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AGENT-BASED PROXEMIC DYNAMICS: CROWD AND GROUPS SIMULATION

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Ph.D. Thesis

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1 Introduction

I do not aim with my hand;
He who aims with his hand has forgotten the face of his father.
I aim with my eye.
I do not shoot with my hand;
He who shoots with his hand has forgotten the face of his father.
I shoot with my mind.

Roland Deschain

Starting from the pioneering work of Schelling (1971) and passing through Epstein and Axtell (1996), the use of *computer simulations* for social sciences was widely used from 1990s, but from the beginning its capability in modeling and understanding social processes came out introducing the new idea about the emergence of complex behaviors from relatively simple activities (Simon, 1996).

It is not the aim of this section neither to discuss computer simulation in social sciences and to give a comprehensive presentation of epistemologic issues, motivations and background of this kind of research effort, but rather to introduce a schema in which better set the current thesis and its main contributions.

In particular, simulation can be seen as a particular type of modeling (Gilbert and Troitzsch, 2005), a way to understand phenomena from real-world which we are interested in reproducing. Every phenomenon can be seen as a *target*, object of the study: the logic of simulation method starts from the definition of a model as abstraction with respect to the target. Despite the fact that model will be simpler than the target, it has to be able to reproduce its dynamics in terms of behavior and structure, dynamically changing over time and depending on the environment.

Figure 1.1 graphically represents the logic of simulation methodology: after the definition of the model (as computational tool rather than statistical equation system), this methodology is used to generate simulated data on the basis of which its behavior can be evaluated by a comparison with empirical data directly collected on the target. The scope is essentially to check if the model generates outcomes which are similar to the ones produced by the target.

We can identify three main steps (here presented in an atomic way, but usually requiring several middle passages) in building simulations: first, the *definition* of a model starting from an analysis of the target by means of experiments and observations is required. Then, a step of *building* model has to be performed providing both its (formal) specifications and its development in terms of computational programs, allowing the *verification* and the *validation* of the model based on a comparison among simulated data and real data on target. If the model is able to pass the validation process, it can be used to deepen the study on the target, understanding and predicting its behaviors in specific situations.

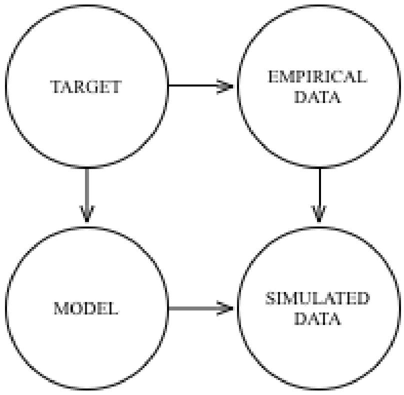

Figure 1.1: *Simulation as method*

This is, in general, the methodological approach to investigate complex real-world phenomena. Although there are some objections about the simplified level of correspondence between simulations and real phenomena (Axtell, 2000), the use of simulations as a method to study complex system from a different layer of abstraction is largely used in the analysis and for reproduction of complex systems. What are complex systems? According to Meyers and Kokol (2009), they are systems that comprise many interacting parts with the ability to generate a new quality of collective behavior through self-organization, evolving and containing self-driving feedback loops. They are often characterized as having extreme sensitivity to initial conditions as well as emergent behavior that are not readily predictable or even completely deterministic.

The dynamics of a *crowd and pedestrians* is a clear example of complex system, covering all the aspects state before: according to Challenger and M. (2009) a crowd can be defined as a gathering of at least 20 people, standing in close proximity at a specific location to observe a specific event, who feel united by a common social identity, and who are able to act in a socially coherent way. Starting from this assumption, it can be seen as a collection of several entities interact each others and with the environment, producing emergent behaviors that derived from local dynamics. In this research field, the methodology of modeling and simulation is applied as necessary to understand pedestrian behavior and to develop a model to study and predict the overall dynamics of a crowd from an analytic point of view focusing on pedestrians dynamics.

Today, gatherings of a large number of people can be found in several places and for several occasions. Very large events like sports events, musical events, cultural or religious events collect a lot of people in different environments and they usually take place in the cities. The organization of big events[1] is becoming a consolidated urban policy to promote and refurbish urban areas (Krantz and Schätzl (1997)). The scarcely predictable impact of the unexpected pedestrian flows makes difficult for organizers

[1] Properly named as "festivalization" of the city.

and authorities the design, the planning and the management of these events: serious safety issues have to be taken into account, in order to be prepared in case of emergency situations.

Furthermore, in the last years, a process of urbanization can be detected: in Desa (2012), data show that more than 70% of people live in the cities considering Europe, Oceania and the Americas, estimating an increasing of urbanization process in the next 20 years all over the world.

This context supports the growing need of tools and models, able to reproduce in a realistic way the pedestrian behavior, and to provide applicative results strictly linked with the management of large events, the design of public spaces and the improvement of living conditions of pedestrians in the city, also considering peculiar situations as aging population process. First proposals derived from Physics and Mathematics, modeling behavior of a crowd in terms of equation systems in which variables represented all the aspects influencing pedestrian movement. More recently, proposals belong to the area of Computer Science, in particular considering agent-base approach, have been proposed to face the modeling of pedestrian behavior, providing computational tools with a high-level of detail hardly achievable by physical approaches, particularly suitable to support designers and crowd managers in the development of simulations.

These computational models are thus growingly investigated in the scientific context, and these efforts led to the realization of commercial off-the-shelf simulators often adopted by firms and decision makers, showing their usefulness in supporting architectural designers and urban planners in their decisions by creating the possibility to envision the behavior of crowds of pedestrians in specific actual environments and planned designs and to elaborate what-if scenarios and evaluate their decisions with reference to specific metrics and criteria.

Despite the substantial amount of research efforts researchers are far from a complete understanding of the complex phenomena related to crowds of pedestrians in the environment: some main open issues in Pedestrian Dynamics community are highlighted as specific modeling requirements. From this point of view, theoretical studies and empirical evidences demonstrated that crowd is composed of pedestrian groups (Challenger and M., 2009; Rogsch et al., 2010; Peacock et al., 2011) rather than single and autonomous entities (the commonly used point of view). Few studies devoted to modeling groups of pedestrians and to collect empirical data on their behavior can be found in the literature and the majority of these proposals just focused on simple and little groups (from 2 to 4 members).

Considering the general overview here provided, this thesis is focused in the area of *pedestrian dynamics simulation*, with the goal to study the phenomenon of groups as constitutive elements that compose a crowd, analyzing if their presence influences the dynamics of pedestrian flow and evaluating the impact of their contribution. As methodology to ensure the scientific relevance of the work, we will refer to the above mentioned cycle in Fig. 1.1, starting from a model proposal related to basic pedestrian behavior and groups, and comparing and validating the model on empirical data according to the traditional methods recognized and commonly used in the literature. In the next section main contributions of this work with respect to the schema before presented will be discussed, followed by a summary of the contents of the thesis in Sec. 1.2 and relevant and selected publications in Sec. 1.3.

1.1 Contributions

The thesis presents contributions to different levels, starting with an investigation on the *phenomenon of groups of pedestrians*, by means of (i) an analysis on empirical and relevant observations in the literature, (ii) a multidisciplinary study including psychological and anthropological aspects and (iii) an analysis on current models that include group modeling aspects in the pedestrian dynamics area. All these analyses allowed an investigation on the target of the project, both in terms of pedestrian dynamics and group behavior, to support the building of a formal model as abstraction of the crowd as real-world phenomenon. Due to the complexity of the target (in terms of crowd of pedestrians), the application of a commonly employed methodology that works on macro phases[2], well-used to design agent-based systems, is not sufficient to guarantee a whole and complete representation of the investigated phenomenon. Reasons of this consideration are connected with the peculiarity of the target (what is an agent?) and the granularity level of the desired model. In this work I applied the methodology mentioned in Fig. 1.1, starting from already defined approaches in order to focus on group modeling, taking into account the necessity to systematically analyze and validate modeling results.

The definition of the model was composed of several processes: first, we conducted a study on *Proxemic theory*, and its application and formalization defining spatial relationships among pedestrians with respect to *inter and intra relationships* in groups, with the scope to provide a general (as much as possible) framework for modeling groups identifying the main elements necessary for their definition. On the basis of this first level of abstraction, we defined an innovative *agent-based model* for the representation of behavioral dynamics of pedestrians, explicitly including the concept of groups of pedestrians based on proxemic aspects.

The definition of the model also included the development of a computational tool with the scope to support the generation of simulated data to compare and validate the model against empirical data. In particular, we performed an analysis and an evaluation of the influence and the impact of the presence of groups on pedestrian flow dynamics, also focusing on the analysis within groups, with respect to the concept of *spatial group dispersion*. We obtained these evaluations with a comparison between simulated data and empirical and collected data on the phenomena (pedestrian dynamics and group

[2]i.e. identification of requirements, analysis, architectural design, implementation, testing (Wooldridge, 1997)

behavior), allowing the process of validation of the model.

Regarding the collection of data on the target, we performed a *data gathering activity* during an admission test in our University, adding *new sets of data and statistical information to the literature* related to the phenomenon of pedestrian groups.

1.2 Thesis Overview

A summary of the contents of this thesis is now provided.

In Chapter 2, thesis will start with an overview on different approaches for the pedestrian dynamics simulation, according to a set of features well-know in the literature, analyzing their differences and focusing on the microscopic modeling of individuals in Sec. 2.1. The necessity to investigate and to model related emergent phenomena such as groups of pedestrians will be pointed out in Sec. 2.2, with an analysis on group definition and their proxemic behavior, and a comparison among modeling proposals in the literature, in order to introduce in Sec. 2.3 the strategies we will use in the definition of our model.

Chapter 3 will be focused on the definition of a behavioral model just considering the main elements <*groups, agents, relationships*> necessary in modeling pedestrian groups, without taking into account other behavioral components, and being independent from time and space specification, in order to be general enough to be applied for every environment definition. First, in Sec. 3.1, the main elements will be formally defined to introduce an analysis of proxemic relationships among agents in Sec. 3.2. An expansion of the model to include the definition of structured group ends Chapter 3 along with some considerations about the generality of the model respectively in Sec. 3.3 and Sec. 3.4.

The complete computational agent-based model will be discussed in Chapter 4, based on a floor-filed approach, in which pedestrians are represented by means of agents rather than cells, in order to model heterogeneous and more complex behaviors. A complete explanation of a model for the analysis of the impact of groups on the overall dynamics of pedestrians is provided in Sec 4.1: in particular, the movement choice of pedestrians will be discussed with reference to all the behavioral components that concur in its definition. The model of pedestrian group will be deepen in Sec. 4.2, also considering structured groups, and providing a discussion related to a trade-off analysis between attractive elements. Chapter ends with an analysis of the limits of the approach in Sec. 4.3, an analysis of the requirements necessary to develop a tool based on this model in Sec. 4.4 and with some conclusions on used approach in Sec. 4.5.

In Chapter 5 the process of validation of the model is presented, first including a description of the methodology traditionally used in the validation step in the literature in Sec. 5.1. Several scenarios will be introduced for the evaluation of the model and to study the impact of the presence of groups and their inner spatial behavior on pedestrian flows, along with an evaluation of the capability of the model to reproduce reasonable and plausible pedestrian trajectories, focusing on the behavior of a bidirectional flow in Sec. 5.2. Chapter ends with a discussion on simulation results and on the capabilities to reproduce peculiar scenarios in Sec. 5.3.

In Chapter 6 a summary of thesis contributions will be further analyzed, along with possible extensions of the work, also considering other research fields such as computer vision for tracking of pedestrians and groups of pedestrians.

Other activities, parallel to the model presented in thesis but relevant to give a complete overview on the work here presented, will be proposed in the last part of the thesis: in Appendix A some details about the tool developed on the basis of the agent-based model in Chapter 4 and used for the validation process in Chapter 5 will be introduced, with an analysis of the software architecture in Sec. A.1. Then, in Sec. A.2 and A.3 the customization of the tool and the output of the simulation will be discussed, along with some conclusions about the capability of the tool (Sec. A.4).

Appendix B will be focused on a survey performed during an admission test at the University of Milano-Bicocca to collect data related to group behavior. The methodological framework used in the observation will be given in order to provide the context of the observation in Sec. B.1, followed by a full analysis of the collected data in Sec. B.2 and ending with a summary and a discussion on results of the analysis in Sec. B.3.

A real-world scenario in which the presented model was used will be presented in Appendix C, to perform an evaluation on pedestrian management strategies and on possible changes in the geometry of the environment in Sec. C.2, focusing on the analysis of entrance process in the station of Arafat I on Mashaer line in Saudia Arabia, in the context of CRYSTALS project C.3.

1.3 Selected and Relevant Publications

Contents of this thesis were published and presented in workshops and conferences relevant in the pedestrian dynamics and agent-based systems research fields (selected and relevant publications):

- Vizzari, G., Manenti, L., Ohtsuka, K., Shimura, K. (submitted): *An agent-based pedestrian and group dynamics model applied to experimental and real world scenarios*. Journal of Intelligent Transportation Systems;
- Bandini, S., Manenti, L., Mondini, M., Vizzari, G. (submitted): *Modeling Negative Interactions Among Pedestrians in High Density Situations*. Transportation Research Part C: Emerging Technologies;
- Federici, M. L., Gorrini, A., Manenti, L., and Vizzari, G. (2012 (in press)). *An innovative scenario for pedestrian data collection: the observation of an admission test at the university of Milano-Bicocca*. In Weidmann U., Kirsch U., Puffe, E. and Weidmann, M., editors, Pedestrian and Evacuation Dynamics;

- Manenti, L., Manzoni, S., Vizzari, G. and Dijkstra, J. (2012). *Towards Modeling Activity Scheduling in an Agent-based Model for Pedestrian Dynamics Simulation*. In De Paoli, F. and Vizzari, G., editors, WOA, volume 892 of CEURWorkshop Proceedings. CEUR-WS.org;
- Vizzari, G. and Manenti, L. (2012). *An agent-based model for pedestrian and group dynamics: experimental and real-world scenarios*. In van der Hoek, W., Padgham, L., Conitzer, V., andWinikoff, M., editors, AAMAS, pages 1341-1342. IFAAMAS.
- Federici, M. L., Gorrini, A., Manenti, L., and Vizzari, G. (2012). *Data collection for modeling and simulation: Case study at the University of Milan-Bicocca*. In Sirakoulis, G. C. and Bandini, S., editors, ACRI, volume 7495 of Lecture Notes in Computer Science, pages 699-708. Springer;
- Manenti, L., Manzoni, S., Vizzari, G., Ohtsuka, K., and Shimura, K. (2011). *An agent-based proxemic model for pedestrian and group dynamics: Motivations and first experiments*. In Villatoro, D., Sabater-Mir, J., and Sichman, J. S., editors, MABS, volume 7124 of Lecture Notes in Computer Science, pages 74-89. Springer;
- Bonomi, A., Manenti, L., Manzoni, S., and Vizzari, G. (2011). *Makksim: Dealing with pedestrian groups in mas-based crowd simulation*. In Fortino, G., Garro, A., Palopoli, L., Russo,W., and Spezzano, G., editors, WOA, volume 741 of CEUR-Workshop Proceedings, pages 166-170. CEUR-WS.org;
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- Bandini, S., Manenti, L., Manzoni, S., and Sartori, F. (2011). *A knowledge-based approach to crowd classification*. In Peacock, R. D., Kuligowski, E. D., and Averill, J. D., editors, Pedestrian and Evacuation Dynamics, pages 515-525. Springer US;
- Manenti, L., Manzoni, L., and Manzoni, S. (2010). *Towards an application of graph structure analysis to a mas-based model of proxemic distances in pedestrian systems*. In Omicini, A. and Viroli, M., editors, WOA, volume 621 of CEUR Workshop Proceedings. CEUR-WS.org;
- Lembo, P., Manenti, L., and Manzoni, S. (2010). *Towards patterns of comfort: A multi-layered model based on situated multi-agent systems*. In Bandini, S., Manzoni, S., Umeo, H., and Vizzari, G. editors, ACRI, volume 6350 of Lecture Notes in Computer Science, pages 439-445. Springer.

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[3] http://www.crowdyxity.com/

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

2 Pedestrian Dynamics Modeling

From the socio-psychological perspective the definition of crowd is still controversial, because of the lack of standard guidance for data collection. The empirical investigation of the phenomenon is further made difficult by ethical-practical reasons and its variability with respect to size and typology of the observed situation.

Early interest in studying crowd behavior started from the pioneering study of Gustave Le Bon (Le Bon (1897)) who defined a crowd as a potential threat to society: as members of a crowd people display an altered state of consciousness, with a consequent loss of sense of self-awareness, and an increase of irrational and violent behaviors. In complete opposition, the Elaborated Social Identity Model (Reicher, 2001) proposes a social-normative conception of collective behavior arguing that social norms continue to shape behavior of people also within the crowd, by means of the spontaneous transition from an individual identity to a common social identity (Turner, 1981).

Starting from these theoretical assumptions, the most currently accepted definition of crowd from Challenger and M. (2009) is:

> *A crowd can be defined as a gathering of 20 people (at least), standing in close proximity at a specific location to observe a specific event, who feel united by a common social identity, and who are able to act in a socially coherent way, despite being strangers in an ambiguous or unfamiliar situation.*

It is clear that the interaction between members is the basic element on which a crowd is built on: it is very important to understand how people live the environment around them, and the way in which they interact. For this reason, modeling crowd is analyzed following an analytic process, investigating pedestrian dynamics as emergent phenomenon starting from the definition of the local behavior. The latter is essentially based on two aspects: the *social attitude*, the way in which pedestrians interact each other, and the *achievement of the goal* that is the main reason that moves pedestrians within the crowd.

The aim of this Chapter is twofold: (i) to give an overview on different approaches for the pedestrian dynamics simulation, according to a set of features well-know in the literature, analyzing their differences and focusing on the microscopic modeling of individuals in a crowd (Sec. 2.1); (ii) to present some open issues in the field of pedestrian dynamics, focusing on the necessity to investigate and to model related emergent phenomena such as groups of pedestrians: a definition of the topic and an analysis of computational models including this concept will be presented, also from a multidisciplinary viewpoint (Sec. 2.2). Some remarks related to the current state of the art and what will be considered as starting points for this work ends the Chapter (Sec. 2.3).

2.1 General Overview on Pedestrian Dynamics Models

Despite the fact that the approach to modeling crowd behavior starts from an analytic perspective, it becomes complicated to merge all the elements that influence pedestrian behavior in a whole and single model: in this case, elements related to the management of the practical movement such as scheduling of desires and activities, strategies and more complex behaviors of pedestrians should be integrated in just one framework, with the resulting problems in the calibration and validation perspectives.

