Chapter 5
Modeling a Crowd of Groups: Multidisciplinary and Methodological Challenges

Stefania Bandini and Giuseppe Vizzari

Abstract The main aim of the chapter is to introduce a recent and current trend of research in the modeling, simulation and visual analysis of crowds: the study of the impact of groups on the overall crowd dynamics, and its implications of the aforementioned research activities as well as their outcomes. In most situations, in fact, a crowd of pedestrians is more than a simple set of individuals, each interpreting the presence of the others in a uniform way, trying to preserve a certain distance from the nearest person. A crowd is rather a composite assembly of individuals, some of which are bound by different types of ties, not only representing the presence of other pedestrians as a repulsive force, influencing their attitude towards the movement in the environment. Current models for the simulation of crowds of pedestrians have just started to analyze this phenomenon, and we still lack a complete understanding of the implications of not considering it, either in a real simulation project supporting decision making activities of designers or planners, or in the analysis and automatic extraction of information, for instance from video footage of events or crowded environments.

5.1 Introduction

The modeling and simulation of pedestrians and crowds is a consolidated and successful application of research results in the more general area of computer simulation of complex systems. Results of different approaches from researchers in

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S. Bandini (✉) • G. Vizzari
Department of Computer Science, Systems and Communication, Complex Systems and Artificial Intelligence (CSAI) Research Center, University of Milan – Bicocca,

Viale Sarca 336/14, 20126 Milano, Italy
e-mail: bandini@disco.unimib.it; vizzari@disco.unimib.it

S. Ali et al. (eds.), *Modeling, Simulation and Visual Analysis of Crowds*, The International Series in Video Computing 11, DOI 10.1007/978-1-4614-8483-7_5,

different disciplines, from physics and applied mathematics, to computer science, often influenced by (and sometimes in collaboration with) anthropological, psychological, sociological studies and the humanities in general, can be found in the literature. The level of maturity of these approaches was in some cases sufficient to lead to the design and development of commercial software packages, often offering interesting and advanced functionalities for the end user (e.g. CAD integration, CAD-like functionalities, advanced visualization and analysis tools) in addition to a simulation engine.[1] Nonetheless, as testified by a recent survey of the field [46] and by a report commissioned by the Cabinet Office [11], there is still room for innovations in models improving their performances both in terms of *effectiveness* in modeling pedestrians and crowd phenomena, in terms of *expressiveness* of the models (i.e. simplifying the modeling activity or introducing the possibility of representing phenomena that were still not modelled by existing approaches), in terms of *efficiency* of the simulation tools.

The unit of analysis of most the above mentioned approaches is represented by the single pedestrian, and this is also testified by the fact that most approaches claim to be agent–based (even though the different approaches do not necessarily employ agent models and/or technologies [4]): most pedestrians and crowd simulation approaches can be legitimately and safely classified in the category of micro-simulation. The analyses on simulation results are generally focused on aggregated data and emerging macro phenomena, such as average total travel times for specific classes of pedestrians, average or peak pedestrian densities in various points of the simulated environment. Generally, models do not include any meso-level [15] concept besides the aforementioned idea of class of pedestrians, i.e. a set of agents sharing behavioral rules and goals but otherwise completely unrelated.

The main aim of the chapter is to highlight a recent and current trend of research in modeling, simulation and visual analysis of crowds: the study of the impact of groups on the overall crowd dynamics, and its implications of the aforementioned research activities as well as their outcomes. In most situations, in fact, a crowd of pedestrians is more than a simple set of individuals, each interpreting the presence of the others in a uniform way, that is, trying to preserve a certain distance from the nearest person. A crowd is rather a composite assembly of individuals, some of which are bound by different types of ties, not only representing the presence of other pedestrians as a repulsive force, influencing their attitude towards the movement in the environment. Current models for the simulation of crowds of pedestrians have just started to analyze this phenomenon, and we still lack a complete understanding of the implications of not considering it, either in a real simulation project supporting decision making activities of designers or planners, or in the analysis and automatic extraction of information, for instance from video footage of events or crowded environments. The chapter, in addition to describing

[1]See http://www.evacmod.net/?q=node/5 for a large although not necessarily complete list of pedestrian simulation models and tools.

the current state of the art on this topic and discussing some recent results and open challenges, will also attempt to clarify that this research enterprize requires a coordinated and multidisciplinary effort along both the lines, that is, the synthesis and the analysis of crowds comprising groups of pedestrians. The chapter aims first of all at suggesting a relevant selection of literature in area of cultural studies and anthropology that represents a useful framework suggesting approaches both the modeling and to the analysis of the relevant phenomena. In particular, the work on proxemics by Edward T. Hall encompasses both a justification of the tendency of individuals to keep a certain distance from the others, unless they belong to a specific set of special persons (e.g. friends, relatives, loved ones).

The chapter then provides a thorough review of the current landscape in models for the simulation of crowd pedestrians that, to a different extent and in a more or less comprehensive way, extend the basic pedestrian models to provide an account for this sort of meso-level concept that is the notion of *group*.

A detailed example of one of these models, explicitly considering groups as first class abstractions and modelled entities that, on one hand, influence individuals in their decisions and, on the other, can represent an observed entity per se whose status depends on the individuals it is composed of. The model will be described in its principles and mechanisms, and it will be exemplified in an experimental situation and in a real world scenario. Some traditional approaches will be employed to evaluate, measure and describe the results of the simulated pedestrians' behaviors and some hypotheses will be done on the possibility to observe, characterize and possibly validate phenomena that are specifically related to groups and therefore not yet considered in the previous researches: new observations and metrics, in fact, must be defined and analyzed to root the results of the new models on actual data.

Finally, and as a consequence of this last consideration, this chapter presents a reflection on the current landscape in the area of crowd analysis, proposing a multidisciplinary research direction in which the efforts on crowd analysis and synthesis can benefit from the mutual challenges, methods and results.

