The simulation of crowd dynamics at very large events

Calibration, empirical data, and validation

Hubert Klüpfel

TraffGo HT GmbH, Office Duisburg, Falkstraße 73—77, 47057 Duisburg, Germany; kluepfel@traffgo-ht.com

Abstract

In this article, we show three examples for the application of pedestrian flow simulation and analysis: the Haj to Makkah, the World Youth Day 2005 in Cologne, and the egress (non-emergency) from a football stadium. The former two are among the largest events in the world – concerning the number of participants. Various circumstances are specific for religious events. The persons might perform rituals and therefore the patterns of movement or gathering are governed by rules that go beyond simple necessity or comfort. Furthermore, the persons are usually very much attracted by the (idealistic) aim of their pilgrimage. For the Haj to Makkah, the Jamarat Bridge, where the symbolic stoning of the devil takes place, is the most interesting part concerning crowd dynamics. The same holds for the final service at the World Youth Day 2005 in Cologne, celebrated by the Pope. The paper is divided into five parts: The first section is concerned with model building and the second with the calibration of parameters by empirical data. The following two sections are dealing with simulation results and their verification. The final section summarizes the results, provides recommendations and concludes with the most important implications for the field of crowd dynamics simulation.

1 Model Building

Empirical data is used for model building on the one hand and for verification of results on the other hand. Straightforward approaches of model building are so called empirical models. They use empirical results like the relation between flow and density directly. Examples are the approaches of Pauls [4] and Predtetschenski [11]. These models are usually macroscopic, i.e., they describe the homogenous flow of persons. Adapting the nomenclature of Figure 5, they would be called global queuing models. When individual persons are distinguished, one speaks of microscopic models. The further aspects of this classification scheme are provided in Figure 5. Individual means in this context, that persons can have different abilities and characteristics which are represented directly (individually) in the model.

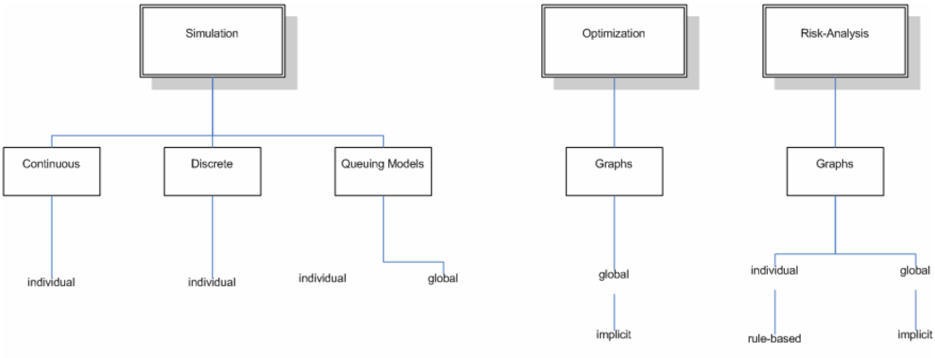


Figure 1: Classification of models.

This is usually combined with a detailed (microscopic) representation of space – either continuously or discrete. However, it is not the major intention of this paper to classify models. Rather, practical examples and empirical observations are used to highlight the applicability of the different modeling approaches.

2 Empirical Data and Calibration of Parameters

All the empirical observations shown in this paper relate to large scale events. Two of them are religious events, the Haj to Makkah and the World Youth Day in cologne. The third is the egress from a football stadium after the match (non emergency). The former two are very large events with several hundred thousand pilgrims. In the later case, the stadium has a capacity of 80,000 persons. There is another distinction – of course – between the Haj and the World Youth Day concerning the operation and the staffs' training. The Haj takes place every year at the same place, the World Youth Day neither takes place every year, nor does it always take place at the same location. This is a major difference, especially concerning the location and the experience of the officials.

Table 1: Dependence of walking speed on group size.

