# Chapter 10

# Crowd Dynamics Phenomena, Methodology, and Simulation

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## Abstract

This chapter deals with the modeling and simulation of pedestrian flow and evacuation processes, i.e., crow dynamics in emergency and nonemergency situations. This comprises three major areas (1) theory, (2) data, and (3) application. The terms used in this chapter conjecture a hierarchical structure (motivated by the terminology of mathematical logic), where models are derived from theories by interpretation and a simulation is derived from a model by implementation. Of course, theory, data, and application influence each other and neither can be investigated separately. Data collection requires an idea of what to collect (i.e., a theory) and later on interpretation. The application of a model is based on its implementation (simulation). Measurements contain assumptions about the observables. In the context of crowds, one of the questions is: Is the focus on trajectories or aggregated data? A model must be validated, the simulation verified. Validation (doing the right thing) is addressing the interpretation (of the theory) and verification (doing it right) addresses the implementation (of the model).

Data is used to calibrate models on the one hand and to test theories (by means of models and simulation results) on the other. In the case of crowd dynamics, there are, on all three levels (theory, data, and application), two major components of the system: population and geometry. And the major aim (from an engineering perspective) of the effort is of course to apply it for design and procedural improvements of crowd management in emergency (evacuations) and nonemergency (commuters, spectators, etc.) contexts.

The detailed structure of this chapter is as follows: (1) Theory (Models and Simulations); (2) Empirical Data: Literature Review (Population); (3) Design


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Elements (Geometry); (4) Models (Hydraulic and Individual); (5) Application (Simulation); (6) Summary (Conclusion and Outlook). The first section introduces the basic principles and terminology. The second section is devoted to a literature review of empirical data on crowd movement (i.e., mainly referring to the sub-system ‘‘population’’). The geometry is addressed in detail in the third section ‘‘design elements.’’ The two major model classes, namely hydraulic (macroscopic) and individual (microscopic) models will be described and compared in section four. The fifth section is dedicated to the application of crowd simulations in emergency (evacuation) and nonemergency scenarios. The chapter concludes with a summary (containing a list of major information resources), conclusion, and outlook.

## 10.1. Theories, Models, and Simulations

The connection between theory, model, and simulation is depicted in Figure 10.1. AU :4 This connection will be discussed in more detail when the influences on crowd dynamics and the modeling criteria will be identified in the next paragraph.

### *10.1.1. A Theory for Crowd Dynamics*

What would be a theory of crowd dynamics? When thinking about theories in other scientific disciplines, two prominent examples might come to mind: theory of special relativity (TSR) and the theory of evolution (TE). The former is based on the two postulates ‘‘all inertial systems are equivalent’’ and ‘‘the speed of light in vacuum is constant.’’ The latter is based on the principles of ‘‘mutation’’ and ‘‘selection.’’ In that sense, the arrows in Figure 10.1 can be read as ‘‘restrict’’ (downwards) or ‘‘must comply with’’ (upwards). Therefore, an elevator is no valid model for TSR; a platform and train with constant speed is a valid model.

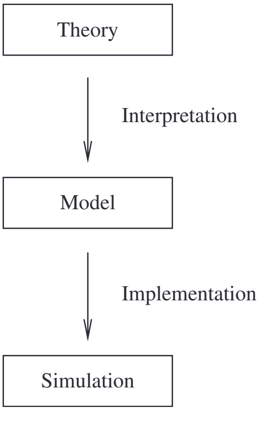



Figure 10.1: Theory, model, and interpretation.

Of course, the problem for crowd dynamics is the absence of comprehensive principles or postulates in the sense above. The first step would be to specify the meaning of crowd: "A group temporarily sharing the same place and focus" (cf. Figure 10.2).

In the terminology used in Figure 10.2, the subject of this chapter would be called "escape panics" or "gathering" (including commuters as "casual crowds"). The occurrence of "panics" or usefulness of the term itself shall not be discussed, here. Just note that the term itself is controversial (Clarke, 2001). The conclusion for the time being is that there is probably no "theory for crowd dynamics" like there is a "quantum field theory" or "quantum mechanics." Therefore, let us start with models.

### *10.1.2. Models for Crowd Dynamics*

It might be interesting to look at the different models that have been developed for hydrogen to explain scattering experiments. Each model might be able to explain different aspects of crowd movement. A general framework for classifying models is shown in Figure 10.3.

The most important distinctions are probably the "discrete/continuous" and "microscopic/macroscopic" pairs. Additionally, the "estimation/first principles" can be further evaluated as shown in Figure 10.4.

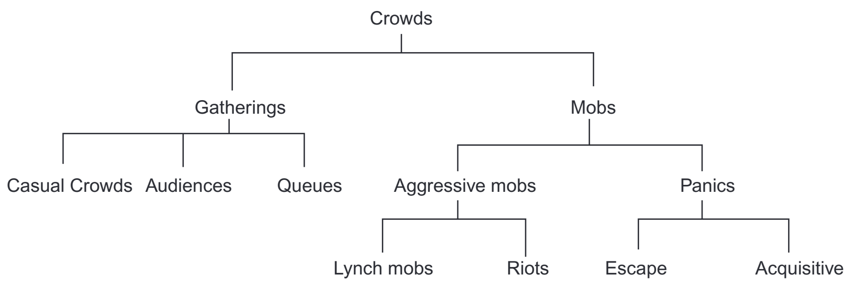



Figure 10.2: Classification of crowds (Forsyth, 1994).

specific ⟷ general
estimation ⟷ first principles
discrete ⟷ continuous
numerical ⟷ analytical
stochastic ⟷ deterministic
quantitative ⟷ qualitative
macroscopic ⟷ microscopic

Figure 10.3: Modeling criteria.

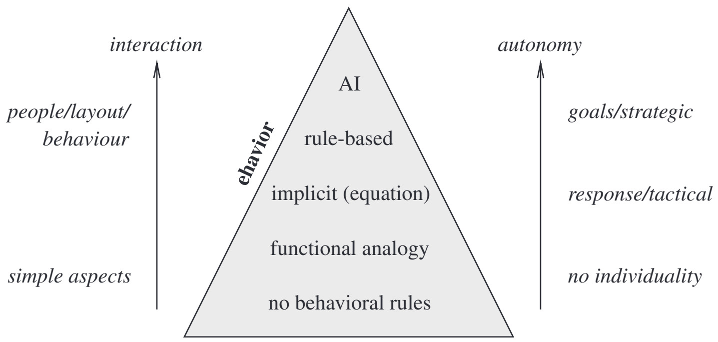



Figure 10.4: Autonomy and behavior modeling.

The term autonomy on the right axis connects the behavior modeling to a concept from computer science: multi agent simulation (MAS — which might also be read multi agent systems). Coming back to Figure 10.1, the term simulation is used in the sense of "model implementation," i.e., "system" might be the model. The term agent in MAS can be translated "autonomous entity," i.e., showing some sort of behavior that is "internally motivated." Finally, the term "multi" in MAS refers to the interaction (shown in the left vertical axis in Figure 10.4) between the agents. The interaction between an agent and its environment is already present in the (single) agent concept.

Usually, the internal motivation is represented on three different levels (BDI framework):

- Desires ("get out as fast as possible")
- Beliefs ("the best way is along the escape routes")
- Intentions ("I do not want to harm anyone")

In the context of egress from a building these levels might be the ones given in parentheses. These three motivational levels determine the decision-making process. Again, for the egress example this might be: "follow the exit signs, circumvent other people and obstacles; do not push"). Based on these assumptions (theory), a model can be formulated by defining a set of rules that applies for the agent's decision making and behavior. In MAS, usually, three different decision levels are distinguished: AU :6

- strategic
- tactical
- operational

The strategic level comprises "long-term goals," the tactical level a simple set of rules (that would be called conscious in humans), and the operational level the automatic responses ("subconscious" or mere physical like distance keeping or slowing down upstairs or how to avoid collisions). All three BDI aspects can be connected to the decision levels (STO). In general, the D–S, B–T, and I–O connections are strongest.