5.2 Influential Contributions on Pedestrians and Crowd Modeling

In this section of the chapter we want to briefly introduce some selected contributions from disciplines in the humanities, and especially anthropology and sociology, that to a certain extent influenced previous pedestrian and crowd modeling approaches or that represented a useful resource in the development of innovative models considering groups as a first class abstraction influencing the overall system dynamics. In addition, we also report here some works describing reports on relevant observations that represent useful evidences and potentially also data to support innovative modeling and simulation efforts.

5.2.1 Proxemics

The term *proxemics* was first introduced by Edward T. Hall with respect to the study of a set of measurable distances between people as they interact [23]. In his studies, Hall carried out analysis of different situations in order to recognize behavioral patterns. These patterns are based on people's culture as they appear at different levels of awareness. In [22] Hall proposed a system for the notation of proxemic behavior in order to collect data and information on people sharing a common space. Hall defined proxemic behavior and four types of perceived distances: *intimate distance* for embracing, touching or whispering; *personal distance* for interactions among good friends or family members; *social distance* for interactions among acquaintances; *public distance* used for public speaking. Perceived distances depend on some additional elements which characterize relationships and interactions between people: posture and sex identifiers, sociofugal-sociopetal (SFP) axis, kinesthetic factor, touching code, visual code, thermal code, olfactory code and voice loudness.

Proxemic behavior includes different aspects which could be useful and interesting to integrate in crowd and pedestrian dynamics simulation. In particular, the most significant of these aspects being the existence of two kinds of distance: *physical* distance and *perceived* distance. While the first depends on physical position associated to each person, the latter depends on proxemic behavior based on culture and social rules.

It must be noted that some recent research effort was aimed at evaluating the impact of proxemics and cultural differences on the fundamental diagram [12], a typical way of evaluating both real crowding situations and simulation results. Moreover, first attempts to explicitly include proxemic considerations not only as a background element in the motivations a behavioral model is based upon, but rather as a concrete element of the model itself are present in the most recent literature [33, 51].

5.2.2 Groups: Contributions from Anthropology

The term *group* appears in very different and varied contexts of the anthropological literature, both ethnographic and theoretical [16]. The term, per se, is not endowed with specific characteristics and it is generally accompanied by additional specifications such as "domestic group," "ethnic group," and so on. With reference to the term in general and common sense usage, anthropology borrows sociological considerations, defining a group as a set of individuals related by a common project, a common identity, that can be perceived by the members of the group and by external observers.

The common element between the different strains of research related to groups is the topic of social cohesion that, to a certain extent, pervades the works of researchers since the end of the Nineteenth century. The existence of a group considered as a set of (at least two) individuals does not necessarily imply the presence of a formal organization, even though this characteristic could represent a group classification criterion; other classification criteria are related to the degree of homogeneity/heterogeneity in the group, the mechanisms of recruitment of new members, the presence or absence of common interests towards goods (e.g., territory, domestic herds) or ritual knowledge. Generally groups are aimed at the execution of a plan for the achievement of some final goal. Therefore, groups exist since they carry out specific 'functions'; the latter can be classified into three types: executive, control and expressive functions. The executive aspect deals with the need of a group to successfully adapt to the natural and social environment in which it is set in order to achieve the goals of the group (e.g., the management of resources, the performance of some ritual). The control aspect deals with the enactment of mechanisms (e.g., behavioral norms, recruitment practices, rituals) for the preservation of group characteristics, namely structure and goals. The expressive aspect consists in the ability of the group to gratify on a psychological and emotional level of its own members.

5.2.3 Canetti's Crowd Theory

Elias Canetti's work [10] proposes a classification and an ontological description of the crowd phenomenon; this description represents the result of 40 years of empirical observations and studies from psychological and anthropological viewpoints. Elias Canetti can be considered as belonging to the tradition of social studies that consider the crowd as an entity dominated by uniform moods and feelings. This uniformity, the loss of individuality, however, are not the normal state of a set of pedestrians in an environment, although maybe densely populated.

The normal pedestrian behavior, according to Canetti, is based upon what can be called the *fear to be touched* principle:

> There is nothing man fears more than the touch of the unknown. He wants to see what is reaching towards him, and to be able to recognize or at least classify it.
>
> All the distance which men place around themselves are dictated by this fear.

The normal situation can however be interrupted by a *discharge*, a particular event, a situation, a specific context in which this principle is not valid anymore, since pedestrians are willing to accept being very close, within touch distance. Canetti provided an extensive categorization of the conditions, situations in which this happens and he also described the features of these situations and of the resulting types of crowds. Finally, Canetti also provides the concept of *crowd crystal*, a particular set of pedestrians that are part of a group willing to preserve its unity, despite crowd dynamics. Canetti's theory (and precisely the fear to be touched principle) is apparently compatible with Hall's proxemics, but it also provides additional concepts that are useful to describe phenomena that take place in several relevant crowding phenomena, especially from the Hajj perspective.

Recent developments aimed at formalizing, embedding and employing Canetti's crowd theory into computer systems (for instance, supporting crowd profiling and modeling) can be found in the literature [2, 3] and they represent a useful contribution to the present work.

5.2.4 Direct Observations

Direct observations, when carried out in a systematic way, represent a fundamental instrument aimed at, on one hand, at highlighting phenomena to be modelled, behavioral tendencies to be included in model mechanisms and, on the other, they also represent a way to acquire quantitative information on some pedestrian and crowd related phenomenon. Data and information deriving from the observation can directly support some specific form of decision by an expert designer or planner, or they can represent a useful element for the calibration of a simulation model.

Two relevant examples of direct observations that report relevant information from the perspective of a modeler trying to capture elements of the behavior of groups of pedestrians are represented by two video-based observational studies [48, 52]: the first paper, presents an analysis of three mixed-use (residential/retail) uncluttered urban environments close to the city centers of Edinburgh and York (essentially in free flow conditions), while the second analyzes an area between the check-in facilities and the security control at the Dresden International Airport. Both studies analyze the effect of the presence of groups, as well as other variables like gender, age and even travel purpose (only for the second observation). Both the observations conclude that members of groups tend to assume a lower speed than individuals, very likely due to the tendency of each group member of adapting his/her own movement to stay close to the other members. Similar considerations are also discussed in [17], where a situation in which authors were expecting groups to be less frequently identified and relevant, that is, an admission test to a programmed number university course. Another recent study in the vein of Hall's proxemics [13] supports the above interpretation and also adds an analysis of the spatial patterns and formations assumed by the group members.