Group size	# Groups	Walking Speed / (m/s)
1	95	1,38
2	149	1,28
3	59	1,24
4	17	1,24
5	10	1,22
6	2	1,10
total	332	1,30

The data shown in Table 1 has been measured on the pedestrian bridge at the World Exhibition (Expo) 2000 in Hannover (Germany).

2.1 Identification of Key Parameters

Different models are of course based on different assumptions. Often, these assumptions are implicit. This means, that they are not explicitly stated but can be concluded from, e.g., the parameters used in the model. However, even experiments or observations are not assumption free. In the context of such measurements, a distinction is usually made between independent and dependent variables. The former are varied freely and the latter are determined by the former. An example would be age and walking speed. Age would in this context be the independent and walking speed the dependant variable. This is highlighted in the following Table 2. This table contains further important concepts and terms.

Table 2: Glossary.

Validation	Validation and Verification are used synonymously.
Simulation	The systematic application of a (mathematical) model to obtain quantitative statements (i.e. numbers) that correspond to real world phenomena.
Validity	A number is valid, if it actually describes what it is intended to describe.
Reliability	A quantity is reliable, if repeated measurements (with the same boundary conditions) provide the same results.
Objectivity	The fact that the same results can be obtained by several persons (if the same assumptions are made).
Calibration	The adjustment of a parameter to obtain correct simulation results.
Dependent Variables	are those quantities that are actually measured. Measurement is not restricted to empirical observations but comprises also simulation results.
Independent Variables	are those that can be tuned by the user
Parameter	Parameters are independent variables in models.

From the connection between age and walking speed it can be seen that there is no one to one correspondence between independent variables and model parameters. In a simulation model, independent as well as dependent variables can be parameters. One can either define age as a parameter that has to be specified by the user. Or one can “directly” use walking speed as a parameter. Since the relation between age and walking speed is pre-determined, these two approaches are analogous.

However, for other parameters, the case is more complicated. Physiological variable can usually be accessed directly. Therefore, their distribution within a given population is usually known or can be derived via relations to other known variables. However, for psychological (or even sociological) parameters, like orientation capability, decision making abilities or group binding, this is not the case. Therefore, these are typically calibration parameters. The general question arises, whether they should be included in a model as parameters at all. Figure 2 shows different individual strategies for egress. They could be connected to the orientation capability shown in Table 3. This schematic relation between geometrical complexity, individual movement ability and egress strategy is neither functional nor quantitative. Therefore, it is not suited in this form for implementation in a simulation model. In stochastic models, however, parameters that represent probabilities can be used. One such parameter is for example an orientation frequency, which specifies the frequency of abrupt stops due to the need for orientation. The range of this parameter is per definition restricted to the interval from 0 to 1.

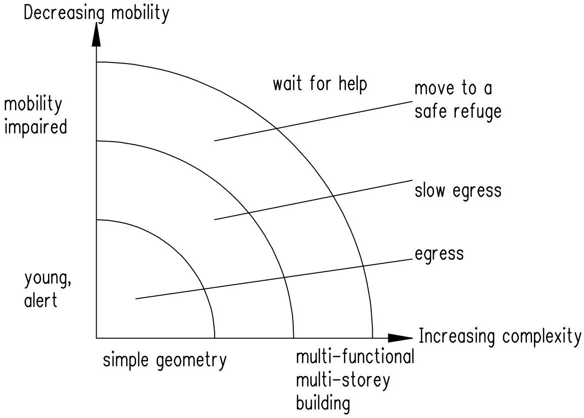


Figure 2: Different strategies for egress depending on the individual movement ability and the complexity of the surroundings.

2.2 Quantification of Parameters

When quantifying parameters of phenomenological models, some of the parameters are per definition calibration parameters. This means, that they cannot be directly measured, but are calibrated by adapting simulation results to measured quantities.

Table 3: Relation between model parameters and empirical quantities.