In summary, MAS are (cf. Figure 10.3) general, estimate, numerical, quantitative, and microscopic. They can be both, "continuous" or "discrete" as well as "stochastic" or "deterministic," i.e., these two categories are indeterminate in MAS for crowd dynamics.

### *10.1.3. Calibration, Validation, Verification*

As can be seen from Figure 10.5, model development is a creative process. Even though the calibration is often supposed to be at the beginning of model development, it is possible only after having formulated and implemented a model, i.e., after running a simulation (or performing a calculation) and evaluating simulation results.

Those simulation results are then compared to empirical data and the model parameters changed to get simulation results close to the empirical results (fitting). There are two important restrictions that apply to this process:

- the model parameters must be fewer than the data points
- the verification data must be different from the calibration data

Once these three steps have been carried out, the model is calibrated, verified, and validated. In the context of legal compliance of building or ship designs, validation is of course crucial, as stated above; the validation for models for the evacuation simulation of passenger ships is regulated in MSC.1/Circ. 1238.

**10.1.3.1. Verification** Verification is the check for the correct implementation, i.e., the mathematical part. It comprises the following four major activities:

- Analytical tests
- Numerical tests
- Sensitivity analysis
- Code checking

Of course, numerical tests are only applicable for numerical models.

| | |
|---|---|
| Interpretation (Theory → Model) | Validation (high level checking) |
| Implementation (Model → Simulation) | Verification (low level checking) |
| Evaluation (Simulation → Results) | Calibration (fitting) |

Figure 10.5: Validation, verification, calibration.

**10.1.3.2. Validation** Validation is to check whether the model represents the part of the reality it is supposed to accurately enough. At this point it is helpful to keep in mind three major criteria for scientific results:

1. Valid
2. Objective
3. Reliable

The first has just been described. The second is the fact that different persons obtain the same results (under the same initial and boundary conditions), and the third requires the results to be repeatable. This might be considered common sense and trivial at first glance. It is not easily fulfilled in the context of pedestrian and crowd simulation, though.

**10.1.3.3. Calibration** Calibration is necessary for heuristic, phenomenological, or estimate models (cf. Figure 10.3). For first principle models, like the Navier–Stokes Equations for fluid dynamics, calibration is not part of the modeling process.

### *10.1.4. Models for Evacuation*

Evacuation processes can be considered a special type of crowd dynamics. There are two special circumstances for evacuation: (1) the presence of hazards, (2) the absence of the strategic level of decision making. The second point requires some further consideration. In case of an evacuation process, people usually have a clear aim: getting to a safe place. Therefore, there is a clear desire. Of course, there might be tactical differences like either trying to get out through the main entrance/exit or follow the exit signs. They are considered not strategic, here.

**10.1.4.1. Influences on the evacuation processes** As already mentioned, apart from the absence of the strategic level, in an evacuation scenario, the presence of hazards is the second major difference to normal crowded situations. In Figure 10.6 the ‘‘population’’ in the center represents the crowd/population. The term population is

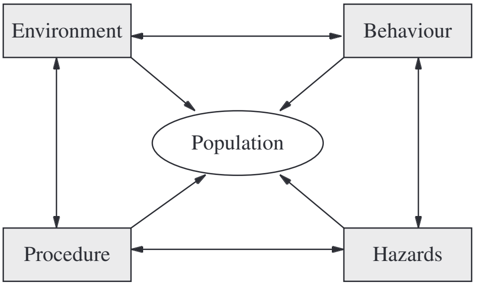



Figure 10.6: Influences on the evacuation process.

used here, since all the considerations also apply to smaller groups of people that usually are not considered a crowd.

The different influences shown by the rectangles are connected to the population via the tactical level of decision making. Hazards, which could be summarized under "environment" in the MAS framework and is shown here explicitly to stress the dynamical aspect, i.e., an environment changing with time. Similarly, the procedure is partially environmental, partially represented by the agents and the behavior represents the BDI or STO part of the agents, i.e., the decision making and action. Finally, the various interactions between the influences are depicted by the double-sided arrows.

Figure 10.7 shows different evacuation strategies. It is important to keep in mind that (especially but not only in complex environments) there are people who are forced to defend in place, i.e., cannot leave the potentially hazardous place on their own.

**10.1.4.2. Evacuation exercises and emergencies** In addition to the general sources for empirical data on crowd movement, there are two special sources for the evacuation case: evacuation exercises (announced or unannounced) and reports from actual incidents. The connection between these two with respect to stress level is depicted in Figure 10.8. One model for the analysis of evacuation processes are so-called simplified analyses. These range from prescriptive rules for the determination of escape route widths and lengths to flow calculations (macroscopic models). These

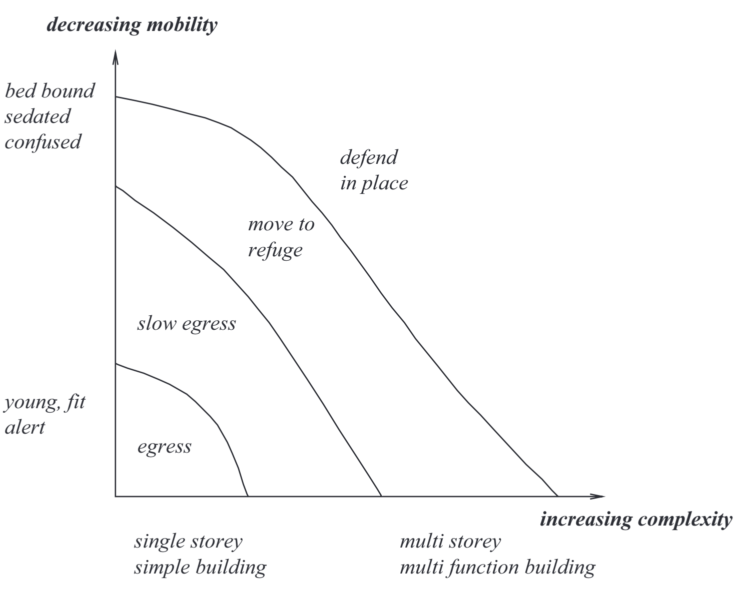



Figure 10.7: Different evacuation strategies depending on building layout and mobility.

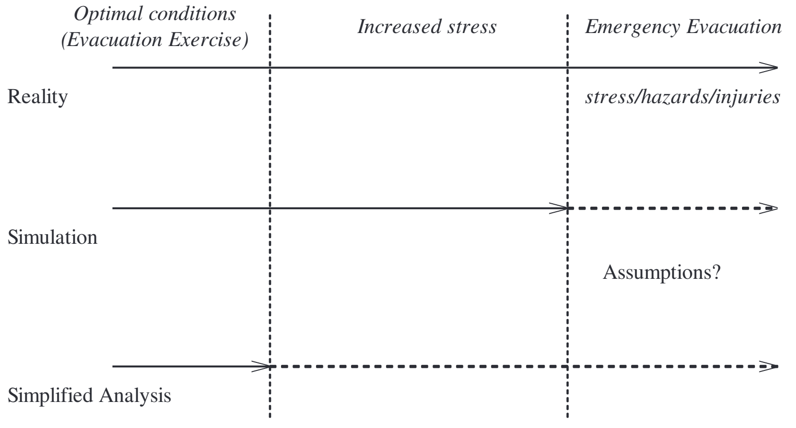



Figure 10.8: Exercise and emergency.

usually do not take into account behavioral aspects and can therefore not cover the increased stress level already present in some evacuation exercises (especially unannounced ones). It is questionable, however, if simulations (in this context used as a synonym for microscopic models or MAS, they may be deterministic or stochastic, discrete or continuous) can cover (e.g., predict) most aspects of an emergency evacuation, especially increased stress, hazards, and injuries (cf. Figure 10.8). A major part of the total evacuation time is pre-movement time (or response time), which usually is not predicted by simulations but is an input parameter. If this parameter is calibrated wrongly, the complete result is useless. This is of course a common observation.

Additionally, the increased stress present in an emergency evacuation is usually hard to extrapolate from the exercise situation. It might well be the case that it is a different realm and extrapolation is not allowed. Finally, in many disasters, there were quite specific influences like locked doors that could not be predicted by a simulation.

