Department of Mathematics and Systems Analysis

Pedestrian Behavior in Evacuations – Simulation Models and Experiments

Simo Heliövaara

Aalto University

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Simo Heliövaara

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Abstract

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Abstract

In Today's built environment, it is common that large numbers of people gather in buildings. Also evacuations of such large crowds take place frequently all over the world. Standard safety requirements for buildings cannot always ensure safe evacuation of people in such situations, and thus, computational evacuation simulations have become a common practice in building design. The currently available simulation models are able to produce quite realistic movement and egress flows. However, there has not been much focus on modeling evacuees' behavior and decision making, which may significantly affect the outcome of evacuations.

This thesis develops new modeling methods to describe the behavior of pedestrians in evacuation situations. The developed models are implemented in a state-of-the-art simulation software that combines evacuation simulation with fire simulation. The models apply game theory, which is the mathematical framework for describing strategic interaction between individuals.

A novel game theoretic model for occupants' exit route selection is proposed. It describes how evacuees react to the surroundings and other evacuees' actions when deciding which exit to use. Another presented model uses spatial game theory to describe pedestrian behavior and interaction in threatening and congested situations at egress route bottlenecks. The model shows that reasonable behavior by pedestrians may lead to pushing and slow down the egress flow. In addition, a new physical approach for modeling pedestrian counterflow is given.

The thesis also gives the results of an experimental study on pedestrian behavior and decision making in evacuations. It is observed that, even in simple experimental settings, people are often unable to select the fastest egress route. Another interesting finding is that the participants' attempts to cooperate may lead to slower evacuation.

The developed models enable building more realistic tools for evacuation simulation, which help to better assess the safety of different venues. Also, the game theoretic models improve the understanding of how crowd-level movement and phenomena emerge from the behavior and decisions of individual crowd members. The experimental results presented in the thesis provide new insights into human behavior in evacuation situations. The results of the experiments can also be used to validate computational simulation models.

Keywords evacuation, simulation, game theory, experiment, crowd, behavior

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Tekijä
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Käyttäytyminen evakuointitilanteissa – simulointimallit ja kokeelliset tulokset

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Tiivistelmä

Nykyään on yleistä, että suuria ihmismääriä joudutaan evakuoimaan rakennuksista. Pelkkä rakennusmääräysten noudattaminen ei aina takaa evakuoinnin turvallisuutta, joten evakuoinnin tietokonesimulaatiot ovat yleistyneet rakennusten suunnittelussa. Olemassa olevat simulaatiomallit kuvaavat ihmisjoukkojen liikkumista varsin realistisesti. Sen sijaan ihmisten käyttäytymisen ja päätöksenteon mallinnus ei ole yhtä kehittynyttä, huolimatta näiden tekijöiden merkittävästä vaikutuksesta evakuointien lopputuloksiin.

Väitöskirjassa kehitetään menetelmiä evakuoitavien ihmisten käyttäytymisen ja päätöksenteon laskennalliseen mallintamiseen. Kehitetyt mallit on toteutettu simulointiohjelmistossa, joka yhdistää evakuoinnin ja tulipalon simuloinnin. Mallit perustuvat peliteoriaan, joka on matemaattinen kehikko yksilöiden välisen strategisen vuorovaikutuksen mallintamiseen.

Väitöskirja esittelee uuden menetelmän evakuoitavien poistumisreitin valinnan kuvaamiseksi. Peliteoreettinen malli kuvaa, kuinka ihmiset reagoivat ympäristöön ja muiden ihmisten toimintaan valitessaan poistumisreittiä. Toinen esitelty malli kuvaa evakuoitavien vuorovaikutusta tiiviissä väkijoukoissa ja uhkaavissa tilanteissa soveltaen spatiaalista peliteoriaa. Malli osoittaa, että uhkaavissa olosuhteissa järkeenkäypä toiminta voi johtaa työntämiseen, mikä aiheuttaa tukoksia ja hidastaa poistumista. Työssä kehitetään myös malli vastakkaissuuntaisten ihmisvirtojen liikkeen kuvaamiseksi.

Väitöskirjassa esitetään tuloksia myös kokeellisesta tutkimuksesta, jossa tutkittiin ihmisten käyttäytymistä evakuointitilanteissa. Tuloksista havaitaan, että ihmiset eivät usein pysty valitsemaan nopeinta poistumisreittiä yksinkertaisissakaan valintatilanteissa. Toinen kiinnostava havainto on, että evakuoitavien pyrkimys yhteistyöhön voi hidastaa poistumista.

Kehitetyt mallit mahdollistavat realistisempien simulaatiomallien rakentamisen ja näin auttavat turvallisempien rakennusten suunnittelussa. Peliteoreettiset mallit auttavat myös ymmärtämään yhteyttä yksittäisten ihmisten käyttäytymisen ja koko väkijoukon tasolla havaittujen ilmiöiden välillä. Esitetyt kokeelliset tulokset lisäävät ymmärrystä ihmisten käyttäytymisestä evakuointitilanteissa. Kokeiden tuloksia voidaan myös käyttää laskennallisten simulointimallien validointiin.