According to Schadschneider et al. (2009) modeling crowd behavior can be divided considering three different levels, not stand-alone but with the necessity to interact each other in order to represent a whole process of modeling the behavior of a pedestrian in an environment (Fig. 2.1): the description of pedestrian behavior focusing on walking process, taking into account the interactions with other pedestrians and with obstacles belongs to the so-called *operational* level. *Tactical* and *strategic* levels are respectively what activities are to be performed, according to pedestrian goals, conditions and context: the main questions are *what are the activities* to be performed and *in which order* they should be carried out. Some proposals model the latter problem applying discrete choice modeling and determining a finite number of routes through the walking infrastructures (Gipps and Marksjö (1985)) or expected cost minimizer functions (Hoogendoorn (2001)), modeling a set of variables like distance, preferences and desires that influence pedestrian choices (Borgers and Timmermans (1986); Dijkstra et al. (2005)).

Considering, instead, the operational level, the main question is *which will be the precise path*[1] that pedestrian will follow reaching his/her goal and, more in detail, *which will be the next position* of the pedestrian moving towards his/her desire? Several factors have to be considered answering this question (Batty and Longley (2003)) along which the current position of pedestrian with respect to the environment and to his/her goal, the presence of obstacles, walls and no walk-able areas, the presence of other pedestrians in the neighborhood, both as negative element with respect to strangers and as positive element with respect to acquaintances:

[1]Where "precise" has a different acceptation for different modeling approaches in the spatial representation of the environment.

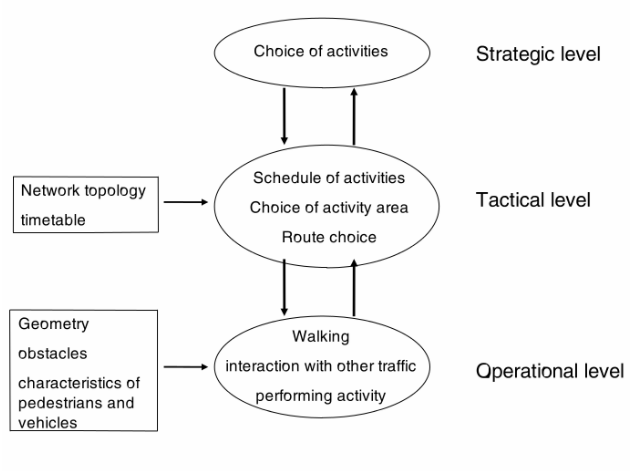


Figure 2.1: *The three levels of modeling pedestrian behavior, from Schadschneider et al. (2009)*

$$[\text{new position}] = [\text{old position}] + [\text{desired position}] + [\text{geometric repulsion}]$$

$$+ [\text{social repulsion}] + [\text{social attraction}] + \epsilon$$

Obviously, identifying the next movement of a pedestrian can not be reduced just to the evaluation of these elements: this is clearly a reduction of a potentially much more complex form of reasoning[2]. Therefore, to give an account of our ignorance and imprecision an ϵ random factor is generally added.

Given this "meta-level" representation, that is generally accepted in the literature, the issue of defining a precise and formal model has been tackled from different perspectives that depend on the level of aggregation of pedestrians with respect to the overall system "crowd". In particular, pedestrian dynamics has been studied from macroscopic and microscopic approaches as explained in Shiwakoti et al. (2008):

- *macroscopic models* focus on the aggregate representation of pedestrian dynamics considering flow, density and speed (Daamen (2004); Still (2000)). This kind of analysis is useful in high-density situation, in which the behavior of groups is more significant with respect to the behavior of single: pedestrian movement is modeled without taking into consideration the behavior of individuals despite the fact that it could change the overall dynamics of the system;

- *microscopic models* describe each pedestrian in a crowd as a single element occupying a certain space at a certain time. This kind of models are based on the assumption that pedestrians move themselves towards their destination considering interactions among pedestrians and interactions with the environment.

[2]But also a semi-automatic procedure non really involving any form of reasoning.

These models give a more realistic representation of pedestrian movements but problems related to their computational costs are well-known in the literature.

Considering the description of the model based on the definition of space, time and variables, models can be classified into *continuous models*, in which these features are described in a continuous way, and *discrete models*, in which they are described following a discrete approach. Sometimes, it is not possible to clearly classify a model according to these features because a part of the variables are modeled in a continuous way while the others in a discrete way.

Related to the behavior representation and the dynamics of pedestrians, according to Schadschneider et al. (2009), the dynamics of pedestrians at a certain time can be determined by means of the current state: the model uses a *deterministic* approach, i.e. there is not possibility to have two different behaviors starting from the same conditions. Differently, in *stochastic* models a pedestrian can behave differently under the same conditions: the reason is that the dynamics is also influenced by a probability value. Moreover, if pedestrians take decisions considering their current state in the system and according to rules that are inside their minds, these models are *rule-based*. On the contrary, if pedestrians are guided by means of external forces emitted by the environment or by other pedestrians (e.g. the floor field method we will discuss later), the model is called *force-based*.

Classifying a model according to the previous characteristics could be difficult under some circumstances: the majority of the combinations among features are possible, and sometimes the distinction in classes is ambiguous. For instance, also the classification between macroscopic and microscopic approach can not be considered enough general to categorize all the models in the literature, because it depends on the level of detail which the model is investigated from.

In general, another approach is used in the literature to propose a classification of pedestrian dynamics model, focusing on the representation of pedestrians:

- pedestrians as *particles*: models based on physical and analytic approaches, in which pedestrians are considered as particles subjected to forces modeling the interactions among pedestrians and with the environment;
- pedestrians as *cells*: models based on a discrete modeling of the environment using Cellular Automata (CA), in which pedestrians are considered as occupied states of the cells;
- pedestrians as *agents*: agent-based approaches, with pedestrians as autonomous agents, situated in an environment.

In the following sections, an overview on related works exploiting physical, CA-based and agent-based models is proposed, including a comparison on their characteristics and their capabilities in pedestrian dynamics modeling.

2.1.1 Pedestrians as Particles

Several models for pedestrian dynamics are based on an analytic approach, representing pedestrians as particles subject to forces: actually, pedestrian dynamics has some similarities with fluid-dynamics. Starting from this assumption, an interesting approach was proposed in Okazaki and Matsushita (1993), considering the behavior of pedestrians as the result of magnetic forces applied to the system. Similar to these previous models, the *social-force model* (Helbing and Molnár (1995)) is based on the assumption that interactions between pedestrians and the environment are implemented by means of the concepts of fields and forces that guide the behavior of pedestrians in the environment. Also interactions among pedestrians can be modeled by means of forces, as in Helbing et al. (1997). Forces of attraction lead the pedestrians/particles towards their destinations, while forces of repulsion are used to represent the tendency to stay at a distance from other points of the environment. Figure 2.2 shows a diagram exemplifying the application of this approach to the representation of an intersection that is being crossed by three pedestrians: the gray pedestrian, in the intersection, has an overall velocity v that is the result of an aggregation of the contributions related to the effects of attraction by its own reference point (a), and the repulsion by other pedestrians (b and c).

Social-force models (Helbing (2001); Hughes (2000)) describe interactions as a collision process in which particles exchange energy, so an entire crowd can be described by the kinetic theory of gases: the innovation of these models is the introduction of the concept of private space: they reflect the fact that people do not want to stay too close each other and to obstacles and other elements in the environment. The implementation of these rules is given by means of a repulsion force, that, together with attractive forces, guide the dynamics of the pedestrians in the simulations.

Social-force model is nowadays the most successful approach used in the pedestrian modeling in particular when a macroscopic analysis of crowd dynamics is required: several works that expand its basic idea can be found in the literature.

2.1.2 Pedestrians as States of CA

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 represents the environment and every cell has an own state that indicates if the site is occupied by a pedestrian or by an obstacles. The discreteness in terms of time and space can be done according to empirical evaluation with respect to the speed of pedestrians and the space requirement for a person (in a basic model, a cell can be occupied just by one person for every step).

Transition rules must be defined in order to specify the evolution of every cell state: they are based on the concept of neighborhood of a cell, i.e., a specific set of cells whose

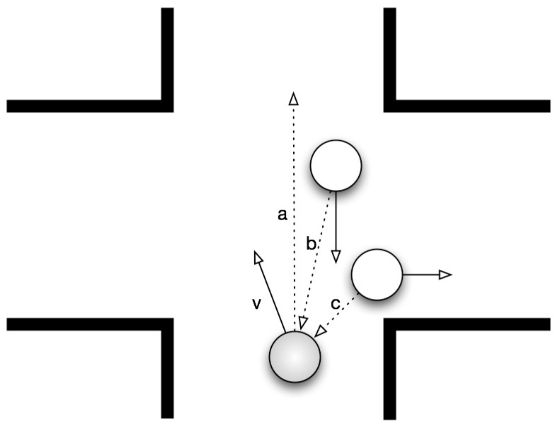


Figure 2.2: *A diagram exemplifying an analytic model for pedestrian movement*

state will be considered in the computation of the transition rule. The transition rule, in this kind of model, generates the illusion of movement. The probabilities to move in a particular cell are influenced by the desired direction and by the presence of other pedestrians and obstacles. Figure 2.3 shows a sample effect of movement generated by the subsequent application of a transition rule in the cellular space: the black cell is occupied by a pedestrian that moves to the right (*t=1*) and to the down (*t=2*).

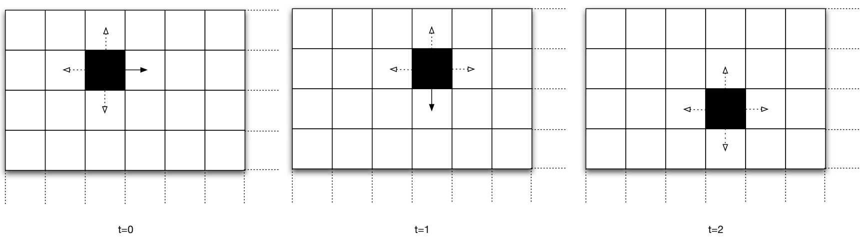


Figure 2.3: *A diagram showing a sample effect of movement in a CA*

First proposals of CA models (Blue and Adler (2000, 2001)) for pedestrian dynamics came from traffic model for multi-lane highway presented in Nagel et al. (1992) and in Rickert et al. (1996). In this model, the interactions among local cells can produce collective crowd behaviors like the formation of lanes in bidirectional pedestrian flows and the resolution of conflicts in multi-directional crossing pedestrian flows.

Other CA models are inspired by natural processes like chemotaxis[3] used by insects, like ants, to communicate information and to guide other individuals to food sources.

[3]The characteristic movement or orientation of an organism or cell along a chemical concentration gradient either toward or away from the chemical stimulus.

The translation of this natural phenomenon into a computational model is achieved by the introduction of the *floor field* method (Burstedde et al. (2001); Kirchner and Schadschneider (2002)). Floor fields work as virtual traces that influence pedestrian transitions: in Schadschneider et al. (2002) a static floor field that not change on time and that just considers the presence of obstacle in the environment is presented. This model associates to each cell a predefined desirability level, that, combined with more dynamic effects generated by the passage of other pedestrians, guide the transition of states associated to pedestrians. Differently, in Nishinari et al. (2003) a dynamic version of floor field approach is proposed, taking into account also the movement of pedestrians as elements that influence the future decisions of other 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 (Suma et al. (2012)). Moreover, particular attention is given to solve conflicts caused by parallel update of the CA: in Kirchner et al. (2003) an analysis related to how to solve these conflicts is proposed also considering the possibility of a stagnant situation (no pedestrian moves in case of conflict) rather than used a sequential shuffle update instead of a parallel update.

2.1.3 Pedestrians as Autonomous Agents

The last approach proposed in the pedestrian dynamics starts from modification introduced in the basic CA-approach (Henein and White (2005); Dijkstra et al. (2006); Bandini et al. (2004)), exploiting a cellular space representing spatial aspects in which a system of autonomous entities moves according to rules or desires. In fact, the approach is based on the definition of a *Multi-Agent System* (MAS), made up of a set of autonomous components which interact according to collaboration or competition schemes, in order to realize an overall behavior that could not be generated by single entities by themselves. Agent-based models have emerged as an interesting alternative to physical and discrete approaches, especially due to the adequacy of the approach to the definition of models in which autonomous and possibly heterogeneous agents can be defined, situated in an environment, provided with the possibility to perceive it and to interact with other agents as well as the environment itself, carrying out the chosen actions (Batty and Longley (2003); Toyama et al. (2006); Bandini et al. (2007)). All these approaches are characterized by the fact that agents encapsulate different kind of behaviors in order to represent elements like attraction/repulsion, generated by points of interest or reference in the environment but also by other pedestrians.

A preliminary model to reproduce the coordination of animal motion such as bird flocks and fish schools was proposed in 1986 in Reynolds (1987), based on three dimensional computational geometry in which creatures called boids moved on the basis of three simple steering behaviors: *separation*, steer to avoid crowding local flockmates, *alignment*, steer towards the average heading of local flockmates, and *cohesion*, steer towards the average heading of local flockmates. The main difference between the boid approach and the agent-based approach is that, in the first case, the entities do not move following a desired goal but just according to the overall trend of the system.

Some of the agent-based approaches to the modeling of pedestrians and crowds were developed with the primary goal of providing an effective 3D visualization of the simulated dynamics (Paris and Donikian (2009); Shao and Terzopoulos (2007)): 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. However, these virtual reality focused approaches to pedestrian and crowd simulation were not tested in paradigmatic case studies, modeled adopting analytic approaches or CA and validated against real data.

2.1.4 Evaluating Pedestrian Dynamics Models

Considering all the characteristics analyzed in Sec. 2.1 and indications presented in Gilbert and Troitzsch (2005), it is possible to provide the classification in Tab. 2.1: it is clear that the majority of the combinations can be found considering the overall state of the literature.

Approach	Fluid-based	Social-force	CA-based	Agent-based
Macroscopic	√	√		
Microscopic		√	√	√
Deterministic	√	√	√	
Stochastic			√	√
Continuous	√	√		√
Discrete			√	√
Force-based	√	√		√
Rule-based			√	√

Table 2.1: *A comparison among fluid-dynamics, social-force, CA-based, agent-based approach.*

From this analysis appears that the social-force and the CA-based approach are opposing methods, and the choice on their use is just based on the scope of the modeler. In a different way, the agent-based approach represents the richest model to represent heterogeneous systems, taking inspiration from all the other approaches and allowing to create more sophisticated simulation.

In the literature, several models exist and try to represent pedestrian behavior following different mechanisms: for these reasons it is necessary that models are evaluated considering their capability to reproduce observable phenomena both in a *qualitative* and in a *quantitative* way. If a model is not able to reproduce these effects, something is missing in reproducing pedestrian behavior.

Considering observable phenomena, the following effects should be reproduced:

jamming and density waves, and *lane formation*. The first effect typically occurs for high densities, where the inflow exceeds the capacity of the environment, for example in bottleneck situations (see Fig. 2.4a). The reason of jamming formation is the exclusion principle: space occupied by one particle is not available for others. The same phenomenon can be identified in crowded corridor in which density fluctuations can be detected.

(a) *Bottleneck* **(b)** *Lane formation*

Figure 2.4: *Phenomena collected in crowd observation*

Concerning the lane formation, the phenomenon can be detected when groups of people move in opposite directions in a crowded environment and they spontaneously organize themselves into different lanes for each direction of travel (Navin and Wheeler (1969); Yamori (1998)). The formation of lanes prevents strong interactions with oncoming pedestrians and allows higher walking speeds. Fig. 2.4b presents a situation in which two lanes of pedestrians can be detected, according to the movement directions.

From a measurable point of view, another way to compare model results is the evaluation of the *pedestrian flow*, defined as the number of pedestrians crossing a fixed location of a facility per unit of time (Schadschneider et al. (2009)). There are different ways to measure flow: the most common used is to determine the time t at which pedestrians passed a measured location. Another way is the consider flow as the product between the average density and the average speed of a pedestrian stream through a measured facility. The latter is also called *specific flow*. The empirical relationship between the density of pedestrians and their flow is expressed by the so called *fundamental diagram*: in the literature it is possible to find several studies related to the analysis of fundamental diagram in different scenarios and the discussion about the evaluation of different fundamental diagrams is still open in the community.

In Fig. 5.1 a comparison between different experimental studies is presented in the scenario of a corridor (from Schadschneider et al. (2009)). In general, velocity decreases with an increasing of the density, and flow increases until a critical value of density. Diagram on the left shows the variation of the velocity with respect to the density, while diagram on the right shows the variation of the pedestrian flow with respect to the density. Data used are from Nelson and MacLennan (2002) (SFPE), Predtechenskii and Milinski (1978) (PM), Weidmann (1992) (WM), Older (1968); Helbing et al. (2007). Despite some controversial results exist, fundamental diagram is actually used as quantitative benchmark to validate the plausibility of pedestrian dynamics models (Daamen (1999); Seyfried et al. (2006)).

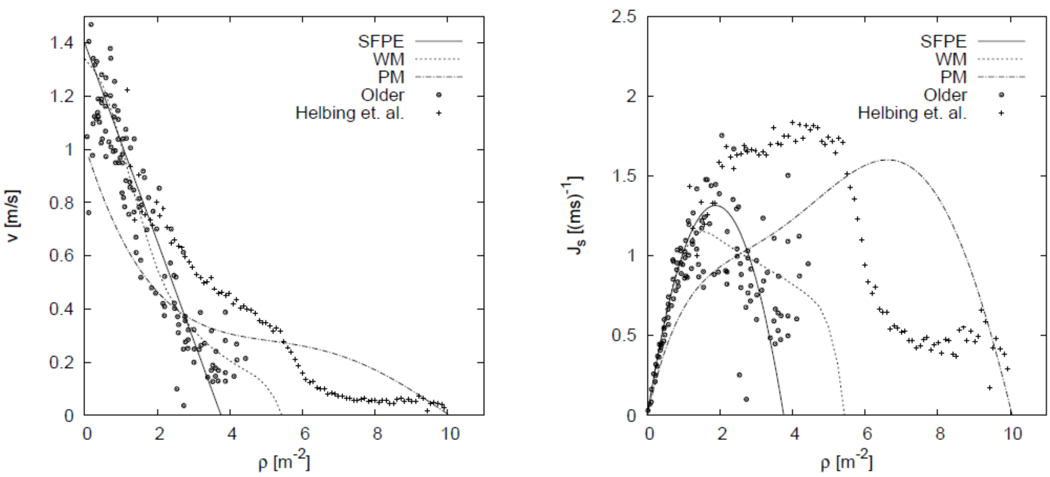
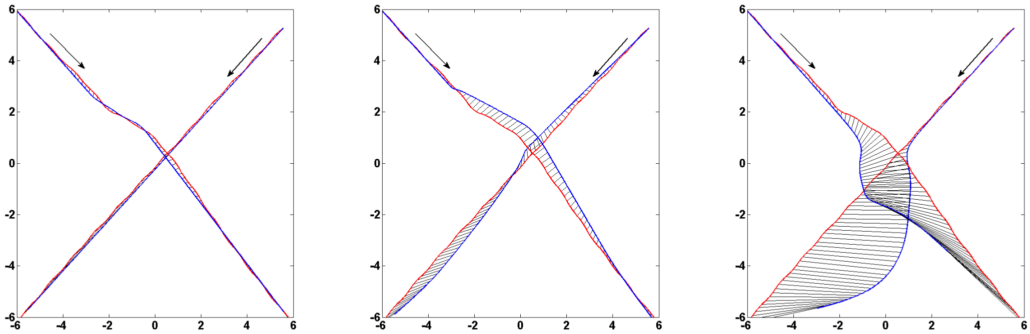


Figure 2.5: *A comparison between fundamental diagrams derived from experimental studies in the scenario of a simple corridor (from Schadschneider et al. (2009))*

In general, the fact that a model is able to support these qualitative and quantitative validation does not automatically imply that it produces realistic and reliable results in any situation and from any perspective[4]: in Pettré et al. (2009) authors propose a force-based model calibrated on experimental data that is able to reproduce an interaction between two humans when they walk with converging trajectories (Fig. 2.6). In this work, authors also compare their results with well-know and recognized models (Reynolds' model and Helbing's model): this study revealed that the latters are not able to reproduce the human behavior in this particular scenario.

