An Agent-Based Pedestrian and Group Dynamics Model Applied to Experimental and Real World Scenarios

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Abstract

Pedestrian simulation is a consolidated area of application in which agent-based models are often employed: successful case studies are described in the literature and commercial, off-the-shelf simulators are commonly employed by decision makers and consultancy companies. Most state of the art models, however, generally do not consider the explicit representation of pedestrians aggregations (groups) and their implications on the overall system dynamics. This work is aimed at discussing the relevance and significance of this research effort with respect to the need of empirical data about the implication of the presence of groups of pedestrians in different situations (e.g. changing density, spatial configurations of the environment). The paper describes an agent-based model encompassing both traditional individual motivations (i.e. tendency to stay away from other pedestrians while moving towards the goal) and a simplified mechanism considering the cohesion effects related to the presence of groups in the crowd. The model is tested in a simple scenario to evaluate the implications of some modelling choices and the presence of groups in the simulated scenario. Moreover, the model is applied in a real world scenario characterised by the presence of organised groups as an instrument for crowd management. Results are discussed and compared to experimental observations and to data available in the literature.

1 Introduction

Agent–based approaches to the simulation of complex systems represent a relatively recent (considering earlier simulation approaches adopting, for instance,

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[1] The present work is a revised and extended version of a paper presented in the context of the 7th International Workshop on Agents in Traffic and Transportation (ATT 2012). This work is a result of the Crystal Project, funded by the Centre of Research Excellence in Hajj and Omrah (Hajjcore), Umm Al-Qura University, Makkah, Saudi Arabia.

physical models or operational research) but extremely successful application area of concepts, abstractions and models defined in the area of autonomous agents and multi–agent systems (MAS), as discussed by Bandini et al. (2009). Results of this area have been adopted to model complex systems in very different contexts, ranging from social and economical simulation to logistics optimisation, from biological systems to traffic. Crowds of pedestrians represent a typical example of complex system: the overall behaviour of a crowd can only be defined in terms of the actions of the individuals that compose it, and the decisions of the individuals are influenced by the previous actions of other pedestrians sharing the same space. The interaction patterns are sometimes *competitive*: pedestrians might have conflicting goals, since they often wish to occupy the same spot of the shared environment (e.g. the entrance/exit from a subway station). On the other hand *collaborative* patterns can also be identified (e.g. leave room to people getting off a subway train before getting on). The overall system is characterised by self-organisation mechanisms and emergent phenomena.

Despite the complexity of the studied phenomenon, the relevance of human behaviour, and especially of the movements of pedestrians, in built environment in normal and extraordinary situations, and its impact on the activities of architects, designers and urban planners are apparent (see, e.g., Batty, 2001). This relevance is even more evident considering dramatic episodes such as terrorist attacks, riots and fires, but also considering the global trend of urbanisation and the growing issues in facing the organisation and management of public events (ceremonies, races, carnivals, concerts, parties/social gatherings, and so on) and in designing naturally crowded places (e.g. stations, arenas, airports). Computer models for the simulation of crowds are thus growingly investigated in the scientific context, and these efforts led to the implementation of commercial off-the-shelf simulators often adopted by firms and decision makers[2]. Models and simulators have proved their usefulness in supporting architectural designers and urban planners in their decisions by creating the possibility to envision the behaviour of crowds of pedestrians in specific actual environments and planned designs, to elaborate what-if scenarios and evaluate their decisions with reference to specific metrics and criteria. Despite the substantial amount of research efforts this area is still quite lively and we are far from a complete understanding of the complex phenomena related to crowds of pedestrians in the environment: one of the least studied and understood aspects of crowds of pedestrians is represented by the implications of the presence of groups (Challenger et al., 2009). In particular, little work in the direction of modelling and simulating relatively large groups within a crowd of pedestrians encompassing some form of validation (either quantitative or qualitative) against real data can be found in the literature.

This work is set in the context of the Crystals project[3], a joint research effort between the Complex Systems and Artificial Intelligence Research Center of the University of Milano–Bicocca, the Centre of Research Excellence in Hajj and Omrah and the Research Center for Advanced Science and Technology of the University of Tokyo. The main focus of the project is on the adoption of an agent-based pedestrian and crowd modelling approach to investigate the impact of the

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[2] see `http://www.evacmod.net/?q=node/5` for a significant although not necessarily comprehensive list of simulation platforms.

[3] `http://www.csai.disco.unimib.it/CSAI/CRYSTALS/`

contributions of anthropology, cultural characteristics and existing results on the research on crowd dynamics, and how the presence of heterogeneous groups influence emergent dynamics in the context of the Hajj and Omrah. As previously mentioned, implications of particular relationships among pedestrians in a crowd are generally not considered or treated in a very simplistic way by current approaches. In the specific context of the Hajj, the yearly pilgrimage to Mecca that involves over 2 millions of people coming from over 150 countries, the presence of groups (possibly characterised by an internal structure) and the cultural differences among pedestrians represent two fundamental features of the reference scenario. Studying implications of these basic features is the main aim of the Crystals project.