Avainsanat evakuointi, simulaatio, peliteoria, kokeellinen tutkimus, väkijoukko, käyttäytyminen

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The dissertation consists of the present summary article and the following articles:

- [I] Ehtamo H., Heliövaara S., Korhonen T., Hostikka S. (2010) Game Theoretic Best-Response Dynamics for Evacuees' Exit Selection. *Advances in Complex Systems*, Vol. 13, No. 1, pp. 113-134.
- [II] Korhonen T., Heliövaara S. (2011) FDS+Evac: Herding Behavior and Exit Selection. *Fire Safety Science – Proceedings of the tenth International Symposium*, pp. 723-734
- [III] Heliövaara S., Korhonen T., Hostikka S., Ehtamo H. (2012) Counterflow model for agent-based simulation of crowd dynamics. *Building and Environment*, Vol. 48, pp. 89-100
- [IV] Heliövaara S., Ehtamo H., Helbing D., Korhonen T. (2013) Patient and impatient pedestrians in a spatial game for egress congestion. *Physical Review E*, Vol. 87, 012802
- [V] Heliövaara S., Kuusinen J-M., Rinne T., Korhonen T., Ehtamo H. (2012) Pedestrian behavior and exit selection in evacuation of a corridor – An experimental study. *Safety Science*, Vol. 50, pp. 221-227

Contributions of the author

Paper [I] was initiated and primarily written jointly by Ehtamo and Heliövaara. In addition, Heliövaara had the main responsibility for programming the simulation models and running the calculations.

Paper [II] was equally contributed and jointly written by Heliövaara and Korhonen.

Paper [III] was initiated jointly by Heliövaara and Korhonen. The paper was primarily written by Heliövaara.

Paper [IV] was initiated and mostly written jointly by Heliövaara and Ehtamo. Heliövaara and Korhonen were jointly responsible for programming the simulation models and running the calculations.

Paper [V] was initiated by Heliövaara. The paper was primarily jointly written by Heliövaara and Kuusinen.

Preface

This thesis has been made possible by several people whom I have the privilege to thank here.

First, I wish to warmly thank Professor Harri Ehtamo, the instructor and supervisor of this thesis. His ideas and enthusiasm have inspired me and made this thesis possible. Second, I thank my other supervisor, Dr. Timo Korhonen, who greatly contributed to this work. I am also very grateful to Timo (and the Academy of Finland) for arranging the funding for my research.

During this work, I have had the privilege to collaborate with many skillful and innovative researchers. Thank you Professor Simo Hostikka, Mr. Juha-Matti Kuusinen, Mr. Tuomo Rinne, and Professor Dirk Helbing, I have enjoyed working with you. I also appreciate the insightful comments of the preliminary examiners Professor Daniel Nilsson and Dr. Gregor Lämmel.

The Systems Analysis Laboratory has provided me an extraordinary place to work and study. Many great and funny moments from conference trips, Monday seminars, quiz breaks, and floorball matches will always stay in my mind. I thank Professor Raimo P. Hämäläinen, the founder and head of the laboratory, and all of my colleagues over the years. In particular, I want to acknowledge Kimmo Berg, Anssi Käki, Juuso Liesiö, Juuso Nissinen, Ville Mattila, Jirka Poropudas, Antti Punkka, and Eeva Vilkkumaa.

I wish to thank my parents Marjukka and Antti, who have always supported and encouraged me, but also let me find my own path. My final thanks go to my own family: Sanna and Siiri, you are the best!

Helsinki, May 12, 2014,

Simo Heliövaara

Contents

1 Introduction

In today's society, people living in large cities continuously face situations where they are a part of a large crowd. Railway stations, subways and shopping centers are packed with people during rush hours and people have to adapt to the movement of the others to find their ways. Also mass events with crowds of tens of thousands of individuals take place constantly all over the world. Such crowds can easily create massive forces if their movement is not controlled and organized.

Recent history contains many large-scale crowd disasters with large numbers of casualties and injuries. For example, the crowd disasters in Mecca during the Hajj pilgrimage in 2006 (Helbing et al., 2007) and in the Love Parade in Duisburg in 2010 (Helbing and Mukerji, 2012) can be characterized as situations where high densities in extremely large crowds led to turbulent flows, high pressure, and people falling down and crushing under the uncontrollable crowd.

Evacuation situations create a different challenge, as the forces created by the crowd are not the only threat to the individuals. In evacuations, people need to leave the building or facility quickly due to a spreading fire, bomb threat, etc. Such threats affect people's behavior, which in turn may affect the outcome of the evacuation. In evacuation situations, the key question is the speed of egress, which is largely affected by crowd dynamics at egress route bottlenecks. A key finding on the egress speed is the *faster is slower effect* (Helbing et al., 2000), which states that a crowd pushing too hard towards an exit door creates friction forces between the people that cause clogging and slow down the egress flow. In the Station Night Club in Rhode Island, USA, in 2001, 100 people died and 230 were injured in a quickly spreading fire (Grosshandler et al., 2005). One main reason for the large number of victims was severe clogging at the main exit of the building that caused people to fall down completely blocking the exit. Another quite similar disaster occurred in 2009 in the Lame Horse nightclub in Perm, Russia, where more than 150 people died in a quickly spreading fire that started from fireworks.