## 10.2. Empirical Data: Literature Review (Population)

For the investigation of pedestrian motion, there are three fundamental options:

- field surveys or observations,
- (evacuation) exercises, and
- experiments in a laboratory.

All these options have specific advantages and disadvantages. Observations are effortless with regard to preparation. They have the disadvantage, though, that the external influences (Figure 10.6) cannot be controlled. For experiments, the control on the external influences is better. On the other hand, this might introduce external factors not present in a more realistic situation. And it is of course the first priority to avoid injuries. There are, in summary, practical, ethical, and financial constraints on experiments in the field of crowd dynamics. For examples on crowd experiments see Müller (1999) and Predtetschenski (1964).

### *10.2.1. Individuals and Crowds*

It has been briefly mentioned in the context of evacuation simulation in the previous section that some of the aspects of crowd dynamics are specific for crowds (like formation of lanes, oscillation at bottlenecks, to name just a few); others are not and are present in individual motion (like movement characteristics, influence of fire and smoke in an evacuation situation, etc.).

**10.2.1.1. From a single person to a crowd** What is the difference between a few persons and a crowd? There are several ways to draw the line. Starting with the definition ''a crowd is group of people sharing the same place and the same focus'' the next question pops up: How many people are necessary to form a crowd? At the end of the day, the definition will (and must) remain vague with respect to this question. Next to the definition given above, the best approach seems to be a phenomenological one: ''a crowd is a group of people sharing the same space and focus and where typical crowd phenomena like lane formation or speed reduction due to high density are observed.'' For the sake of this contribution, this definition is sufficient.

**10.2.1.2. The concept of ''panic''** Clarke (2002) writes: ''pictures of mass panic and collective chaos are ubiquitous in Hollywood films, the mass media and the rhetoric of politicians. In contrast to those popular depictions, mass panics are rather rare. In a disaster, humans usually act quite civilized and cooperative.'' Using that scheme, AU :7 panic is in the public perception something like mass hysteria. In line with Clarke, this ''mass hysteria'' concept of panic is considered useless. When talking about an incident with many pedestrians involved, the term crowd accident might be more appropriate.

**10.2.1.3. Social influences and group formation** An important aspect for crowd dynamics and evacuation processes is social behavior. In Figure 10.2 the classification of groups (Forsyth, 1999) was shown. As said above, characteristic for a group are size, commons space, and focus. The following two pictures show large crowds in situations at spare time activities (Figures 10.9 and 10.10).

The common focus in the previous two examples is music. Of course, there are many other activities, where there is a large group of people, sharing space and focus: commuting, all kind of audiences. The occurrence of crowds is a characteristic phenomenon of modern societies and cities.

Figure 10.9: Love parade in Berlin with high person densities (>4 per sqm) (http://www.backpacker.co.uk/images/loveparade/love.gif).

Figure 10.10: Realistic person densities in a dance club. They usually range, in contradiction to assumptions made in many building codes, between three and four persons per sqm (Forell, 2004). AU :1

**10.2.1.4. Group size** One major aspect of crowd dynamics (next to phenomena like lane formation, arching, and oscillation at bottlenecks) is the influence of group size and person density on the walking speed. The first one is conjectured to depend on the fact that a group's velocity is determined by the walking speed of the slowest group member. In Table 10.1, the results for groups up to the size of six members are summarized.

Table 10.1: Results for the walking speed of groups of different sizes.

| Group size | No. of groups | Mean speed |
|---|---|---|
| 1 | 95 | 1.38 |
| 2 | 149 | 1.28 |
| 3 | 59 | 1.24 |
| 4 | 17 | 1.24 |
| 5 | 10 | 1.22 |
| 6 | 2 | 1.10 |
| Sum | 332 | 1.30 |

The observation area was a flat pedestrian bridge of width 7 m. Video recordings were done from a bird's eye perspective and the group size and walking speed were determined by analyzing the videotape. The velocity was measured between two clearly visible wooden elements the bridge was composed of, which were 7 m apart. The time difference between the crossing of the first of those wooden planks by the last group member was evaluated and the velocity calculated ($v = \mathrm{d}s/\mathrm{d}t$), where $\mathrm{d}s = 7\,\mathrm{m}$.

A clear tendency is the decrease of the group's velocity with its size. The highest observed (average) speed was 1.38 m/s for single persons, the lowest 1.10 m/s for groups of size six (Figure 10.11).

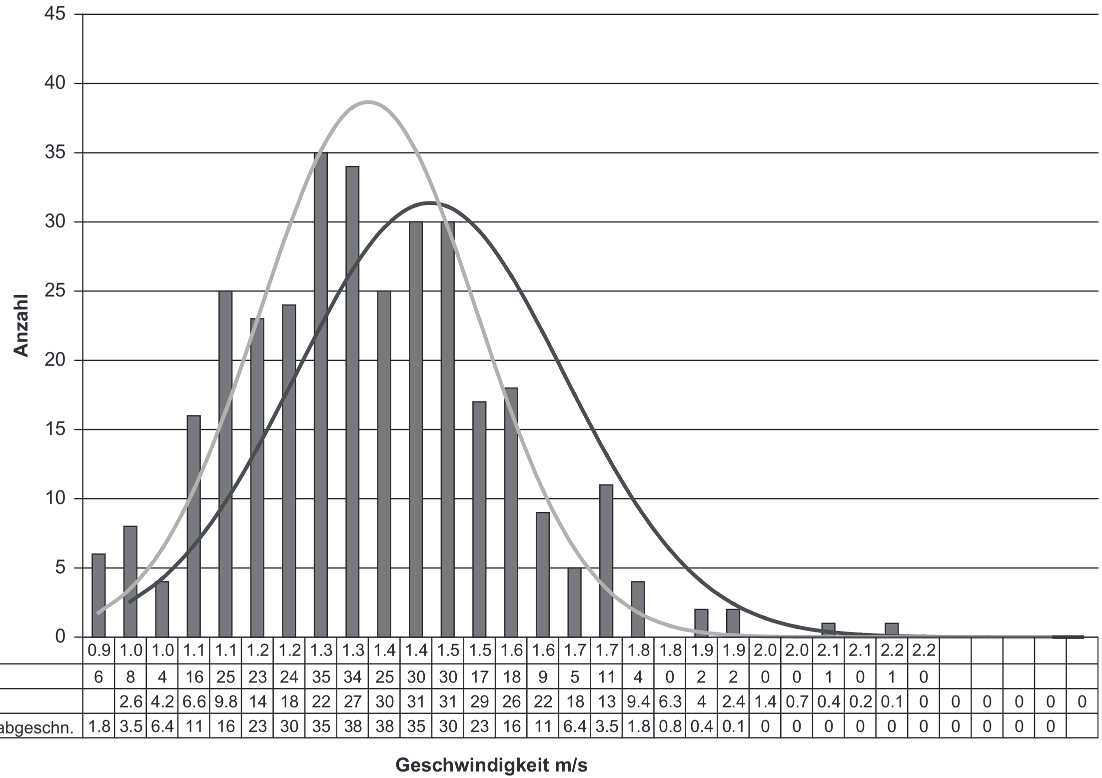
**10.2.1.5. Audible exit signs** Finally, and for the sake of completeness, a rather new development in marking exits shall be briefly mentioned. The basis of directional sound is to make exits not only visible but also audible. Such an exit marking by sounders is not a replacement for conventional exit signs but an addendum. It is especially useful in case of smoke (Figure 10.12).

The directional information is encoded by frequency, volume, and sound patterns. The length of consecutive tone and silence phases gets shorter as the sounder AU :8 becomes closer to the exit from the building or the assembly point. The frequency of these sound/silence phases, on the other hand, gets higher.