Name	Empirical quantity	Measurement
Free walking speed	Same	Video footage
Orientation capability	Decision time (?)	Video footage
Age	Same	Statistical tables
Gender	Same	Statistical tables
Further person parameters	Same	Statistical tables
Route choice	Strategy	Questionnaire
Motion impairment	speed reduction lateral deviation	Video footage

It is usually not possible to directly determine the parameters for a population. Therefore, standard populations, e.g. an average population, must be defined. One approach is to use census data. The column “measurement” in Table 3 indicates how each quantity can be “measured” respectively determined. The parameter “route choice” is illustrated in Figure 2. Many additional parameters can be defined, of course.

3 Simulation Results

Simulation results are the only way to verify (or falsify, if one prefers the Popperian concept) a model as a whole. Of course, there is no first principles approach pedestrian movement. The term “ball bearing models” might partly results from this misunderstanding, either because the application range of a model based on first principles (i.e. non-phenomenological) has not been clearly stated or the fact that every model is based on simplifications is misunderstood.

3.1 Haj

The empirical data concerning the Haj is manifold [1]. Since it takes place every year, much information has been collected concerning the pilgrims movement.

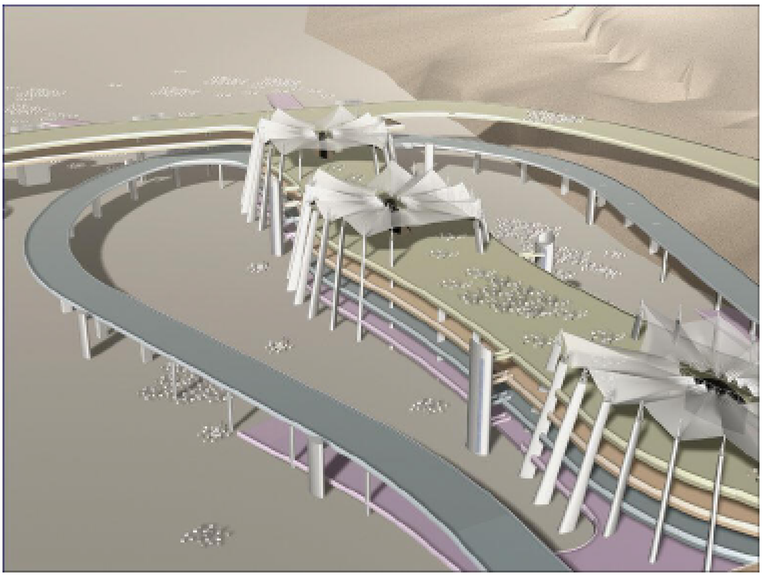


Figure 3: Proposed new design for the Jamarat Bridge [16].

Currently, a major restructuring of the Mina area is under-way. The situation is different for the WYD however, where there is basically no quantitative data available. For the first case the data is used to calibrate the model and then simulations are performed to support the planning for the improvement of the structures. By comparing the performance of different procedures, operation guidelines can be formulated. Since, empirical data will be available in the future; too, the impact of the changes can be scrutinized and compared to the simulated predictions. The proposed bridge is shown in Figure 4. In the scenario considered here, there are 100,000 persons distributed equally on the bridge. The persons are indicated by the small red dots. This is an extreme case which is rather a worst case test. It does not imply that such a situation will occur regularly in this environment. As can be seen from Figure 5, the simulation results (in this case the position of the persons after 10 minutes) depend on the assumptions made. The major influence in this case is the route choice of the persons. In the simulation, this route choice is modeled via a so called potential. Other authors call this “distance metric” [2] or static field [3]. However, the method is always based on using the distance to the exit or some intermediate goal to determine the direction of motion.