Prof. Keith Still has gathered an extensive list of crowd disasters to his website, see (Still, 2013). Even though the list is not comprehensive, it shows that several large scale crowd disasters occur every year. According to Still, many of the disasters are not caused by misbehavior of the crowd, but by failures in the design of spaces and the management of events.

Computational crowd simulation models are useful tools for many purposes. Computer simulation enables testing the functioning and safety of different venues and architectural solutions before they are built and without involving large numbers of people in real-life evacuation tests. The models can be used, e.g., to design a railway station in a way that the movement of pedestrian crowds is as fluent as possible, or to estimate the time it takes to evacuate a crowded shopping center. Some evacuation models also enable coupling the egress simulation with the simulation of a spreading fire and making the simulated pedestrians react to the fire.

The study of pedestrian crowds is an interdisciplinary area, as different communities focus on different aspects of crowds. Psychologists and socio-psychologists study pedestrian interaction and decision making mechanisms in threatening conditions. Fire and safety engineers apply the results and methods to assess the safety of different venues. Physicists study the phase transitions and self-organization phenomena occurring in crowds. Biologists are interested in the similarities between pedestrian crowds and animal swarms. Computer scientists develop simulation models and apply pattern recognition techniques to study video material of real crowds. Due to this variety of approaches, the research of the field is also published on very different forums, creating some challenges in the interaction of the different communities. However, there are also many people in the field working across these boundaries.

This dissertation develops new methods for modeling pedestrian crowds and presents new experimental results on pedestrian decision making. Paper [I] presents a game theoretic model for evacuees' exit route selection. The game's properties are analyzed and it is shown that if the agents adjust their target exits according to a simple best-response rule, the strategies converge to the game's Nash equilibrium. Paper [II] further develops the model to consider agents with different behavioral types. Paper [III] presents a new method for modeling pedestrian movement in counterflow situations. Simulation results with the model are found to match well with experimental data. Paper [IV] applies spatial game theory to describe pedestrian behavior in congested situations at egress route bottlenecks. The agents are considered to play a game with their nearest neigbors, where they select to behave either patiently or impatiently. The study shows that, under threatening conditions, agents acting according to reasonable intuitive rules may start pushing towards the exit and cause increased pressure and jams reducing the flow through the exit. The experimental study of paper [V] focuses on exit route selection and pedestrians' ability to cooperate efficiently. The results show that, even in a quite simple setting, people are not always able to select the fastest exit route. It was also found that when the participants tried to minimize their individual egress times the evacuation was faster than when attempting to cooperate.

The modeling methods used in the dissertation are mainly based on game theory. Even though it is the mathematical framework for modeling strategic interaction between intelligent agents, game theory has not been previously very widely used in evacuation modeling. Especially, this work's approach to apply game theoretic learning models and spatial games to pedestrian modeling are new to the field. The principal ideas of the presented models are not restricted to any specific software or modeling framework, and thus, the methods can be applied in any agent-based pedestrian modeling approach.

This summary article is structured as follows. Section 2 introduces the relevant theory and results on human behavior in crowds. Section 3 discusses the modeling methods used for computational crowd simulation. Section 4 summarizes the contribution of this dissertation. Conclusions and directions for future research are given in Section 5.

2 Human Behavior in Crowds

When building a simulation model for crowd movement and behavior, the most important starting points are observations on real people in real crowds. The thorough reviews by Kuligowski (2008) and Proulx (2001) go through the different aspects of evacuation behavior. This section will discuss the aspects of pedestrian behavior that link closely to the topics of this thesis.

Occupants' exit route selection is essential for the outcome of evacuations. The prescriptive building codes determine the minimum amount of exits in each building but in real evacuations only a small part of the exits may be in active use. Especially people who are not familiar with the building are likely to attempt to leave the building the same way they entered it even if other exits would provide a faster way out (Sime, 1985, Proulx, 2001, Pan, 2006).

It is also a common observation that evacuating people tend to select the exit where the majority of the others are heading (Helbing et al., 2002, Pan, 2006, Hostikka et al., 2007b, Rinne et al., 2010). This behavior is called *herding* and in addition to pedestrian crowds, herding behavior is common among animals (e.g., Couzin et al., 2005). Studies by Dyer et al. (2008, 2009) show that the characteristics of herding are similar between people and animals.

A common belief about human behavior in evacuations is that occupants will panic. Panic is considered to be irrational behavior, where people adopt a selfish attitude (Keating, 1982). Despite the term's popularity in media, since the 70s social scientists have had a consensus that panic rarely occurs (Keating, 1982, Sime, 1980, Johnson, 1987, Quarantelli, 2002). On the contrary, people appear to apply rational decision making in relation to their understanding of the situation (Proulx, 2001).