This work presents motivations, fundamental research questions and directions, and current results of an agent–based modelling and simulation approach to the multidisciplinary investigation of the complex dynamics that characterise aggregations of pedestrians and crowds. In particular, in this paper we will present an agent–based model of pedestrians considering groups as a first–class abstraction influencing the behaviour of its members and, in turn, of the whole system. The model has been tested (i) in a schematic situation that has also been analysed by means of field experiments to characterise the implications of groups in the overall pedestrian dynamics and (ii) in a real world scenario in which pedestrians were organised in large groups for sake of crowd management.

The paper breaks down as follows: the following section will set the present work in the state of the art of pedestrian and crowd modelling and simulation, with specific reference to recent works focusing on the modelling and implications of groups. Section 3 will introduce the model that was adopted in an experimental scenario, described in section 4, and in a real world scenario, described in section 5. The scenarios will be described and the achieved results will be discussed. Conclusions and future developments will end the paper.

2 Related Works

A comprehensive and, at the same time, concise overview of the different approaches and models for the simulation of pedestrian and crowd dynamics is not easily defined: entire scientific interdisciplinary workshops and conferences are in fact specifically devoted to this topic (see, e.g., the proceedings of the first edition of the International Conference on Pedestrian and Evacuation Dynamics edited by Schreckenberg and Sharma, 2001, and consider that this event has reached the sixth edition in 2012). A possible schema to classify the different approaches is based on the way pedestrians are represented and managed. From this perspective, pedestrian models can be roughly classified into three main categories that respectively consider pedestrians as *particles subject to forces*, particular *states of cells* in which the environment is subdivided in Cellular Automata (CA) approaches, or *autonomous agents* acting and interacting in an environment. While the differences between particle based models and CA are apparent and mainly related to the representation of time and space, that is continuous in the former and discrete in the latter, boundaries between these categories and agent-based models are more fuzzy. In fact, some agent-based model employ a continuos spatial representation and therefore they actually adopt mechanisms defined by particle based approaches; the main difference, however, is that in agent-based models the laws of motion are internalised by agents in their own behavioural specifications, whereas in particle based approaches agents are essentially passive in nature and managed by the simulation environment (Klügl et al., 2004). Similarly, some agent-based approaches adopting a discrete spatial representation borrow techniques from CA models, but they provide a clearer separation between the environment and the active entities situated in it.

The most successful particle based approach is represented by the *social force model* by Helbing and Molnar (1995), which implicitly comprises fundamental proxemic (Hall, 1966) concepts like the tendency of a pedestrian to stay away from other ones while moving towards his/her goal. Proxemics essentially represents a fundamental assumption of most modelling approaches, although very few authors actually mention this anthropological theory (in particular, Was, 2010 and Manenti et al., 2010).

CA based approaches can be roughly classified in ad-hoc approaches for specific situations (like the case of bidirectional flows at intersections described in Blue and Adler, 1999) and general approaches, whose main representative is the floor-field approach by Schadschneider et al. (2002) in which the cells are endowed with a discretised gradient guiding pedestrians towards potential destinations.

While particle and CA based approaches are mostly aimed at generating quantitative results about pedestrian and crowd movement, agent based approaches are sometimes aimed at the generation of effective visualisations of believable crowd dynamics, and therefore the above approaches do not necessarily share the same notion of realism and validation. Works like the one by Bandini et al. (2004) and by Henein and White (2005) essentially extend CA approaches, separating the pedestrians from the environment, but they essentially adopt similar methodologies. Other approaches like those described by Musse and Thalmann (2001) and by Shao and Terzopoulos (2007) are more aimed at generating visually effective and believable pedestrians and crowds in virtual worlds. Other approaches, like the one by Paris and Donikian (2009), employ cognitive agent models for different goals, but they are not generally aimed at making predictions about pedestrian movement for sake of decision support.