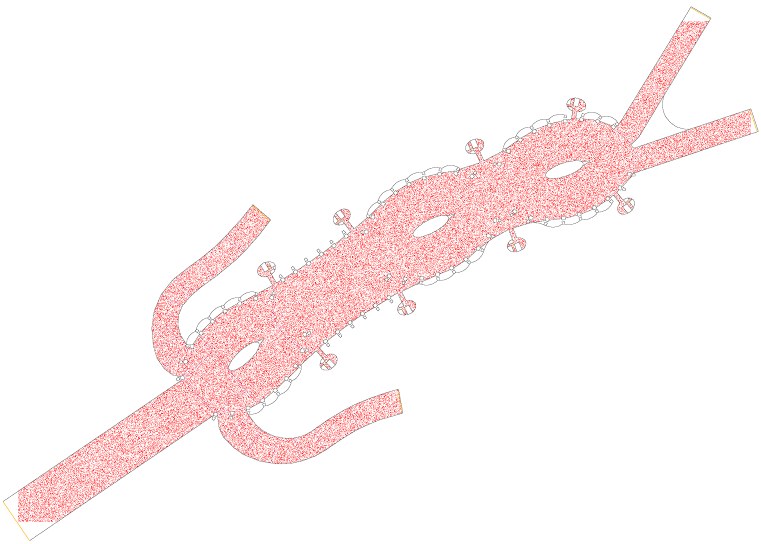


Figure 4: One level of the proposed new Jamarat Bridge.

Furthermore, the results of the simulation depend strongly on the assumptions made, especially concerning route choice. In this example, it is crucial where the persons move.
Of course this method can be refined by defining groups of persons and areas within the geometry where the potential is adapted due to certain further assumptions (e.g., doors through which the potential spreads preferably).
The term potential is quite intuitive in this context, since the distance metric is similar to an electrostatic potential with a single source for a simple geometry.
There are additional boundary conditions, e.g. the walls which basically have a potential of minus infinity, i.e. cannot be penetrated. This boundary condition do not compare to any boundary conditions used in electrostatics, however.

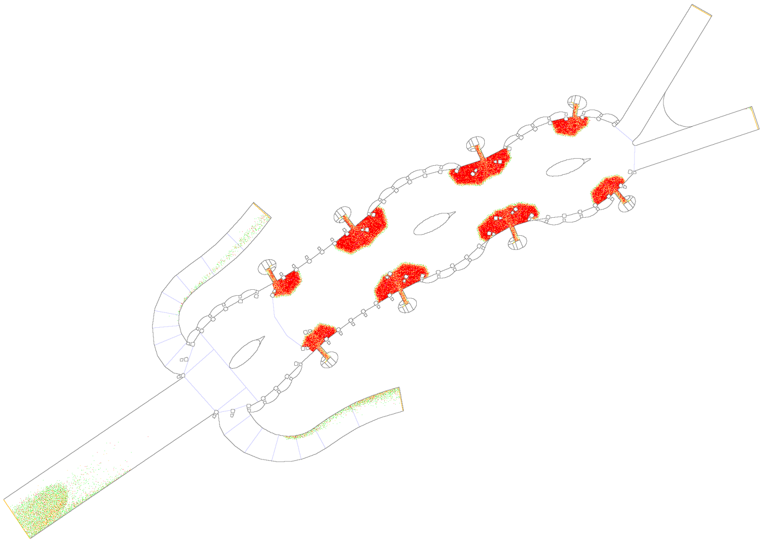


Figure 5: Situation after 10 minutes.

The important point is that these assumptions concerning the route choice often determine the simulation results. The route-choice is normally not a result of the simulation, but is pre-defined simulation parameters. Even if a complex method is applied, i.e. definition of several groups, guiding via a route choice graph, additional limitations or boundary conditions for the determination of the walking direction (which corresponds to the potential), all these have to be set by the user of the simulation.
This argumentation becomes quite clear, when one takes into account the fact that otherwise, an artificial intelligence approach is necessary. The decisions made by the persons would then require a mental representation of the geometry every agent can access. Furthermore, there would have to be rules which model the decision making process of the individual. Whether these rules are deterministic or stochastic does not matter.
At the end of the day, parameters must be defined, which describe the different strategies of the agents. The decision, how to tune these parameters would again be the task of the user.
Another argument for the importance of the user's settings is the analogy between a simulation and an evacuation trial or real evacuation. It is not only the evacuees themselves who autonomously decide which route to take. Of course, the staff members, the signage and other parts of the evacuation system influence the movement behavior and route choice. In this sense, a model simplifies and quantifies these influences. Since there are no first-principle rules, every model is phenomenological. This means, that its intended use is to correctly reproduce phenomena but not to describe the agents' behavior on a microscopic level.