The use of one of the previously analyzed models depend on the aim of the simulation: the study of evacuation time and process, the design of buildings and emergency exits, the design of experiments or data collection required different analysis and calibrations of the used model.

[4]In the perspective term we definitely include the aims of the simulation activity.



(a) *Pettré et al. (2009)'s model* **(b)** *Reynold's model* **(c)** *Helbing's model*

Figure 2.6: *Comparison between real interactions (in red) and simulated interactions (in blue) from Pettré et al. (2009)*

In Chapter 5 these details will be deeply analyzed, focusing on the validation both from a qualitative and quantitative point of view.

2.2 Modeling Groups of Pedestrians

The research trend in pedestrian dynamic community is today oriented towards the improvement of modeling performances, suggesting the importance of taking into account the presence of elements that can be easily detected considering crowd observation. In particular, in the last conferences related to the theme of pedestrian and evacuation dynamics (Rogsch et al. (2010); Peacock et al. (2011)) the attention was focused on the effects of the presence of groups of pedestrian within a crowd and on the influence of cultural and psychological aspects with respect to the dynamics of pedestrians.

In the following, an analysis related to the concept of *groups of pedestrians* is presented, such as an overview of pedestrian dynamics model including groups, following the previous classification into social-force, CA-based and agent-based models.

2.2.1 Definition and Identification of Pedestrian Groups

In general, models for the simulation of pedestrian dynamics are the result of a first generation of research efforts considering individuals, their interactions with the environment and among themselves, but generally neglecting aspects like the interactions and the cultural heterogeneity among individuals, and the effects of the presence of groups in a crowd. In order to understand how modeling groups of pedestrians, an analysis related to the definition of "group" such as observations related to this phenomenon are required.

Although the word "group" is commonly used to indicate a set of persons/objects, the definition of the term is still not clear: it is not possible to find a shared and unambiguous definition, in particular considering that several disciplines can apply the term to their specific field.

Considering the specific case in which the term is associated to pedestrians and pedestrian behavior, within the sociological and anthropological literature, the term group appears in different contexts, both from an ethnographic and theoretical point of view. Anthropology defines a group as a set of individuals related to one another on the basis of a common plan or a shared self-perceived identity. Furthermore, a group should be recognized as such by both its members and the outside community.

Anthropology classifies groups on the basis of the following criteria: *residence* (geographical origin), *ethnicity*, *gender*, *religion*. In this way, four main groups can be identified (Fabietti (1992)):

1. *primary* groups, the basic units social communities are built on, consisting in small units whose members have daily direct relationships (e.g. families);
2. *residential* groups, characterized by homogeneous spatial localization and geographical origin;
3. *kinship* groups, based on descent;
4. *functional* groups, "artificial" groups which exist only to perform a specific functions (i.e. executive, control, expressive function). Relationships among members are only based on the fulfillment of a goal.

From a psychological point of view, a group can be defined as two or more people who interact for a shared goal, perceiving a membership based on a shared social identity (Turner (1981)). Starting from these considerations, it is easy to understand that a crowd can be seen as a *collection of groups of pedestrians*.

More in details, considering group structure and organization, some studies can be found in the psychological literature related to leadership structures in small organized groups. In Stogdill (1950) the leadership is defined as "*the process of influencing the activities of an organized group in its task of goal setting and goal achievement*". He also suggested a distinction between formal and informal group organizations: the first are created a priori or by external entity, such as touristic groups, work groups, school groups or similar. In these situations, usually a leader (forced by the external entity or by the current situation) can be detected: differently, in the informal groups (e.g. families and friend groups), it is not possible to identify a leader. Following the previous definition, any person who influences the group is playing a leader's role and, in this sense, several individuals may be viewed as leaders at different times (Gross et al. (1953)).

Actually, different works in the pedestrian dynamics literature detected the presence of groups of pedestrians within a crowd: these works are the starting point to consider the effects of groups on the pedestrian flow. In particular, in Moussaïd et al. (2010) and Costa (2010) observations made in an shopping-urban environment are presented: the motion of pedestrian groups is analyzed showing that social interactions among group members generate typical group walking patterns that influence crowd dynamics such as the walking speed of single pedestrians and groups. The works are based on empirical observations, underlining that only one third of pedestrians in a crowd walks alone: the others are organized in groups with typical patterns which emerge from local interactions. Moussaïd et al. (2010) shows that at low density, group members usually tend to walk side-by-side in a *line-abreast* configuration: when the local density level increases, the group adapts its shape to reduce the occupancy of the available space, turning into *V-like* or *U-like* walking pattern with three and four members, respectively. When high levels of density are reached, usually groups tend to walk in a *river-like* configuration, walking one behind another. In Figure 2.7 an example of different walking patterns is depicted.

Figure 2.7: *Walking patterns according to Moussaïd et al. (2010) and Costa (2010). Figures from left to right show respectively the line-abreast, the V-like and the river-like patterns*

Differently, for bigger groups, observations show that they typically split into subgroups of 3-4 persons. The main reason for this behavior is the necessity to support communications between members of the group. The analysis of the impact of group walking patterns underlines that the dynamics of a crowd is not only influenced by physical constraints, but also by communicative and social interactions among individuals.

It is clear that the interaction between group members is the basis on which a group is built on: it is very important to understand how people live the environmental area around them, and in which way the interactions depend on the degree of relationships among pedestrians. Moreover, 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 the so-called proxemic behavior based on culture and social rules. The study of how people spatially interact each others is called Proxemics, and it was first introduced in Hall (1966) by

Edward T. Hall[5].

The proxemic behavior is one of the main topics of the Environmental Psychology, which emerged as autonomous discipline during the 1960s from Behavioral Science and Social Psychology, and turned its attention to the relationships between the socio-physical features of the environment and some psychological processes, such as perception, cognition, learning, and development. Hall introduced the term Proxemics for the study of human spatial behavior starting from previous studies on animal behavior, as a type of nonverbal communication[6] that conveys information about the nature of relationship. In his studies, Hall carried out analysis of different situations in order to recognize behavioral patterns. These patterns are based on personal culture as they appear at different levels of awareness.

Proxemics is also compatible with the so-called *"fear of being touched"*, another interesting concept derived from the work of Elias Canetti[7], presented in Canetti (1962) along with a precise classification of crowds on the basis of quantitative feature[8]. Single individuals avoid physical contact due to fear of being touched: the value of the distance between strangers depend on cultural and personal aspects.

In Hall (1963) he 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 (see Tab. 2.2): *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.

Distance	Measurements	Relationships & activities
Intimate	0cm - 45cm	intimate contact and physical sports
Personal	45cm - 120cm	contacts between close friends, as well as everyday interactions with acquaintances
Social	120cm - 360cm	impersonal and business-like contacts
Public	300cm - 600cm	formal contacts between an individual and the public

Table 2.2: *Types of perceived distance according to Hall (1963)*

Perceived distances depend on some elements which characterized relationships and interactions between people: posture and sex identifiers, sociofugal-sociopetal (SFP) axis[9], kinesthetic factor, touching code, visual code, thermal code, olfactory code

[5] Edward Twitchell Hall, Jr. (May 16, 1914 - July 20, 2009) was an American anthropologist and cross-cultural researcher.

[6] Non-verbal communication plays an important role in the exchange of information outside spoken language, in the form of facial expressions, kinesics, visual behavior, and Proxemics.

[7] Elias Canetti (July 25, 1905 - August 14, 1994) was a Swiss modernist novelist, playwright, memoirist, and non-fiction writer. He won the Nobel Prize in Literature in 1981.

[8] See Bandini et al. (2011b) for an ontological representation of the classification.

[9] These terms were first introduced in 1957 in Osmond (1957).

and voice loudness. In the already mentioned Costa (2010) another study related to interpersonal distances among group members reveals that proxemic relationships exist also in pedestrian group: proxemic behavior reveals the psychological bonding among group members, and, in high-density situations, it represents an adaptive stress-reducing behavior to crowding , by producing spatial boundaries that shield group members from the invasion of personal space (Baum and Paulus (1987)). In motion situation, group proxemic behavior generates typical patterns (already discussed in Sec. 2.2, Fig. 2.7), which allow communication and spatial cohesion among members. This kind of dynamics has only recently been investigated by pedestrians and crowd modelers, and also on the observation and analysis side much work is still necessary to achieve a comprehensive characterization of this kind of phenomenon.

In conclusion, the contribution of proxemic interaction can be seen as a double rules: a *separation* desire from strangers and a *cohesion* desire with the members who belong to the same group. The first contribution is already applied in all the classical models analyzed in Sec. 2.1, and explicitly used in terms of Proxemics among pedestrians in Was (2010); Was et al. (2006) and among vehicles in Furutani (1976). A multi-layered model based on MAS based on the definition of a Proxemics layer is published in Lembo et al. (2010). The second contribution will be used as key element in the next Section, in which an overview of works presented in the literature about group modeling is proposed.

2.2.2 Groups and Social Force Models

Some proposals about how to model the presence of groups in a pedestrian crowd come from the area related to the physical approach.

In Moussaïd et al. (2009) an expansion of the social force model (Helbing and Molnár (1995)) exploiting the impact of pedestrian interactions is proposed, starting from observable behaviors of pedestrians moving in a corridor under different conditions: in absence of interactions, with standing pedestrian, with pedestrians moving in opposite direction. The effects on the behavior of pedestrians were then formalized in mathematical terms and implemented, in order to compare the results of the model with the experimental results and the empirical data collected in a real scenario of a crowded commercial street. In accordance with the classical social-force model, the motion of a pedestrian is described by equations based on three components: the internal acceleration behavior towards a particular direction at a certain speed, the effects of obstacles in the environment and the interaction among pedestrians. Using experimental data the work is focused on the analysis and the calibration of the last parameter, the *interaction law*, described as a function depending on the interaction distance and on the angle of perception. The model is validated in two different conditions: considering only binary interactions involving two pedestrians and considering a large number of pedestrians exposed to many simultaneous interactions. In this case, it is assumed that the behavior of all pedestrians is given by the sum of all binary interactions with other pedestrians in the neighborhood. Experimental results reveal that the decision process to avoid other pedestrians decreases the walking speed.

Starting from this work in which interactions among pedestrians are explicitly considered, in Moussaïd et al. (2010) the motion of pedestrian groups is analyzed showing that social interactions among group members generate typical group walking patterns (line-abreast, V-like and river-like patterns) that influence crowd dynamics. The authors describe these spatial patterns extending the model in Moussaïd et al. (2009), including a term to describe the response of a pedestrian with respect to other group members. Simulations underline that V-like and U-like configuration are emergent patterns resulting from the tendency of each pedestrian to find a comfortable walking position supporting communication, despite that the presence of these shapes reduces the pedestrian flow because they do not have aerodynamic features.

In Xu and Duh (2010) another extension of Helbing and Molnár (1995) is proposed focusing on the definition of bonding forces as opposite to repulsive forces. By means of bonding forces groups are modeled reproducing interpersonal cohesion between pedestrians. Bonding effect is calibrated by means of data collected during observations, in order to represent distances that exists between people belonging to the same group or between strangers. The work is focused on the effects of bonding force in couples, underling that in an evacuation scenario, escape time of bonded groups is worst with respect to escape time of single walkers, as reported in Fig. 2.8.

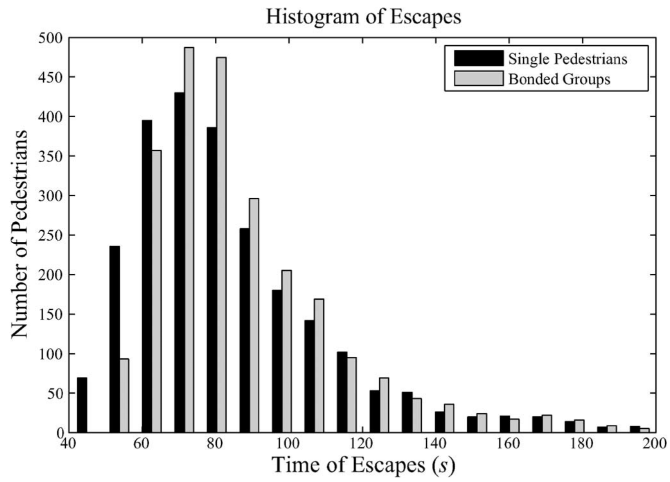


Figure 2.8: *Comparison of escape time between single walkers and bonded groups, from Xu and Duh (2010)*

In Singh et al. (2009) an existing crowd modeling program called CrowdDMX (Langston et al. (2006)) has been modified according to observations performed in a shopping street and public transport locations, including subgroup behavior with the desire to stay together. Subgroups are modeled by means of psychological forces that implement interactions among members of a subgroup and interactions among subgroups. The improvement to the basic model of CrowdDMX were validated by means of a face validation process through simulations and with a direct comparison with respect to the video footage.

2.2.3 Groups and CA-based Models

CA approach has already applied and validated in different scientific researches on complex systems. Currently, several CA-based models with relative algorithms exist to represent crowd behavior: despite that, only few works about the creation on a CA-based group-aware model can be found in the literature.

In Sarmady et al. (2009) a variation of the basic CA-algorithm considering the effect of pedestrian groups on crowd movement is proposed. In this model, different rules for moving pedestrian from one cell to another are introduced: basically, the movement probabilities are being identified based on the desirability of each of the neighboring cells on the basis of the proximity and the shortest path to reach the target. The classical algorithm is changed to include the idea of group considering that pedestrians in a group tend to maintain a short distance from a special member of the group: every group is characterized by only one leader. Leader can observe its distance from the group and decide to slow down or stop to allow group members to reach him. The transition probability equation of the algorithm is modified to consider the behavior of followers and leader. The model is tested in a simple walkway scenario in which pedestrians enter the long walkway from one side and move toward the other end. The size of pedestrian groups is derived from empirical data, and are distributed according to a Poisson distribution (James (1953)). The results of this work suggest that increasing the average size and the number of groups has effect on the average speed of pedestrians in a crowd: the presence of groups of pedestrians slow down the overall speed of the crowd.

In Koster et al. (2011) a CA-based model with hexagonal cells that can be empty or occupied by a person, an obstacle or a target is presented. This model is near to fluid-dynamics models in the sense that pedestrians are treated as negatively charged particles and they are attracted by positive charges (goals) and repelled by negative charges (other pedestrians and obstacles): pedestrians are driven by potential fields. Groups are easily modeled turning off the negative charges between members of group: in order to solve problems related to orientation function of a group, the concept of leader is introduced. The latter is a particular kind of pedestrian that has an attractive field towards other group members and he/she guides all of them towards the goal. The model has been tested in two scenarios, a simple corridor and an evacuation from a classroom (calibrated starting from an experiment): results underline that a direct dependency between the mean walking speed and group size can be detected. In particular, an increasing of group size corresponds to a decreasing of walking speed.

2.2.4 Groups and Agent-based Models

The issue to model entity cohesion was already faced out in the first experiments in Carlson (2000) considering boids-approach, in which the concept of cohesion among local flockmates is included in the definition of the behavior of the elements. More recently, a proposal exploiting the concept of holonic-MAS is already been introduced in Gaud et al. (2008). The authors suggest the use of an holonic organizational model in which an holon can be seen either as an autonomous atomic entity or as an organization of holons, depending on the level of observation. Groups are described in the following way: each individual is associated to an atomic holon and they are grouped into super-holons according to their affinity (i.e., if they share the goal). These super-holons are grouped in their turn and so on, to obtain a single and complete holarchy. A holon can change its super-holons during the simulation if the goal changes: so, the configuration of groups is dynamic during the simulation. An example of possible holonic structure is presented in Figure 2.9.

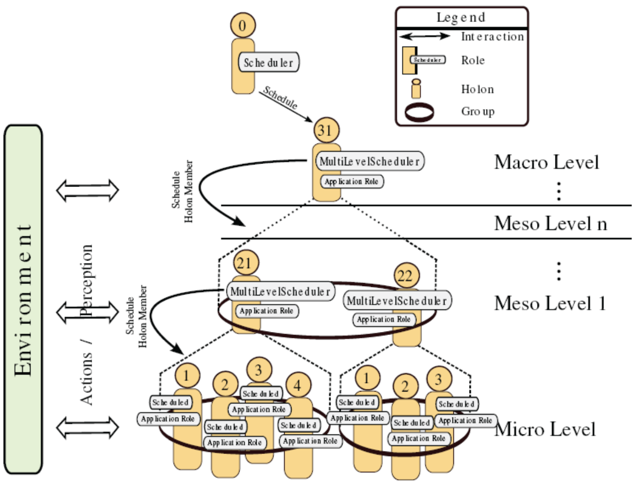


Figure 2.9: *Graphical representation a possible holonic structure with n meso-levels, from Gaud et al. (2008)*

Actually, in this work the concept of group is not explicitly modeled: the only relation among group members is sharing the goal. Differently, other works are related to an analysis of group structure, studying changes in the relationships during the simulation.

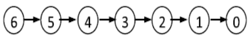
Qiu and Hu (2010a) describe a novel model to simulate dynamic groups based on both utility theory, social comparison theory (Festinger (1975)) and leader-follower model. In particular, authors propose a framework to study dynamic grouping through two-step decisions: group formation and individual selection. The first step is based on the assumption that, comparing the degree of desirability of group behavior, a pedestrian can choose to remain in the current group or to change. For each behavior, the preference is specified though an utility function: pedestrians perform the behavior with a higher preference value. The second step is based on the social comparison theory: usually, a pedestrian tends to follow a particular member in its group, and, in particular, the one which is most similar. Parameters like social degree related to change group and similarity degree with other agents are then exploited to build functions to support the steps of group formation and individual selection.

In Qiu and Hu (2010b) a deeper analysis about groups from a structural point of view is proposed. In this work, the crowd is composed of a set of groups and each individual belongs to one and only one group. A group size is associated to every group: also the concept of leader is introduced. Every group has one and only one group leader, while other pedestrians are defined as group members or followers.