Pedestrian movement and behavior have also been studied with experiments. A popular field of study has been the speed of pedestrian flow under different circumstances. The relationship between crowd density and walking speed, called the *fundamental diagram*, has been studied extensively (e.g., Seyfried et al., 2005). Also the speed of pedestrian flow through bottlenecks has been widely studied, e.g., (Daamen and Hoogendoorn, 2003, Hoogendoorn and Daamen, 2005, Kretz et al., 2006b, Seyfried et al., 2009). Gwynne et al. (2009) showed that the flow speed does not only depend on the width of the exit door but also on the design of the doorway. Experiments with pedestrian counterflows have been analyzed by Isobe et al. (2004) and Kretz et al. (2006a).

Somewhat less attention has been given to experimental studies on pedestrian decision making. Was (2010) studied the exit selection under different behavioral objectives, cooperative and selfish. Muir and Cobbett (1995) and McLean et al. (1996) used a quite similar approach as Was, but also gave monetary rewards to the participants depending on their performance. Nilsson and Johansson (2009) analyzed evacuation experiments performed in a cinema theatre and studied the social influence, i.e., how people are influenced by the actions of the others.

The experiment by Mintz (1951) is seminal. Aluminium cones were put inside a bottle with strings attached to them. Each participant was given a string to one cone and only one cone could fit out of the bottle at a time. The bottle was slowly filled with water and the participants tried to take the cones out before the water rises. In the experiments the passing of the bottleneck became uncoordinated and jams occurred even though it was clear that the participants could not have been in real panic as there was no danger.

A natural approach to studying pedestrian behavior is to analyze video-material of actual crowd disasters. The recent developments in computer vision and pattern recognition have enabled computer based tracking of the trajectories of individual crowd members (e.g., Helbing et al., 2007, Johansson, 2009, Ma et al., 2013), which makes video-analysis much more efficient. In the future, it is expected that automated video analysis will become more and more important for crowd research.

3 Computational Crowd Modeling

The recent significant improvements in computational power have enabled running crowd simulations with very detailed models and large numbers of agents.

Currently there is a rather wide range of publicly available pedestrian simulation models. The existing models use very different approaches to modeling pedestrian movement. Some models simulate the movement in continuous time and space (e.g., Helbing et al., 2000), while other approaches use discrete grids where move from one cell to another (e.g., Schadschneider et al., 2001). Also coarse network models, where buildings are divided into nodes representing rooms, corridors, etc. have been developed (e.g., Kisko et al., 1998). A thorough review of the approaches of different models is given by Kuligowski and Peacock (2005) and Kuligowski et al. (2010). Another comprehensive review is given by Gwynne et al. (1999b). For a more recent review, see (Radianti et al., 2013). Many of the models reviewed in these papers are commercial products, and for that reason, the details of the models' properties are not usually published.

The social-force model is an agent-based simulation model for crowd dynamics that is continuous in both space and time (Helbing and Molnár, 1995, Helbing et al., 2000, 2005). The model takes into account different forces that affect each agent and sums them up to calculate a total force, which then drives the agent's movement based on Newtonian mechanics. The forces affecting the agents include contact forces with walls and other agents, a motive force that describes the agents' attempt to move towards their desired direction, and the so-called *social force* that describes the tendency to keep some distance to the others.

One of the main advantages in the social force model is that it describes and calculates the actual forces occurring in crowds. The key reason for fatal clogging and jams at egress route bottlenecks are the pressure and friction forces occurring between the occupants. High pressure can also lead to suffocation, see ,e.g., (Nicholson and Roebuck, 1995). The social force model calculates these actual forces in the simulations, and thus, can rather realistically detect the situations that create lethal forces.

Another great benefit of the social force model is that by adjusting the size and direction of the agents' individual motive forces, it is possible to describe all kinds of different behaviors. This enables, e.g., the modeling of agents changing their target exits, agents pushing forward harder than the others, and agents trying to follow others.

The original social force model described the agents as circles in a horizontal two-dimensional plane. As a circle is not a very good approximation of the cross-section of a human body, Thompson and Marchant (1995), Langston et al. (2006) and Korhonen et al. (2008) modified the model by describing each agent with three overlapping circles. One larger circle describes the torso and two smaller circles the shoulders to approximate the elliptical shape of the cross-section. With this modification, the agents are no longer symmetrical, and thus, also the rotation movement needs to be modeled. This means giving each agent an individual rotational equation of motion in addition to the translational equation of motion. The rotational equation of motion consists of three torques corresponding to the contact, social and motive forces.

Another widely used approach to pedestrian modeling is based on cellular automata (Blue and Adler, 2001, Kretz and Schreckenberg, 2006, Schadschneider et al., 2001, Schadschneider, 2001). A general cellular automaton (CA) is a grid of cells, where each cell can have different states. Time is discrete and, over time, the states of the cells change according to some rules. Originally CA was created by John von Neumann, when he was working on self-replicating systems, see (von Neumann, 1966).