3.2 World Youth Day

The World Youth Day took place in August in Cologne, Germany. The final event was a service with Pope Benedict XVI. It took place on a large ground (around 92 ha) with a stage in the centre. The geometry is shown in Figure 6.
Altogether around 700 to 800 thousand pilgrims were expected. Apart from the requirements to the roads and public transportation systems, the footpaths play of course also an eminent role in the mobility concept.

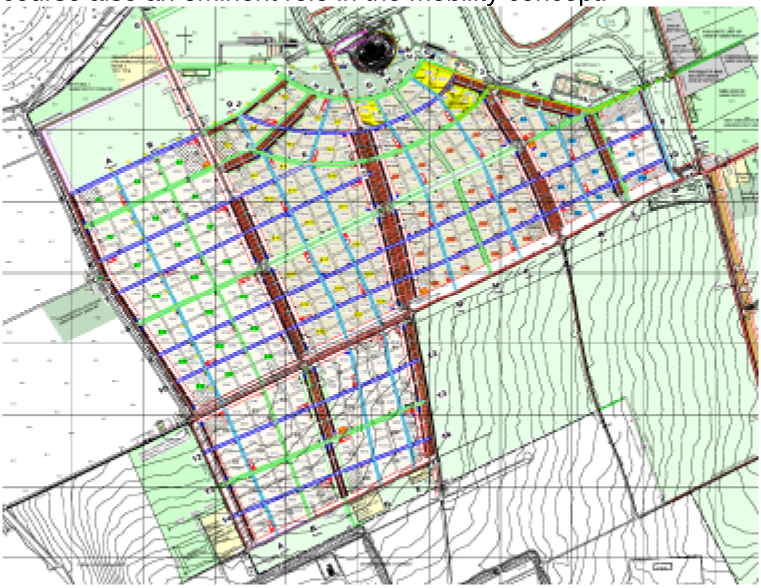


Figure 6: The area where the World Youth Day 2005 was held.

Two cases must be distinguished, when analyzing the geometry and operational performance: a normal case of getting to and back from the area and the emergency case, when part of the site has to be evacuated. In the former case, a time frame of 8 to 10 hours was considered.

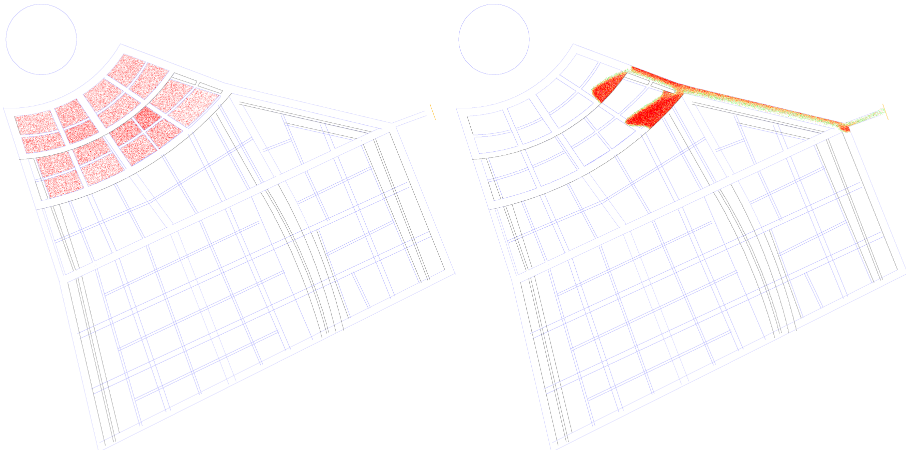


Figure 7: Simulation of the egress from four zones at the world youth day. The left part shows the initial population distribution and the right part the situation after 30 minutes.