A small number of recent works represent a relevant effort towards the modelling of groups, respectively in particle-based (in particular, by Moussaïd et al., 2009, and by Xu and Duh, 2010, that extend the social force model and Singh et al., 2009, that defines ad-hoc social rules later discretised in a discrete element model), in CA-based by Sarmady et al. (2009)(with ad-hoc approaches) and in agent-based approaches (in particular by Qiu and Hu, 2010, Rodrigues et al., 2010, Tsai et al., 2011, and Manzoni et al., 2011) (introducing specific behavioural rules for managing group oriented behaviours): in all these approaches, groups are modelled by means of additional contributions to the overall pedestrian behaviour representing the tendency to stay close to other group members. However, the above approaches only mostly deal with small groups in relatively low density conditions; those dealing with relatively large groups (tens of pedestrians) were not validated against real data. The last point is a crucial and critical element of this kind of research effort: computational models represent a way to formally and precisely define a computable form of theory of pedestrian and crowd dynamics. However, these theories must be validated employing field data, acquired by means of experiments and observations of the modelled phenomena, before the models can actually be used for sake of prediction.

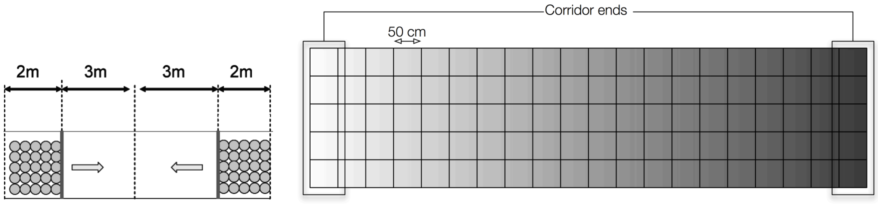

Figure 1: Schematic representation of a simple scenario: a 2.5 by 10 m corridor, with exits on the short ends and two sets of 25 pedestrians. The discretisation of 50 cm and the floor-field directing towards the right end is shown on the right.

3 GA-PED Model

We will now briefly introduce the Group Aware Pedestrian model (GA-PED) based on simple reactive situated agents based on some fundamental features of CA approaches to pedestrian and crowd modelling 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 Bandini et al. (2011).

3.1 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 discretisation 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 6.25 and 4.0 pedestrian per square meter. The choice of the scale of discretisation also influences the length of the simulation turn: the average speed of a pedestrian can be set at about 1.5 meters per second (see, e.g., as discussed by Willis et al., 2004) therefore, assuming that a pedestrian can perform a single movement between a cell and an adjacent one (according to the Moore neighbourhood), the duration of a simulation turn is about 0.33 seconds in case of a 50 cm discretisation and 0.27 in case of a finer 40 cm discretisation.

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 Schadschneider et al. (2002). 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.1 in which a simple scenario and the relative floor-field representation are shown). The GA-Ped 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* (like in Nishinari et al., 2004), in our model are managed through the agent perception model.

3.2 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 generated every turn: this agent activation strategy, also called *shuffled sequential updating* by Klüpfl (2003), is characterised by the fact that conflicts between pedestrians are prevented. In crowd simulation CA models, parallel update is generally preferred , as discussed by Schadschneider et al. (2009), even if this strategy can lead to conflicts that must be solved. Some works, like Kirchner et al. (2003), claim even that simulations are more realistic if the conflicts that arise are not solved, but to prevent the movement of all pedestrians involved in a conflict with a certain probability. When employing sequential updates the order of each move becomes unrealistically important, since as each entity moves, the next entity re-positions in relation to the previous entity. Thus, the first entity would act the position of all entities over the whole lattice.

Nonetheless, we chose to investigate the effects of allowing the possibility of this form of micro coordinated movements and therefore we adopted a shuffled sequential update scheme for the activation of agent behaviours according to the fact that one of the elements involved in the prediction of movement is the previous position of the pedestrian in the environment and that conflicts may be represented by proxemic separation, rather than space exclusion.

Pedestrians are characterised by basic 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 characterised by a *schedule*, in terms of a sequence of floor-fields and therefore intermediate destinations to be reached.

The behaviour 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 environment sequentially wakes up (in a random order) 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 Moore neighbourhood. 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, a level of desirability, 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 utility of a cell $c_{x,y}$ is defined as:

$$li(c_{x,y}, g, t) = w_t \cdot goal(t, (x, y)) + w_g \cdot group(g, (x, y)) - w_o \cdot obs(x, y) \\ - w_s \cdot others(g, (x, y)) + \varepsilon$$

where the function obs counts the number of obstacles in the Moore neighbourhood 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, after a sort of lottery among possible movements. This means that for a pedestrian generally there is a higher probability of moving towards his/her destination and according to proxemic considerations, but also that a step back (i.e. away from the goal) or the choice to move far from his/her group are still possible. Although this may lead to trajectories that in specific situations present single movements that appear as erratic it also makes floor-field model more robust and precise in the reproduction of observed pedestrian dynamics in medium/high density situations (see, e.g., Kirchner et al., 2003, or Schadschneider et al., 2009). In this work, we decided to include a small random factor to the utility of each cell and to choose directly and deterministically the movement that maximises 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 paper and it is object of future works.