In pedestrian modeling, the common approach is to use two-dimensional CAs, where each cell corresponds to the size of a human body, approximately 40 cm $\times$ 40cm. Each cell can be either empty or occupied by one agent. On each time step, each agent can either stay in its current cell or move to an unoccupied neighboring cell. Cellular automata can have many kinds of different rules to describe the different phenomena in pedestrian movement. In literature, rules have been used, e.g., to model pedestrian tendency to follow others (Schadschneider et al., 2001) and the creation of jams in dense crowds (Kirchner et al., 2003).

The main advantage of CA models compared to the social force model is fast computing. The discreteness of time and space and the property that agents usually only observe the states of their neighboring cells enables very fast computing. Cellular automata have been successfully used in modeling freeway traffic by Nagel and Schreckenberg (1992).

The main restriction of cellular automata models is that the actual physical contact forces occurring in dense crowds are not modeled. Hence, the models have difficulties to accurately reproduce phenomena like clogging at egress route bottlenecks.

3.1 FDS+Evac

The models of this dissertation are implemented in the FDS+Evac software (Hostikka et al., 2007a, Korhonen and Hostikka, 2009).

Fds+Evac is an egress calculation module that is designed to work on the platform of the fire simulation software Fire Dynamics Simulator (FDS) (McGrattan et al., 2009a,b,c,d, McGrattan, 2009). FDS simulates fire in buildings by computing the temperature, density, pressure, velocity and chemical composition of fire gases in a fine grid. In addition FDS computes temperature and various other quantities of the solid surfaces of the simulated building.

Coupling the evacuation simulation with fire simulation has many benefits. It enables the egress program to use the simulation results of FDS, like gas temperature, smoke, and radiation levels to affect the behavior of the evacuating agents. It is also possible to calculate the doses of many lethal and harmful fire products inhaled by the agents.

FDS+Evac uses the effective flow-calculation algorithms of FDS to calculate egress routes through different exits in arbitrary building geometries. A vector field leading to the exits is obtained by solving a potential flow problem, where the exit door acts as a fan extracting fluid out of the building (Korhonen et al., 2005). The routes created like this will not be the shortest routes but close to it. The egress modeling of FDS+Evac is based on the social force model that was described above. Setting the agents' motive forces to follow the created vector field makes the agents follow the calculated route to the exit.

FDS+Evac simulations of large crowds are intensive on computing time and memory consumption. With more than a few thousand agents, the calculation becomes very CPU expensive. In dense crowds also the simulation time steps have to be very small, which increases computing times.

3.2 Game theoretic learning models

Many of the decisions that evacuating pedestrians face can be formulated mathematically with game theory. The sub-fields of game theory that are especially useful in crowd modeling are *game theoretic learning* (e.g., Fudenberg and Levine, 1998) and *evolutionary game theory* (Maynard Smith, 1982, Weibull, 1995).

Game theory is the mathematical framework for modeling strategic interactions between intelligent agents, see, e.g., (Fudenberg and Tirole, 1991, Osborne and Rubinstein, 1994). Game theory studies the decision making situations, where the agents' payoffs do not only depend on their own decisions but also on the decisions of other agents. The key solution concept of game theory is *Nash Equilibrium*, in which the players choose such strategies that none of them can gain anything by changing her strategy unilaterally (Nash, 1950).

The traditional game theoretic approach is largely based on the assumption of *common knowledge*. It means that the players are assumed to know the other players' payoff functions and that all players are fully rational. It is also assumed that the players know that also the other players know these things. Under these assumptions, each player can calculate the Nash Equilibrium of a given game.

Game theoretic learning studies the situations, where the common knowledge assumption cannot be made. In learning models, the equilibrium arises as the outcome of an iterated process in which the agents react to the actions of the others. One of the first published learning models is the Cournot duopoly model (Cournot, 1838). It describes how two competing firms, by turns, adjust their supply by optimally reacting to the other firm's actions. The process was found to converge to the equilibrium of the game. The learning process presented by Cournot is an example of *myopic best-response dynamics*, see, e.g., (Ellison, 1993, Gilboa and Matsui, 1991, Matsui, 1992). The best response dynamics is widely used in the economics literature (e.g., Hopkins, 1999), but the models have also been used, e.g., to describe traffic in telecommunication networks (Altman and Basar, 1998, Korilis and Lazar, 1995). Examples of other widely used learning models are *fictitious play* (Fudenberg and Levine, 1998), *reinforcement learning* (Sandholm and Crites, 1996, Roca and Helbing, 2011), and *replicator dynamics* (Maynard Smith, 1982, Nowak and May, 1992).