While these works are extremely important in pointing out the fact that the presence of groups can have a noticeable influence on walking behavior of pedestrians, and therefore not considering this aspect can present a problem when making predictions on pedestrians' behaviors, they are not sufficient to actually characterize this impact in general, since they essentially analyze situations in which pedestrians have an almost unconstrained possibility to choose their walking direction and speed due to the low level of density. Moreover, the analyzed groups are in most cases of relatively small size: the analysis carried out in the context of the airport terminal considered that larger groups split into smaller ones and focused on the latter, not considering the potential influence of the larger group on the smaller ones. The real world scenario that will be analyzed in Sect. 5.6 will instead consider the presence of potentially large groups (i.e. 250 members), although it does not consider the presence of comprised smaller groups.

5.3 Pedestrians and Crowd Modeling Approaches

The aim of this section is to provide a compact but as comprehensive as possible overview of the different approaches to the representation and simulation of crowd dynamics: entire workshops and conferences attracting researchers from different disciplines are focused on this topic (see, e.g., the proceedings of the first edition of the International Conference on Pedestrian and Evacuation Dynamics [47] and consider that this event will reach the sixth edition in 2012), therefore we are not pretending to even mention the most significant approaches and model. We will try, instead, to present broad classes identified according to the way pedestrians are represented and managed, and in particular: (i) pedestrians as *particles subject to forces* of attraction/repulsion, (ii) pedestrians as particular *states of cells in a CA*, (iii) pedestrians as *autonomous agents*, situated in an environment.

5.3.1 Particle-Based Approach

A significant number of models and experiences of simulation of pedestrian dynamics are based on an analytical approach, considering pedestrian as particles subject to forces, and representing in this was the various forms of interaction between pedestrian and the environment (and also among pedestrians themselves, in the case of *active walker* models [26]). Forces of attraction lead the pedestrians/particles towards their destinations, whereas forces of repulsion are used to represent the tendency to stay at a distance from other points of the environment. This kind of effect was introduced by a relevant and successful example of this modeling approach, the *social force* model [25]; this approach introduces the notion of social force, representing the tendency of pedestrians to stay at a certain distance one from another; other relevant approaches take inspiration from fluid-dynamic [24] and magnetic forces [39] for the representation of mechanisms governing flows of pedestrians.

While this approach is based on a precise methodology and has provided relevant results, it represents pedestrian as mere particles, whose goals, characteristics and interactions must be represented by means of equations, and it is not simple thus to incorporate heterogeneity and complex pedestrian behaviors in this kind of model. Nonetheless, recent extensions of the basic social force model introduce a contribution to the general laws of motion representing a form of cohesion between members of a group [34, 53]: the authors of these works focus on small unstructured groups and they analyze the impact of this modification to the starting model in low to moderate density scenarios.

5.3.2 Cellular Automata Approach

A different approach to crowd modeling is characterized by the adoption of Cellular Automata (CA), with a discrete spatial representation and discrete time-steps, to represent the simulated environment and the entities it comprises. The cellular space includes thus both a representation of the environment and an indication of its state, in terms of occupancy of the sites it is divided into, by static obstacles as well as human beings. Transition rules must be defined in order to specify the evolution of every cell's state; they are based on the concept of neighborhood of a cell, a specific set of cells whose state will be considered in the computation of its transition rule. The transition rule, in this kind of model, generates the illusion of movement, that is mapped to a coordinated change of cells state. To make a simple example, an atomic step of a pedestrian is realized through the change of state of two cells, the first characterized by an *"occupied"* state that becomes *"vacant"*, and an adjacent one that was previously *"vacant"* and that becomes *"occupied"*. This kind of application of CA-based models is essentially based on previous works adopting the same approach for traffic simulation [36].

Local cell interactions are thus the uniform (and only) way to represent the motion of an individual in the space (and the choice of the destination of every movement step). The sequential application of this rule to the whole cell space may bring to emergent effects and collective behaviors. Relevant examples of crowd collective behaviors that were modelled through CAs are the formation of lanes in bidirectional pedestrian flows [7], the resolution of conflicts in multidirectional crossing pedestrian flows [8]. In this kind of example, different states of the cells represent pedestrians moving towards different exits; this particular state activates a particular branch of the transition rule causing the transition of the related pedestrian to the direction associated to that particular state. Additional branches of the transition rule manage conflicts in the movement of pedestrians, for instance through changes of lanes in case of pedestrians that would occupy the same cell coming from opposite directions.

It must be noted, however, that the potential need to represent goal driven behaviors (i.e. the desire to reach a certain position in space) has often led to extend the basic CA model to include features and mechanisms breaking the strictly locality principle. A relevant example of this kind of development is represented by a CA based approach to pedestrian dynamics in evacuation configurations [45]. In this case, the cellular structure of the environment is also characterized by a predefined desirability level, associated to each cell, that, combined with more dynamic effects generated by the passage of other pedestrians, guide the transition of states associated to pedestrians. Recent developments of this approach introduce even more sophisticated behavioral elements for pedestrians, considering the anticipation of the movements of other pedestrians, especially in counter flows scenarios [38].

As for the particle–based approaches, also in CA pedestrians and crowd models the impact of the presence of groups has been recently investigated [44]: once again, group members have a tendency to stay close to each others, but this model also includes the possibility to represent leader and followers roles. The paper, however, does not present a validation against real data or an application in a real–world scenario.

5.3.3 Autonomous Agents Approach

Recent developments in this line of research (e.g. [14, 27]), introduce modifications to the basic CA approach that are so deep that the resulting models can be considered much more similar to agent–based and Multi Agent Systems (MAS) models exploiting a cellular space representing spatial aspects of agents' environment. A MAS is a system made up of a set of autonomous components which interact, for instance according to collaboration or competition schemes, in order to contribute in realizing an overall behavior that could not be generated by single entities by themselves. As previously introduced, MAS models have been successfully applied to the modeling and simulation of several situations characterized by the presence of autonomous entities whose action and interaction determines the evolution of the system, and they are growingly adopted also to model crowds of pedestrians [1, 6, 20, 50]. All these approaches are characterized by the fact that the agents encapsulate some form of behavior inspired by the above described approaches, that is, forms of attractions/repulsion generated by points of interest or reference in the environment but also by other pedestrians.

