Chapter 33
Collective Phenomena in Pedestrian Crowds and Computational Simulation of Design Solutions

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Abstract We discuss various phenomena of crowd dynamics and pedestrian evacuation in places with a large public. From the simulations of flows, we analyze the design solutions that promote the stabilization of walking paths in opposite directions, the induction and stabilization of flows at intersections, and the improvement of flows in bottlenecks.

Keywords Pedestrian crowd dynamics · Improved design elements · Computer simulation

33.1 Introduction

Increasing the frequency and proportions of mass events has made mass disasters, and simulations of pedestrian flows become important and emerging areas of research [14]. A crowd, according to Helbing and Johansson [6], occurs from the agglomeration of many people in the same area and at the same time, and their density must be presumed to be high enough to cause continuous interactions or reactions in other individuals. Duives et al. [2] affirm that the greater the density, the greater the problem of coordination, since a large number of people tend to dispute some small gaps.

Understanding the crowd behavior during collective displacements is at the heart of pedestrian traffic engineering, according to Helbing et al. [8] and Shiwakoti et al. [16, 17]. And an overview of the collective phenomena observed in pedestrian crowds includes concepts related to the formation of corridor pathways and oscillations in bottlenecks in normal situations, as well as different types of blocked states produced by panic situations [3]. In this sense, the authors distinguish pedestrian dynamics between normal situations and situations of panic and argue that, although the characteristic problems of each of these situations are investigated by different scientific communities, they can be treated consistently by the same model.

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For Shiwakoti and Sarvi [18], the most critical reason to study the collective dynamics of pedestrians in emergency situations is the lack of complementary data to develop and validate an explanatory model. The lack of knowledge about the impact of the built environment and its geometric characteristics on the crowd dynamics is also linked to the difficulties in finding empirical data on the basis of which different aspects of human behavior can be examined [15]. According to Moussaïd et al. [14], many models of pedestrian behavior have been proposed in order to explain the laws underlying the crowd dynamics. Among them, approaches that are based on physics are quite common, such as models of fluid dynamics and social force, both inspired by Newtonian mechanics.

This work discusses several phenomena of crowd dynamics, in normal and extreme situations, characterized by high densities or panic. From simulations based on the social force model, we analyze the flow of pedestrians in different design solutions, which aim to: (i) promote the stabilization of walking paths in opposite directions; (ii) induce the stabilization of flows at intersections; and (iii) smooth bottleneck flows with the adoption of the funnel shape. The results, especially the qualitative ones, point out that it is possible to achieve more efficient flows through the insertion of obstacles or the adoption of ways that induce the walking path of pedestrians in a crowd.

33.2 Concept of Social Force and Computational Simulation

The social force model proposed by Helbing et al. [9–11] and Helbing and Molnar [4] is based on the method of modeling fluid crowds. It is a continuous, microscopic model whose deterministic interactions are based on force. The concept of the model is grounded on the assumption that changes in pedestrian movement are guided by fields of social force. Briefly, it is based on the overlapping effects of attraction and repulsion, which are responsible for determining the behavior of individuals.

According to Helbing et al. [11], the social force model is able to reproduce self-organizing phenomena in crowds of pedestrians, which have been neglected for a long time but essential for determining the degree of efficiency (average speed in relation to desired speed) of optimized and potential flow sources of obstructions. Thus, the use of this model aims to develop design elements that increase the efficiency and safety of pedestrian facilities. Currently, although the experimental base has improved due to the availability of video technology, the development of image analysis software and infrared detectors, quantitative experimental studies are still scarce [11].

Helbing and Johansson [6] state that collective behavior can be translated into complex phenomena represented by self-organized patterns of movement. These patterns demonstrate, according to the authors, that an efficient and intelligent collective dynamic can be based on simple and local interactions. They warn that, under extreme conditions, such coordination may fail and give rise to critical conditions in crowds. For them, understanding these conditions may have significant implications for the optimization of pedestrian mechanisms, particularly for evacuation situations.