Group structure is investigated from two aspects, intra-group structure and inter-group relationship. The first refers to the network relationship among the members inside a group, the second to the relationships among groups (groups influence each other). Authors propose the use of influence matrices, one for the intra-group relationship and one for the inter-group relationship, specified a priori by the user.

On the basis of the values in the matrices, it is possible to model group behavior as composition of two aspects of movements, *aggregation*, that means an individual moves towards the center of the group and *following*, that means the leader of a group moves towards a different group.

The model is tested considering two typical group shapes (a linear shape and a leader-follower configuration, see Fig. 2.10) and a mixed group shape, in order to indicate how to build a intra-group matrix to obtain the desired group shape. Despite that, the validation of the model is hard to be shown, due to the complexity of this model and the calibration of all the parameters (the use of influence matrices required to calibrate several parameters). Currently, results of simulations underline that, considering a leader-follower configuration, when the group is not so large, the pedestrian flow increases as the group size increases: differently, when the group is very large and without a leader-follower configuration, the pedestrian flow decreases. Despite that, these results are not compared with collected or experimental data.



ID	0	1	2	3	4	5	6
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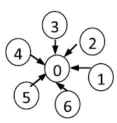
1	1						
2		1					
3			1				
4				1			
5					1		
6						1	

(a)



ID	0	1	2	3	4	5	6
0							
1	1						
2	1						
3	1						
4	1						
5	1						
6	1						

(b)

Figure 2.10: *Graphical representation and intra-group matrix of linear group shape (Fig. 2.10a) and leader-follower group shape (Fig. 2.10b), from Qiu and Hu (2010b)*

From the area of real-time crowd simulation and computer graphics, a novel approach to simulate the walking behavior of small groups of pedestrian is presented in Karamouzas and Overmars (2012). The proposed model is directly inspired from empirical study presented in Moussaïd et al. (2010) and it is based on the assumption that groups tend to maintain a configuration that facilities the social interactions among group members. Another assumption is related to the large groups: authors claim that, in this situation, pedestrians tend to form smaller sub-groups consisting of three members. The model is based on a two-step approach:first, each group has to determine its new velocity and formation. Then, using the computed solution velocity and formation, the desired velocity of each group member is identified. The model was tested on test-case scenarios, predicting the emergence of empirically observed walking patterns, generating smooth and visually convincing motions.

2.2.5 Group-aware Models: a Comparison

In this section a comparison among previous group-aware models is proposed in order to underline the common elements in modeling groups and to discuss some aspects. Dealing with groups, the following elements can be identified as fundamental in the analysis of groups:

- the *features* associated to a group, considering in particular:
  - the *size* of a group: the size can be fixed, variable or not explicitly modeled;
  - the presence of *leader* in every group;
  - the *shape* of a group: it can be fixed or not explicitly modeled;
- the presence of *relationships* among different elements of models: in fact, different types of relationships require to be analyzed:
  - relationships among individuals belonging to the same group: they can be fixed or variable (in terms of intensity) during the simulation, or not explicitly defined;
  - relationship between individuals and their own group: the groups of individuals assigned to a group in the beginning of the simulation can be fixed or variable during the simulation;
  - relationships among different groups: groups can influence each others;

Table 2.3 proposes a comparison on the previous analyzed models about group features while Table 2.4 resumes the differences among the presented models about the management of relationships inside and outside groups.

On the basis of this analysis, some remarks related to the evolution of models considering group presence in a crowd can be made: first works were related to the

Model	Size	Leader	Shape
Moussaïd et al. (2009)			
Moussaïd et al. (2010)	fixed (< 4)	fixed	fixed
Xu and Duh (2010)	fixed		
Singh et al. (2009)	fixed		fixed
Sarmady et al. (2009)	fixed	fixed	
Koster et al. (2011)	fixed	fixed	fixed
Gaud et al. (2008)	variable		
Qiu and Hu (2010a)	variable	fixed	
Qiu and Hu (2010b)	fixed	fixed	
Karamouzas and Overmars (2012)	fixed (< 4)	fixed	fixed

Table 2.3: *An overview about group features, considering the size of group, the presence of leader and the shape of group*

Model	btw Individuals	btw Groups
Moussaïd et al. (2009)	variable	
Moussaïd et al. (2010)	variable	influenced
Xu and Duh (2010)	fixed	
Singh et al. (2009)	variable	influenced
Sarmady et al. (2009)	fixed	
Koster et al. (2011)	fixed	influenced
Gaud et al. (2008)		
Qiu and Hu (2010a)	variable	influenced
Qiu and Hu (2010b)	fixed	influenced
Karamouzas and Overmars (2012)	fixed	

Table 2.4: *An overview about relationships inside and outside groups: relationships among individuals in the same group and relationships among different groups*

analysis of interactions among pedestrians, not explicitly considering the group as a whole and independent concept that is necessary to investigate.

Considering Table 2.3, new models focus on complex aspects of groups, such as size, shape and configuration. In Moussaïd et al. (2009); Xu and Duh (2010); Gaud et al. (2008) these aspects are not deeply analyzed, paying attention to interaction among pedestrians and roles, respectively. Singh et al. (2009); Qiu and Hu (2010a,b) partially cover these features, while in Moussaïd et al. (2010); Koster et al. (2011); Karamouzas and Overmars (2012) all the aspects of size, shape and configuration are considered and modeled. In particular, the majority of the models investigate groups with fixed sized during the simulation: the reason is that the goal of these studies is to analyze the impact of groups on the overall dynamics of the crowd instead of studying the dynamics of group formation and dispersion, such as in Bosse et al. (2011). Note that the majority of the models just focus on little groups from 2 to 4 individuals, without taking into account more complex structures.

The majority of the models previously presented (Moussaïd et al. (2010); Sarmady et al. (2009); Koster et al. (2011); Qiu and Hu (2010a,b); Karamouzas and Overmars (2012)) are based on the concept that, in every group, only one leader can be founded. The presence of leader simplifies the management of group position and the goal, that is, in fact, assigned to the leader and not to all the members of the group. Despite that, the presence (and the necessity) of leadership inside a group is not universally recognized, such as the identification of a fixed leader in the group structure, as previously discussed.

Moreover, Table 2.4 underlines the importance of the concept of relationship among individuals in a group according to the psycho-sociological definition. Recent works (Koster et al. (2011); Qiu and Hu (2010a,b)) retrieve the importance of relationships in modeling groups: these fundamental elements are explicitly considered and well-represented in these models.

On the basis of this analysis, it is clear that the majority of the models are obtained adding a new element in well-know models in order to include groups in the simulation: Moussaïd et al. (2009, 2010); Sarmady et al. (2009); Qiu and Hu (2010a) reflect this idea, adding a new attractive forces, changing a rule or the utility function with respect to previous models. Differently, the works in Koster et al. (2011) and in Qiu and Hu (2010b) are more complex, proposing very rich models that try to take into account a lot of aspects related to group modeling. Despite that, this richness also implies very difficult way to calibrate and validate these models, both for the lack of empirical data and for the novelty of the issue.

Finally, we want to analyze if results of these models highlight an influence of groups on pedestrian flow: currently, there is no agreement from this point of view. In Moussaïd et al. (2009); Singh et al. (2009); Gaud et al. (2008); Qiu and Hu (2010a); Karamouzas and Overmars (2012) the problem of group influence is not dealt with due to the fact that the focus is more related to how model group features with respect to evaluate their influence on pedestrian flow. Differently, in Moussaïd et al. (2010); Xu and Duh (2010); Sarmady et al. (2009) an evaluation of group impact on results is done, showing that they have a negative impact slowing down the pedestrian flow. In contrast with these results, in Koster et al. (2011) and Qiu and Hu (2010b) an increasing of the flow is identified in particular in case of small groups (from 2 to 4 individuals).

2.3 Conclusions

Simulation of crowd behavior is an active research area and grouping is a common phenomenon in pedestrian crowds: group modeling is still an open challenge problem (Braun et al. (2003))in this area. In the last years, researchers have presented a variety of approaches trying to capture different features of social groups and in this analysis an overview about the most recently and complete approaches has been proposed.

It is clear that agent-based prospective appears as the most capability approach to build a pedestrian dynamics model also including the definition of groups, by means of proxemic interactions and relationships as basic elements to face the simulation of simple and structured pedestrian groups. In particular, our proposal will cover the possibility to model structured as well as simple groups, modeling mechanism ensuring different levels of cohesion in different types of group. The model will not reproduce the phenomenon of group leader (but opening the possibility of analyzing this kind of scenario with the introduced mechanisms) and it will not take into account the steps of creation and break-up of groups. These lines of research will be used in this work with the scope to investigate the phenomenon of pedestrian groups, identifying their peculiar features and evaluating their influence on the overall dynamics of crowd.

3

Groups, Agents and Proxemic Relationships

This Chapter can be considered as the first part of the forward modeling contribution of this thesis . It deals with groups in pedestrian dynamics simulation, deepening the concept of group of pedestrians, modeling the relationships between persons inside and outside groups and between groups, providing tools to analyze how their presence influence the overall crowd dynamics.

In this Chapter, we define an agent-based system explicitly taking into account motivational aspects in the agent movements with respect to proxemic relationships with other agents, without referring to a specific definition of attraction towards goals and repulsion from obstacles and non-walkable areas. These elements have already been elaborated and discussed in the literature. and can quite simply be integrated within this modeling proposals.

In this model, are in particular pointed out the definition of relationships and functions that connect the elements of the system: the proposed model Bandini et al. (2011a) is independent from time and space specification, and it can be general enough to be applied to heterogeneous scenarios of pedestrian dynamics, in which space and time are generally handled in different ways according to different settings based on discrete and continuous approaches[1].

First, the main elements of the model will be formally defined (Sec. 3.1), to introduce an analysis of proxemic relationships among agents (Sec. 3.2). An expansion of the model to include the definition of structured group ends the Chapter along with some considerations about the generality of the model (Sec. 3.3 and Sec. 3.4).

3.1 Definition of the System

Starting from the definition of groups as primary elements within a crowd, an agent-based system is here introduced as composition of a *finite population of agents $\mathcal{A}$ on which a set of groups $\mathcal{G}$ are defined*. In a system, particular types of groups can be defined, on the basis of the relationship between group members: in order to model this aspect, a set of relationships $\mathcal{R}$ is associated to the system, specifying the allowed relationships.

[1] see Sec. 2.1.4 for details

Formally, a pedestrian system is described as:

$$S = \langle \mathcal{G}, \mathcal{A}, \mathcal{R} \rangle$$

where:

- $\mathcal{G} = \{G_1, \dots, G_m\}$ is a finite set of groups;
- $\mathcal{A} = \{a_1, \dots, a_n\}$ is a population of agents;
- $\mathcal{R} = \{r_1, \dots, r_l\}$ is a finite set of binary relationships defined on the system.

In the next sections every element will be defined such as functions and relationships between them.

3.1.1 Groups

Building the definition of a group, different studies in the literature have been considered (Canetti (1962); Turner (1981); Stogdill (1950); Costa (2010)), summarizing the definition of a pedestrian group as *a whole of individuals in a relationship with a common goal and/or a common perceived identity*. Two aspects are pointed out as fundamental parts of this definition: first, the relationship between group members, that defines in which way they interact with each others in the system; second, the importance of the goal, that is shared between all the members of a group. In this model, the focus will be on the first factor, explicitly modeling the relationships between pedestrians.

Starting from these assumptions, in the system every group $\in \mathcal{G}$ is defined by a set of agents $\in \mathcal{A}$ and by a relationship $r \in \mathcal{R}$ that defines the membership of agents to the group. In particular, every group is defined a priori by a set of agents: this set has a *size* (i.e. the cardinality of the group) and the composition of members can not change. As previously introduced, among group members a relationship already exists: the kind of relationship determines the type of group, such as a family, a group of friends, a working group and so on.

In order to characterize pedestrian groups, it is possible to identify *a set of features* $\mathcal{C}$, shared among all the groups in a system: these features allow to analyze and describe more in detail different aspects which is necessary to take into account in the modeling of the system due to their potential impact on the simulation. A vector with the values of features is associated to every group, i.e. $\mathcal{C} = \{C_1, C_2, \dots, C_s\}$, where $\mathcal{C}$ is a family of features defined on the system regarding the groups and each C_i is a set of possible values that the i^{th} feature can assume. These values are shared and homogeneous on agents belonging to the same group.

We define a group G_i as:

$$G_i = \langle A_i, z_i, r_i \rangle$$

where:

- $A_i \subseteq \mathcal{A}$ is a finite set of agents belonging to G_i;
- $z_i \in C_1 \times C_2 \times \ldots \times C_s$ is a vector with the values of features related to G_i group;
- $r_i \in \mathcal{R}$ is an irreflexive, symmetric relationship among agents which belong to the group G_i and such that for all $a, b \in A_i$ with $a \neq b$, the pair (a, b) is in the transitive closure of r_i.

In the system, agents can not belong to two different groups at the same time, that is:

$$A_i \bigcap A_j = \emptyset \ \forall i, j = 1, \ldots, m \text{ and } i \neq j$$

The population of agents $\mathcal{A}$ can be described as the union of the populations of every group:

$$\mathcal{A} = \bigcup_{i=1}^{m} A_i$$

Each group can be represented as a graph $GA_i = (A_i, E_i)$ where A_i is the set of agents belonging to G_i and E_i is the set of edges given by the relationship r_i. GA_i is a non-oriented and connected graph (i.e. for every pair of distinct nodes in the graph there is a path between them) without self-loops.

3.1.2 Agents

A fundamental element on groups is the agent population $\mathcal{A}$ in which every agent represents a pedestrian. In order to introduce characteristics related the pedestrians, we introduce $\mathcal{L} = \{L_1, \ldots, L_q\}$ as a family of agent features where every L_i is a set of possible values that the i^{th} feature can assume. Every agent can have different values related to a set of characteristics $\mathcal{L}$:

$$a = \langle w_a \rangle$$

where $w_a \in L_1 \times L_2 \times \ldots \times L_q$ is a vector with the values of features related to agent a.

3.2 Proxemic Relationships

After the definition of groups and agents, the focus of the model is on the modeling of proxemic relationships between agents. As already analyzed in Sec. 2.2, Proxemic theory is related to the way in which pedestrians perceive each other and to the distances between them, both inside and outside groups. The perceived distances depend on different factors such as personal characteristics and the features of the group which he/she belongs to.

Proxemics identifies a *separation desire* from strangers and not group members, and a *cohesion desire* between the members of the same group. Starting from proxemic contribution, in the model two kinds of relationships are considered: *separation proxemic* relationship and *cohesion proxemic* relationship.

3.2.1 Separation Proxemic Relationship

The first proxemic aspect is related to the behavior during interactions between a pedestrian and other pedestrians belonging to a different group. According to proxemic point of view, taking into account the relevance to model personal differences in a pedestrian system, derived, for instance, by cultural attitude and social context a personal distance $d_a \in \mathcal{D}$ is associated to every agent $a \in \mathcal{A}$ belonging to a group G_i. Considering the feature values associated to the agent and to its group, a function da is defined as follows:

$$da : \left(\prod_{C \in \mathcal{C}} C\right) \times \left(\prod_{L \in \mathcal{L}} L\right) \mapsto \mathcal{D}$$

Given an agent $a \in G_i$, with $a = \langle w_a \rangle$ and its group G_i with features z_i, its personal distance is $da(z_i, w_a) = d_a$.

Considering the distance among a and the other agents not belonging to its group, we require that the proxemic distance[2] between $a \in A$ and $b \in \mathcal{A} \setminus A_i$ is above d_a for all $b \in \mathcal{A} \setminus A_i$ that are included in the portion of the system that agent a can perceive.

Formally, an agent $a \in G_i$ is in a *safe proxemic condition* iff:

$$\nexists b \in \mathcal{A} \setminus A_i \ : p_a(b) \leq d_a$$

Separation proxemic relationship models the fact that pedestrians tend to maintain a minimum distance from pedestrians belonging the other groups and, if the safe proxemic condition is violated, agents tend to restore the condition of proxemic safeness.

[2] A set of functions p (perception functions) is introduced to evaluate proxemic distances (proxemic relationships) among agents. Perception functions measure distances among agents in the case of pedestrians inside and outside a group. On $\mathcal{A}$, a pseudo-semi-metric p is defined as:

$$p : \mathcal{A} \times \mathcal{A} \mapsto \mathcal{D},$$

to measure distances between agents, such that, given two agents $a, b \in \mathcal{A}$, $p(a, b) = p(b, a)$ (i.e., p is symmetric) and $p(a, a) = 0_{\mathcal{D}}$, where $\mathcal{D}$ is a domain of distances, described as a totally ordered set with $0_{\mathcal{D}}$ as a minimal element. $\mathcal{D}$ is introduced with the aim to not restrict the definition of the environment in a specific given spatial domain. From p, for any specific agent $a \in \mathcal{A}$, a function $p_a : \mathcal{A} \mapsto \mathcal{D}$ is derived, that associates to a its distance from any other agent in $\mathcal{A}$. Given two agents $a, b \in \mathcal{A}$,

$$p_a(b) = p_b(a)$$

Perception function p is here used to calculate the distance among agents and to interpret proxemic relationships among agents inside and outside groups.

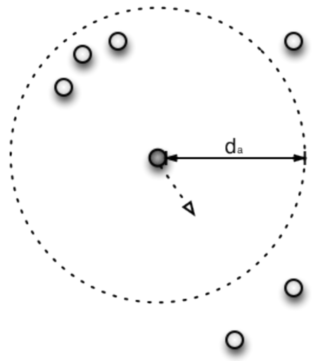


Figure 3.1: *Graphical representation of separation proxemic mechanism: agent a (in dark grey) moves away from other agents that entered/are into its personal space (delimited by the proxemic distance d_a)*

Figure 3.1 represents the situation in which an agent a (in dark grey) moves away from other agents that entered/are into its personal space (delimited by the proxemic distance d_a).

3.2.2 Cohesion Proxemic Relationship

Every group G_i is characterized by a private defined distance $\delta_{G_i} \in \mathcal{D}$ that depends on the values of group features z_i. A function dg that calculates δ_{G_i} is introduced as follows:

$$dg : \prod_{C \in \mathcal{C}} C \mapsto \mathcal{D}$$

Given a group G_i, $dg(z_i) = \delta_{G_i}$.

The introduction of time into the model gives the possibility to define relationships that are time dependent: due to the fact that time can be modeled in a continuous or discrete way, the proposed model is defined in a way applicable to both continuous and discrete modeling. Considering a particular time $t \in \mathcal{T} \subseteq \mathbb{R}$ and t_0 as the starting time, the evolution of the system is given by a map $\varphi : \mathcal{S} \times \mathcal{T} \mapsto \mathcal{S}$, where $\mathcal{S}$ is the space of possible systems. The state of the system at time t is $\varphi(S_0, t)$, where S_0 is the state of the system at time t_0.

