. in a fire or nerve gas attack.

The last room simulation is shown in figure 5, and the results of the first steps of the simulation are shown in figure 4. As one can see, most of the traffic gets caught

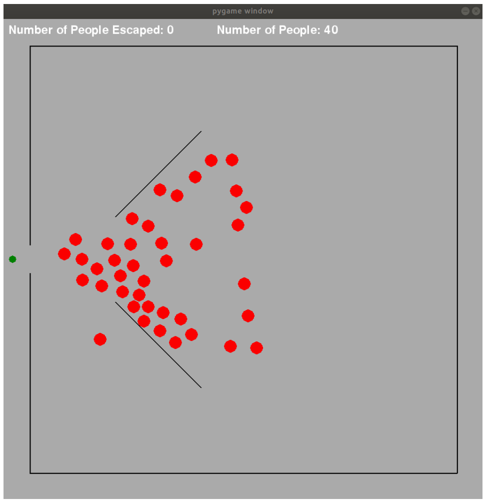

Figure 5: Simulation with 40 agents and diagonal walls used to narrow the flow of people

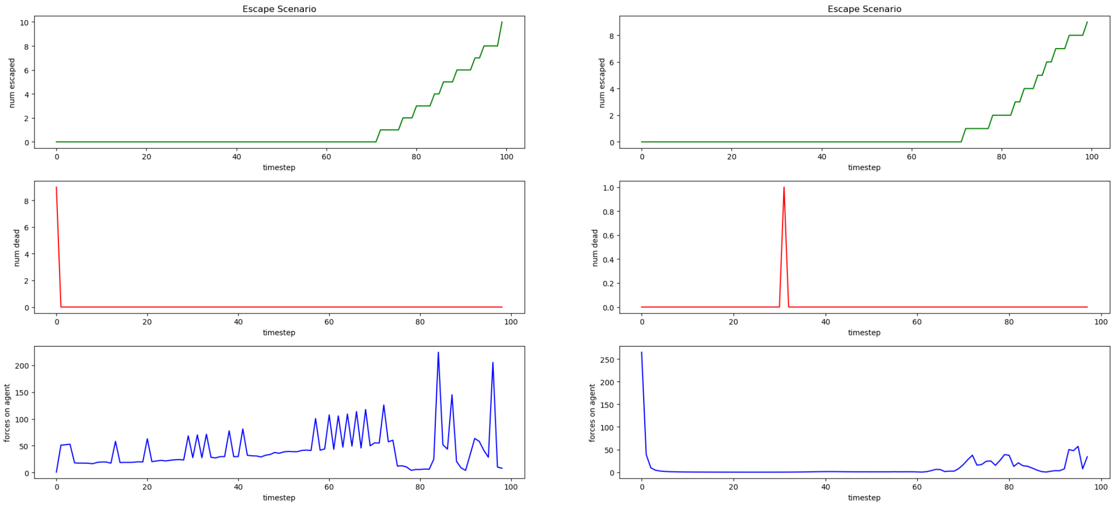

Figure 6: Simulation results for two runs (40 agents, diagonal walls, integrator: ode45)

between the walls, and the flow afterwards is narrower than before. Interestingly enough, no deaths are recorded at the walls.

6.2 Long room

In some disasters, according to footage, there are cases in which two masses consisting of more than 100 people collide into each other. The model simulates 40 people, 20 trying to get to one side and 20 trying to get to the other. The simulation is shown in figure 7 and the results are shown in figure 8. As one can see, there is no significant

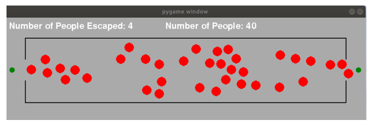

Figure 7: Simulation with 40 agents in a thin room in order to analyze collision of masses