**10.2.1.6. Capacity of exit route elements** The major elements, exit routes (i.e., the path from the initial position to the exit or assembly point) consist of:

- Doors
- Stairs
- Hallway

Usually, stairs are considered to have the lowest capacity, therefore being the bottleneck in the escape route system (Figure 10.13).




| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.9 | 1.0 | 1.0 | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 | 1.5 | 1.6 | 1.6 | 1.7 |
| Daten | 6 | 8 | 4 | 16 | 25 | 23 | 24 | 35 | 34 | 25 | 30 | 30 | 17 | 18 | 9 | 5 |
| Gauß | | 2.6 | 4.2 | 6.6 | 9.8 | 14 | 18 | 22 | 27 | 30 | 31 | 31 | 29 | 26 | 22 | 18 |
| Gauß abgeschn. | 1.8 | 3.5 | 6.4 | 11 | 16 | 23 | 30 | 35 | 38 | 38 | 35 | 30 | 23 | 16 | 11 | 6.4 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.7 | 1.8 | 1.8 | 1.9 | 1.9 | 2.0 | 2.0 | 2.1 | 2.1 | 2.2 | 2.2 | | | | | |
| Daten | 11 | 4 | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | | | | | |
| Gauß | 13 | 9.4 | 6.3 | 4 | 2.4 | 1.4 | 0.7 | 0.4 | 0.2 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gauß abgeschn. | 3.5 | 1.8 | 0.8 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |

Figure 10.11: Distribution of walking speeds for groups of different size observed at the world exhibition Expo 2000 in Hannover, Germany.

Figure 10.12: Directional sound.


Figure 10.13: Simple escape route element.

A very rough estimate for the capacity is the following set of equations: AU :9

$$T = t_{\text{flow}} + t_{\text{walk}} \tag{10.1}$$

$$t_{\text{flow}} = w.\frac{N}{j_{\text{specific}}(\rho)} \tag{10.2}$$

$$t_{\text{walk}} = \frac{l}{v(\rho)} \tag{10.3}$$

In this case $v(\rho)$ is the walking speed of the slowest individual, $\rho$ the density, $w$ the door width, and $l$ the walking distance. With $v = 1\,\text{m/s}$, $j = 1\text{P/(ms)}$, $w = 1\,\text{m}$, the number of persons being $N = 100$, $l = 100\,\text{m}$, the overall time would be $T = 1\,\text{m} \times 100\text{P}/1\text{P/(ms)} + 100\,\text{m}/1\,\text{m/s} = 200\,\text{s}$. In our example, the overall time for this escape route element would be 200 s. For higher densities, the walking time increases.

**10.2.1.7. Lifeboat capacity** A recent concern that has been raised in the context of demographic change is the capacity of lifeboats for passenger ships. This is a prominent example for a more general concern in the context of design calculations: most of the formulas have been calibrated by data obtained 30 or more years ago. If a lifeboat is designed for 200 persons and the assumption is that the average mass is 75 kg and the shoulder width is 55 cm, then this might not hold for modern cruise ships any more since the population characteristics are different from those calibration parameters.

### 10.2.2. Properties of Pedestrian Flow (Operational)

Having covered the more general aspects of pedestrian and crowd movement in the previous section on "Individuals and Crowds," we will now turn to a more "physical" or statistical approach, i.e., neglecting individuality and AU :10

**10.2.2.1. Flow–density relationship (fundamental diagram)** One major result of empirical investigations is the so-called fundamental diagram, i.e., the relationship between density and specific flow (or velocity). For flow models and simulations based on microscopic models it has got a different use. In flow models (e.g., Predtetschenski, 1964; Mehl, 2003) it is the foundation of the calculations, i.e., an input parameter.

For simulations, it is used to calibrate the parameters on the one hand. On the other hand it is used for the validation of the simulation results, i.e., it is a simulation result itself (Figure 10.14).

**10.2.2.2. Flow on stairs** Finally, the vicinity influences the movement characteristics. Figure 10.15 shows the walking speed on stairs in a football stadium. A distinction between upstairs and downstairs was not made in this case.

For steeper stairs (upper curve: 30°, lower curve: 38°) a lower flow was observed. The density area covered is up to three persons per sqm. For that density range, the flow is increasing with the density. A higher density was not reached in the observation, which is probably due to safety precautions taken by the subjects, i.e., a higher density on stairs is perceived to be dangerous and therefore avoided.

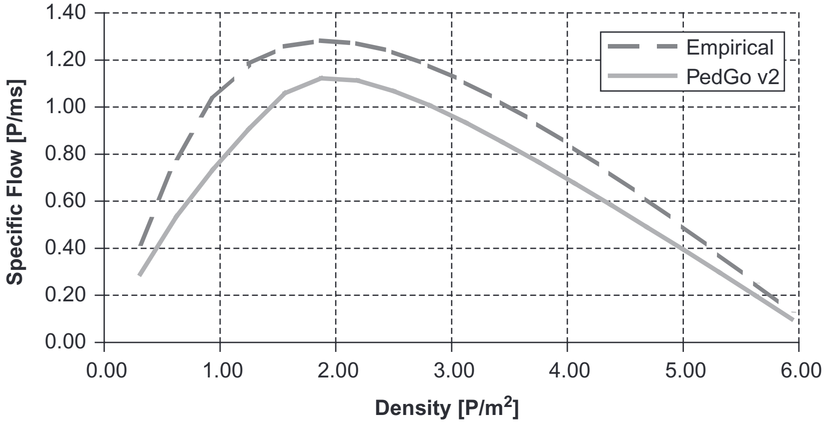



Figure 10.14: Fundamental diagram of pedestrian movement.

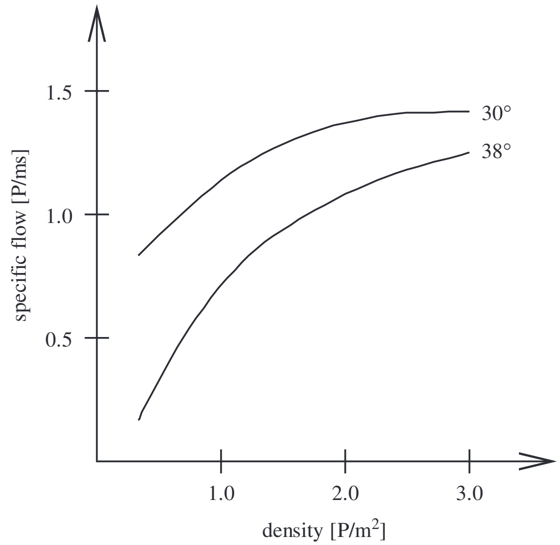



Figure 10.15: Specific flow on stairs (in a football stadium, Graat, 1999).

Figure 10.16: Density fluctuations in a long hallway (simulation).

When using flow–density relations, a single or unique flow for a specific density is usually assumed. For the measurement of density as the number of persons per area, the measurement area has a considerable influence on the outcome. This is elaborated in more detail in the next section on density fluctuations.

**10.2.2.3. Density fluctuations** As can be seen from Figure 10.16, the density varies in, e.g., a hallway. Density fluctuations and density waves are well known in traffic flow for vehicular traffic.

Such inhomogeneous densities, density fluctuations, and density waves cannot easily be accounted for in flow models. In simulations based on spatially and temporarily discrete models, on the other hand, such influences can be represented.