Evolutionary game theory was originated by Maynard-Smith and Price (1973) to mathematically describe the evolving populations in biology. Evolutionary game theory focuses on the dynamics of strategies with different learning models. Spatial evolutionary games are an extension of evolutionary game theory to situations where the agents only interact with their geographical neighbors. This is the interesting field considering crowd modeling. The most common learning approach used in spatial games is the replicator dynamics (Nowak and May, 1992, Hauert and Doebeli, 2004), as it closely mimics biological evolution. Also the best-response dynamics have been used in the spatial setting (Sysi-Aho et al., 2005). Rather than biological evolution over generations, the spatial best-response dynamics can be considered to describe the short term reactions of intelligent agents to their neighbors' strategies. In this sense, the best-response can be considered to be a suitable model for the behavior of pedestrians in a crowd.

Game theory has been quite rarely applied to evacuation modeling. The first approach was given by Brown (1965), who explained the emergence of pushing behavior in egress with game theory by applying the prisoner's dilemma game. Coleman (1990) presented an extension to Brown's model using iterated prisoner's dilemma and contingent strategies. Hoogendoorn and HL Bovy (2003) applied optimal control and differential games to calculate walking trajectories for pedestrians. Lo et al. (2006) presented a game theoretic approach for exit selection. Hao et al. (2011) applied evolutionary game theory to modeling unidirectional pedestrian flows with cellular automata. Recently, Shi and Wang (2013) applied the snowdrift game (hawk-dove game) to modeling pedestrian movement in a grid.

4 The Dissertation

This dissertation studies the behavior of pedestrian crowds by introducing new modeling methods and experimental findings. Papers [I], [II] and [IV] apply game theoretic learning models to describe the interactions between pedestrians in evacuation situations. Paper [III] develops a new modeling method for pedestrian counterflow situations and Paper [V] presents the results of an experimental study on pedestrian exit selection.

This Chapter presents the objectives and contributions of the dissertation. Section 4.1 outlines the objectives of the thesis and Sections 4.2 to 4.5 give detailed descriptions of the dissertation's contributions.

4.1 Research Objectives

This thesis has two main research objectives: 1) to develop new methods for simulating the behavioral aspects of pedestrian evacuations, and 2) to enhance the understanding of human behavior in evacuations and the connection between the behavior of individual crowd members and the outcome of evacuations. One key objective in model development is to apply game theory in modeling pedestrian behavior. Game theory is the mathematic framework for modeling strategic interaction and it has not been actively applied in the existing literature on crowd modeling. The main goals of each paper of the thesis are outlined below.

The objective of Paper [I] is to develop a computational model to describe evacuees' exit selection. The goal is to apply game theory in the model, as it gives tools for modeling the behavioral interaction between pedestrians. The objective is also to base the assumptions of the model on existing literature and observations on evacuation behavior.

The objective of Paper [II] is to further develop the model of Paper [I] by taking into account the common observation that different people may behave very differently in evacuations. The goal is to use simulations to study how different behavioral types affect the outcomes of evacuations.

The objective of Paper [III] is to develop a simulation model for describing situations with multi-directional pedestrian flows, especially counterflows. The aim is to build a model that works well in both dense and sparse crowds and to validate the model with experimental data.

The goal of Paper [IV] is to build a spatial game theoretic model for describing evacuees' behavior in congested and threatening situations. The objective of the paper is not to build a completely realistic model for egress congestion. Rather, the aim is to study the possible causes for jams at egress route bottlenecks and to develop better understanding of the connection between individuals' behavior and the clogging that occurs on crowd-level.

Paper [V] has three main objectives: 1) to provide data on exit selection behavior for validating computational egress models, 2) to study whether people are able to select the fastest egress route, which is the assumption of many simulation models, and 3) to test people's ability to efficiently cooperate during egress.

The following sections describe the contributions of each paper of the dissertation. First, Table 1 gives an overview of the papers.

4.2 Exit Route Selection

Paper [I] presents a new game theoretic model for evacuees' exit route selection. The exit selection of all agents is formulated as an N-player normal form game. The goal of the agents is to select the fastest evacuation route. In their decision making, the agents take into account the distance to the exits and the time it takes to queue in front of the exits. The queue length in front of different exits depends on the other players' strategies, which makes this a genuine game model. It is shown that the presented game has a Nash Equilibrium (NE) in pure strategies and a necessary and sufficient condition for the uniqueness of the NE is given. It is also shown that iterative best-response algorithms converge to the NE in limited time and an upper limit for the required iterations is derived. Simulations with best-response algorithms are run to show that in

Table 1. The papers

Paper	Context	Methodology	Contribution
[I]	Modeling evacuees' exit selection	Game theoretic modeling	A novel game theoretic model for exit selection with implementation to a continuous time simulation model
[II]	Modeling evacuees' exit selection including different behavioral types	Game theoretic modeling	Extension of the model of Paper [I] to include different agent types
[III]	Modeling pedestrian counterflow	Agent-based modeling	A novel method for modeling intersecting pedestrian flows with simulation results fitting well to experimental data
[IV]	Modeling pedestrian congestion at egress route bottlenecks	Spatial game modeling	A spatial game model that gives an explanation for the causes of clogging at egress route bottlenecks
[V]	Experimental study on pedestrian egress through two exits	Experiment and statistical analysis	Results on pedestrians' exit selection behavior and the effect of attempted cooperation on egress times

practice the algorithms converge much faster than the theoretical upper limit.