Some of the agent based approaches to the modeling of pedestrians and crowds were developed with the primary goal of providing a realistic 3D visualization of the simulated dynamics: in this case, the notion of realism includes elements that are considered irrelevant by some of the previous approaches, and it does not necessarily require the models to be validated against data observed in real or experimental situations. The approach described in [35] and in [49] is characterized by a very composite model of pedestrian behavior, including basic reactive behaviors as well as a cognitive control layer; moreover, actions available to agents are not strictly related to their movement, but they also allow forms of direct interaction among pedestrians and interaction with objects situated in the environment. Other approaches in this area (see, e.g., [40]) also define layered architectures including cognitive models for the coordination of composite actions for the manipulation of objects present in the environment. Another relevant agent–based effort described in [41], although adopting the social force model for some internal mechanisms (i.e. local collision avoidance), employs guidance fields to achieve a goal directed agent movement.

A recent effort [42] represents instead an attempt to define a model able to reproduce composite forms of groups related dynamics: this modeling effort, although it represents an interesting investigation of how expressive an agent–based approach to the modeling of pedestrian groups can be, was not validated in a real world scenario.

5.4 GA-PED Model

We will now briefly introduce a model based on simple reactive situated agents based on some fundamental features of CA approaches to pedestrian and crowd modeling and simulation, with specific reference to the representation and management of the simulated environment and pedestrians; in particular, the adopted approach is discrete both in space and in time. The present description of the model is simplified and reduced for sake of space, reporting only a basic description of the elements required to understand its basic mechanisms; an extended version of the model description can be found in [5].

5.4.1 Environment

The environment in which the simulation takes place is a lattice of cells, each representing a portion of the simulated environment and comprising information about its current state, both in terms of physical occupation by an obstacle or by a pedestrian, and in terms of additional information, for instance describing its distance from a reference point or point of interest in the environment and/or its desirability for pedestrians following a certain path in the environment.

The scale of discretization is determined according to the principle of achieving cells in which at most one pedestrian can be present; traditionally the side of a cell is fixed at 40 or 50 cm, respectively determining a maximum density of 4 and 6.5 pedestrian per square meter. The choice of the scale of discretization also influences the length of the simulation turn: the average speed of a pedestrian can be set at about 1.5 m/s (see, e.g., [52]) therefore, assuming that a pedestrian can perform a single movement between a cell and an adjacent one (according to the Von Neumann neighborhood), the duration of a simulation turn is about 0.33 s in case of a 50 cm discretization and 0.27 in case of a finer 40 cm discretization.

Each cell can be either vacant, occupied by an obstacle or by a specific pedestrian. In order to support pedestrian navigation in the environment, each cell is also provided with specific floor fields [45]. In particular, each relevant final or intermediate target for a pedestrian is associated to a floor field, representing a sort of gradient indicating the most direct way towards the associated point of interest (e.g., see Fig. 5.1 in which a simple scenario and the relative floor field representation are shown). The GA-Ped (Group Aware Pedestrian model) model only comprises *static* floor fields, specifying the shortest path to destinations and targets. Interactions between pedestrians, that in other models are described by the use of *dynamic floor fields*, in this modeling approach are managed by the agent interpretation of the perceived situation.

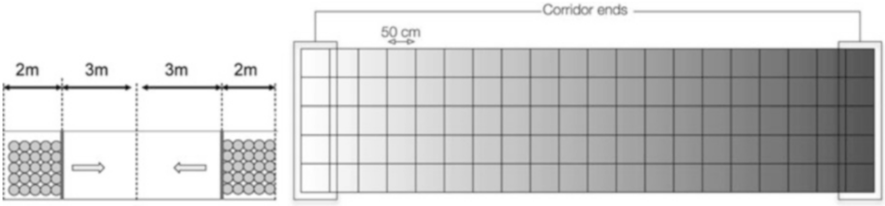

Fig. 5.1 Schematic representation of a simple scenario: a 2.5 by 10 m corridor, with exits on the short ends and 2 sets of 25 pedestrians. The discretization of 50 cm and the floor field directing towards the right end is shown on the *right*

5.4.2 Pedestrians

Pedestrians in the GA-PED model have a limited form of autonomy, meaning that they can choose were to move according to their perception of the environment and their goal, but their action is actually triggered by the simulation engine and they are not thus provided with a thread of control of their own. More precisely, the simulation turn activates every pedestrian once in every turn, adopting a random order in the agent selection: this agent activation strategy, also called *shuffled sequential updating* [30], is characterized by the fact that conflicts between pedestrians are prevented.

Each pedestrian is provided with a simple set of attributes: $pedestrian = \langle pedID, groupID \rangle$ with *pedID* being an identifier for each pedestrian and *groupID* (possibly null, in case of individuals) the group the pedestrian belongs to. For the applications presented in this paper, the agents have a single goal in the experimental scenario, but in more complex ones the environment could be endowed with multiple floor fields and the agent could be also characterized by a *schedule*, in terms of a sequence of floor fields and therefore intermediate destinations to be reached.

The behavior of a pedestrian is represented as a flow made up of three stages: *sleep*, *movement evaluation*, *movement*. When a new iteration starts each pedestrian is in a sleeping state. The system wakes up each pedestrian once per iteration and, then, the pedestrian passes to a new state of movement evaluation. In this stage, the pedestrian collects all the information necessary to obtain spatial awareness. In particular, every pedestrian has the capability to observe the environment around him, looking for other pedestrians (that could be part of his/her group), walls and other obstacles, according to the Von Neumann neighborhood. The choice of the actual movement destination between the set of potential movements (i.e. non empty cells are not considered) is based on the elaboration of an utility value, called *likability*, representing the desirability of moving into that position given the state of the pedestrian.