4 Experimental Scenario

The GA-Ped model was adopted to conduct 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.

4.1 Experiments

The environment in which the experiments took place is represented in Fig. 1: a 2.5 by 10 m corridor, with exits on the short ends. The experiments were characterised by the presence of two sets of 25 pedestrians, respectively starting at the two 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). Two photos of the experiments to give an idea of the level of density in the related situation is shown in Figure 2.

Figure 2: Experiments on facing groups: several experiments were conducted on real pedestrian dynamics, 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.

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 (3 experiments); (ii) 3 couples of pedestrians for each direction (2 experiments); (iii) 2 triples of pedestrians for each direction (3 experiments); (iv) a group of six pedestrians for each direction (4 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 seconds while the average completion time over 12 experiments is about 15 seconds.

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 modelled in Moussaïd et al. (2009), and this caused a total travel times that were higher than average in two of the three experiments involving this type of group.

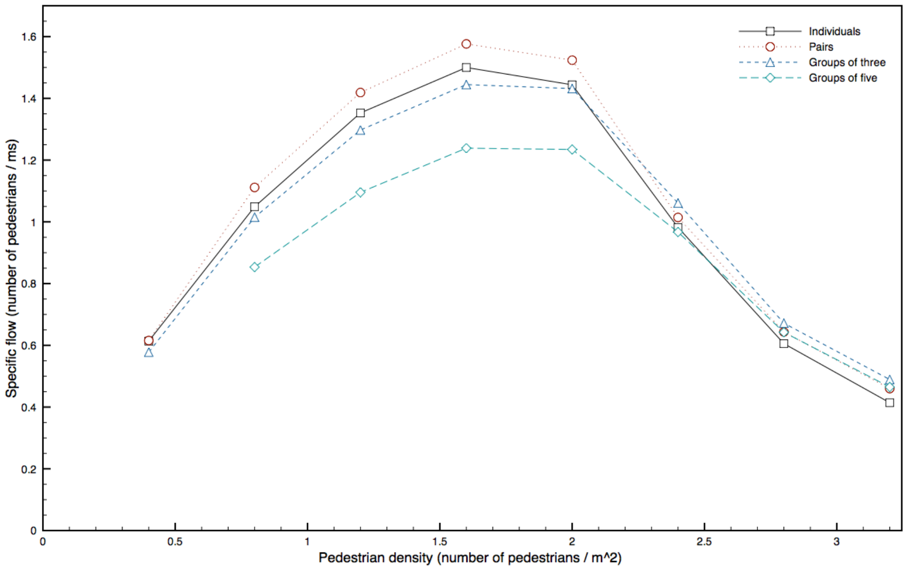

Figure 3: Fundamental diagram comprising simulations of the corridor scenario with a counterflow; in different densities, alternative configurations of the pedestrian populations were tested to evaluate the impact related to the presence of groups of different size in the simulated scenario.

4.2 Simulation Results

We applied the model described in Sect. 3 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 Bonomi et al. (2011). 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, with a growing level of density. 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 behaviour).

We investigated the capability of our model to fit the fundamental diagram proposed in the literature for characterising pedestrian simulations, as discussed by Schadschneider et al. (2009), 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 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 figure 3 is related to at least 1 hour 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, separating a regime of free flow from jam situations. If the system density is increased beyond that value, the flow begins to decrease significantly as the friction between pedestrians makes movements more difficult. The achieved diagram is in good agreement with design manuals (see, e.g., Weidmann, 1993) and empirical observations (such as Mori and Tsukaguchi, 1987).

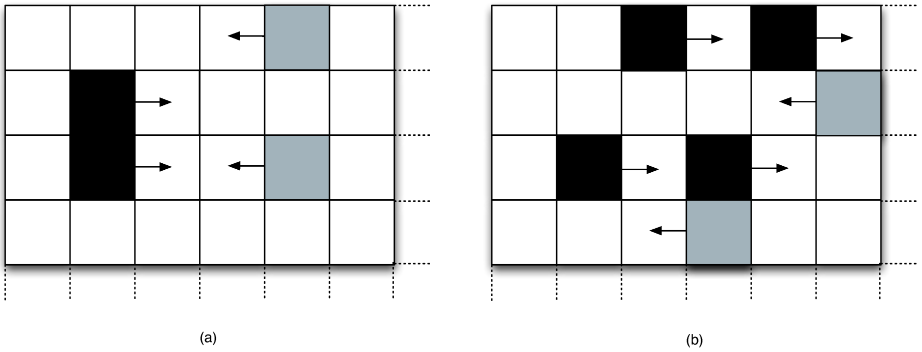

Figure 4: In the left figure, the black pedestrians have not formed a line and they offer a larger profile to the counter flow. In the right figure, they formed a line and the follower has a lower probability to find an opposing pedestrian due to the presence of a sort of "emergent" leader.