A new kind of time-dependent relationship (differently from the previously defined $\mathcal{R}$), defined as a function $\mathfrak{r}$ such that $\mathfrak{r}_t$ is a dynamic irreflexive and symmetric relationship among agents which belong to the group G_i. $\mathfrak{r}_t$ represents the relation at time t that is dependent on the whole evolution of the system from time t_0 to time t. For each group G_i at time t it is possible to consider the graph given by the relation $\mathfrak{r}_t$. To model the proximity relationship between agents, $\mathfrak{r}_t$ is defined as:

$$\forall a, b \in G_i,\ (a, b) \in \mathfrak{r}_t \text{ iff } p(a, b) \leq \delta_{G_i}$$

It is possible to define a group as satisfying the *safe group condition* at time t on the basis of the history of the evolution of the graph structure given by $\mathfrak{r}_t$. Let $\mathfrak{S}$ be the function that defines the presence or absence of the safe group condition. In other words $\mathfrak{S}\left(\langle \mathfrak{r}_j \mid j \leq t \rangle\right) \in \{0, 1\}$. The fact that $\mathfrak{S}$ is dependent on the whole history of the graph structure is motivated by the necessity to take care of particular conditions that can temporary change the graph structure but that can be quickly recovered. By using the whole history it is possible to avoid to consider unsafe (with respect to safe) a group that is, in fact, in a safe (with respect to unsafe) condition. For instance, considering a simulation placed into two rooms separated by a turnstile: the passage of a group through the turnstile can divide the group, but the group has not to be considered in an unsafe condition if the passage through the turnstile can be detected as a temporary condition.

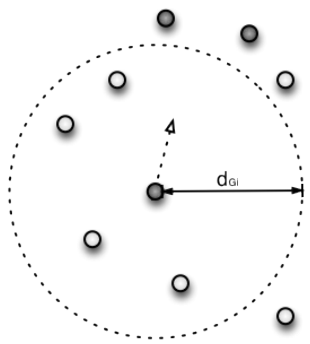


Figure 3.2: *Graphical representation of cohesion proxemic mechanism: agent a (in the center of the figure and in the dark grey) moves towards other agents that belong to the same group (in dark grey) try to not overcome the maximum distance δ_{G_i} with respect to them*

Cohesion proxemic aspect represents the fact that pedestrians in a group tend to not overcome a maximum distance from other agents belonging to the same group: if the safe group condition is violated, agents tend to restore the condition of group safeness. Figure 3.2 represents the situation in which an agent a (in the center of the figure and in the dark grey) moves towards other agents that belong to its group (in dark grey) to try to not overcome the maximum distance δ_{G_i} with respect to them.

3.2.3 System Dynamics According to Proxemic Relationships

After the introduction of the separation and cohesione proxemic relationships, an analysis of the system about the dynamics of these two factors can be made. Four states are possible for each agent in the system:

1. *separation and cohesion safeness* (SCS), if an agent is both in a safe proxemic condition inside and outside its group;

2. *separation safeness* (SS), if only the separation aspect is verified;

3. *cohesion safeness* (SC), if only the cohesion aspect with group members is verified;

4. *unsafe state* (U), if neither separation nor cohesion aspects are verified.

All the transitions among the four conditions are admitted: Figure 3.3 represents transitions among all the states formalized by means of a FSA - Finite State Automata $\langle Q, \Sigma, q_0, \delta \rangle$ where:

- $Q = \{SCS, SC, SS, U\}$ is the finite set of states that agents can assume;
- $\Sigma = \{a, b, c, d, e, f, g, h\}$ is the input alphabet (a finite, non-empty set of symbols) that defines all the possible transitions among states;
- q_0 is the initial state of the FSA: in this system, every state that belongs to Q can be an initial state;
- $\delta : Q \times \Sigma \rightarrow Q$ is the transition function.

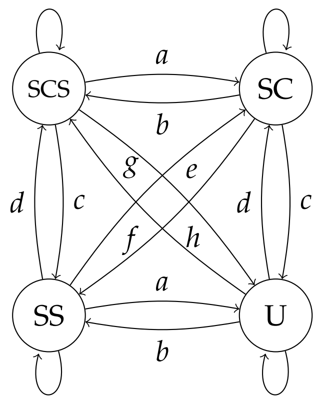


Figure 3.3: *FSA representing the transitions among agent internal conditions*

Considering two agents $a \in G_i$ and $b \notin G_i$:

1. SCS $\Longleftrightarrow$ SC: if a is in the SCS state and an agent b approaches it at a distance less than d_a, a passes in the SC state (transition *a*). Otherwise, if a is in SC state and increases its distance from all the other agents $\notin G_i$ to a value greater than d_a, a passes in the SCS state (transition *b*);

2. SCS $\Longleftrightarrow$ SS: if a is in the SCS state and the safe group condition on G_i becomes not verified, a passes in the SS state (transition *c*). Otherwise, if a is in SS state and the safe group condition on G_i becomes verified, a passes in the SCS state (transition *d*);

3. SCS $\Longleftrightarrow$ U: if a is in the SCS state and an agent b approaches a at a distance less than d_a, and the safe group condition on G_i becomes not verified, a passes in the U state (transition *e*). Otherwise, if a is in U state and a increases its distance from all the other agents $\notin G_i$ to a value greater than d_a, the safe group condition on G_i becomes verified, a passes in the SCS state (transition *f*);

4. SS $\Longleftrightarrow$ U: if a is in the SS state and an agent b approaches a at a distance less than d_a, a passes in the U state (transition *a*). Otherwise, if a is in U state and a increases its distance from all the other agents $\notin G_i$ to a value greater than d_a, a passes in the SS state (transition *b*);

5. SC $\Longleftrightarrow$ U: if a is in the SC state and the safe group condition on G_i becomes not verified, a passes in the U state (transition *c*). Otherwise, if a is in U state and the safe group condition on G_i becomes verified, a passes in the SC state (transition *d*);

6. SS $\Longleftrightarrow$ SC: if a is in the SS state and an agent b approaches a at a distance less than d_a, and the safe group condition on G_i becomes verified, a passes in the SC state (transition *g*). Otherwise, if a is in SC state and a increases its distance from all the other agents $\notin G_i$ to a value greater than d_a, and the safe group condition on G_i becomes not verified, a passes in the SS state (transition *h*).

Two particular configurations with respect to agent population $\mathcal{A} = \{a_1, a_2, \ldots, a_n\}$ and a set of groups $\mathcal{G} = G_1, \ldots, G_m$ are:

- if $m = 1$ there is only one group coinciding with the whole $\mathcal{A}$. In this case, only two states are admissible: SCS and SS. In fact, SC and U states are not possible because all agents of the population belong to the same G_i group (Fig. 3.4):

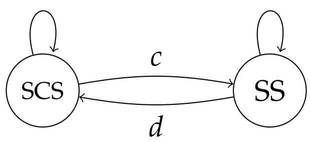


Figure 3.4: *Simplification of FSA (I)*

- if $m = n$, $|A_i| = 1\ \forall i = 1, \ldots, m$, all the groups have a size equal to 1 and every agent in the population is a singleton. In the FSA, only two states are admissible:

SCS and SC. In fact, SS and U states are not possible because every agent is always in a safe group condition (Fig. 3.5):

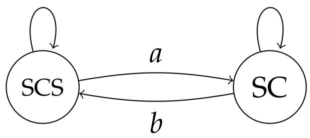


Figure 3.5: *Simplification of FSA (II)*

3.3 Inter-group Relationships

In the previous Section, the definition of group and the relationships between group members was focused only on the representation of *simple* or informal groups (following the definition in Sec. 2.2), in which the structure is based only on a high cohesion level, for instance families and friends: they move all together towards the same goal due to endogenous desires.

Another kind of group that has to be considered in modeling pedestrian group is related to the notion of *structured* or artificial groups, more complex structures in which all the groups created by an external entity or created to face particular situations can be collected. An example of this type of group may be represented by touristic groups. These groups are usually bigger than simple groups (more than 4 individuals) and they can be seen in a recursive way as composed of sub-groups.

Figure 3.6 shows a structured group on three levels: the starting point is G_1 (level 0) composed of G_2, G_3 and G_4 (level 1). While G_3 is a leaf in the hierarchical structure, G_2 and G_4 branch out respectively into G_5 and G_6, and G_7 (level 2). G_8 and G_9 end the structure as children node of G_7 (level 3).

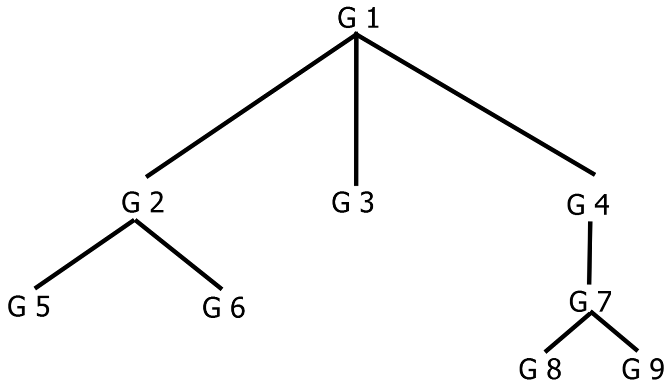


Figure 3.6: *Graphical representation of a structured group on three levels*

Formally and considering the previous definition of group in Sec. 3.1, a structured group is defined as

$$\mathscr{G} = \{\mathscr{G}_1, \ldots, \mathscr{G}_n\}$$

where $\mathscr{G}_1, \ldots, \mathscr{G}_n$ are structured groups: every simple group is also a structured group.

If $\mathscr{G} = \langle A, z, r\rangle$ (i.e., $\mathscr{G}$ is a simple group), $A(\mathscr{G})$ is defined as A; otherwise, if $\mathscr{G}$ is a structured group,

$$A(\mathscr{G}) = \bigcup_{i=1}^{n} A(\mathscr{G}_i)$$

,

i.e. the set of agents that belongs to $\mathscr{G}$ is obtained joining the agents of the sub-groups.

Moreover, considering $\mathcal{G}$ as the set of all the structured groups. For every $\mathscr{G}_1, \mathscr{G}_2 \in \mathcal{G}$ with $\mathscr{G}_1 \neq \mathscr{G}_2$, one of the following conditions have to be verified:

- $A(\mathscr{G}_1) \cap A(\mathscr{G}_2) = \emptyset$;
- A group chain $\mathscr{H}_1, \ldots, \mathscr{H}_k$ exists, such as:

$$\mathscr{G}_1 = \mathscr{H}_1 \in \ldots \in \mathscr{H}_k = \mathscr{G}_2$$

- A group chain $\mathscr{K}_1, \ldots, \mathscr{K}_k$ exists, such as:

$$\mathscr{G}_2 = \mathscr{K}_1 \in \ldots \in \mathscr{K}_k = \mathscr{G}_1$$

The first condition models the situation in which two structured groups do not have common agents (groups G_5 and G_6 in Fig. 3.6), while the second and the third conditions identify the case in which $\mathscr{G}_1$ is included into $\mathscr{G}_2$ and vice versa ($G_5 \subset G_2$ and $G_6 \subset G_2$ in Fig. 3.6).

Note that considering a structured group $\mathscr{G}$ it is possible to obtain a tree of structured group with $\mathscr{G}$ as root ($\mathscr{G} = G_1$ in Fig. 3.6); in this structure, arcs are defined by the set inclusion principle.

In this Chapter just the definition of structured group is pointed out: all the other aspects related to relationships among sub-groups in terms of inter-cohesion value will be analyzed in the next Chapter, also providing an analysis of the dynamics between intra and inter relationships in simple and structured groups.

3.4 Conclusions

The model hereby proposed is based on a multi-agent system approach, and it explicitly formalizes proxemic aspects among individuals, both with members of the own group and with strangers. Methods of network analysis can be applied in order to identify relevant structures, such as borders and spatially located groups (Manenti et al. (2010)).

Proxemics aspects were introduced to deepen the main object of this thesis, group modeling, and to understand if and in which way pedestrian relationships influence the whole dynamics of a system.

Despite that, it is necessary to provide a comprehensive model of pedestrian dynamics, in which goals and desires along with all the other behavioral components that concur in the definition of pedestrian behavior have to be taken into account: these aspects required the development of a model in which the representation of space and time is explicit, and in which a work of composition, trade-off and calibration among all the aspects that influence pedestrian dynamics is carried out.

The next Chapter will be devoted to the presentation of a computational agent-based model with discrete space and time, in which simple and structured groups are expressly treated on the basis of the analysis on proxemic relationships here proposed.

4

Modeling Pedestrian Groups: a Discrete Proposal

This Chapter presents how the formal specifications for groups, agents and proxemic relationships presented in the previous Chapter can be adopted in a computational discrete proposal that takes into account all the behavioral components that have to be integrated to develop a complete (from the operational point of view) model of pedestrian dynamics. As it has been underlined in Chapter 2 the representation choice about space and time, influenced by the goals of the modeling and simulation effort, affects the final simulation results.

In this thesis, the choice of using an agent-based discrete approach is justified by several reasons, among which the possibility to take advantage of the substantial body of mechanisms and approaches adopted in CA pedestrian models.

The model here proposed is based on a floor-field approach, in which pedestrians are represented by means of agents rather than cells, in order to model heterogeneous and more complex behaviors. In particular, in this Chapter, a complete explanation of a model for the analysis of the impact of groups on the overall dynamics of pedestrians is provided in Sec 4.1: in particular, the movement choice of pedestrians will be discussed with reference to all the relevant factors. The model of pedestrian groups will be deepen in Sec. 4.2, also considering structured groups, and providing a discussion related to a trade-off analysis between different behavioral components in group modeling.

Chapter ends with an analysis of the limits of the approach (Sec. 4.3) and requirements necessary to develop a tool on the basis of the proposed model (Sec. 4.4). Some conclusions close the Chapter in Sec. 4.5.

4.1 Basic Pedestrian Model for Analysis of Group Impact

In this section, a complete explanation of a basic pedestrian model for the representation and the study of pedestrian systems including pedestrian groups impact is proposed. The representation of the environment is described by means of the specification of space and time, and also of virtual elements that allow the definition of simulation scenarios. Then, the representation of pedestrians, by means of agents endowed with perception capabilities, and potentially belonging to groups, is proposed. Finally, all the behavioral components that take part in the mechanism of movement evaluation will be discussed.

4.1.1 Representation of the Environment

The physical environment is represented in terms of a discrete grid of square cells:

$$Env = \{c_0, c_1, c_2, c_3, ...\} \qquad \forall c_i : c_i \in Cell$$

The size of every cell is $40cm \times 40cm$ according to standard measure used in the literature and derived from empirical observation and experimental procedure (Weidmann, 1993; Fruin, 1992):

Every cell has a row and a column index, which indicates its position in the grid:

$$\begin{aligned} Row(c_i) : Cell &\rightarrow \mathbb{N} \\ Col(c_i) : Cell &\rightarrow \mathbb{N} \end{aligned}$$

A cell is also indicated by its row and column on the grid, with the following notation:

$$Env_{j,k} = c : c \in Env \ \wedge \ (Row(c) = j) \ \wedge \ (Col(c) = k)$$

Every cell is linked to other cells, that are considered its neighbors according to the Moore neighborhood, that is all the cells surrounding the cell being considered, even in diagonal directions: it is possible to express Moore neighborhood as joining of orthogonal cells, also called Von Neumann neighborhood, and diagonal cells.

$$\begin{array}{ll} N(Env_{j,k}) = Env_{j+1,k}, & S(Env_{j,k}) = Env_{j-1,k}, \\ E(Env_{j,k}) = Env_{j,k+1}, & W(Env_{j,k} = Env_{j,k-1}, \\ NE(Env_{j,k}) = Env_{j+1,k+1}, & SE(Env_{j,k}) = Env_{j-1,k+1}, \\ NW(Env_{j,k}) = Env_{j+1,k-1}, & SW(Env_{j,k}) = Env_{j-1,k-1} \end{array}$$

$$\begin{array}{l} VonNeumanneighbors(c) = \{N(c), S(c), E(c), W(c)\} \\ Diagonalneighbors(c) = \{NE(c), SE(c), NW(c), SW(c)\} \end{array}$$

$$neighbors(c) = VonNeumanneighbors(c) \cup Diagonalneighbors(c)$$

Every cell in the environment can be in three possible states: *free*, *occupied by an obstacle*, or *occupied by a pedestrian*. In the third case the cell contains also a reference to the specific pedestrian occupying it (the structure of pedestrians will be described later in Sec. 4.1.4):

$$State(c) = s : s \in \{FREE, OBSTACLE, PEDESTRIAN_i\}$$

In addition to the potential presence of physical objects (pedestrians and obstacles) each cell is also linked to additional structures that contain information useful to support pedestrian movement.

Definition of Spatial Markers

Space can be annotated at design-time with different markers, a set of cells that play particular roles in the simulation. Three kinds of marker are defined in the model:

- *start areas*, places (cells) were pedestrians are generated: they contain information for pedestrian generation both related to the type of pedestrians and to the frequency of generation. In particular, a start area can generate different kinds of pedestrians according to two approaches:
  - *frequency-based generation*, in which pedestrians are generated during all the simulation according to a frequency distribution;
  - *en-bloc generation*, in which a set of pedestrians is generated at once in the start area when the simulation starts;
- *destination areas*, final places where pedestrians want to go;
- *obstacles*, non-walkable cells defining obstacles and non-accessible areas.

Space annotation allows the definition of virtual grids on the environment, as containers of information for agents.

Definition of Floor Fields

Following the approach of the *floor field* model (Sec. 2.1.2), the environment of the basic model is composed also of a set of superimposed virtual grids, structurally identical to the environment grid, that contains different floor fields that influence pedestrian behavior.

The goal of these grids is to support long range interactions by representing the state of the environment (namely, the presence of pedestrians and their capability to be perceived from nearby cells) in terms of field modifications. In this way, a local perception for pedestrians consists in actually gathering the necessary information to carry out a plausible and effective decision making activity about movement. This reduces computational complexity and then time resources required by the simulation (at the price of a relatively small increase in memory resources requirements).

Some of the floor fields are *static* (creating at the beginning and not changing during the simulation) or *dynamic* (changing during the simulation). Three floor fields are considered in the model:

- the *path field* assigned to each destination area, that indicates for every cell the distance from the destination, acting as a potential field that drive pedestrians towards it (static floor field);
- the *obstacles field*, that indicates for every cell the distance from an obstacle or a wall (static floor field);
- the *density field* that indicates for each cell the pedestrian density in the surroundings at the current time-step (dynamic floor field).