Formally, given a pedestrian belonging to a group g and reaching a goal t, the *likability* of a cell c is defined as:

$$li(c,g,t) = w_t \cdot goal(t,c) + w_g \cdot group(g,c) - w_o \cdot obs(c) - w_s \cdot others(g,c) + \varepsilon$$

where the functions *obst* counts the number of obstacles in the Von Neumann neighborhood of a given cell, *goal* returns the value of the floor field associated to the target t in a give cell, *group* and *other* respectively count the number of members and non-members of the group g, ε represents a random value. Group cohesion and floor field are positive components because the pedestrians wish to reach their destinations quickly, while staying close to other group members. On the contrary, the presence of obstacles and other pedestrians have a negative impact as a pedestrian usually tends to avoid them. A random factor is also added to the overall evaluation of the desirability of every cell.

In the usual floor field models, after a deterministic elaboration of the utility of each cell, not comprising thus any random factor, the utilities are translated into the probabilities that the related cell is selected as movement destination. This means that for a pedestrian generally there is a higher probability of moving towards his/her destination and according to proxemic considerations, but there is also the probability, for instance, to move away from his/her goal or to move far from his/her group. In this work, we decided to include a small random factor to the utility of each cell and to choose directly the movement that maximizes the agent utility. A more thorough comparison of the implications of this choice compared to the basic floor field approach is out of the scope of this chapter and it is object of future works.

5.5 Experimental Scenario

The GA-Ped model was adopted to realize a set of simulations in different starting conditions (mainly changing density of pedestrians in the environment, but also different configurations of groups present in the simulated pedestrian population) in a situation in which experiments focused at evaluating the impact of the presence of groups of different size was being investigated.

5.5.1 Experiments

The environment in which the experiments took place is represented in Fig. 5.1: a 2.5 by 10 m corridor, with exits on the short ends. The experiments were characterized by the presence of 2 sets of 25 pedestrians, respectively starting at the 2 ends of the corridor (in 2 by 2.5 m areas), moving towards the other end. Various cameras were positioned on the side of the corridor and the time required for the two sets of pedestrians to complete their movement was also measured (manually from the video footage).

Several experiments were conducted, some of which also considered the presence of groups of pedestrians, that were instructed on the fact that they had to behave as friends or relatives while moving during the experiment. In particular, the following scenarios have been investigated: (i) single pedestrians (three experiments); (ii) three couples of pedestrians for each direction (two experiments); (iii) two triples of pedestrians for each direction (three experiments); (iv) a group of six pedestrians for each direction (four experiments).

One of the observed phenomena was that the first experiment actually required more time for the pedestrians to complete the movement; the pedestrians actually learned how to move and how to perform the experiment very quickly, since the first experiment took them about 18 s while the average completion time over 12 experiments is about 15 s.

The number of performed experiments is probably too low to draw some definitive conclusions, but the total travel times of configurations including individuals and pairs were consistently lower than those not including groups. Qualitative analysis of the videos showed that pairs can easily form a line, and this reduces the friction with the facing group. Similar considerations can be done for large groups; on the other end, groups of three pedestrians sometimes had difficulties in forming a lane, retaining a triangular shape similar to the 'V' shaped observed and modeled in [34], and this caused a total travel times that were higher than average in two of the three experiments involving this type of group.

5.5.2 Simulation Results

We applied the model described in Sect. 5.4 to the previous scenario by means of an agent-based platform based on GA-Ped approach. A description of the platform can be found in [9]. We employed the gathered data and additional data available in the literature to perform a calibration of the parameters, essentially determining the relative importance of (a) the goal oriented, (b) general proxemics and (c) group proxemic components of the movement choice. In particular, we first identified a set of plausible values for the w_t and w_o parameters employing experimental data regarding a one-directional flow. Then we employed data from bidirectional flow situations to further tune these parameters as well as the value of the w_g parameter: the latter was set in order to achieve a balance between effectiveness in preserving group cohesion and preserving aggregated measures on the overall pedestrian flow (an excessive group cohesion value reduces the overall pedestrian flow and produces unrealistic behavior).

We investigated the capability of our model to fit the fundamental diagram proposed in the literature for characterising pedestrian simulations [46] and other traffic related phenomena. This kind of diagram shows how the average velocity of pedestrians varies according to the density of the simulated environment. Moreover, we wanted to distinguish the different performance of different agent types, and essentially individuals, members of pairs, groups of three and five pedestrians over a relatively wide spectrum of densities. To do so, we performed continuous

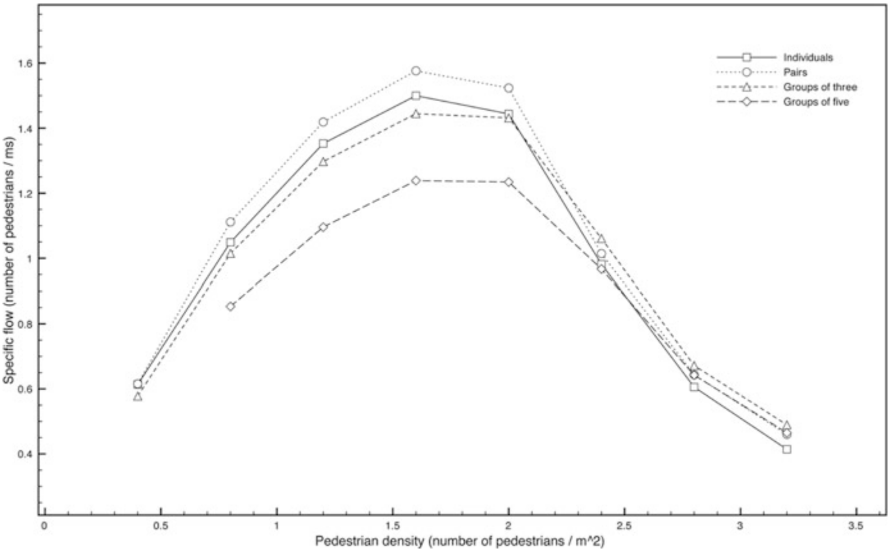

Fig. 5.2 Fundamental diagram for different pedestrian densities in the corridor scenario

simulations of the bidirectional pedestrian flows in the corridor with a changing number of pedestrians, to alter their density. For each density value displayed in the graph shown in Fig. 5.2 is related to at least 1 h of simulated time.