The simulation results are also in tune with the experimental data coming from the experiments: although the latter were only performed with a specific density (i.e. two pedestrians per square metre) and therefore they cannot represent a way to provide a complete validation of the simulation results, they indicated that the presence of groups is beneficial for the overall pedestrian flow. In our simulations, 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. 4b. 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. 4a: the points related to groups of three and five members are below those associated to 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.

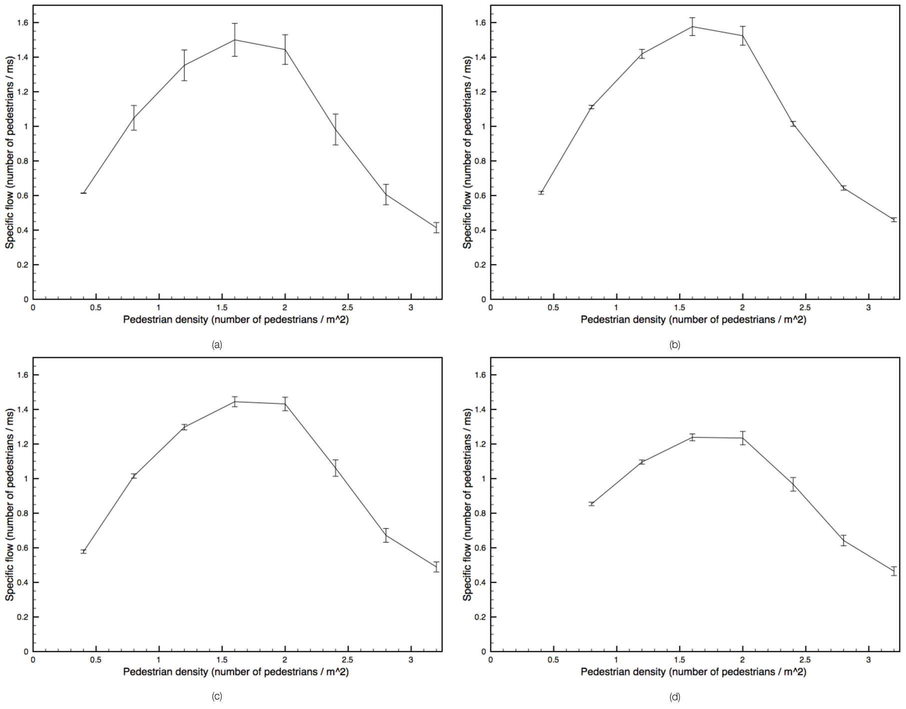

Figure 5: Fundamental diagrams including error bars (related to the standard deviation of the flow) related to different types of groups in the corridor simulation, respectively (a) individuals, (b) pairs, (c) groups of three and (d) groups of five.

Groups, in the model, act therefore as an element adding order and stability, facilitating the formation of lanes and allowing their members to move in a more uniform way. This is also apparent when considering the standard deviation of the flow of different categories of pedestrians, as shown in Fig. 5: individuals have the higher standard deviation in all density situations, being therefore able to quickly and smoothly move throughout the corridor in certain situations but also remaining stuck in jams in other cases. Groups, on the other hand, sometimes move slower but the variability of their speed, given a certain level of density, is quite low. A consideration that is valid both for groups and individuals, on the other hand, is the fact that the highest variability is generally reached when the density is close to the above mentioned critical value: in other words, in free flow situations and in severely congested situations the speed variability is low, since in the former case most pedestrians are almost always able to move and, in the latter, most of them are blocked most of the time.

An additional consideration that we can make is that this mechanism for introducing a group cohesion component in agents' behaviours is not sufficiently strong to avoid a dispersion of the group in cases of relatively high local densities. Similarly as for a related modelling effort described in Bandini et al. (2011), the simple cohesion component is simply not sufficient to force a group member to wait for other members that were blocked due to conflicts with the opposing pedestrian flow. The definition of different mechanisms able, on one hand, to generate this kind of phenomenon and, at the same time, preserving the overall plausible dynamical properties of the model, such as the fundamental diagram, implies some form of adaptation, potentially reducing the tendency to move towards the goal in order to preserve the cohesion of the group. One of the previously cited models defining specific mechanisms for the representation of group influence on overall crowd dynamics by Singh et al. (2009) is actually able to reproduce some forms of adaptive group behaviour, according to a qualitative validation employing field data about low density situations. In this model, subgroups into which a large group can be subdivided due to contextual factors, set up a common intermediate aim point in order to regroup. An extension of the present model described in Vizzari et al. (2013), instead, is characterised by the possibility of dynamically adjusting the model parameters according to the level of dispersion of a group in order to reduce the influence of (individual) goal orientation and to boost the importance of the group cohesion behavioural component. Results on this line of work are promising but they require additional empirical data on the modelled phenomenon for a complete validation.