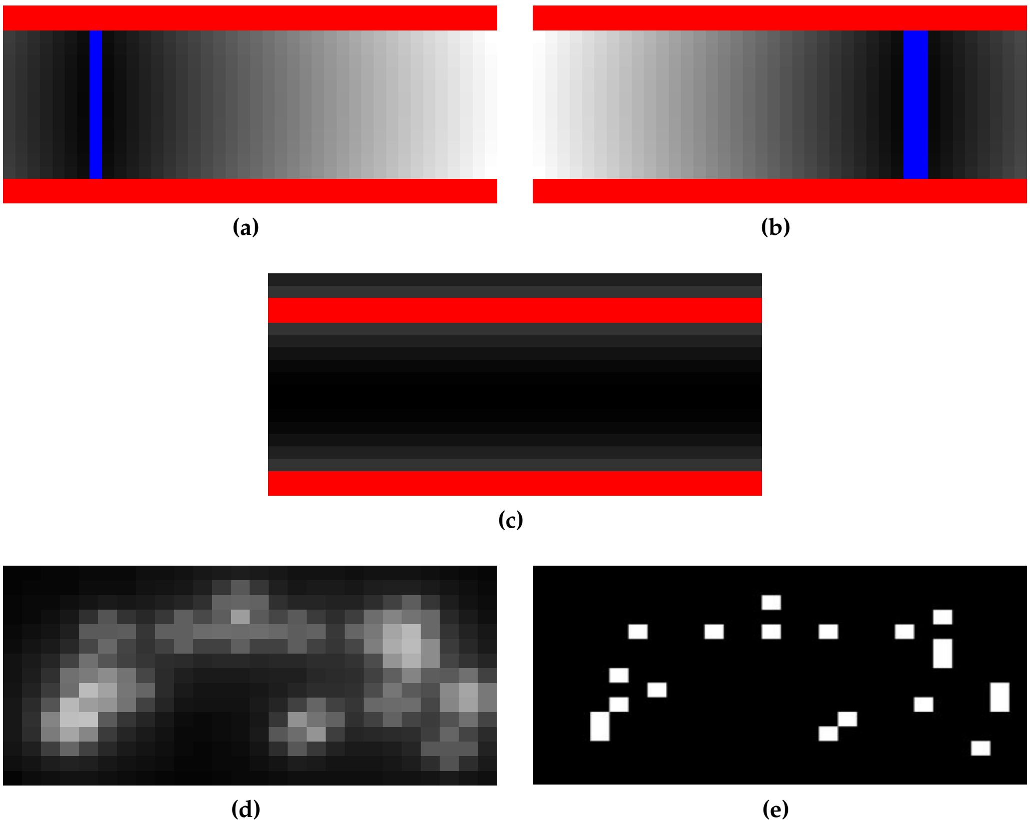


Figure 4.1: *Graphical representation of different floor fields in a simple corridor scenario: Figures 4.1a and 4.1b represent two path fields associated to different destination areas. Figure 4.1c represents the obstacle fields provided by walls. Figure 4.1d and 4.1e show the density field with the relative pedestrian position at a precise time step*

All these fields can be seen as grids identical to the environment grid: a function that extracts the values of the fields for the given cell is defined as follows:

$$Val(f, c) : Field \times Cell \rightarrow \mathbb{R}$$

The following notation will be used to indicate these grids, assuming that pedestrians know only the path field associated to their own destination:

$$PathF_{j,k} = Val(PathF, c) : c \in Env \ \wedge \ (Row(c) = j) \ \wedge \ (Col(c) = k)$$
$$ObsF_{j,k} = Val(ObsF, c) : c \in Env \ \wedge \ (Row(c) = j) \ \wedge \ (Col(c) = k)$$
$$DensF_{j,k} = Val(DensF, c) : c \in Env \ \wedge \ (Row(c) = j) \ \wedge \ (Col(c) = k)$$

The definition of every type of floor field is now illustrated.

Path Field

Each destination is associated to a *path field* indicating the shortest path between each cell in the environment and the destination. These floor fields act as a potential, driving pedestrian towards the destination (one floor field exists for every destination): starting from every destination defined in the scenario, the information are spread into the environment according to a particular method. In Kretz et al. (2010) authors analyzed different methods for the calculation of the distance potential field: starting from the considerations in this work, we decided to apply the Chessboard metrics to manage the Von Neumann neighborhood using the $\sqrt{2}$ variation over corners. According to Kretz et al. (2010), this metric with the $\sqrt{2}$ variation allows a good management of Moore neighborhood.

For every path field and for every cell, the value of the distance is calculated with this metric and it is associated to every cell: value increases if the distance increases.

Figure 4.1 proposes a graphical representation of the floor fields used in the model in a simple corridor scenario: in Fig. 4.1a and 4.1b the path fields associated to destination areas (in blue) are proposed: darker tonalities indicate the approaching to the destination.

Obstacle Field

This floor field contains all the information related to the position of obstacles in the scenario: just one grid exists for all the non-walkable areas in the environment. Chessboard metrics with $\sqrt{2}$ variation over corners is used also to produce the spreading of the information in the obstacle field: a particular radius r is considered as the border of propagation of information about he presence of the obstacle.

The algorithm works as follows: after the initialization of all the cell with a null value, the distance for all the cells that lie under the radius r_{ob} from the obstacle is calculated using Chessboard metrics. A non-null value is then associated to these cells (i.e. higher values represent cells nearest to the obstacles) according to the following functions:

$$Val(ObsF, c) = max\{0, r_{ob} - dist(c_{obs}, c)\}$$

Fig. 4.1c represents obstacle field in which lightest values indicate the approaching to the obstacles (in red).

Density Field

This floor field is the more complex in terms of meaning of information stored: in this grid, information necessary to the management of interaction between pedestrians and to the calculation of statistics related to the mean density in the scenario are saved.

In general, the concept of *density* is usually related to the number of persons in a fixed portion of space: despite that, density can be measured in different ways and the concept of mean density in a particular cell of the scenario has to be analyzed more in detail. In the pedestrian dynamics literature, the concept of *cumulative mean density* (CMD) indicates the density experienced by pedestrians in a cell: the concept was first introduced in Still (2000), where the author defined that CMD is measured only when a pedestrian passes over there, by counting the number of people in the surroundings of the pedestrian (given a distance range). At the end of simulation, average on all the measurements is computed for each of the cells of the space. It is a local and pedestrian-based concept of density, that gives information about how pedestrian experienced the space, ignoring the time periods in which a space has been empty.

In Castle et al. (2011), CMD evaluation in LEGION[1] and STEPS[2] software is analyzed and compared: in LEGION, the surrounding of a pedestrian is identified into a radius $r = 1.5$ m with an area[3] of $Area = r^2 * \pi = 7.07m^2$. STEPS adopts a similar approach calculating the density in a discrete way using the cells that fall within $r = 1.25$ m of each persons: the area considered is $Area = r^2 = 6.25m^2$.

In our model, the management of density field is a bit more complicated with respect to previous cases. It is modified according to the following mechanism: when a pedestrian p moves in a cell c, the density field is modified in the grid adding 1 to the cell in which he/she moves, and subtract 1 from the cell he/she just left. The modification is applied also to neighbor cells in a range given by a radius $r = 2$ m (equal to five cells from c), but the value added/subtracted decreases with the inverse of the square of the distance between the cell and p:

$$v = \frac{1}{d^2}$$

[1]LEGION is the most famous and used commercial software for pedestrian dynamics simulation, see http://www.legion.com/legion-software

[2]STEPS is an agent-based micro-simulation tool developed by Mott MacDonald for the simulation of pedestrian movement under both normal and emergency conditions, see http://www.steps.mottmac.com/

[3]Note that LEGION works on continuous representation of environment, so the area is calculated as the circle area around the pedestrian.

Figures 4.1d and 4.1e represent the density field (in which lightest values that indicate highest values of the density) and an instant position of agents, respectively.

4.1.2 Simulation Time

Simulation time is modeled in a discrete way by dividing time into steps of equal duration: we assume that a pedestrian moves exactly 1 cell per time step. The average velocity of a pedestrian, which can be estimated in real observations or experiments (Fruin, 1992) in about $1.2\ ms{-}1$, will thus determine the duration of the each time step in terms of second: considering that the size of the cell is 40 *cm* $\times$ 40 *cm*, the average pedestrian velocity in terms of steps is equal to 3 steps/second.

Note that in this way, the maximum of velocity allowed in this model is $1.2\ ms^{-1}$: different works (Weng et al., 2006; Kirchner et al., 2004) investigated how variations in the pedestrian velocity ($1.0\ ms^{-1}$ and $1.5\ ms^{-1}$) can be modeled with CA approach and how these choices influence simulation results. It must be emphasized that, however, this parameter is not strictly embedded in the model and it could be changed, essentially modifying only the analysis and results interpretation phases.

4.1.3 Update Strategy

When running a Ca-based pedestrian model, three update strategies are possible (Klüpfel, 2003):

- *parallel* update, in which cells are updated all together;
- *sequential* update, in which cells are updated one after the other, always in the same order;
- *shuffled sequential update*, in which cells are updated one after the other, but with a different order every time.

The second and third update strategies lead to the definition of asynchronous CA models (see Bandini et al. (2012) for a more thorough discussion on types of a-synchronicity in CA models).

In crowd simulation CA models, parallel update is generally preferred (Schadschneider et al., 2009), even if this strategy can lead to conflicts that must be solved. Some works (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.

In their pioneering work, Gipps and Marksjö (1985) used a sequential update, despite that Blue and Adler (2001) point out that "*with 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 behaviors 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.

Please note that the structure of the model and the defined mechanisms remain valid in case of a parallel update scheme: the model would only need the definition of a mechanism and strategy to manage conflicts to support this schema. Of course, this different choice would have an impact on the simulation results and thus on the calibration phases and a comparison among these different approaches can be pointed out.

4.1.4 Pedestrians

In this model, a pedestrian is defined as an utility-based agent with state. Functions are defined for utility calculation and action choice, and rules are defined for state-change. Pedestrians are characterized as:

$$Pedestrian : \langle Id, GroupId, State, Actions, Destination \rangle$$

where:

1. $Id \in \mathbb{N}$ is the agent identification number;

2. $GroupId \in \mathbb{N}$ is the identification number of the group to which the pedestrian belong to. The entity $Group$ is defined as a container of agents and it is associated with a numerical identifier as well:

   $$Group_j = \langle GroupId, GroupAgents \rangle$$

   where $GroupAgents$ is the set of agents associated to $Group_j$;

3. $State$ that represents the state of the agent related to its position in the space and to its attitude with respect to the simulated scenario. It is defined as:

   $$State : \langle Position, PrevDirection \rangle$$

   where $Position$ indicates the current cell in which the agent is located, and $PrevDirection$ is the direction followed in the last movement;

4. $Actions$ is the set of possible actions that the agent can perform. Possible actions are movements in one of the eight neighbor cells (indicated as cardinal points), plus the action of remaining in the same cell (indicated by an 'X'):

$$Actions = \{N, S, W, E, NE, SE, NW, SW, X\}$$

Admissible actions $AdmAct_p$ ($\subseteq Actions$) are all the actions that move the pedestrian p from cell c in cells that are free at the moment it is updated:

$$AdmAct_p = \{a : a \in Actions \ \wedge \ State(a(c)) = FREE\}$$

The effect of each action is to move the pedestrian p in the direction indicated. This means that when an action a is chosen (for example, N), the new cell is calculated as follows:

$$newCell = a(oldCell)$$

When the movement is completed, the cell is marked as occupied, and the old cell is marked as free:

$$State(newCell) = PEDESTRIAN_p$$
$$State(oldCell) = FREE$$

The last effect of an action is to update the density field by reducing density in the surroundings of $oldCell$ and increasing it in the surroundings of $newCell$;

5. $Destination$ is the goal of the agent in terms of destination area. This term identifies the current destination of the pedestrian: in particular, every destination overlaps with a set of cells that are defined as destination areas by means of the appropriate spatial marker. $Destination$ is used to identify which path field is relevant for the agent:

$$currentPathField = PathField(Destination)$$

where $PathField$ is the precise path field associated to $Destination$ and $currentPathField$ is the path field relevant for the agent.

All these elements take part in the mechanism that manages the movement of pedestrians: as previously introduced, they are essentially utility-based agents. To every movement in the cell neighborhood a value of utility is associated, according to a set of factors that concur in the overall dynamics.

4.1.5 Mechanism of Action Evaluation

In Algorithm 1 the agent life-cycle during all the simulation time is proposed: every time step, every pedestrian perceives the values of path field, obstacle field and density field for all the cells that are in its neighborhood. On the basis of these values and according to different factors, the agent evaluates the different cells around him, associating an utility value to every cell and selects the action for moving into a specific cell.

Algorithm 1 Agent life-cycle

```
for all timestep ∈ SimulationTime do
    for all p ∈ Pedestrian do
        Utility[]
        for all c ∈ neighbors(Position) do
            pf ← Val(PathF, c)
            of ← Val(ObsF, c)
            df ← Val(DensF, c)
            Utility[c] ← Evaluation(pf, of, df)
        end for
        a = Choice(Utility[])
        Move(a)
    end for
end for
```

Action selection strategy starts extracting from the cell in which the pedestrian is located, and considering the eight cells of the neighborhood, the values of the three floor fields. The obtained values will be used in the evaluation of the action choice. Note that in our model, the agent perception mechanism is just based on the perception of floor fields values by means of an opportune function. In other works, the concept of perception and the relative implementation is deeply investigated, starting from the definition of the *field of view* mechanism in humans: in Paris and Donikian (2009) the pedestrian perception from a cognitive point of view is illustrated, while a more physical approach is examined in Shao and Terzopoulos (2007).

Agent then assigns a desirability value to each of the admissible actions (movements), according to several factors: the goal attraction (*Goal*) , the obstacles repulsion (*Obs*), the proxemic separation (*Sep*), the direction value (*Dir*), the overlapping event (*Ov*) and the cohesion group (*Ov*). The utility of a destination cell (which corresponds to an action/direction) is calculated from the utility function $U_a(c)$, where the weighted sum of all these factors is considered:

$$U_a(c) = \frac{k_g \cdot Goal(c) + k_o \cdot Obs(c) + k_s \cdot Sep(c) + k_d \cdot D(c) + k_{ov} \cdot Over(c) + k_c \cdot Coh(c)}{d}$$

where d is the distance of the new cell from the current position, that is 1 for cells in the Von Neumann neighborhood (vertically and horizontally neighbor cells) and $\sqrt{2}$ for diagonal cells: the factor is introduced to penalize the diagonal movement. Note that $k_i \in [0, 100]$: the use of parameters allow also having different types of pedestrian, or even different states of the same pedestrian, changing dynamically its weights. The different contributions in $U_a(c)$ will be described later in this Section: now, different strategies to be used after the utility computation as mechanism of choice are described.

Given the list of possible actions and associated utilities, different strategies are possible to choose the next action.

Two strategies are implemented: *deterministic* behavior and *stochastic weighted* behavior. In the deterministic strategy the action with the highest utility is always chosen. Differently, in the stochastic weighted strategy an action is randomly chosen with a probability that is function of utility. In particular, the probability for an agent a of choosing an action associated to the movement towards a cell c is given by the exponential of the utility, normalized on all the possible actions the pedestrian can take in the current turn:

$$p_a(c) = N \cdot e^{U_a(c)}$$

where N is the normalization factor. The second strategy is the most used, according to the necessity to include a random factor ϵ in the prediction of the movement.

Every element that contribute to the utility calculation is hereby dealt with.

Goal Attraction

Agents are driven towards their goal using information derived from the relative path field, calculating the distance between their current cell and the destination area. The function that manages the goal attraction evaluates the loss of distance moving from cell $Position$ in cell c where $x = Row(Position)$, $y = Col(Position)$, $i = Row(c)$ and $j = Col(c)$:

$$Goal(c) = \frac{PathF_{x,y} - PathF_{i,j}}{\sqrt{2}}$$

where $\forall c \in Cells, Goal(c) \in [-1, 1]$.

Obstacle Repulsion

The interaction between agents and obstacles and non-walkable area in the environment has negative characteristics, because of the tendency of pedestrians to manage the available space without walking too close to obstacles and walls: for instance, considering the scenario of a corridor, pedestrians tend to stay in the center instead of close to the walls. Information for the location and influence of obstacle are stored in the obstacle field: considering a cell c with $i = Row(c)$ and $j = Col(c)$,

$$Obs(c) = -\frac{ObsF_{i,j}}{r_{ob}}$$

where $\forall c \in Cells, Obs(c) \in [-1, 0]$.

Proxemic Separation

All the interactions among pedestrians are subjected to the proxemic separation relationship, standing that all the persons tend to maintain a certain distance with respect to others and according to the local density calculated and saved into the grid of the density field. According to Proxemic theory (Hall, 1963) the public distance among pedestrians is between 3.0 m and 6.0 m. Considering a cell c with $i = Row(c)$ and $j = Col(c)$:

$$Sep(c) = -\frac{DensF_{i,j}}{MaxDensity}$$

where $MaxDensity$ is the maximum global density value that the density field can assume, according to the radius r used in its definition. Output of Sep function are in the $[-1, 0]$ range. In our case, the value of $MaxDensity$ that can reach with the discretion of $40cm \times 40cm$ is equal to $6.25m^{-2}$ with $r = 1$. Graphical representation of the $Sep(c)$ progress is shown in Fig. 4.2.

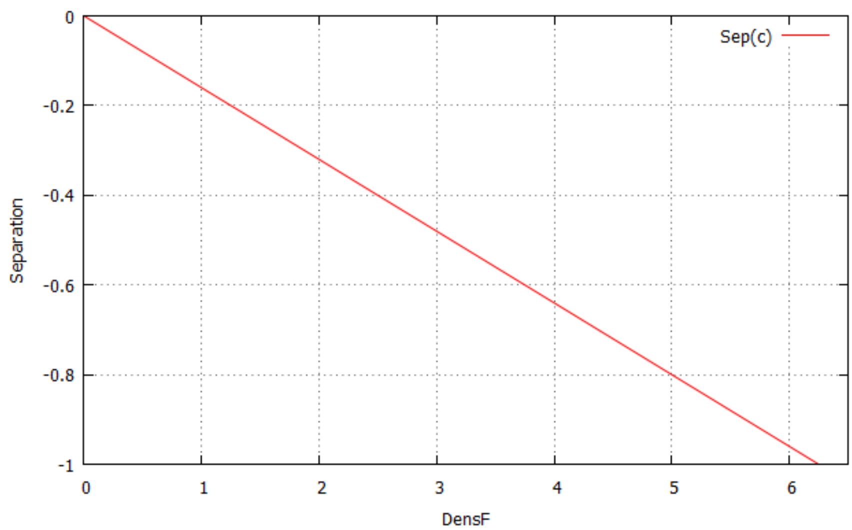


Figure 4.2: *Graphical representation of function $Sep(c)$*

Direction Inertia

This factor represents the fact that pedestrians tend to maintain the direction during movement towards a destination. Unexpected changes of direction are usually avoided by pedestrians: for this reason, a value is added in the case that cell c is located in the same direction with respect to the previous movement (except the case in which agent remained in the same cell, i.e. $PrevDirection = X$):

$$Dir(c) = \begin{cases} 1 & \textit{if } PrevDirection = Dir(c) \\ 0 & \textit{otherwise} \end{cases}$$

where $Dir(c)$ is the direction in which cell c is, with respect to the current position of agent.