Helbing et al. [11] consider in their model that each pedestrian wants to walk with an individual desired speed in the direction of their next destination. In normal situations, the desired speed is approximately Gaussian. Its average value is 1.3 m/s, or less, with a standard deviation of approximately 0.3 m/s. When it is necessary to compensate for delays, the authors point out that the desired speed is often increased in the course of time. The time-dependent parameter reflects nervousness or impatience. When taken together, long waiting periods decrease the actual speed in relation to the desired speed. Such a mechanism, according to Helbing et al. [11], can lead to aggressive behavior as well as generate high pressures in the crowd. Helbing et al. [10] estimate that high pressures may be accompanied by the occurrence of clogging and crushing effects.

For Helbing et al. [11], once calibrated with empirical data of pedestrian flows, the corresponding computational simulations produce realistic results, even when considering new geometries and situations. Therefore, the social force model has predictive value, allowing the investigation of new scenarios, for which the use of experiments would become expensive, difficult to perform or dangerous [11]. This predictive value, according to the authors, is particularly important for the planning and optimization of escape routes.

33.3 Crowd Dynamics

Even if one considers its simplifications, the social force model of pedestrian dynamics describes several phenomena in a realistic way and clarifies self-organized spatio-temporal patterns that are neither planned nor prescribed or organized by external agents [6]. Examples of self-organization phenomena studied in normal situations are: (i) lane formation; (ii) oscillations of flows in bottlenecks; (iii) stripe formation at intersections [6]. Under extreme conditions characterized by high densities or panic, according to the authors, coordination may cease to exist and give rise to effects such as: (iv) freezing-by-heating; (v) faster-is-slower effects; (vi) stop-and-go waves; (vii) crowd turbulence. Each of them will be discussed below:

(i) According to Helbing and Johansson [6], the most relevant factor in the phenomenon of lane formation can be defined by the greater relative pedestrians' speed walking in opposite directions. Comparing them to people who follow each other, pedestrians in opposite motion have more frequent interactions until they separate in different paths, moving away every time another pedestrian is found. The resulting collective motion pattern tends to minimize the frequency and strength of avoidance maneuvers whenever oscillations are weak [3].

(ii) In bottlenecks, it is common to observe oscillatory changes in the direction of bidirectional flows of moderate density [6]. The authors interpret the oscillatory pattern as a phenomenon of self-organization capable of reducing the effects of friction and delays. Studies have shown that when a pedestrian is able to pass through a narrowing passage, other pedestrians with the same walking direction can easily follow him. In this way, the pressure to wait and push becomes smaller than on the other side of the bottleneck, increasing the chance of occupying it. This causes a deadlock situation, which is followed by the change in direction of passage [7].

(iii) For Helbing et al. [11], intersections of pedestrian flows are one of the biggest problems related to crowd dynamics and are practically inevitable. Helbing and Johansson [6] affirm that self-organized patterns of movement were found in situations where flows intersected in only two directions, with the formation of stripes. This configuration makes it possible for two flows to penetrate one another without pedestrians needing to stop, which minimizes obstructive interactions and maximizes average pedestrian speeds.

(iv) In cases of extreme densities, Helbing et al. [11] argue that orderly path formation may fail due to overtaking maneuvers in large disturbances or multitudes of nervous pedestrians. Helbing et al. [8] observed that these pathways are destroyed by the increase of the oscillation force, analogous to the increase in temperature in a fluid. The authors, however, have realized that instead of the direct transition from the fluid state to the gaseous (disordered) state, there is a solid intermediate state. This state is characterized by a blocking or freezing situation. Hence, we call this transition the paradoxical term of freezing-by-heating. Helbing and Johansson [6] point out that, contrary to the simulations; real crowds usually solve the resulting impasses by rotating bodies (or shoulders), allowing people to leave the blocked areas.