In Paper [I], the exit selection model is implemented to the FDS+Evac simulation model, in which the agents move in continuous time and space based on the social force model. The agents are set to update their strategies frequently throughout the egress based on their best-response functions. The simulation results in a test geometry show that applying the model makes egress much faster compared to the common approach to assign each agent to its nearest exit. Figure 1 shows a snapshot of an FDS+Evac simulation using the exit selection model.

As we will see from the results of Paper [V], real people are not always

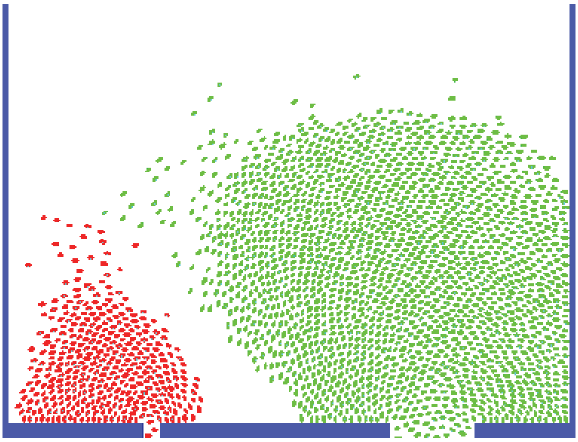

Figure 1. A snapshot of a simulation with FDS+Evac using the exit selection model of Paper [I]. The red agents have selected the narrow exit on the left and the green agents head to the wider exit on the right. The figure illustrates how the agents are able to adapt to different exit capacities when selecting their routes.

able to select the optimal egress route. Hence, it is not realistic to assume that real people would be able to select the fastest route as well as the agents in this model. To reflect this fact, an anchoring parameter is added to the model. As it is likely that people cannot correctly estimate small differences in estimated evacuation times through different exits, the anchoring parameter sets a limit for how much faster an alternative exit has to be for an agent to change its route. Simulations with FDS+Evac show the expected result that increasing the anchoring parameter leads to increased evacuation times.

In evacuations, it is normal that people try to leave the building as fast as possible. Two factors affecting the individuals' evacuation times are naturally the distance to the exit and the possible queue in front of the exit (Gwynne et al., 1999a). Hence, it is a natural assumption that people try to consider these two factors when assessing the goodness of exits. The model of Paper [I] also considers the well-known fact that the estimated evacuation time is not the only factor affecting occupants' exit selection. According to Proulx (1993), evacuees prefer familiar egress routes. On the other hand, fire and smoke may make evacuees reject some routes, and, as FDS+Evac is connected to the fire simulation model, this can be taken into account in simulations. The exit selection model first categorizes the exits based on their familiarity, visibility, and fire-related conditions. The target exit is selected first based on the categorization and only if two or more exits are equally good, the game-theoretic model is applied to make the final decision.

Paper [II] studies how behavioral differences between individuals affect the outcome of evacuations. Three agent types (Active, Conservative, and Herding) are presented to describe different behaviors. The Active agents observe their environment actively to find the fastest route, the Conservative agents prefer familiar routes, and the Herding agents follow their nearest neighbors. As described in the literature review of Section 2, preferring familiar routes and herding are commonly observed phenomena in real crowds. It has also been observed that some people search for alternative exits more actively than others, see Rinne et al. (2010). These new agent types are implemented to the model presented in Paper [I]. Simulations using FDS+Evac show that Active agents, who actively seek for faster and less used exit routes, can have a significant effect on the whole crowd's egress times, as they can also lead the herding agents to these faster routes.

4.3 Pedestrian Counter Flow

Paper [III] presents a method for modeling pedestrians' tendency to avoid collisions in counterflow situations. Differently from some previous approaches (Pelechano et al., 2007, Smith et al., 2009), the agents do not only try to avoid the nearest oncoming agent, but rather look at the bigger picture and try to select the direction with the least counterflow. In addition to changing their walking direction, the agents are also set to rotate their bodies to move shoulder first in counterflow situations. This is a normal way of moving in dense crowds as it occupies much less space in the walking direction.

The model of Paper [III] is implemented to the FDS+Evac software, which uses the Social Force model for pedestrian movement. The agents are set to select their desired walking directions using the counterflow model. Test simulations show that without the counterflow model the social force model can create unrealistic jams in simple counterflow situations. The presented model makes counterflows smoother in the simulations. Simulation results are also compared with previously published experimental data and the results match well.

4.4 Spatial Games in Egress Congestion

Paper [IV] presents a spatial game model for describing pedestrian interaction at egress route bottlenecks. Each agent has two alternative strategies: to behave either patiently or impatiently. The patient agents are considered to patiently wait for their turn in the queue in front of the exit, while the impatient agents behave aggressively and try to overtake the others. Aggressive pushing behavior of some individuals has also been observed in real crowds (Helbing and Mukerji, 2012). The payoffs of the game are derived from simple assumptions and they turn out to correspond to a hawk-dove game.