**10.2.2.4. Formation of lanes and oscillation at bottlenecks** The formation of lanes can be observed in bidirectional pedestrian flow. Yamori has investigated bidirectional flow on pedestrian crossings in Japan and introduced a so-called band-index ranging from 0 to 1. The band-index gives the fraction of pedestrians walking in a lane. If there are no pedestrians opposing each other directly, the index is 1 (see Figure 10.17). In order to calculate the index, the image is divided into

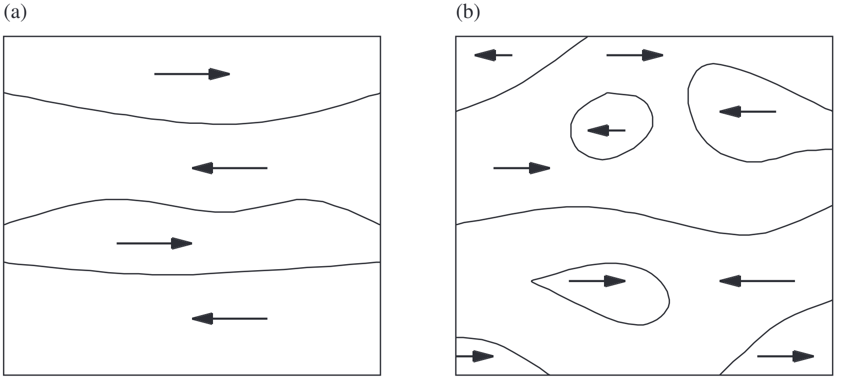



Figure 10.17: Formation of lanes in bidirectional flow (Yamori, 2001).

horizontal stripes. The area of the stripes where no change in the direction of movement occurs is divided by the overall area. Formation of lanes is of course a desirable phenomenon since it leads to a higher flow than a less organized situation. In the ideal case, for example, two lanes are formed leading to a flow for the bidirectional case as high as a one-directional flow. Formation of lanes is a self-organization phenomenon and is interesting from that point of view too. We will not go into the psychological or details of perception and reaction necessary for such a self-organization phenomenon. It can, as all other phenomena in crowd dynamics, be investigated on different length scales, scales of details, and levels (physical or operational, tactical, and strategic). AU :11

Another phenomenon discussed in the literature is the formation of oscillations at bottlenecks (Helbing, 2002; Müller, 1999).

The oscillations at bottlenecks can have dangerous consequences: the flow in one direction can cease completely. Therefore, the people having to wait might get impatient and increase the pressure. Additionally, the oscillations lead to a less homogeneous flow. The phenomenon might be restricted to very narrow bottlenecks, though (at most two persons next to each other). In reality, this might be rarely the case — especially since it only occurs in bidirectional flow (Figure 10.18).

### *10.2.3. Tactical and Strategic Decisions*

Up to now, we have covered mainly external influences on pedestrian movement or physical characteristics of movement (like walking speed, motion impairments, fitness, or the influence of geometry or density on pedestrian flow). This section will cover the internal aspects, i.e., the decision-making process. The strategic level covers desires, beliefs, and intentions; the tactical level is influenced by the beliefs and intentions and covers the movement behavior proper, i.e., the short-scale (concerning time and space) navigation. AU :12

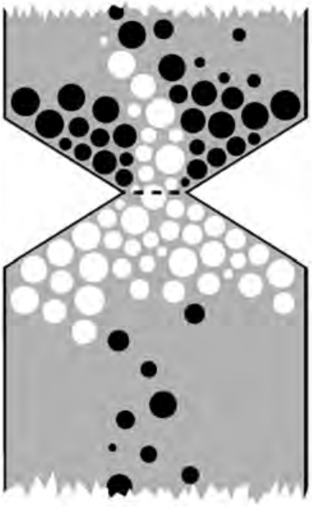


Figure 10.18: Oscillation at bottlenecks (Helbing, 2002; Müller, 1999).

**10.2.3.1. Route choice** Route choice is one of the most important aspects and decisions, in the evacuation scenario as well as in nonemergency activities like commuting or shopping. Figure 10.7 showed the connection between the movement ability or impairment and the geometric complexity of a building and the evacuation strategy. Similarly, the following list summarizes the motivations for and beliefs about route choice for an evacuation exercise in a supermarket:

1. Following the exit signs, public address system announcements, or staff (53%).
2. Taking the nearest exit (25%).
3. Get away from fire or smoke and escaping from immediate danger (12%).
4. Follow other persons (7%).
5. Going to the familiar exit (2%).
6. There was a window next to the exit. It was bright there (1%).
7. There was no crowding at the exit (1%).
8. Others.

These considerations influence the evacuation process. Therefore, the knowledge about the assumptions concerning the population is a prerequisite for the correct interpretation of simulation results.

**10.2.3.2. Cooperation and competition** One aspect that has been briefly mentioned in the context of "panic," is social behavior. In order to use data on human behavior for the simulation of pedestrian flows and calculation of evacuation times, it must be observed objectively and be quantified. This comprises an operational description of concepts, e.g., the concept of "panic." One type of behavior usually associated with "panic" is noncooperative and irrational behavior. Irrationality in this context is

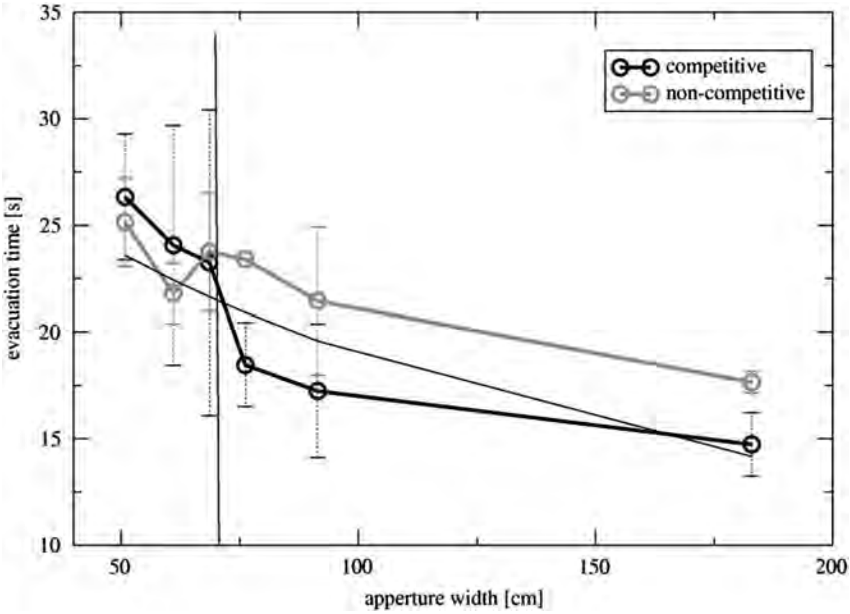



Figure 10.19: Difference between cooperative (black) and competitive (red) behavior in a mockup aircraft evacuation. AU :2

making decisions contrary to its own benefit and contrary to rather clear information pointing in the opposite direction. Usually, both are not the case. "Panic behavior" is used for extreme behavior motivated by immediate danger to one's health or even life. In such a case, running, making very fast decisions, and even jumping out of the window if threatened by great heat is a well-adapted decision.

Concerning the distinction between cooperative and competitive behavior, a well-established motivational clue is the use of a reward system (often money). The results of an experimental investigation in an aircraft mock-up are shown in Figure 10.19.

The empirical data is taken from Muir (1999). The figure shows the evacuation time versus the width of the aperture, for different aperture widths ranging from 50 to 180 cm were used.

**10.2.3.3. Reaction times and wake-up times** Proulx has investigated reaction times (pre-movement times) intensively. They can range from 5 to 30 min for an old-age population. Getting back to Eq. (10.1) above, the overall time for an evacuation is AU :13

$$T = t_{\text{detect}} + t_{\text{alarm}} + \max_i(T_i) \tag{10.4}$$

$$T_i = t_{\text{react},I} + t_{\text{move},I} \tag{10.5}$$

The parameter $i$ denotes the individual in this case. Therefore, the overall evacuation time will not only depend strongly on the time for detection and raising the alarm, but also on the individual reaction or pre-movement times. Of course, in this approach, the evacuation time is defined to be the time it takes all persons to escape.

### *10.2.4. Other Influences*

**10.2.4.1. Influence of alcohol** The influence of alcohol on the level of aggressiveness has been shown in many scientific studies. In the context of crowd dynamics and crowd management, it is sort of obvious that dense crowds and an increased level of aggressiveness provide a very dangerous combination.

**10.2.4.2. Mobility impairments** Persons with mobility impairments often require separate access routes. In order to achieve a nondiscriminatory planning rationale and regime, there is still much to be done. Furthermore, in case of emergency, people with mobility impairments might need special assistance and be required to defend in place until the assistance arrives. This issue has been briefly addressed in AU :14
section

### *10.2.5. Examples of Crowd Disasters*

**10.2.5.1. Heysel Stadium (Brussels)** The Heysel Stadium Disaster occurred in 1985 AU :15
during a football match between Liverpool FC and Juventus Turin. Detailed information on the sequence of events and the strategy of the security is available at www.wikipedia.org/Heysel_Disaster. This incident is often falsely denoted as "mass panic." However, it was rather an occurrence of hooliganism.