The achieved fundamental diagram represents in qualitatively correct way the nature of pedestrian dynamics: the flow of pedestrians increases with the growing of the density of the corridor unit a critical value is reached. If the system density is increased beyond that value, the flow begins to decrease significantly as the friction between pedestrians make movements more difficult.

The simulation results are in tune with the experimental data coming from observations: in particular, the flow of pairs of pedestrians is consistently above the curve of individuals. This means that the average speed of members of pairs is actually higher than the average speed of individuals. This is due to the fact that they easily tend to form a line, in which the first pedestrian has the same probability to be stuck as an individual, but the follower has a generally higher probability to move forward, following the path "opened" by the first member of the pair, as exemplified in Fig. 5.3b. The same does not happen for larger groups, since for them it is more difficult to form a line and therefore they offer a larger profile to the counter flow, as shown in Fig. 5.3a: the curves related to groups of three and five members are below the curve of individuals for most of the spectrum of densities, precisely until very high density values are reached. In this case, the advantage of followers overcomes the disadvantage of offering a larger profile to the counter flow and the combined average velocity is higher than that of individuals.

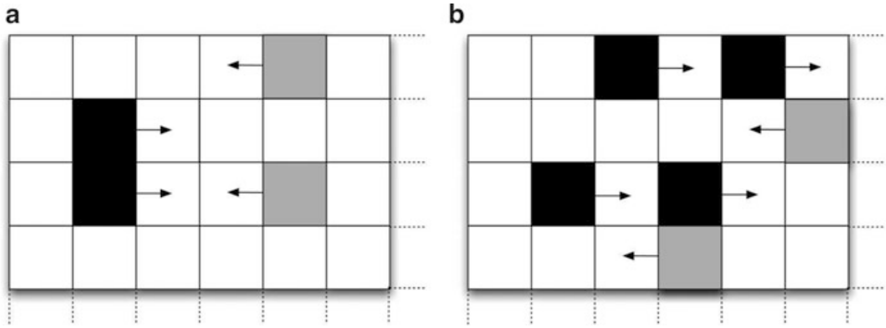

Fig. 5.3 In the *left figure*, the *black* pedestrians have not formed a line and they offer a larger profile to the counter flow. In the *right figure*, they formed a line and the follower has a lower probability to find an opposing pedestrian due to the presence of a sort of "emergent" leader

5.6 Real World Scenario

5.6.1 Environment and observations

The model was also adopted to elaborate different what-if scenarios in a real world case study. In particular, the simulated scenario is characterized by the presence of a station of the Mashaer line, a newly constructed rail line in the area of Makkah. The goal of this infrastructure is to reduce the congestion caused by the presence of other collective means of pilgrim transportation (i.e. buses) during the Hajj: the yearly pilgrimage to Mecca that involves over two millions of people coming from over 150 countries and some of its phase often result in congestions of massive proportions. In this work, we are focusing on a specific point of one of the newly constructed stations, Arafat I. One of the most demanding situations that the infrastructure of the Mashaer Rail line must be able to sustain is the one that takes place after the sunset of the second day of the pilgrimage, which involves the transport of pilgrims from Arafat to Muzdalifah. The pilgrims that employ the train to proceed to the next phase of the process must be able to move from the tents or other accommodation to the station in an organised flow that should be consistent with the movement of trains from Arafat to Muzdalifah stations. Since pilgrims must leave the Arafat area before midnight, the trains must continuously load pilgrims at Arafat, carry them to Muzdalifah, and come back empty to transport other pilgrims.

The size of the platforms was determined to allow hosting in a safe and comfortable way a number of pilgrims also exceeding the potential number of passengers of a whole train. Each train is made up of 12 wagons, each able to carry 250 passengers for a total of approximately 3,000 persons. In order to achieve an organized and manageable flow of people from outside the station area to the platforms, the departure process was structured around the idea of waiting–boxes: pilgrims are subdivided into groups of about 250 persons that are led by specific

Fig. 5.4 Photos and a schematic representation of the real world scenario and the related phenomena: groups of pilgrims move from the tents area according to a precise schedule and flow into the waiting boxes, fenced queuing areas located in immediately outside the station, between the access ramps. The groups wait in these areas for an authorization by the station agents to move towards the ramps or elevators

leaders (generally carrying a pole with signs supporting group identification). The groups start from the tents area and flow into these fenced queuing areas located in immediately outside the station, between the access ramps. Groups of pilgrims wait in these areas, called waiting boxes, for an authorization by the station agents to move towards the ramps or elevators. In this way, it is possible to stop the flow of pilgrims whenever the number of persons on the platforms (or on their way to reach it using the ramps or elevators) is equal to the train capacity, supporting thus a smooth boarding operation.

Three photos and a schematic representation of the real world scenario and the related phenomena are shown in Fig. 5.4: the bottom right photo shows a situation in which the waiting-box principle, preventing the possibility of two flows simultaneously converging to a ramp, was not respected, causing a higher than average congestion around the ramp. This anomaly was plausibly due to the fact that it was the first time the station was actually used, therefore also the management personnel was not experienced in the crowd management procedures.

5.6.2 Simulation Results

Three different scenarios were realized adopting the previously defined model and using the parameters that were employed in the previous case study: (i) the flow of a group of pilgrims from one waiting box to the ramp; (ii) the simultaneous flow of two groups from two different waiting boxes to the same ramp; (iii) the simultaneous flow of three groups of pilgrims, two as in the previous situation, one coming directly from the tents area. Every group included 250 pilgrims. The goal of the analysis was to understand if the model is able to qualitatively reflect the increase in the waiting times and the space utilization when the waiting box principle was not respected.