5 Real World Scenario

5.1 Environment and observations

The agent–based pedestrian and group dynamics model was also adopted to elaborate different what-if scenarios in a real world case study. In particular, the simulated scenario is characterised 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 involves over 2 millions of people coming from over 150 countries and some of its phases, in fact, often imply 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 takes place after the sunset of the second day of the pilgrimage, and it involves the movement 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 area to the station in an organised flow that should be in tune with the movement of trains between the stations of Arafat and Muzdalifah. The ritual prescribes pilgrims to leave the Arafat area before midnight, therefore the trains must continuously allow pilgrims to get on at Arafat, carry them to Muzdalifah, and come back empty to transport other pilgrims.

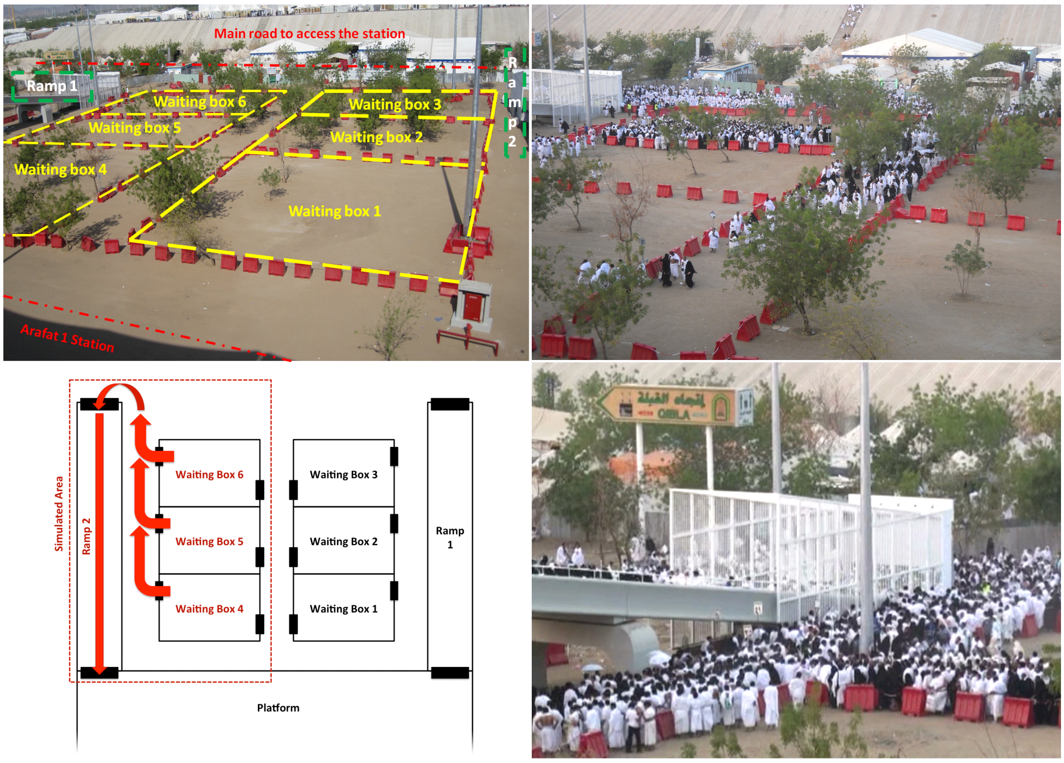

Figure 6: Photos and a schematic representation of the Arafat I station and the related planned flows of pilgrims.

Each train is made up of 12 wagons, each able to carry 250 passengers for a total of approximately 3000 persons. In accordance to safety engineering best practices, 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. Nonetheless, the flow of pilgrims towards the platforms must be managed in order to avoid congestions, both in the platform and also in other areas near the station.

In order to achieve an organised 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 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 for an authorisation 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 Arafat I station and the related phenomena are shown in figure 6: 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. In particular, two groups from waiting areas were simultaneously allowed to move towards the ramp and also another group (from the tents area) went directly towards the ramp, 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. The situation din not imply any risk for the pilgrims but rather an higher than average waiting time and also an uncomfortable situation due to the high density of pedestrians.

5.2 Simulation Results

Different scenarios were analysed adopting the previously defined model and using the parameters that were employed in the previous case study in order to evaluate both different ways to organise and manage the flow of pilgrims and also the impact of a sample change in the geometry of the environment.

The first kind of comparison considered (i) the simultaneous flow of a group of pilgrims from two waiting boxes to the ramp and (ii) 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 utilisation when the waiting box principle was not respected.