Overlapping Extension

In order to allow the model to deal with high densities situations and, in particular, to support counter-flux scenarios in which groups of people have to move through a dense crowd, a proposal to try to overcome the maximum density (and maximum flow) limits of all the CA-based models (Klüpfel, 2003), derived from the discretization of space and the non-interpenetration law was investigated, extending the model with a so-called *overlapping* method, that relaxes the non-interpenetration principle allowing pedestrian overlaps during the simulation.

More in detail, in this extension, we allowed pedestrians to transiently overlap with a small probability: at each time step (a maximum of) two pedestrians are allowed to stay on each cell.

$$State(c) = s : s \in \{FREE, OBSTACLE, ONE\_PED_i, TWO\_PEDS_{i,j}\}$$

State $TWO\_PEDS_{i,j}$ indicates that cell c is occupied at the same time by agent i and agent j. The set of admissible actions $AdmAct$ is modified allowing that also cells already occupied by one other pedestrian are admissible cells, for $j \in Pedestrians$:

$$AdmAct_p = \{a : a \in Act \ \wedge \ (State(a(c)) = FREE \vee State(a(c)) = ONE\_PED_j\}$$

With this extension, we want to model the fact that in some situations, especially in high densities, pedestrians rotate their body to pass in tight spaces. So, densities higher than the limit of $6.25m^{-2}$ are allowed, because of the maximum possible density is $12.5.m^{-2}$, thought that parameters must be fine calibrated to prevent such unreasonable (and not justified by empirical evidences) conditions. Overlapping also influences the calculation of utility function $U_a(c)$, assigning a penalty if the overlapping occurs:

$$Over(c) = \begin{cases} -1 & \textit{if } State(c) = ONE\_PED \\ 0 & \textit{otherwise} \end{cases}$$

Because of overlapping event can happen just in particular situation of densities, a trade-off function on the basis of the density value in the scenario is configured, managing the calibration of overlapping event k_{ov}:

$$Balance_{ov}(c) = \begin{cases} k_{ov} + \delta_{high} - DensF_{i,j} & \textit{if } \delta_{low} \leq DensF_{i,j} < \delta_{high} \\ 0 & \textit{otherwise} \end{cases}$$

where $i = Row(c)$, $j = Col(c)$, $DensF_{i,j}$ is the value of density field in the cell c and δ_{high} and δ_{low} are the two density thresholds that regulate the activation of overlapping.

Proxemic Cohesion

Positive values with respect to group cohesion and according to distances among group members is defined as follow, where the cohesion value is calculated as sum of factors decreasing with respect to the distance:

$$Coh_a(c) = \left[\left(\eta \cdot \sum_{a_i \in G} (DistFunction_{a,a_i}(c)) \right) \cdot 2 \right] - 1$$

where η is a normalization factor that, along with numerical values, allows to translate the cohesion value into the range $[-1, 1]$, and $DistanceFunction$ is a function that represents the gain of agent a with respect to agent a_i belonging to the same group G_a, moving into cell c. In the case of the evaluation of group cohesion, the perception of agents is expanded: every agent is able to perceive the members of the same group considering a distance parametric value g_d. $DistFunction$ is so defined as:

$$DistFunction_{a,a_i}(c) = \frac{distance(Position(a), Position(a_i)) - distance(c, Position(a_i))}{size(G_a) - 1}$$

representing the gain that agent a obtains moving in a particular cell c with respect to agent a_i. In Fig. 4.3 an example of how this mechanism works is provided: agent a is represented by black element in the grid. For every cell in its neighborhoods the evaluation of gain cohesion towards agent a_i, the grey element, is shown: it is clear that the movement that maximize the gain is moving towards NE. Moreover, note that the evaluation of the distance is not related to the real spatial distance because it works on local position of agent a with respect to agent a_i .

4.2 Dealing with Structured Groups

Observing daily experiences with pedestrian dynamics, various types of groups can be detected. The most common kind of group are families or helper with elderly or disable people, in which members are connected by a strong relationship. In this case,

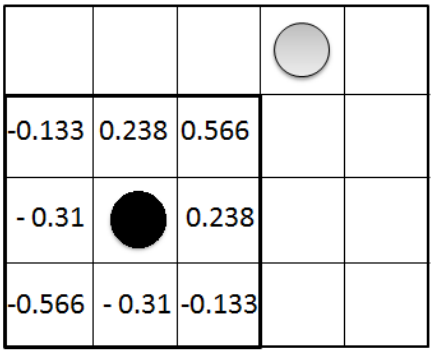


Figure 4.3: *Graphical representation of $Cohesion_a(c)$ function*

no separation rule exists among group members (except, of course, the interpenetration principle): during the movement towards the goal, it is not allowed the splitting of the group. In this case, the cohesion need is so strong that pedestrians admit to stop following the goal in order to reassemble the group. In Fig. 4.4 a picture from the Berlin subway shows clearly the presence of this kind of groups, and, more in detail, a situation in which people stop themselves waiting for all the group components (on the left).

Figure 4.4: *A picture from Berlin subway, underlying the presence of groups with strong relationships*

Other kinds of group are based on not so strong relationships, allowing some separations among members, for instance large groups of friends or work-groups. Moreover, it is possible to detect the so-called artificial groups, in which several minor groups are collected, belonging to one of the previous types of group: for example, tourist groups can be seen as a collection of sub-groups of relatives or friends with the same goal to visit a particular area (see Fig. 4.5).

Figure 4.5: *A picture of a tourist group: sub-groups can be easy detected inside the larger group*

In order to provide a (satisfactory) model including this view on pedestrian group, the previously defined Coh function is not sufficient: mechanisms to regulate cohesion and goal attraction in groups with strong relationships have to be implemented, along with the necessity to represent structured gathering of people, in which a balance metric between sub-groups adjusts the inter-cohesion values. Moreover, a discussion on the evaluation of separation values between members of groups is required.

In this section, first a formal definition of structured group is provided: the focus will be on the structure definition and on the evaluation of distances among groups in the structure as an atomic element. Then, the focus will be on metrics for spatial group dispersion and on a trade-off analysis to introduce in the model mechanisms to regulate cohesion and goal attraction in sub-groups and in simple groups.

4.2.1 Definition of Structured Groups

As already mentioned in Sec. 3.3 while simple or informal groups are based only on a high cohesion level, moving all together towards the same goal due to endogenous desires, structured groups are more complex objects, usually bigger than simple groups (more than 4 individuals) and they can be seen in a recursive way as composed of sub-groups (see Fig.4.6). Structured groups usually are created by an external entity or with the scope to face a particular situations.

Structured groups are formally described as:

$$\bar{Group}_j = \langle Id, Group_1, \ldots, Group_m \rangle$$

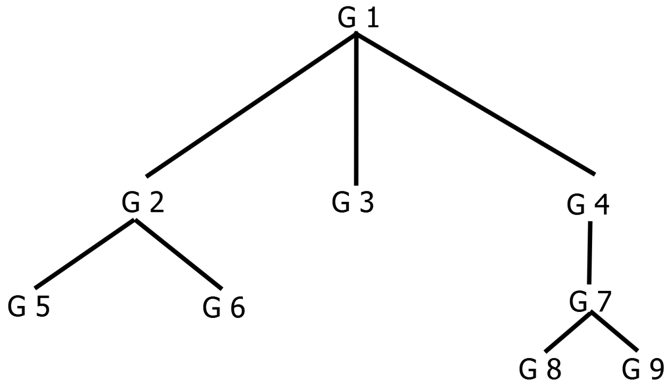


Figure 4.6: *A structured group* $\bar{G}_1$

An appropriate function $InterGroup_a(c)$ with the relative weighed parameter k_i is added to the $U_a(c)$ function:

$$U_a(c) = \frac{k_g \cdot Goal(c) + k_o \cdot Obs(c) + \ldots + k_c \cdot Coh(c) + k_i \cdot InterGroup_a(c)}{d}$$

where $InterGroup_a(c)$ function is defined as:

$$InterGroup_a(c) = \left[\eta \cdot \sum_{a_i \in G - g_a} (DistFunctionI\bar{G}_{a,a_i}(c) \cdot 2 \right] - 1$$

where $\bar{G}_a$ is the macro-group that contains both agent a and a_i, g_a is the simple group which a belongs to, and function $DistFunctionI\bar{G}_{a,a_i}$ works on the tree-structure of the macro-group, identifying the proximity of two sub-groups in the tree of the structure by means of the detection of the nearest common root of the two groups $\in \bar{G}_a$. In Fig. 4.6 a graphical representation of a structured group $\bar{G}_1$ composed of several sub-groups is proposed: considering, for instance, and agent a belonging to group G_5 and agents belonging to group G_6, the function identifies $\bar{G}_2$ as common root between these two elements. The inter-cohesion value between $a \in G_5$ and group G_6 is stronger than to the inter-cohesion value between agent $a \in G_5$ and group G_8.

More formally:

$$DistFunctionI\bar{G}_{a,a_i}(c) = \frac{1}{distance(c, Position(a_i))} \cdot \frac{1}{(Size(mcg(G_a, G_{a_i})) - 1)}$$

where mcg is the smallest sub-group of $\bar{G}_a$ including both G_a and G_{a_i}

This mechanism allows the representation and the evaluation of the structure of an artificial group: despite that, the definition of the simple Coh function previously introduced is not sufficient to the representation of high levels of cohesion. Some tests related to this function underlined that it produces situations in which group members appear too cohesive or, on the contrary, too disperse: the problem is that this function works on local distances among two agents, without considering the overall space covered by the group. Moreover, this function produces situations in which members of a group with strong relationships, for instance families, tend to disperse themselves.

All these considerations, along with the necessity to support the representation of groups with strong relationships, require a deeper analysis on group cohesion in terms of space occupation, and an analysis of trade-off among different attractive elements.

4.2.2 Metrics for Group Dispersion

Intuitively, the dispersion of a group can be seen as the degree of spatial sparseness of their members. The problem to evaluate the dispersion of a group is currently an open issue: just in Müller-Funk (2007) the notion is analyzed in the Computer Science field as a relevant notion in the context of clustering algorithms. Related to the pedestrian dynamics field, the estimation of different metrics for group dispersion is discussed in Bandini et al. (2011c) in which different approaches are compared to evaluate the dispersion of groups through their movement in the environment. In particular, two different approaches are compared: (i) dispersion as occupied area and (ii) dispersion as distance from a centroid.

Formally, the formulas of group dispersion for each approach are defined as follows:

$$Disp(Group) = \frac{\text{Area(Group)}}{Size(Group)} \tag{Area}$$

$$Disp(Group) = \frac{\sum_{i=1}^{Size(Group)} distance(centroid, a_i)}{Size(Group)} \tag{Centroid}$$

with Area(Group) as the area occupied by the group, $Size(Group)$ as the number of its members, $centroid$ as its centroid. Results underline that the second approach suffers the effect of particular configurations in which the value of cohesion appears as low while a face validation of the situation indicates a good group cohesion. These wrong evaluations are detected in particular in medium and high-density situations in which groups tend to stretch themselves to walk through bottlenecks or narrow walk-able areas. The centroid method identifies groups as highly disperse under these conditions, because some pedestrians can be far from the center of the group.

Differently, the first metric, that can appear as more simple, defines the dispersion of the group as the portion of space occupied by the group with respect to the size of the group. Figure 4.7 illustrates how this metric works: the first step works on all the vertices (i.e. the members of the group, see Fig. 4.7a), building a convex polygon with the minimum number of edges that contain all the vertices. The second step works on this output, calculating the area of the convex polygon (see Fig. 4.7b). The dispersion value is calculated as the relationship between the polygon area and the size of the group.

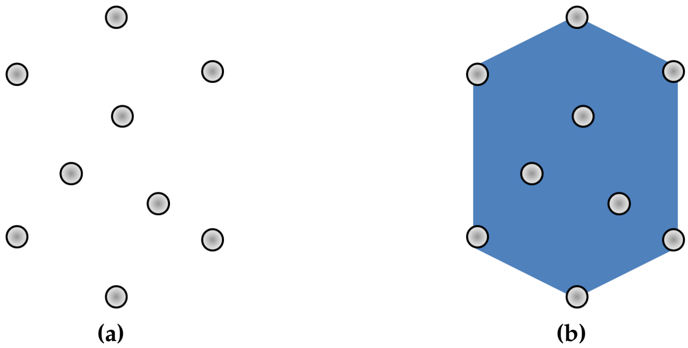


Figure 4.7: *Graphical representation of a group composed of nine members and the area of the convex polygon that contains all the group members*

The evaluation of group dispersion is an element that has to be considered during the management of the dynamics of the simulation, in particular in relationship with the goal attraction force and the attraction in structured groups: as introduced in Sec. 2.2, when pedestrians are involved in a group, their behavior change, liking better the communication, the interaction and the cohesion with respect to the achievement of the goal. Therefore, in the next section, an analysis of the dependence between intra-inter cohesion values and goal attraction value is proposed, such as an evaluation of separation value inside a group.

4.2.3 Trade-off Analysis

A trade-off process between the goal attraction value and the intra-inter cohesion value is required: in the situation in which the spatial dispersion value is low, the cohesion behavior has to count less than the goal attraction behavior. On the contrary, if the level of sparseness of group is high, the cohesion behavior is more important than the goal attraction behavior. A trade-off process between these two values is necessary, by means of a $Balance(k)$ function that can be used and expanded to face out this situation:

$$Balance(k) = \begin{cases} \frac{1}{3} \cdot k + (\frac{2}{3} \cdot k \cdot DispBalance) & \textit{if } k = k_c \\ \frac{1}{3} \cdot k + (\frac{2}{3} \cdot k \cdot (1 - DispBalance)) & \textit{if } k = k_g \vee k = k_i \\ k & \textit{otherwise} \end{cases}$$

where k_i, k_g and k_c are the weighted parameters $U_a(c)$ and

$$DispBalance_\delta = tanh\left(\frac{Disp(Group)}{\delta}\right)$$

is another function that works on the value of group dispersion as the relationship between the area and the size of the group, applying on it the hyperbolic tangent. Note that, in this case, the value of δ is equal to 2.5, allowing the output of $DispBalance$ function in the range $[0, 1]$ according to all elements in $U_a(c)$. The definition of the function is shown in Fig. 4.8: the hyperbolic tangent approaches value 1 when $Disp(Group) \geq 6$ (values $\geq$ 6 indicate a high level of sparseness for small-medium size groups (1-4 members)).

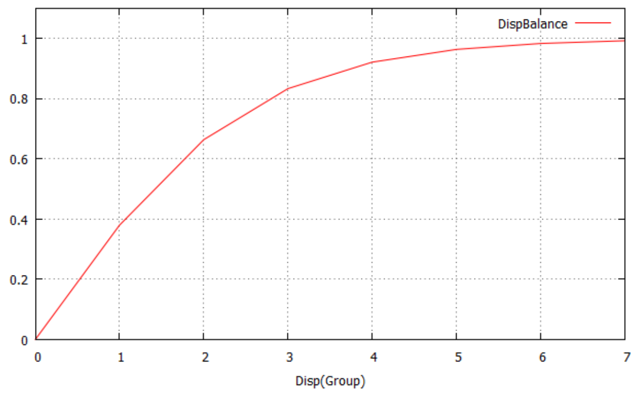


Figure 4.8: *Graphical representation of $DispBalance$ function*

A graphical representation of the trade-off mechanism is shown in Fig. 4.9: red and green boxes represent the progress of parameter k_c and parameter k_g, respectively. Note that the increasing of the dispersion value produces an increment of k_c value and a reduction of k_g parameter.

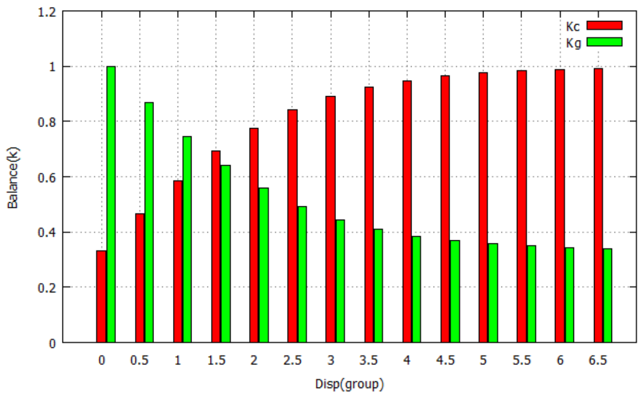


Figure 4.9: *Graphical representation of $Balance(k)$, for $k = 1$*

Furthermore, according to Xu and Duh (2010), the value of separation among group members has to be modified, on the basis of the assumption that pedestrians within a group allow to stay more close each other with respect to strangers: more in detail, the value of separation in a group is equal to the half among strangers.

A new function $SepGroup_a(c)$ is defined, providing the value to discount to the separation repulsion on the basis of the group to which the agent a belongs to (the case in which agent does not belong to a group is also expressed):

$$SepGroup_a(c) = \begin{cases} \displaystyle\sum_{a_i \in G - \{a\}} \frac{1}{distance(a_i, c)^2} \cdot 0.5 & \textit{if } a \in G \\ 0 & \textit{otherwise} \end{cases}$$

The new separation value is now obtained as:

$$Separation_a(c) = Separation(c) - SepGroup_a(c)$$

It must be emphasized the fact that this adaptive balancing mechanism and the current values for its parameters were heuristically established and they actually require a validation (and plausibly a subsequent calibration) by comparing results achieved with this configuration and relevant empirical data about group dispersion gathered from actual observations and experiments in controlled situations.

4.3 Limits of the Model

After the explanation of the model, some limits of the approach are now discussed, which can be interpreted as future extensions without changing the core of the method. The main limit of our approach is the *impossibility to support high levels of density* (more than $4\ m^{-2}$): the CA-approach, along with the chosen size of the cells, does not support the simulation of these density values. The overlapping extension can help from this point of view, but the calibration of the relative parameter is sometimes problematic: little changes produce a large variability in the output of the simulation and produce a too fluid pedestrian flow in particular scenarios. A possible solution could be a redefinition of the size of the cells moving towards smaller cells of size 15 cm $\times$ 15 cm: in this way, every pedestrian could occupy more than one cell. This solution will require several changes in the management of pedestrian movement with respect to the current state of the model.

Another limit of the model is related to *the lack in the definition of intermediate markers*: we define start and destination areas without allowing the generation of more complex path in which several intermediate goals can be included. Compared to the analysis in Sec. 2.1 intermediate points should represent part of the so-called tactical level in Fig. 2.1. Moreover, these intermediate markers could be useful for the detection of statistics during the simulation, for instance for the calculation of pedestrian flow and traveling time in different points of the scenario, to be used in the analysis of results.

From the group point of view, also considering the analysis of the literature in Sec. 2.2.5, in this model the *leader-follower approach* is not explicitly modeled, even though the trade-off method among goal attraction and intra-inter cohesion values allows the identification of temporary leaders that are in front of the group during the simulation and that stop themselves waiting for the reassembling of the group. Leader-follower approach could be implemented in our model considering the possibility to define different types of pedestrians with different parameters and the balance function: the leader should follow the desire to reach the destination with respect to the need to stay close to its followers. The latter should just play a role in the cohesion of the group.