The environment was discretized adopting 50 cm sided cells and the cell space was endowed with a floor field leading towards the platform, by means of the ramp. The floor field was generated according to well known techniques (essentially employing the Manhattan Distance [29] corrected introducing a minor effect of repulsion generated by obstacles, as in [37]). The different speed of pedestrians in the ramp was not considered: this scenario should be therefore considered as a best case situation, since pilgrims actually flow through the ramp more slowly than in our simulation. Consequently, we will not discuss here the changing of the travel time between the waiting boxes and the platform (that however increased with the growth of the number of pilgrims in the simulated scenario), but rather different metrics of *space utilization*. This kind of metric is tightly related to the so called *level of service* [18], a measure of the effectiveness of elements of a transportation infrastructure; it is also naturally related to proxemics, since a low level of service is related to a unpleasant perceived situation due to the invasion of the personal (or even intimate) space.

The diagrams shown in Fig. 5.5 report three metrics describing three different phenomena in the same area, including a ramp (on the left) and three waiting boxes (on the right). The three phenomena are related to (i) a situation in which an agent in a cell of the environment was willing to move but it was unable to perform the action due to the excessive space occupation; (ii) a situation in which an agent actually moved from a cell of the environment; (iii) the "set sum" of the previous situations, in other words, the situations in which a cell was occupied by agent, that either moved out of the cell or remained stuck in there. More precisely, diagrams show the relative frequency of the above events on the whole simulation time. The three metrics are depicted graphically following the same approach: the background color of the environment is black and obstacles are red (gray in a B&W rendering); each point associated to a walkable area (i.e. a cell of the model) is painted in a different shade of gray according to the value of the metric in that specific point. The black color is therefore associated to point if the environment in which the related metric is 0; the white color is associated to the point in which the metric assumes the highest value in the scenario (also shown in the legend). For instance, in all diagrams in the third row the points of space close to the ramp entrance are white or light gray,

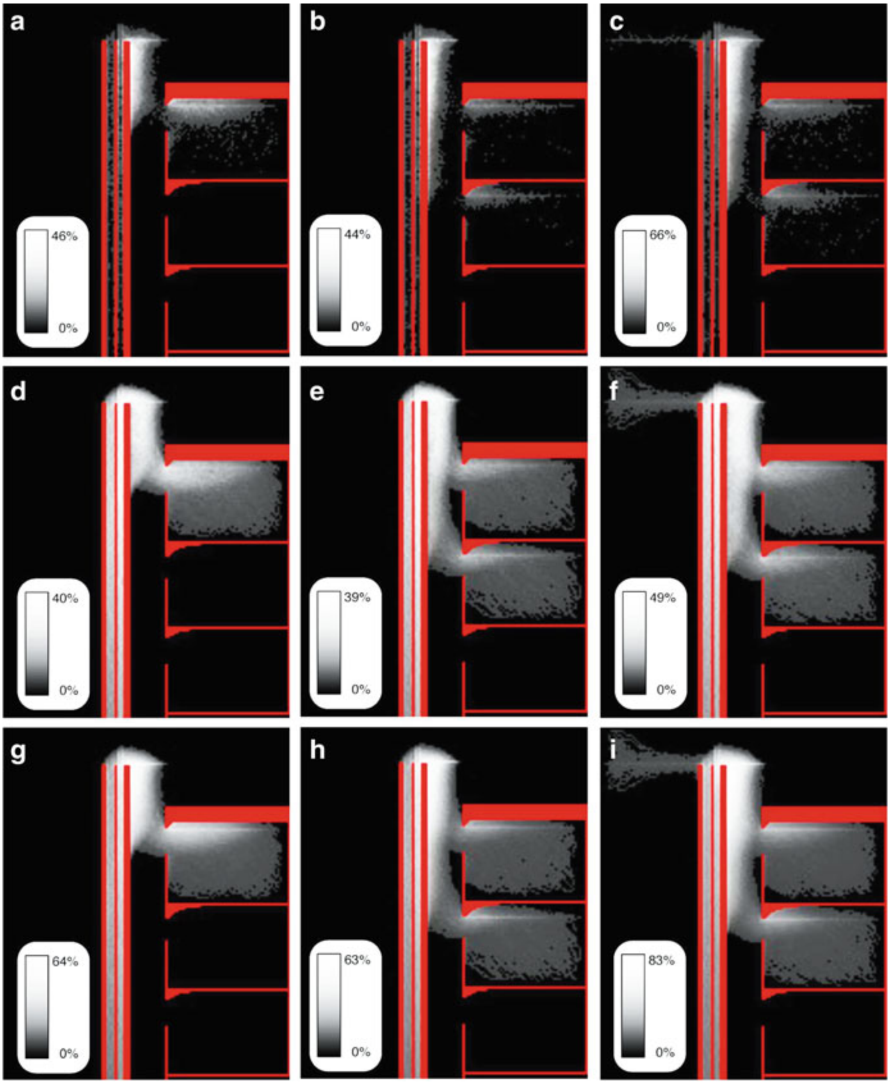

Fig. 5.5 Space utilization diagrams related to the three alternative simulated scenarios in the same area, including a ramp (on the *left*) and three waiting boxes (on the *right*). The different columns depict three space utilization metrics (described in the text) respectively in case of (i) a single group entering the station from one waiting box, (ii) two groups simultaneously approaching the ramp from two waiting boxes and (iii) two groups moving towards the station from waiting boxes and another one directly from the tents area. (**a**) One waiting box – block situations. (**b**) Two waiting boxes – blocks situations. (**c**) Two waiting boxes and external flow – block situation. (**d**) One waiting box – Flow from cell situation. (**e**) Two waiting boxes – flows from cell situation. (**f**) two waiting boxes and external flow – flow from cell situations. (**g**) One waiting box – total space utilization. (**h**) Two waiting boxes – total space utilization. (**i**) Two waiting boxes and external flow – total space utilization

while the space of the waiting area from which the second group starts is black in the first column, since the group is not present in the related situation and therefore that portion of space is not actually utilized.