**10.2.5.2. Acquisitive panics** "Acquisitive Panics" are situations where the motivation driving the crowd is not "get away" or "get out" but "get there" or "get something."
For the AU :16

A more detailed description based on accounts from the media can be found in AU :17
Kretz (2003).

**10.2.5.3. Baghdad** A case of "panic" that was reported in Baghdad occurred because of rumors, there would be an attack by a suicide bomber. This was during a religious event, where many people gathered on a bridge and tried to get away from the location. A more detailed description based on accounts from the media can be found in Kretz (2003).

These few examples give a broad idea of what types of crowd accidents have happened in the past. A more detailed list including incidents at religious sites or events is available at www.crowddynamics.com.

## 10.3. Design Elements

In this section, some basic design elements for pedestrian facilities are investigated with relation to crowd dynamics and crowd management.

### *10.3.1. Some Fundamental Design Elements*

One important aspect about pedestrian movement is its function as a connector between other modes of transport and the fact that the last-mile is usually always in one way or the other covered by walking. An exemption might be the case where parking is available right in front of the origin (e.g., ones own house) and the destination (e.g., the office or a shopping mall). In this case, walking is restricted to inside buildings and the parking lot. On the other hand, walking and pedestrian facilities are ubiquitous in public transport, on airports, in train stations, in subway-stations, in pedestrian zones, etc.

Similar to a trip consisting of a sequence of intermediate destinations, the pedestrian facilities used can be divided into basically seven categories:

- hallways
- ramps
- stairs
- doors
- conveyors
- escalators
- elevators
- others

Out of these elements (together with pedestrian bridges) all pedestrian facilities (that have been specifically been designed and built for this purpose) can be composed. In the following sections, each of these elements will be briefly addressed.

**10.3.1.1. Hallways** Hallways are in a sense the most basic elements. For the sake of simplicity, platforms are summarized under this category.

**10.3.1.2. Ramps** Ramps are similar to hallways but inclined.

**10.3.1.3. Stairs** Stairs are a very specific element. A relation between density and AU :18 walking speed on stairs is shown in Figure 10.15. Additionally, the reduction of walking speed on stairs varies between 0.5 and 1.0 times the normal walking speed on flat terrain, according to various sources.

**10.3.1.4. Doors** Doors are mostly necessary design elements in pedestrian routes for purposes of fire protection. Sometimes, they are of course also necessary to control access.

**10.3.1.5. Conveyors** Conveyors are normally used in large facilities, especially airports. It has been regularly observed, though, that the speed increase due to conveyors is rather small (Fraport, private communication). This is due to the fact that conveyors have to be operated at a descent speed in order to make entering and exiting the conveyor a feasible task for everyone, especially movement impaired or less physically fit people. Of course AU :19

**10.3.1.6. Escalators** Escalators can be portrayed as a combination of conveyors and stairs. The dangerous thing about escalators is the fact, that they increase the inflow to a certain level of a building or a specific area and furthermore provide a constant inflow. This inflow is not reduced by a density increase or crowding after the escalator. Therefore, in dense environments, escalators have either to be equipped AU :20 with an automatic speed reduction or stop mechanism based on crowding observers or have to be operated or supervised manually.

**10.3.1.7. Elevators** Of course, elevators are a ubiquitous element of pedestrian transportation. The development that is interesting in our context is the use of elevators in emergency cases. There are already fire elevators in high-rise buildings. They must adhere to different regulatory requirements than "normal" elevators, though. Therefore, in order to use elevators as a means of evacuation, these requirements have to be applied accordingly.

**10.3.1.8. Others** There are a few other elements for escape paths, especially evacuation slides or chutes. These are used as a standard means of evacuation for aircraft, high-speed passenger craft (HSC), and many types of Ro-Ro passenger vessels (RoPax). For buildings, they are not yet used widely and cannot be used, to replace a required secondary escape route, since this would compromise the evacuation concept.

## 10.4. Flow Models and Individual Models

### *10.4.1. Methodology of Modeling*

A basic approach for quantitative socio-psychological modeling is the field theory of Kurt Lewin. It describes human behavior as a function of person and environment:

$$B = F(P, U)$$

Most continuous models for crowd movement apply this approach to define a force field for the movement of pedestrians.

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i(t) + \vec{\xi}_i$$

$$\vec{f}_i(t) = m_i \frac{v_i^0(t)\vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \left[ \vec{f}_{ij}^{\,\mathrm{soc}}(t) + \vec{f}_{ij}^{\,\mathrm{phys}}(t) + \vec{f}_{ij}^{\,\mathrm{att}}(t) \right] + \sum_b \vec{f}_{ib}(t) + \sum_k \vec{f}_{ik}^{\,\mathrm{att}}(t)$$

The forces acting on an individual are the intrinsic motivation (first term) acting towards the desired velocity and direction. The pedestrians $i$ and $j$ are keeping distance to each other (social), might desire to get close to each other (attractive), and cannot intersect (physical). Finally, there is a repulsive force from boundaries and an attractive force to landmarks and the like (last term) (Figures 10.20 and 10.21).

### *10.4.2. Flow Models*

Flow models treat crowds as (laminar) fluids. To this end, several assumptions are made:

- Continuity equation (inflow = outflow).
- The flow is spatially and temporarily constant for a specific element.
- All flows into a transition point last for the same time.

These assumptions are the starting point and can of course be further enhanced, i.e., turbulent flows, where the capacity is no longer constant. In general, the influence of high pressures is taken into account by the identification of congestion (inflow > outflow) and by a decreased walking speed. For detailed descriptions of these issues, please refer to IMO (2002), Mehl (2003), and DiNenno (1995, 2002). Figure 10.22 illustrates the principle of hydraulic modeling for evacuation processes.

### *10.4.3. Microscopic Models and Simulations*

Microscopic models represent the geometry of a building, the population, and the sequence of events (time) in detail. All three (space, time, agents) are represented on a

| | | |
|---|---|---|
| specific | $\longleftrightarrow$ | general |
| estimation | $\longleftrightarrow$ | first principles |
| discrete | $\longleftrightarrow$ | continuous |
| numerical | $\longleftrightarrow$ | analytical |
| stochastic | $\longleftrightarrow$ | deterministic |
| quantitative | $\longleftrightarrow$ | qualitative |
| macroscopic | $\longleftrightarrow$ | microscopic |

Figure 10.20: Modeling criteria.

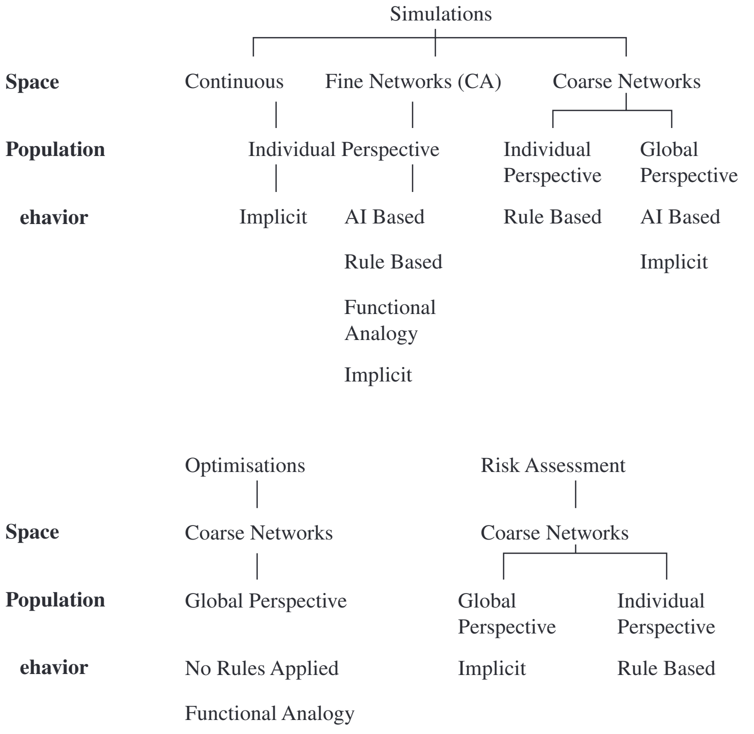



Figure 10.21: Classification of models.