(v) Helbing et al. [3] state that the simulated flow of an environment is well coordinated and regular as long as the desired speeds are normal. According to the authors, for desired speeds of more than 1.5 m/s, which the authors refer to as “hurried people,” there is an irregular succession of arch-like blockings of the exit and avalanche-like bunches of leaving pedestrians, when the arches break. According to Helbing and Johansson [6], the greater the difference between the arrival flow and the departure flow, the greater the likelihood of critical situations occurring, especially if people are trying to achieve a strongly desired goal or trying to escape a source of danger. In these situations, they say that high density causes problems of coordination, when several people start competing for the same few gaps. This can cause interactions of bodies and friction effects, capable of delaying the movement of the crowd or evacuation, hence the term fast-is-slower effect. This term reflects the observation that some processes take more time when they are executed at high speed [6].

(vi) Intermittent flows, or stop-and-go waves, characterize the inconstant outflow from a bottleneck, which is interrupted. Recent empirical studies of the flows of pilgrims in the Mecca region of Saudi Arabia, on January 12, 2006, have shown pronounced stop-and-go waves, which were observed in the entrance area of a 44-meter-wide bridge [6]. Helbing et al. [5] concluded that in high-density congestion, the resolution of obstructions at the output causes a shock wave that moves upstream. At the front of this wave, the density is low and people can leave the congestion. That is, if the density in front of the congestion is small enough, people will move forward to fill this low-density area. Thus, there will be alternating phases of resolution and filling of gaps near the exit, which leads to the alternating propagation of the congestion front [6].

(vii) When analyzing the videos of January 12, 2006, referring to the pilgrimage mentioned previously, the authors recorded the moment when the stop-and-go waves started. On the same day, when the density of the crowd reached even higher values, it was possible to observe a sudden transition of stop-and-go waves to irregular flows, as shown Helbing and Johansson [6]. These flows began to be characterized by random displacements, unintentional and in various directions, pushing people who could not stop even if they found other fallen people in front of them. The result of all this movement and its transitions was one of the biggest disasters in the world involving crowds [6]. The authors refer to this flow as crowd turbulence.

33.4 Improved Project Solutions

According to Helbing et al. [11], designing facilities for pedestrians represents an art that requires efficient flows, especially in the case of a large public meeting. Illera et al. [12] report their concern with the fact that although there has been research on pedestrian dynamics for a long time, preventive measures have not yet been detected in relation to constructions and organizations that bring crowds together. As pointed out by Illera et al. [12], standards and regulations prescribe design measures to ensure the safety of persons entering and exiting buildings. However, such security is restricted to measurable metrics such as escape route distances and doors widths. Qualitative design criteria, related to elements of architectural composition, according to the authors, are rarely formulated.

For Duives et al. [2], assessing the safety of events that gather pedestrians' crowds has proven to be a difficult task. In addition to different layouts of infrastructures, pedestrian movements also present different events. In this sense, Burd et al. [1] state that research on pedestrian dynamics is able to predict that small architectural features of the surroundings can have great effects on crowd behavior as well as pedestrian flow. For Helbing and Johansson [6], one of the main goals during mass events should be to prevent extreme densities. They are, according to the authors, what cause bottleneck congestion as a consequence of the breakdown of free flows and the ratio of increasing degrees of compression. By achieving a certain critical density, the potential for high pressures in the crowd is increased, especially when people are impatient due to long delays or panic [6].

The following simple examples of how to improve some standard elements in pedestrian facilities have been discussed in Helbing et al. [3]: (i) In high pedestrian densities, even walking paths tend to disturb each other when impatient pedestrians try to use any space for overtaking, leading to subsequent obstructions in the opposite direction of walking. Thus, the roads can be stabilized by a series of trees or columns dividing the opposite directions of walks, whose effect resembles a wall; (ii) the flow in the bottlenecks can be improved by a funnel-shaped design, although this format has less space for walking; and (iii) when different flows intersect, there may be oscillatory changes in the walking direction and periods of paralysis between them. Helbing et al. [11] indicate that an obstacle in the middle of an intersection tends to improve the efficiency of the movement, even if it reduces the area available for pedestrians. The explanation for this fact lies in the spatial separation of different directions of flow, so that only two directions can be intercepted in a single location.