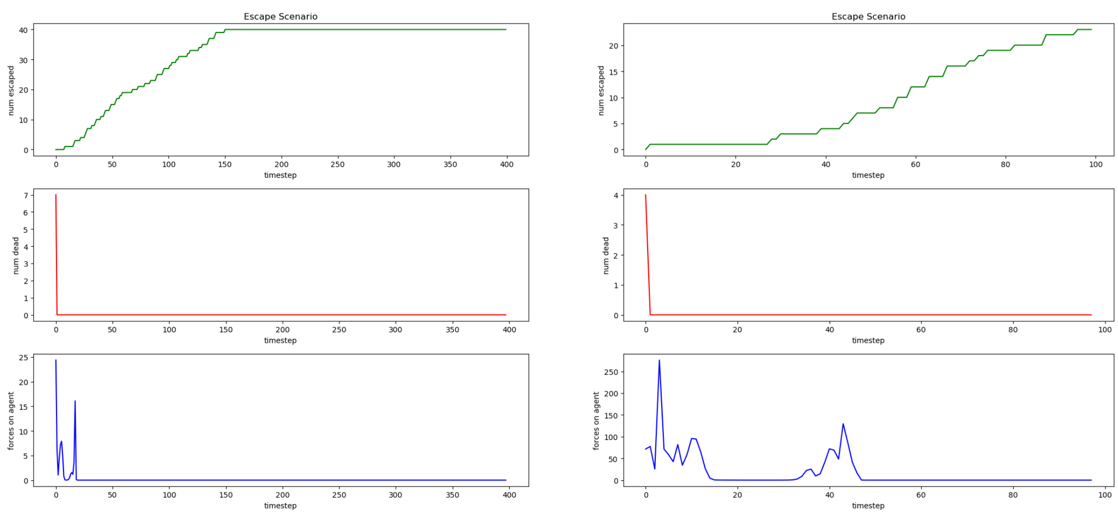

Figure 8: Simulation results for two runs (40 agents, long_room, integrator: ode45)

force acting on the agents, as there are no deaths recorded: the flow is not as chaotic as one would expect.

7 Summary and Outlook

7.1 Summary

Since we could not run our simulations at home and it took longer than expected to run them on the Euler-Cluster, we were not able the get as much samples as we would have liked. Although precise conclusions are not possible, our results still indicate that blocking the direct path of the agents with a wall results in more casualties

than having a clear route available, evidenced by the results in section 6.1. Adding walls to make the flow more narrow do not show any significant effect, at least for a small number of people. In the case of the long room, even though there are no life-threatening forces recorded, it is still necessary to perform the simulations with more agents to get a more complete results.
Nevertheless, the model does work: the non-trivial motion appears to be correctly simulated, with no balls running over each other or over the walls (at least when ode45 is used as a integration method) and the results from [10] to a certain extent have been faithfully reproduced.

7.2 Outlook

Since time for this project was limited and each simulation demanded up to 20 hours and more of computation time even when using Euler, there are lots of possibilities to pursue the research. Some possible future objectives would be the implementation of more efficient, yet accurate integrators and the development of a more user-friendly interface, which would allow more non-trivial rooms to be generated and simulated. One other important objective is running the simulations for the different rooms several times in order to obtain results with higher validity.
An imaginable application of our code - certainly after fully development - would be a program for architects or civil engineers, who design rooms for an audience of many people. The program could simulate possible evacuations and verify the safety. Additionally, there could be feature, which calculates additional walls to make an evacuation safer and/or more efficient.

8 References

[1] A. W. Burks, *Essays on cellular automata.* University of Illinois Press, 1970.

[2] E. Fredkin and T. Toffoli, "Conservative logic," *International Journal of theoretical physics*, vol. 21, no. 3-4, pp. 219–253, 1982.

[3] S. Wolfram, "Statistical mechanics of cellular automata," *Reviews of modern physics*, vol. 55, no. 3, p. 601, 1983.

[4] ——, "Universality and complexity in cellular automata," *Physica D: Nonlinear Phenomena*, vol. 10, no. 1-2, pp. 1–35, 1984.

[5] D. Helbing and P. Molnar, "Social force model for pedestrian dynamics," *Physical review E*, vol. 51, no. 5, p. 4282, 1995.

[6] L. Henderson, "The statistics of crowd fluids," *nature*, vol. 229, no. 5284, p. 381, 1971.

[7] G. Bradley, "A proposed mathematical model for computer prediction of crowd movements and their associated risks," *Engineering for crowd safety. Amsterdam: Elsevier*, pp. 303–11, 1993.

[8] D. Helbing, I. J. Farkas, P. Molnar, and T. Vicsek, "Simulation of pedestrian crowds in normal and evacuation situations," *Pedestrian and evacuation dynamics*, vol. 21, no. 2, pp. 21–58, 2002.

[9] X. Zheng, T. Zhong, and M. Liu, "Modeling crowd evacuation of a building based on seven methodological approaches," *Building and Environment*, vol. 44, no. 3, pp. 437–445, 2009.

[10] D. Helbing, I. Farkas, and T. Vicsek, "Simulating dynamical features of escape panic," *Nature*, vol. 407, no. 6803, p. 487, 2000.

[11] (2011) A dormand prince solver for ordinary differential equations (odes) of the first order. [Online]. Available: https://web.archive.org/web/20150907215914/http://adorio-research.org/wordpress/?p=6565