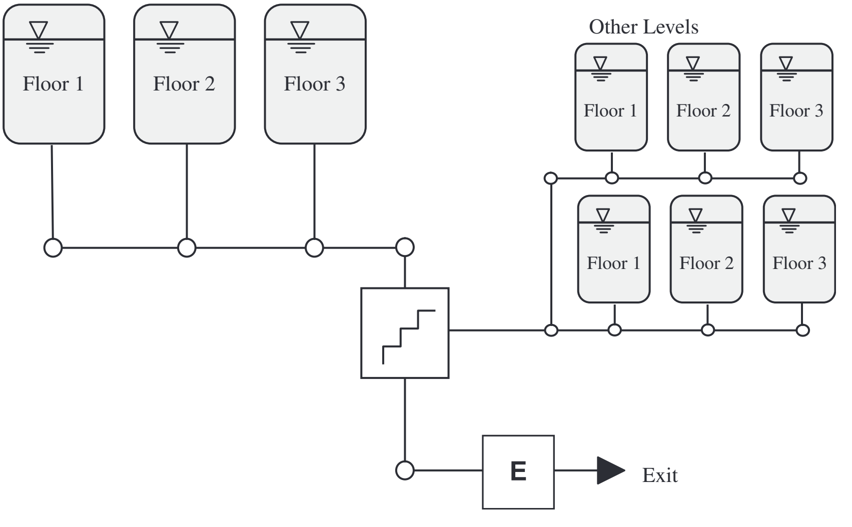



Figure 10.22: Schematic representation of the geometry in a flow model.

microscopic level in the model and the simulation. The term microscopic is a qualitative one. The following criteria can be used, though:

- length scale smaller than 1 m
- time scale in the order of 1 s
- population: single person

This approach is therefore fundamentally different from the previous one (macroscopic or flow models). The flow–density relation, e.g., is not an input parameter in microscopic models. It is an output, i.e., simulation results can be used to calibrate model parameters or validate the model assumptions. Further details of microscopic models will be discussed in the next section.

### *10.4.4. Comparison of Different Model Classes and Selection Criteria*

In summary, the different types of models are shown in *Fehler Verweisquelle konnte nicht gefunden werden*. The basic distinction between simulation, optimization, and risk analysis has the following consequences. A simulation aims at the representation of the state of a system in detail, whereas an optimization aims at minimizing a specific quantity (e.g., the overall egress time). To this end, a functional relation between this quantity and the relevant influences must be established. This function is varied to find the optimum values for the parameters (influences).

Risk analysis is a method to cover all relevant values determining the risk and assessing them. Risk analysis is usually based on a quantitative safety concept: actual risk $<$ acceptable risk.

The different approaches are designed for specific purposes. For rough calculations (which are fast and easy to handle) flow calculations are well suited. For the simplest case, the sum of the exit widths is divided by a constant specific flow to obtain a rough estimate of the overall egress time. One has to keep in mind, though, the assumptions and limitations which are in this case going beyond those mentioned in the previous section.

Nevertheless, such calculations are useful for plausibility checks of simulation results. They can provide a lower limit for overall egress times. If detailed results are required, e.g., about the sequence of an evacuation and spatial and temporal distribution of congestion, hydraulic models are not sufficient in most cases. In this case influences like population characteristics (and a reaction time distribution) are decisive. These can be represented in sufficient detail in microscopic models only.

The representation of space (i.e., the geometry), time, and the population corresponds to the range of application. Simulation and simplified analyses are always a simplification of reality. This is also true for evacuation exercises. Simulations, if calibrated on the basis of evacuation trials and other empirical data, can extrapolate to areas beyond evacuation trials by adapting the personal parameters or taking into account the influence of hazards. Such a change might be a reduced orientation capability or an increased reaction time. Due to practical and ethical constraints, such extrapolations are usually not possible in the former.

In summary the comparison of the different approaches provides insights into assessment criteria for which model to choose. They have first of all to fulfill the requirements of the user. For a rough estimate of egress times simple flow models might be sufficient. This can be a simple multiplication of the sum of exit widths with a constant specific flow. For more detailed analyses and the comparison of different scenarios (with different door and hallway widths, adapted escape way geometry, etc.) simulations are much more appropriate, though.

## 10.5. Application of Crowd Dynamics and Simulation

The comparison of simulation and calculation results with empirical data has two aims: (1) calibration of models and (2) validation of models. As stated before, the verification is the low-level checking of the correct implementation of a model into a simulation and can basically be done without using empirical data. In the context of calibration, specific measurements like the flow–density relation are crucial. Validation, on the other hand, is usually based on more comprehensive data like the actual or trial evacuation of a building. The following section presents such an example: the evacuation exercise in a movie theater.

### *10.5.1. Evacuation Exercise of a Movie Theater*

For the detailed investigation of an evacuation exercise, information about the floor plan, the population characteristics, and the behavior of the persons has to be recorded.

**10.5.1.1. Floor plan** The floor plan of the theater and the relevant areas in the first floor are shown in Figure 10.23.

The sequence of the events was filmed with four cameras, two inside the room and two outside, as shown in the previous figure. Figure 10.24 shows the scale and the details of the seating arrangement.

The theater had 152 seats, 102 persons took part in the evacuation trial. The persons were individually marked by paper hats with numbers. Figure 10.25 shows the screenshots from video recordings in comparison with simulation results. The simulations were performed with the software package PedGo (described in Klüpfel, 2003). After 65 s all persons had left the theater. The simulation came to the same result. Of course, for the trial as well as for the simulation, the overall time depends strongly on the reaction time distribution. In the trial, the emergency exit in front of the room as well as the regular entrance/exit at the rear were used by approximately the same number of persons.

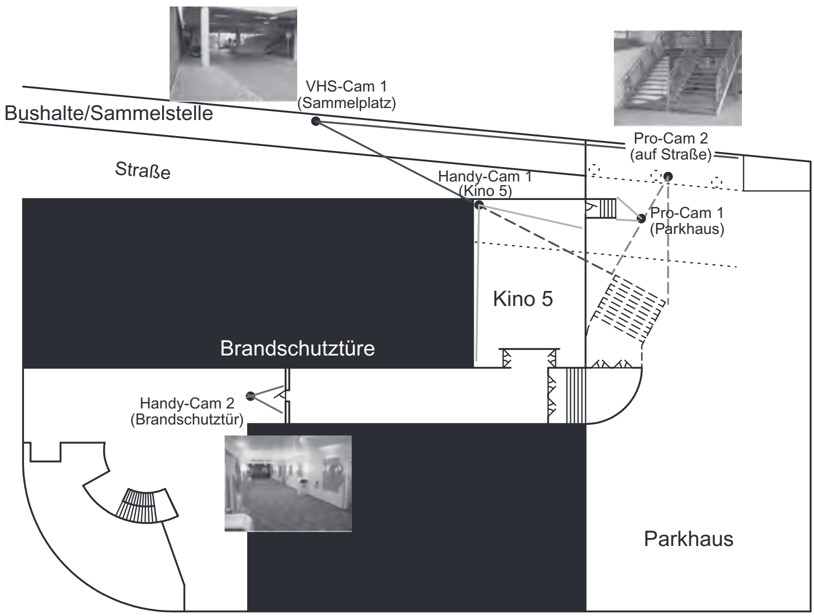



Figure 10.23: Floor plan of the movie theater and camera positions.