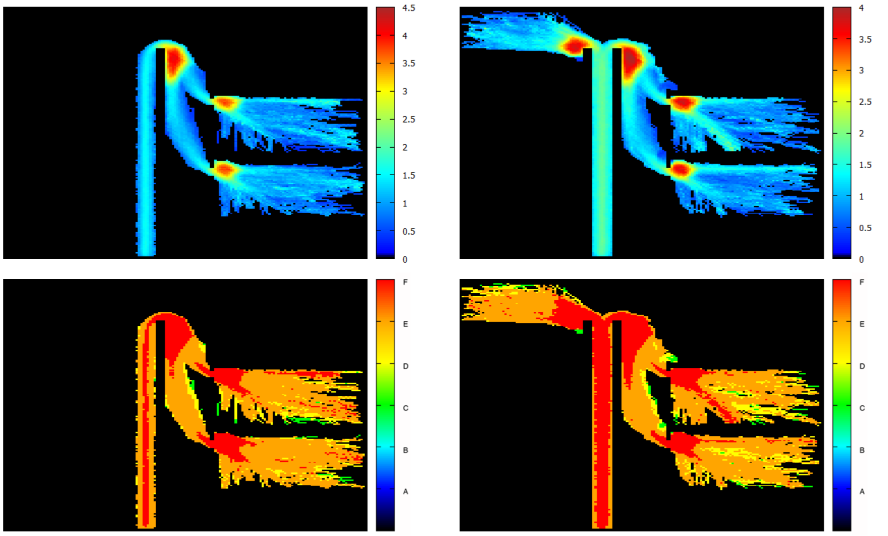

Figure 7: Cumulative Mean Density and Level of Service analyses in two different scenarios including respectively two (the figures on the left column) and three (the figures on the right column) groups simultaneously moving towards the ramp.

The environment was discretised adopting 50cm sided square 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 like in Kirchner and Schadschneider, 2002, corrected introducing a minor effect of repulsion generated by obstacles, as in Nishinari et al., 2004). 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 walk up 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 utilisation*. In particular, the first metric is called *cumulative mean density* (CMD) as discussed by Castle et al. (2011), a measure associated to a given position of the environment indicating the average density perceived by pedestrians that passed through that point. It is quite straightforward to compute this value in a discrete approach like the one described in this work. This kind of metric is tightly related to the so called *level of service* (LOS) by Fruin (1971), a similar measure discretising the average perceived density in a given point into intervals (denoted with letters from A to F in decreasing order of comfort). All these metrics are also naturally related to proxemics, since a low LOS (and high CMD) is related to a unpleasant perceived situation due to the invasion of the personal (or even intimate) space.

The diagrams shown in Figure 7 report these two metrics in the context of the situations characterised by respectively two (the figures on the left column) and three (the figures on the right column) groups simultaneously moving towards the ramp. The metrics are depicted graphically following the same approach: the background colour of the environment is black, which represents the fact that no pedestrian was present in the related cell in any turn of the simulation (in which the CMD is equal to 0 and in which traditionally the LOS value is not considered relevant), whereas each point associated to an area in which the CMD is higher than 0 (and the LOS value is relevant) is painted in a shade of grey according to the value of the metric in that specific point. The legend on the right part of each figure reports the scale of value of CMD (or LOS). The obstacles are not visible (since it is not possible for pedestrians to occupy the related cells), but the reader should be able to easily identify the scenario highlighted in the lower left part of Figure 6, and in particular the ramp and the areas associated to waiting boxes (visible both on the left and right columns), while on the flow associated to the group of pilgrims reaching the ramp directly from the tents area is only visible on the right column. It must be noted that technically inside the ramp a different scale for the computation of the LOS should be employed (since the movement in the ramp is lower it turns out to be essentially a sort of queue), but since we did not model a reduction of speed due to slope we decided to adopt the standard walkway scale.