Since the final service was held in the late afternoon, the mobility concept is also based on a considerable part of the pilgrims staying at the place overnight in tents. The major bottleneck is not the movement of pedestrians anyway, but the capacity of the transportation system. A completely different scenario is emergency evacuation.

4 Verification of the Results

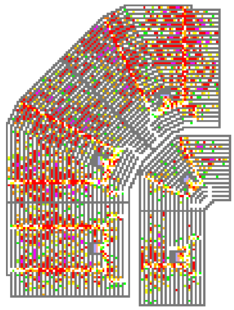
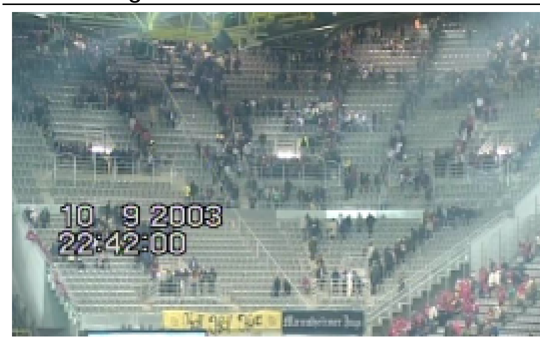
Concerning quantitative verification, movement patterns provide a valuable tool to investigate the reliability of simulation results. In the following table, data from video footage is compared to simulation results. The most prominent aspect is the egress from the seating rows. The lower rows are emptied first. The difference at t=2 min is due to the shorter reaction time of the agents. Similar to reality, in the simulation the lower blocks are emptied earlier.

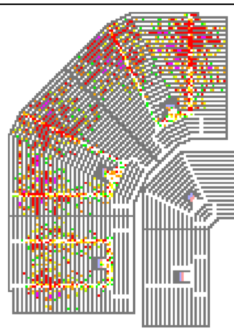
5 Recommendations and Conclusion

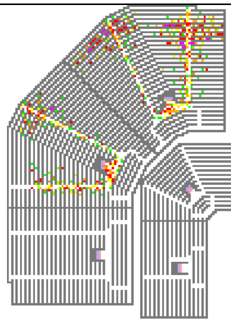
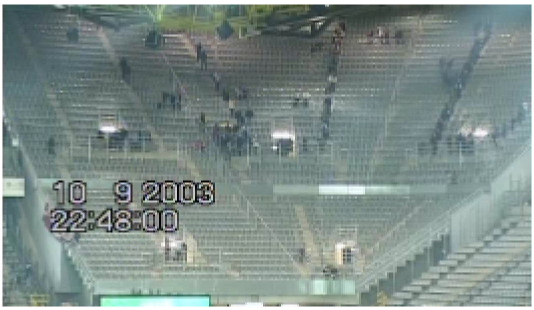
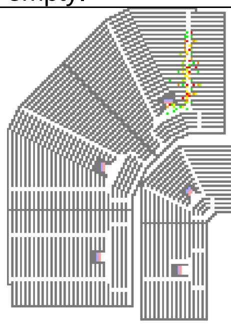
In this paper, three different events with very high numbers of pedestrians were presented. The simulation results are strongly determined by the choice of parameters, especially route choice strategies. An important aspect in the egress from football stadiums is the v-like shapes that are formed since the egress from the lower seating rows is slower. Recommendations can be derived from the observations and simulation results shown two different ways: On the one hand, general recommendations, applicable for all large crowd events. On the other hand, there are specific recommendations that apply only for the specific event. The later takes into account the specific geometry and character of the event.