The agents are set to play the game with their neighboring agents and equilibrium configurations for the game are computed using best-response dynamics. In the resulting spatial equilibria, the patient and impatient agents form patterns, where the proportion of impatient agents is low in front of the exit and increases with the agents' distance to the exit. An example of a spatial equilibrium is shown in Fig.2.

The model is also implemented to the social force model of the FDS+Evac software by using different individual parameters to describe agents' movement under different strategies. The impatient agents are set to push harder towards the exit. The agents are set to update their strategies frequently with best-response dynamics to keep the strategies close to the current equilibrium throughout the simulation. The simulation results show that threatening conditions increase the proportion of impatient agents, which leads to increased pressure, clogging and reduced flows through the exit.

Aggressive behavior and jams at egress route bottlenecks are often considered to be caused by irrational panic behavior. The results of this study show that agents acting rationally according to simple intuitive rules can, under threatening conditions, cause increased pressure and jams blocking the exit.

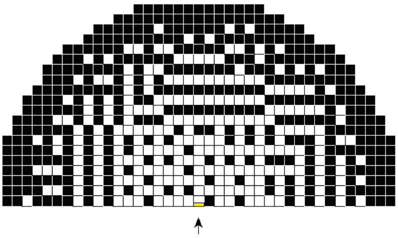

Figure 2. An example of an equilibrium configuration of the spatial game of Paper [IV]. There are 628 agents heading towards the exit, which is represented by the arrow. The white and black squares represent individual patient and impatient agents, respectively.

4.5 Evacuation Behavior – Experimental results

Paper [V] illustrates the results of an experimental study of exit selection in evacuation situations. The experiment was run in a corridor with two exits, one closer and one further away from the participants' starting location. In the experiments, the participants were given a target to either try to cooperate or to pursue self-interest in the egress.

The results show that, with statistical significance, the participants were unable to select the fastest exit route.

It also turned out that trying to minimize individual egress times led to faster egress than attempts to cooperate. One explanation for this difference turned out to be that, when trying to save themselves, the faster participants took over their slower predecessors. When trying to cooperate, overtaking did not occur and the whole crowd moved in the speed of its slowest members. This result could be considered in building design, e.g., by designing buildings that enable easier overtaking. Also in some cases the evacuation could be planned so that faster occupants would use a different exit than the slower ones.

The effect of cooperative and selfish behavior have been previously studied in experiments by Muir and Cobbett (1995) and McLean et al. (1996). The settings of the experiments were quite different from Paper [V] and both of the studies gave monetary rewards to the participants based on their performance. Also in the study of McLean et al. (1996), selfish behavior was found to lead to faster egress, but in the study of Muir and Cobbett (1995) cooperation was faster. The differences between these two studies can be largely explained by the different reward structures that were used. To enable unbiased comparison between selfish and cooperative behaviors, we decided not to use any performance based incentives in the experiments of Paper [V].

Paper [V] presents the results of the experiments in a detailed way. The average egress time and selected target exit are presented for each of the 54 individual starting positions. Also the exact measures of the building geometry are presented. These results enable a detailed comparison of simulation runs with the experimental results.

5 Conclusions and Future Research Directions

This dissertation develops new methods for computational simulation of pedestrian behavior and decision making in crowds. In addition, the dissertation presents new experimental results on pedestrian behavior. The presented models and results focus mainly on evacuation situations.

The developed methods help building more realistic simulation models for pedestrian movement, which can be used to assess the safety of different venues. The results also improve the understanding of the effects that different individual behaviors have on the crowd level.

The existing crowd simulation models do not widely apply game theory when modeling pedestrian interactions but rather use heuristic models to describe pedestrian behavior. The game theoretic modeling methods used in this dissertation, i.e., best-response dynamics and spatial games, have not been previously used to model pedestrian interaction.

A natural direction of future research is further validation of the developed models based on experimental data and observations on real crowds. For example, Paper [I] presents a model for agents' exit selection. The model includes an anchoring parameter that describes how well the agents are able to assess the fastest exit. On the other hand, Paper [V] presents experimental results showing that people are not able to make optimal decisions on the fastest egress route. Hence, estimating the value of the anchoring parameter from the data of the experiment is a natural next step.

Paper [IV] presents a game theoretic model for pedestrian behavior in threatening situations at egress route bottlenecks. This model could be further refined. The presented model assumes that the cost functions of all agents are identical, which is not very realistic as people may behave very differently in similar situations. Applying individual variation to the cost functions could lead to interesting results. One way to include variation would be to randomly select the individual parameters from some distributions. Another approach would be to introduce different agent types with different behavioral properties.

A major challenge in the future research on pedestrian crowds will be to connect the results of the different research groups and sub-communities in the field to a more comprehensive theory. Multiple different models have been published to describe different aspects of pedestrian movement and behavior, but the models have not been extensively compared with each other and with experimental and real life data. Such studies would be valuable for all parties involved in computational crowd modeling.

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