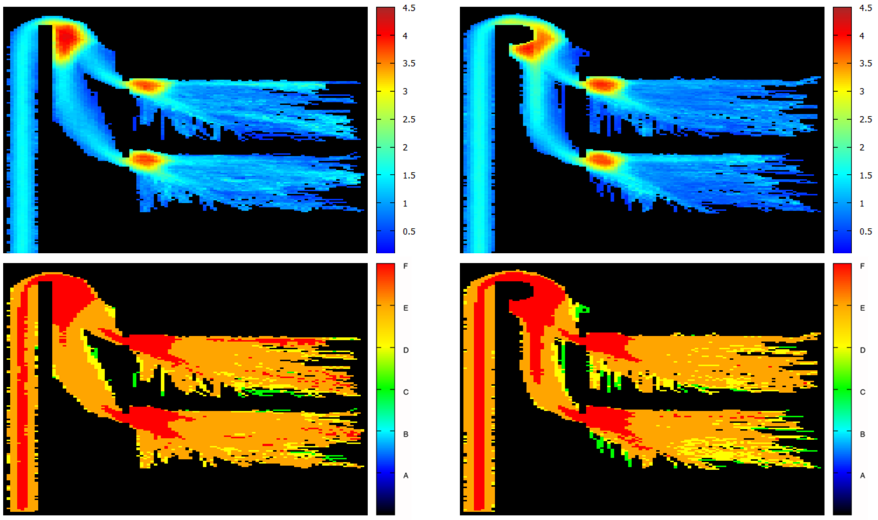

Figure 8: Cumulative Mean Density and Level of Service analyses in two different scenarios respectively representing the real geometry of the environment, on the left column, and a modified geometry including a round obstacle in the proximity of the corner leading towards the ramp, on the right.

This analysis confirms that increasing the number of pilgrims that are simultaneously allowed to move towards the ramp highly increases the CMD in a significant portion of the environment, decreasing the LOS: the area characterised by the F LOS level (the worst one) is significantly larger in the right column. In other words, not respecting the waiting box principle brings to unpleasant situations. 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 simultaneously, which is a negative point since crowd management procedures adopted in the scenario are based on the principle of preserving group cohesion and keeping different groups separated. From this perspective, it must be noticed that the adopted model for the management of group cohesion was able to reduce the actual mixing of members of different groups in the ramp, at least in case of simultaneous flow of two groups from the waiting boxes area. 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.

An additional comparison we carried out was aimed at considering the potential introduction of a modification to the basic geometry of the environment and its impact on the crowding dynamics. In particular, it is known that the introduction of an obstacle in specific situations lead to a counterintuitive effect of smoothening of pedestrian flows (see, e.g., Nishinari et al., 2008). Given the simple possibility to perform an *in–silico* experiment, we simply added a round obstacle making it impossible for pedestrians to move directly towards the corner of the ramp and run a set of additional simulations. The results in terms of impact on the CMD and LOS in the scenario considering the simultaneous arrival of two groups from the waiting boxes are shown in Figure 8, where the left column depicts the real geometry and the right one includes the round obstacle: while in the previous comparison the evaluation of which scenario (and therefore crowd management procedure), in this case the different configurations of the environment do not lead to such a striking difference in the results. Nevertheless, looking at the numerical data that generate this representation, it is possible to detect the fact that the scenario including the round obstacle is characterised by a lower maximum level of CMD that, in the scenario not comprising the obstacle, is reached in the proximity of the corner of the ramp. Moreover, the LOS in the ramp in the obstacle scenario is more uniformly F and this suggests that the flow is more consistent and regular before reaching the ramp. The fact that a modification in the geometry of the simulated environment causing an improvement in one point of the scenario may cause a problem in another one is actually in tune with previous empirical simulation results by Ezaki et al. (2012). Finally, even though the absolute finishing time is not a significant measure, due to above introduced reasons, it must be noted that pedestrians are generally able to complete the obstacle scenario in less time compared to the real scenario (a difference of about 3% of the total duration time). The influence of the addition of a simple obstacle is therefore slightly beneficial even in this case, although the effect is not so significant and therefore should be carefully evaluated.

6 Conclusions and Future Developments

The paper has discussed a research effort aimed at investigating the implication of the presence of groups in pedestrian and crowd dynamics. In particular, the paper has shown a sample situation in which data coming from experimental observations were used to calibrate and validate a simulation model that correctly captures some aspects of the impact of groups in the overall system dynamics. The validation was performed considering both travel times and other data gathered in actual experiments and also by comparing the achieved fundamental diagram with existing results from the literature. In addition, a real-world case study was also described: this work considered a train station in which different policies for crowd management and different geometries of the environment were compared adopting space utilisation metrics. The achieved results are in tune with observations carried out on the field and the model is able to reproduce phenomena related to group behaviours in pedestrian simulation. We also shown that the model is a viable way to qualitatively compare alternative scenarios in terms of geometry of the environment.

Future works are aimed at modelling and simulating more complex group cohesion mechanisms (essentially able to preserve group cohesion even in high density situations), but also more complex group organisation, such as hierarchical group structures (e.g. families, friends, elderly with accompanying persons inside larger groups) and their implications on overall system dynamics, validating results both quantitatively and qualitatively with specific reference to the morphology assumed by the group in medium and high density situations. Additional empirical data from controlled experiments or observations are needed to actually validate the innovative group related elements of the model and this is necessary to be able to evaluate comparisons on the impact of groups on the relevant outputs of simulation models, like travel times and space utilisation metrics.

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