According to Helbing et al. [3], the complex interaction between various types of flows can lead to completely unexpected results. These results are attributed to the nonlinearity of pedestrian dynamics. This means that planning for pedestrian facilities from conventional methods cannot always avoid major congestion, severe and catastrophic obstructions and blockages, especially when dealing with emergency situations. On the other hand, Helbing et al. [11] say that when working with a skillful pedestrian flow optimization, one can increase the efficiency and safety of these facilities, particularly when one makes use of the phenomena of self-organization. The authors also indicate that this increase in efficiency may be accompanied by compensating costs and even space reduction.

33.5 Research Method

The proposal of this paper is limited to simulating the three examples explained above, suggested in Helbing et al. [3], to improve some standard features in pedestrian facilities. These are: (i) insertion of obstacles to the stabilization of walking paths in opposite directions; (ii) adoption of the funnel shape to improve bottleneck pedestrian flow; and (iii) insertion of an obstacle in the center of an intersection to improve the efficiency of pedestrian movement (Fig. 33.1). In order to do so, we adopted the PTV Vissim software, its PTV Viswalk module, which allows the use of the social force approach. From this approach, pedestrians can walk independently of their destination, without a predefined network model for their trajectories. The speed imputed in each of the propositions was 1.32 m/s, which corresponds to a normal

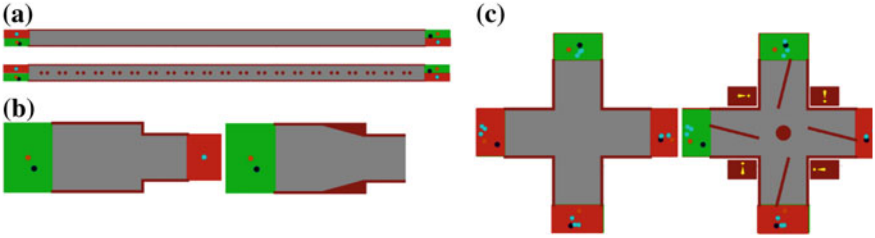


Fig. 33.1 Simulation of design solutions for the improvement of pedestrian flows

walking speed inside a crowd [11]. Due to the stochastic nature of the simulation model adopted in this work, random fluctuations occur influencing the results in each simulation performed. A stochastic simulation model, according to Lima et al. [13], has a random component, which is not controlled by the researcher.

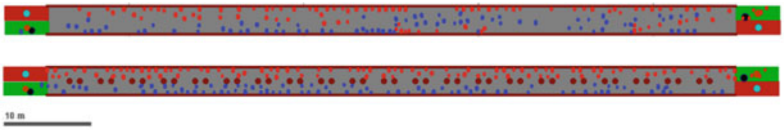
In Fig. 33.1, it is possible to observe the six design solutions simulated in this paper: (a) stabilization of walking paths with the insertion of obstacles (below) and conventional (above), where obstacles are represented by solid circles in brown color; (b) smoothing bottleneck flows with the funnel shape (right) and conventional (left); (c) induction of flow stabilization at intersections with the insertion of obstacles (right) and conventional (left), where obstacles are represented by solid brown circles and diagonal bars that induce the path to be followed by pedestrians, and yellow exclamation points represent elements of attraction, such as posters. Each of the six design solutions was simulated during the time of 300 s, during which the pedestrian flows were analyzed visually (qualitative analysis) and quantitative data were extracted that will be presented in the sequence.