The different columns depict three space utilization metrics respectively in case of (i) a single group entering the station from one waiting box, (ii) two groups simultaneously approaching the ramp from two waiting boxes and (iii) two groups moving towards the station from waiting boxes and another one directly from the tents area. The difference between the first and second scenario is not apparent in terms of different values for the maximum space utilization metrics (they are actually slightly lower in the second scenario), but the area characterized by a medium-high space utilization is actually wider in the second case. The third scenario is instead characterized by a noticeably worse performance not only from the perspective of the size of the area characterized by a medium-high space utilization, but also from the perspective of the highest value of space utilization. In particular, in the most utilized cell of the third scenario, an agent was stuck about 66% of the simulated time, compared to the 46 and 44% of the first and second scenarios.

This analysis therefore confirms that increasing the number of pilgrims that are simultaneously allowed to move towards the ramp highly increases the number of cases in which their movement is blocked because of overcrowding. Also the utilization of space increases significantly and, in the third situation, the whole side of the ramp becomes essentially a queue of pilgrims waiting to move towards the ramp. Another phenomenon that was not highlighted by the above diagrams is the fact that groups face a high pressure to mix when reaching the entrance of the ramp, which is a negative factor since crowd management procedures adopted in the scenario are based on the principle of preserving group cohesion and keeping different groups separated. According to these results, the management of the movement of group of pilgrims from the tents area to the ramps should try to avoid exceptions to the waiting box principle as much as possible.

5.7 Opportunities and Challenges for Crowd Analysis Methods

A comprehensive framework trying to put together different aspects and aims of pedestrians and crowd dynamics research has been defined in [28]. The central element of this schema is the mutually influencing (and possibly motivating) relationship between the above mentioned efforts aimed at synthesizing crowd behavior and other approaches that are instead aimed at analyzing field data about pedestrians and crowds in order to characterize it different ways. It must be noted, in fact, that some approaches have the goal of producing aggregate level quantities (e.g. people counting, density estimation), while others are aimed at producing finer-grained results (i.e. tracking people in scenes) and other ones are instead aimed at identifying some specific behavior in the scene (e.g. main directions, velocities, unusual events). The different approaches adopt different techniques, some performing a *pixel–level analysis*, others considering larger patches of the image, i.e. *texture–level analysis*; other techniques require instead the detection of proper objects in the scene, a real *object–level analysis*.

From the perspective of the requirements for the synthesis of quantitatively realistic pedestrian and crowd behavior, it must be stressed that both aggregate level quantities and granular data are of general interest: a very important way to characterize a simulated scenario is represented by the previously mentioned fundamental diagram [46], that is, the relationship in a given scenario between the flow of pedestrians in a section and their density. Qualitatively, a good model should be able to reproduce an empirically observed phenomenon characterized by the growth of the flow until a certain density value (also said *critical density*) is reached; then the flow should decrease. However, every specific situation is characterized by a different shape of this curve, the position of critical density point and the maximum flow level; therefore even relatively "basic" counting and density estimation techniques can provide useful information in case of observations in real world scenarios. Density estimation approaches can also help in evaluating qualitatively the patterns of space utilization generated by simulation models against real data. Tracking techniques instead can be adopted to support the estimation of travelling times (and length of the followed path) by pedestrians. Crowd behavior understanding techniques can help in determining main directions and the related velocities. In this perspective, some relevant and fruitful experiences can already be mentioned: in [41] the authors are able to essentially derive guidance fields, that is, significant elements of the modeling approach managing goal driven tendencies of pedestrian agents directly from video footage. In [19] an anticipative system integrating computer vision techniques and pedestrian simulation is used to suggest crowd management solutions (e.g. guidance signals) to avoid congestion situations in evacuation processes. In [31] a pedestrian model is instead exploited to improve the performance of a multiple–people tracker in semi–crowded conditions. Finally, in [43] the authors propose to employ the social force model to support the detection of abnormal crowd behavior in video sequences.

It is important to emphasize that anthropological considerations about human behavior [23] are growingly considered as crucial both in the computerized analysis of crowds [28] and in the synthesis of believable pedestrian and crowd behavior [32, 51]. They can also represent a useful source of considerations on the analyzed phenomenon and they can guide some relevant modeling choices.

One of the currently least investigated pathways in this articulated research context is characterized by new requirements coming from novel research questions that were defined in the area of synthesis of pedestrians and crowd behavior. In particular, we think that the first results in the modeling of the implications of groups of pedestrians in larger crowds, supported by empirical observations possibly deriving from the manual analysis of video footages of ad hoc experiments, can lead to the identification of patterns, particular shapes and morphologies, recurrent situations, that can represent a form of *contextual information* from which automated computer vision techniques can benefit [21]. The automatic identification, tracking and characterization of groups (e.g. shapes, estimation of the number of members) by means of computer vision techniques could lead, in turn, to a substantial improvement of the possibility to effectively calibrate and validate pedestrian models considering groups in challenging innovative scenarios.

5.8 Conclusions and Future Work

The chapter has introduced a recent and current trend of research in the modeling, simulation and visual analysis of pedestrians and crowds, that is, the study of the impact of groups on the overall crowd dynamics, and its implications of the aforementioned research activities as well as their outcomes. The chapter has described some relevant influential contributions from anthropological and sociological disciplines, and it has presented a brief state of the art of pedestrians and crowd modeling and simulation. An effort aimed at modeling crowds in terms of groups has been introduced and its results in an experimental and a real-world scenario have been discussed. Finally, the opportunities arising from a more systematic interaction between the efforts aimed at synthesizing and analyzing pedestrians and crowd behaviors have been discussed. Future works in this framework are naturally aimed at extending the modeling approach to allow the representation of more composite forms of groups and extending the range of analyzed scenarios with a validation against empirical data.

Acknowledgements This work is a result of the Crystal Project, funded by the Center of Research Excellence in Hajj and Omrah (Hajjcore), Umm Al-Qura University, Makkah, Saudi Arabia. Our acknowledgement for the common work in the project and for fruitful discussions goes to Katsuhiro Nishinari (RCAST – Research Center for Advanced Science and Technology, The University of Tokyo, Japan), our valuable partner within the Crystals Project. We also thank Ugo Fabietti (CREAM – University of Milano-Bicocca) for his contribution from the area of Anthropology.

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