<table>
<tr><th>Reality</th><th>Simulation</th></tr>
<tr><td>

t = 2 min: Only few spectators have started moving.</td><td>
t = 20 s: Some of the agents have moved.</td></tr>
<tr><td>

t = 5 min: Most of the spectators have reacted. Congestion forms on the stairs and in the seating rows.</td><td>
t = 3 min: Most of the agents have reacted.</td></tr>
<tr><td>

t = 7 min: All spectators move.</td><td>
T = 6 min: The lower blocks are already empty.</td></tr>
</table>

 t = 10 min: Congestion remains only on the stairs.	 t = 10 min: Different from reality the blocks 85, 86, and 89 are already empty.
 t = 13 min: Blocks 85, 86, and 89 are empty.	 t = 13 min: Apart from block 87, all blocks are empty.

Especially concerning the geometry, simulations can provide valuable hints on the creation, duration, and location of congestion.

Acknowledgements

I would like to thank Svenja Knothe who has rendered some of the input files for the World Youth Day simulation. My special thanks goes to Tim Meyer-König, the developer of the PedGo simulation software on which the simulation results shown in this paper are based.

References

1. AlGadhi, S., H. Mahmassani, and R. Herman: A speed-concentration relation for bi-directional crowd movements with strong interaction. In: M. Schreckenberg and S.D. Sharma, *Pedestrian and Evacuation Dynamics,* Springer, Berlin, 2002. pp. 3–20.

2. Thompson, P., J. Wu, and E. Marchant: Modeling evacuation in multi-storey buildings with ‘Simulex’. *Fire Engineers Journal 56* (185), 6–11, 1996.
3. Burstedde, C., K. Klauck, A. Schadschneider, and J. Zittartz: Simulation of pedestrian dynamics using a 2-dimensional cellular automaton. *Physica A 295*, 507–525, 2001.
4. Pauls, J.: *Movement of People* [2nd ed.]., Chapter 3-13, pp. 3–263—3–285. In DiNenno [10], 1995.
5. Ullrich Weidmann, Transporttechnik der Fußgänger, Transporttechnische Eigenschaften des Fußgängerverkehrs, Literaturauswertung, Schriftenreihe des IVT 90, ETH Zürich, Jan. 1992
6. Hubert Klüpfel, A Cellular Automaton Model for Crowd Movement and Egress Simulation, Dissertation, Universität Duisburg, 2003
7. RiMEA-Projekt, *Richtlinie für Mikroskopische Entfluchtungsanalysen*, www.rimea.de
8. Fruin, J.: *Pedestrian Planning and Design*. New York: Metropolitan Association of Urban Designers and Environmental Planners, 1971.
9. Transportation Research Board: *Highway Capacity Manual*. Washington, D.C.: Transportation Research Board, 1994.
10. DiNenno, P. (Ed.): *SFPE Handbook of Fire Protection Engineering* (2nd Ed.). National Fire Protection Association, 1995.
11. Predtetschenski, W. and A. Milinski: *Personenströme in Gebäuden – Berechnungsmethoden für die Modellierung*. Köln-Braunsfeld: Müller, 1971.
12. Ando, K., H. Ota, and T. Oki: Forecasting the flow of people. *Railway Research Review 45*, 8–14. (In Japanese), 1998.
13. Joachim Westphal: *Untersuchungen von Fußgängerbewegungen auf Bahnhöfen mit starkem Nahverkehr.* Institut für Verkehrswesen, Eisenbahnbau und –betrieb, Technische Universität Hannover, Dissertation, 1971.
14. Statistisches Bundesamt [Hrsg.]: Datenreport 1999 – Zahlen und Fakten über die Bundesrepublik Deutschland. Bonn, 2000.
15. Friedrich Mehl: *Bauaufsichtliche Akzeptanz von Ingenieurmethoden im baulichen Brandschutz – Anwendungsbereiche, Grenzen.* Promat Fachbeitrag, Ratingen, 2003. www.promat.de
16. Haj & Umra. Volume 59, Issue 2, April 2004. Ministry of Haj, Riyadh, Saudi-Arabia.