33.6 Results and Discussions

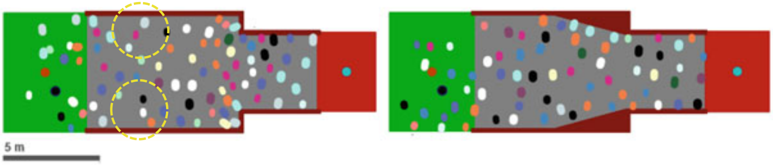
The qualitative analysis (Fig. 33.2) showed that the insertion of obstacles and the adoption of the funnel shape brought gains for the organization of the pedestrian flow in all situations analyzed. Stabilization of walking paths (Fig. 33.2a) proved to be faster in the proposition that included obstacles separating flows, although allowing the passage of pedestrians between them. With respect to the smoothing of flows in bottlenecks (Fig. 33.2b), it was also observed that the adoption of the funnel shape avoided the agglomerations that can be visualized in the conventional solution (left), highlighted in yellow, promoting a more continuous flow. Similarly, in the propositions aiming to stabilize the flow of pedestrians at intersections (Fig. 33.2c), the insertion of obstacles promoted a flow with less amount of avoidance maneuvers, as can be observed in the conventional proposition (left), with highlighted in yellow.

The quantitative analysis, presented in Table 33.1, shows that there were no significant changes between the conventional and obstacle propositions, when the data obtained after 300 s of simulation were compared. Some considerations, however, are necessary: (i) In the proposals for the analysis of the formation of walking ways, the conventional scenario was more efficient than the scenario with obstacles; (ii) in the propositions whose objective was to evaluate bottlenecks and intersections, both were more efficient after the insertion of driving obstacles and flow; (iii) the flows were calculated based on the number of pedestrians who entered the network in each simulated proposition, including those who did not complete the course at the end of the simulated 300 s.

(a) stabilization of walking paths with the insertion of obstacles (below).



(b) smoothing of bottleneck flows with the adoption of the funnel shape (right).



(c) induction of the stabilization of flows at intersections with the insertion of obstacles (right).

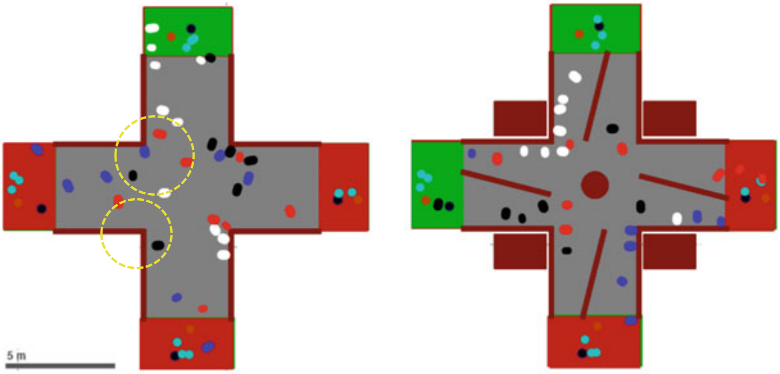


Fig. 33.2 Qualitative comparison between simulated design solutions

33.7 Final Considerations

Considering the relevance of understanding the consequences of collective movements considered complex, especially in the design phase of architectural spaces intended for large audiences, modeling based on social forces has been effectively used for pedestrian simulations in normal and panic situations. However, few studies have focused on understanding the impact of the built environment and its geometric characteristics on crowd dynamics. Thus, it was the intention of this research, besides discussing several phenomena of the crowd dynamics in normal and extreme situations, to analyze the flow of pedestrians from different design solutions. The qualitative and quantitative results indicate that it is possible to obtain more efficient flows with the insertion of obstacles or with the adoption of architectural forms that induce the walking path of pedestrians in a crowd. Since they do not represent an exhaustive approach, the simulations analyzed here require further studies to confirm the observed trend.

Table 33.1 Quantitative results of analyzed propositions

	Walking paths		Bottlenecks		Intersection	
	Conventional	W/obstacles	Conventional	W/obstacles	Conventional	W/obstacles
Efficiency[a] (%)	85.17	79.45	68.39	70.85	80.47	84.12
Flow (persons/s)	2.21	2.49	4.39	4.27	2.79	2.72

[a] Relation between the average speed and the desired average speed

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