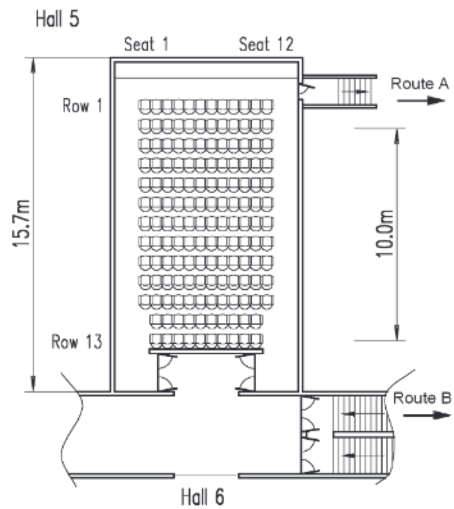



Figure 10.24: Detailed floor plan and seating arrangement.

**10.5.1.2. Simulation results** When comparing the evacuation sequence, the difference between the simulated flow at the doors and the experimental flow is prominent: In the simulation, the outflow at the doors is steadier. This can be seen

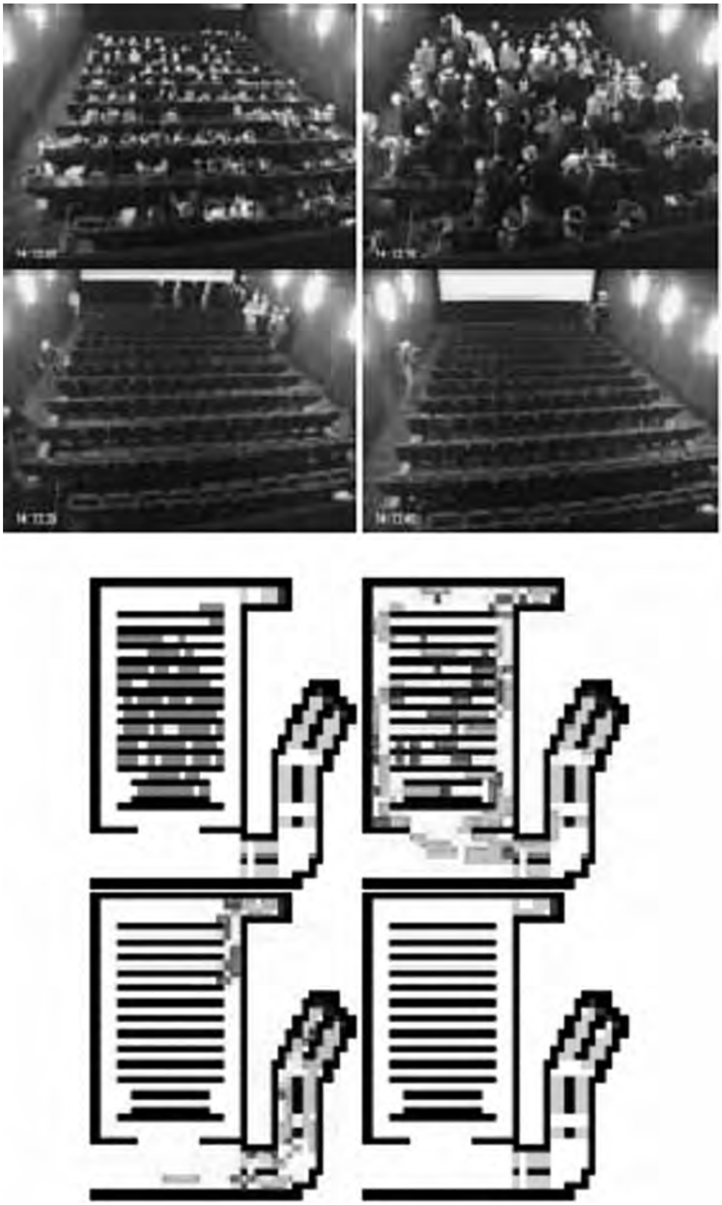


Figure 10.25: Video recordings and simulation screenshots at $t = 0\,\mathrm{s}$, $t = 10\,\mathrm{s}$, $t = 60\,\mathrm{s}$, and $t = 65\,\mathrm{s}$.

AU :3

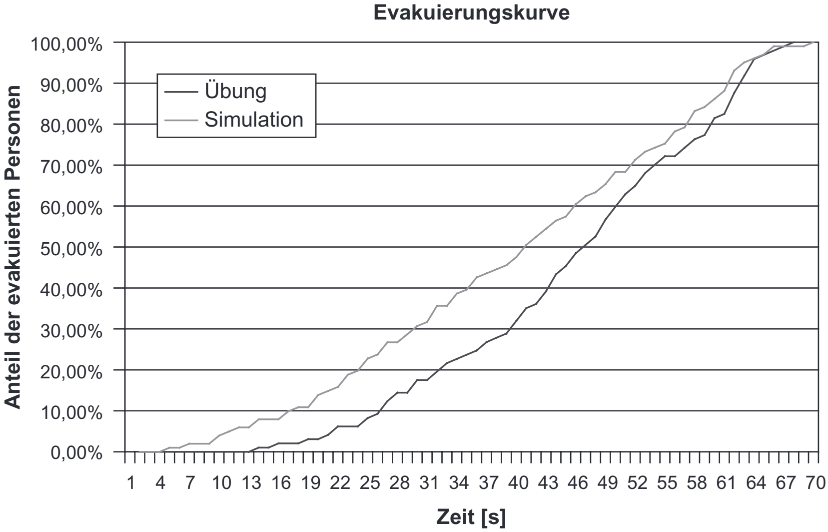



Figure 10.26: Evacuation curve.

from the evacuation curve in Figure 10.26. The simulations have been performed by the PedGo model described elsewhere.

In the simulation, the orientation was more effective. In spite of the same reaction time, the first person reached the exit earlier than in the exercise. In summary, the results for simulation and reality (exercise) are in good agreement. Differences are mainly due to high flow at high densities for the exercise, which is not the case in the simulation (Figure 10.26). Such a "synchronized flow" can also be observed at railway stations for commuter traffic. Such "synchronized flow" might be unstable, i.e., small disturbances might lead to a breakdown of the synchronized state and a substantial decrease in flow.

### *10.5.2. Carnivals and Parades*

The "Love Parade" which was held in Berlin until then in Dortmund in 2007, in AU :21 Essen in 2008, and will be held in Duisburg in 2010 (www.wikipedia.de/wik/LoveParade).

### *10.5.3. High-Rise Building: Phased Evacuation and Elevators*

**10.5.3.1. Phased evacuation** Phased evacuation refers to the fact that the evacuation process is divided into separate phases for different groups of persons within the building. This is mainly applied for high-rise buildings since the stair capacity is not designed for an immediate and concurrent evacuation.

**10.5.3.2. Use of elevators for evacuation** The use of elevators for evacuation is discussed in the recent years more and more in the affirmative. General resources can be found on www.evacmod.net.

### *10.5.4. Hospital Evacuation*

Hospital evacuation is a very specific case. It is first of all not determined by pedestrian movement but by the movement of persons lying in bed or being impaired in their mobility. Hospital evacuation poses special challenges. A general scheme for determining evacuation times for hospitals is given in Wolf (2001).

## 10.6. Summary, Outlook, and Conclusions

We have addressed several topics of pedestrian and crowd motion. In the following section, recommended reading and information resources are listed.

### *10.6.1. Information Resources*

**10.6.1.1. Literature databases**
- www.evacmod.net/literature
- www.safetylit.org
- www.ped-net.org/literature

**10.6.1.2. Bulletin boards**
- http://www.ped-net.orgwww.ped-net.org
- www.ped-net.org/forum
- www.evadmod.net/forum

**10.6.1.3. Internet groups**
- www.linkedin.com/ped
- www.xing.de/net/fed

**10.6.1.4. Model surveys**
- www.firemodelsurvey.com
- www.wikia.com/ped
- www.evacmod.net/models

**10.6.1.5. Books and review articles**
- Schadschneider et al., Pedestrian and Evacuation Dynamics. In: Springer Encyclopedia of Complexity and Systems Science. Springer, Berlin, 2009.
- Helbing: Fußgängerdynamik. Springer, Berlin, 1999.

- Fruin: Pedestrian Planning and Design.
- SFPE Handbook on Fire Protection Engineering.
- Tubbs: Egress Design Solutions.
- NFPA 101, Life Safety Code.
- Predtetschenski and Milinski: Foot Traffic for Building Design.

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