The last aspect we want to underline is about the impossibility to define *heterogeneous velocities* in the model: a shuffled sequential update is here used as strategy to define the dynamics of the model. A possible solution can be the use of parallel update strategy, supporting the definition of different velocities (in terms of update turns): it may be useful in modeling pedestrians with disabilities or elderly people, such as stairs or other structural elements that usually influence the velocity of pedestrians.

4.4 Developing the Model: Analysis of Requirements

As expressed in Chapter 1, every theoretical model needs a validation on the basis of data collected by means experiments or observations directly on the target, in order to show its capability to reproduce pedestrian behavior in a qualitative and quantitative way. In order to support the process of validation of the model, it is necessary to develop a tool that, on the basis of the model, supports the testing process.

In this section an analysis about requirements that a tool implementing the model hereby explained should have is pointed out: the main capability of the system is the possibility to offer a set of functionality that allows the management of environment and pedestrians and, more in general, of the simulation engine.

Focusing on the management of the simulated scenario, the platform should support the handling of discrete environments, providing instruments for spatial annotations to represent start-end areas and the generation of floor fields. In addition, the tool should provide functionality for the generation and the management of agents, along with the definition of simple and structured groups.

A simulation engine is also required, that allows the management and the interaction between the spatial annotations and, more in general, the scenario of the simulation, and the mechanism of perception and movement of pedestrians: beside the implementation of a sequential shuffle update strategy, other mechanisms as parallel update can be implemented, enabling the possibility to compare different approaches on the same scenario by means of the same tool.

Another characteristics of the tool should be to allow a graphical evaluation of the simulation, by means an instantaneous visualization of the output and the possibility to record video results.

Actually, a tool following these directions and based on the model here proposed was developed by the CSAI Research Group: an overview of the platform is available in Appendix A.

4.5 Conclusions

In this Chapter, a model based on a floor-field method, in which utility-based agents represent pedestrian behavior according to elements derived from the literature (i.e., goal attraction, obstacle and pedestrians repulsion) and to innovative aspects investigated in this thesis (i.e, simple and structured groups of pedestrians) was proposed. Representation of the environment and of pedestrians such as the mechanisms besides operational movement of agents were pointed out, also with an extension to cover high-density situations.

The definition of agents is richer with respect to the definition given in Chapter 3, due to the expansion of the model and the integration of the agents in a spatially defined environment. With respect to groups and structured groups, the definition provided are aligned with Sec. 3.1 and Sec. 3.3. Regarding the definition of proxemic separation and proxemic group cohesion, it is possible to underlined that also in the discrete model the behavior of agents is strictly influenced by these elements: distance functions are implemented to manage the spatial relationships among pedestrians, also introducing the definition of spareness of a group as dispersion value.

The dynamics of the system is obtained as the composition among all the forces that influence the single agent behavior: the trade-off work among components is here engaged with the introduction of balance functions, and interactions are modeled by means of floor fields.

In the next Chapter, the process of validation of the model hereby proposed will be discussed, using the tool presented in Appendix A, focusing on common (but well-know and deeply analyzed) scenarios used in the literature for model validation.

5

Experimenting Model

As previously introduced in Sec.2.1, models on pedestrian dynamics have to be evaluated according to a specific and well-know methodology in order to be validated respect with data from observations and experiments. A possible strategy for the evaluation of a pedestrian dynamics model is the comparison of its results in the case of benchmark scenarios, for instance corridors, corners and bottlenecks, for which observations and empirical data already exist in the literature. Note that, as already stated in Sec. 2.1.4, a pedestrian dynamics model has to be able to reproduce both *quantitative* and *qualitative* phenomena.

Starting from these consideration, in this Chapter, the process of validation of our model is described, first including a description of the methodology traditionally used in the validation step in the literature (Sec. 5.1). Several scenarios will be introduced for the evaluation of the model and to study the impact of the presence of groups and their inner spatial behavior on pedestrian flows, along with an evaluation of the capability of the model to reproduce reasonable pedestrian trajectories, focusing on traditionally employed benchmark scenarios characterized by both unidirectional and bidirectional flow, with and without bends (Sec. 5.2). Chapter ends with a discussion on simulation results and on the capabilities of the model to reproduce peculiar scenarios in Sec. 5.3.

5.1 Traditional Methodology of Validation

The state of the art in this research field is full of models to represent pedestrian dynamics and behaviors, based on different approaches for the representation and management of environment and pedestrians. From the beginning, the problem of the evaluation of models appears as significant, mainly due to the scarce presence of collected and empirical data on the topic. Data are difficult to collect both for ethical and privacy issues, and for methodological problems in planning experiments and observations.

In recent years, several efforts were done to face this open issue, and set of data from experiments and observations related to pedestrian flow are now available to researchers[1]: these data allow defining a set of features that models have to be able to reproduce to cover the majority of the aspects that characterize pedestrian dynamics.

The validation is conducted comparing particular types of output of the model with selected experiments and observations on the basis of methods well-know in the literature (Axtell et al., 1996). The validation process is not a simple task: for instance, in Pettré et al. (2009) experiments on a well known and widely adopted model (Helbing, 2001), that is able to generate plausible and realistic dynamics from both qualitative and quantitative perspectives (e.g. formation of lanes, patterns at intersections and bottlenecks), show that it does not faithfully reproduce a pedestrian avoidance pattern among just two individuals (Fig. 2.6).

For this reason we used both quantitative and qualitative methods in the validation process: in the following, an overview on all the methods we used, aiming at validating the model with respect to the traditional methodologies and in several benchmark scenarios, will be introduced.

5.1.1 Validation on Fundamental Diagram

One of the most diffused methods to evaluate the plausibility of a model is the so-called *fundamental diagram* in which the relationship between the variation on the flow with respect to an increasing of the density is represented. It is useful to evaluate the effectiveness of the model to represent its degree of thinness describing the empirical dependency between pedestrian density ρ and the flow J, defined as the number of pedestrians in a portion of space in a temporal unit.

Usually, the analytic definition of flow according to the fluid-dynamics point of view is:

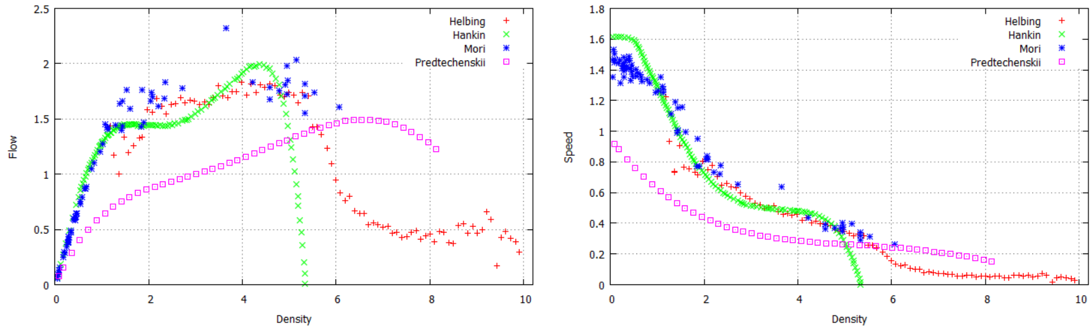
$$J = \rho \times v$$

where v is the average speed of pedestrians in the scenario. Starting from this definition, two observables usually concur in the evaluation of the model, analyzing the relationship between the specific flow and the density $J_s(\rho)$ and between the velocity and the density $v(\rho)$.

Both velocity and flow are connected to the measurement of travel time of pedestrians. Considering the specific nature of pedestrian dynamics models, but also the nature of the simulated reality (that sometimes proposes very complex environmental structures), it is more appropriate to talk about average travel time associated to a given path[2] working on aggregate data, due to the fact that simulations can reproduce both optimistic and downbeat situations: results of pedestrian and crowd models should therefore be considered and analyzed at an aggregate level.

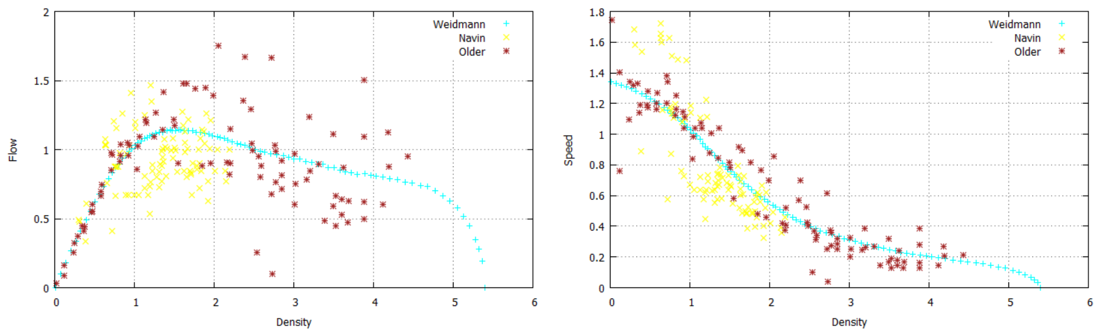
[1]See http://www.ped-net.org/ as one of the main resource for data on pedestrian dynamics

[2]And sometimes to a given type of pedestrian, whenever the model can deal with different types of agents in the simulated scenario.



(a) (b)

Figure 5.1: *Fundamental diagrams in case of unidirectional flow (data source* `http://www.ped-net.org/`*)*



(a) (b)

Figure 5.2: *Fundamental diagrams in case of bidirectional flow (data source* `http://www.ped-net.org/`*)*

Figure 5.1 and 5.2 represent fundamental diagrams in terms of relationships between velocity and density (on the right) and between flow and density (on the left): these charts are based on data collected in `http://www.ped-net.org/` by several research groups all over the world.

From the analysis of these fundamental diagrams, it is clear that different experiments gathered different values of empirical data. In general, there is a decrease in the velocity when density grows; the flow, instead, initially grows, since it is also directly proportional to the density, until a certain threshold value is reached (also called *critical density*), then it decreases.

Consensus on the shape of the function is wide, but the range of the possible values has even big differences: in Fig. 5.1 and 5.2 several differences can be detected in the set of fundamental diagrams, both between lines related to design manuals (Predtechenskii and Milinski (1978) and Weidmann (1992)) and also between data points related to experimental measurements, respectively carried out in the context of the Hajj (Saudi Arabia) (Helbing et al., 2007), in a London subway stations (UK) (Hankin and Wright, 1958), in the city of Osaka (Japan) (Mōri and Tsukaguchi, 1987), in the University of Missouri (USA) (Navin and Wheeler, 1969) and in a shopping street in London (UK) (Older, 1968).

Another categorization can be also done according to the type of the flow represented by data, as unidirectional or bidirectional flow. While Fig. 5.2 collects data from bidirectional studies, Fig. 5.1 shows the trend in case of unidirectional flow: several differences in terms of variation of flow and critical density reached can be easily detected between Fig. 5.1 and Fig. 5.2.

Moreover, also considering series under the same condition of unidirectional or bidirectional flow, variations in diagrams can be detected. For instance, the maximum possible value for density before congestion arise is also disputed. Different motivations have been proposed so far to understand the reasons of variations, such as the impact of psychological factors on pedestrian movements, cultural differences that works on proxemic spaces (Chattaraj et al., 2009; Morrall et al., 1991) and the impact of the scenario in which measurements are detected (Ye et al., 2008) (e.g. in shopping areas pedestrian walking speeds will be different with respect to stations).

Despite the inconsistency in terms of range of data, the consensus on the shape of the function is shared among researchers: for this reason, the validation of a model works on its capability to reproduce the same variation in terms of relationship between flow and density (as a bell-shaped function) and between velocity and density (as a monotonically decreasing function).

5.1.2 Validation on Space Utilization

Another aspect that the majority of the models in the literature does not consider is the capability to reproduce plausible behavior of pedestrians in terms of movement and effective utilization of space. Despite the fact that a model can be able to reproduce the fundamental diagram, also it has to be able to manage the use of space and the trajectories of pedestrians.

In opposite with respect to the *empirical* validation reached by means of fundamental diagram, these components can be analyzed by means of a *face validation* approach: according to Klügl (2008) this paradigm collects all methods that rely on natural human intelligence showing that processes and outcomes are reasonable and plausible within the frame of theoretic basis and implicit knowledge. It is often also called *plausibility checking* in which the output of the model has to show believable behavior and movements. This analysis can be supported also by means of diagrams reproducing the way in which pedestrians use the environment of the simulation in terms of space occupation and level of service. If a model is not able to reproduce these effects, something could be wrong in reproducing pedestrian behavior.

The main scope of this kind of analysis is to verify the capability of the model to reproduce emergent and collective phenomena that characterize the behavior of a crowd and that can be easily detected by observations:

- *jamming and density waves*. They first typically occur in high density situations, where the inflow exceeds the capacity of the structural environment, for example in bottleneck scenarios. The reason of jamming formation is the exclusion principle: space occupied by one pedestrian is not available for others. The same phenomenon can be identified in crowded corridor in which density fluctuations can be detected;
- *lane formation*. It can be detected when groups of people move in opposite directions in a crowded environment and they spontaneously organize themselves into different lanes, one for each direction of travel (Navin and Wheeler, 1969; Yamori, 1998). The formation of lanes prevents strong interactions with oncoming pedestrians and allows reaching higher walking speeds;
- *trajectories* of pedestrians. In particular scenarios, pedestrians usually follow well-know and observable trajectories: for instance, considering a corner scenario, the use of space by pedestrians close to the angle is interesting to evaluate trajectories of pedestrians and their behavior in turning (Zhang et al., 2011b).

The following methods are usually considered to study the presence of the above mentioned elements:

- *space utilization* diagram: it represents the use of space by pedestrians showing information related to the occupation of space[3] during a simulation, in order to derive pedestrian trajectories. It can be useful for the detection of lane formation, jamming and congestion situations. For instance, considering a corridor scenario with a bidirectional flow, studying the space utilization diagrams associated to the two single flows it is possible to compare the trajectories and derive the presence of lanes. Particular type of space utilization diagram are the follows:
  - *space movement* diagram that just represents movements (from one point to another one) in the environment, without taking into account situations of congestion in which pedestrians do not change their position;
  - *space block* diagram that, on the contrary, represents block situations in which pedestrians do not change their position;
- *level of service* diagram: this concept was first used in the field of traffic engineering. In the same way, the level of service concept can be applied in the design of pedestrian space and it is based on qualitative evaluation of pedestrian movement on the basis of freedom to select normal locomotion speed, the ability to

[3]According to a value of discretization used in the model or set ad-hoc for this analysis.

bypass slow-moving pedestrians and the relative ease of cross-and reverse-flow movements at various pedestrian traffic concentrations.

Levels of service (LOS) for pedestrians were first introduced in Fruin (1992): different standards are defined for (i) walkways, (ii) stairways and (iii) queuing scenarios, providing values and ranges for the average pedestrian area occupancy and the average flow rate in every scenario. Breakpoints for the ranges and the various levels have been determined on the basis of walking speed, pedestrian spacing and the probabilities of conflicts. Six LOS are defined: the application of the specific ranges depend on the kind of scenario we are interested in analyzing. Fig. 5.3 shows the LOS scale in case of walkways[4] both as flow rate and pedestrian occupancy.

LOS	FLOW RATE *(ped/min/met)*	PED OCCUPANCY *(m2/ped)*
A	≤7	≥12
B	7–23	3.7 -12
C	23–33	2.2 -3.7
D	33–49	1.4 - 2.2
E	49–82	0.6 - 1.4
F	Var.	≤ 0.6

Figure 5.3: *Level of service in walkways from Fruin (1992) and adapted in Rouphail et al. (1998)*

While the first one describe the number of pedestrians passing for a (linear) portion of space in a temporal unit (usually, 1 minute), the second one is derived from the density in the scenario, referring to the concept of cumulative mean density (already introduced and discussed in Sec. 4.1.1) to evaluate the perceived density of a pedestrian in a particular point in the environment. Indeed, another way to represent LOS concept is to study the density profile as graphical representation of the CMD of the scenario. It is possible to provide also the following LOS textual description (Fruin, 1992)

1. *A*-LOS: sufficient area is provided for pedestrians to freely select their own walking speed, to bypass slower pedestrians, and to avoid crossing conflicts with others;
2. *B*-LOS: sufficient area is available to select normal walking speed, and to bypass other pedestrians in primarily one-directional flow;
3. *C*-LOS: freedom to select individual walking speed and freely pass other pedestrians is restricted;

[4] The one we used in our analyses.

4. *D*-LOS: restriction in moving with normal speeds for the majority of pedestrians, due to difficulties in bypassing slower-moving pedestrians and avoiding conflicts;
5. *E*-LOS: restriction in moving with normal speeds for all the pedestrians, requiring frequent adjustments of gait;
6. *F*-LOS: all pedestrian walking speeds are extremely restricted, and progress can be made only by shuffling.

LOS approach it is commonly used and applied by several designing manuals (sometimes with little variations, according to more recent observations taking into account differences by cultural aspects in different countries) (Rouphail et al., 1998) and by commercial software as a standard for the analysis and the evaluation of a scenario (Fig. 5.4).

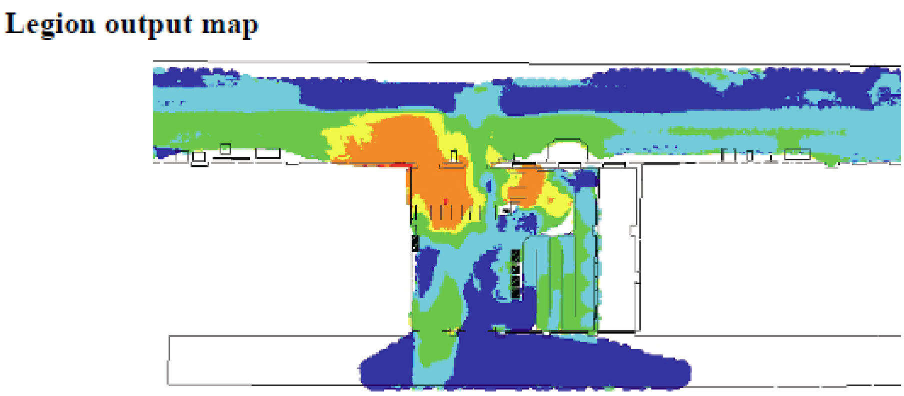


Figure 5.4: *Legion cumulative mean density (Walkway LOS) output map from Castle et al. (2011)*

5.1.3 Validation on Groups

Unfortunately, the issue of group modeling appeared in the literature very recently (from 2009), so data related to this phenomenon are very scarce: Moussaïd et al. (2010), Costa (2010), Willis et al. (2004) and Schultz et al. (2010) work on observations to manually derive elements related to the presence of groups within a crowd, such as the spatial pattern of groups and the walking speed. This is not a simple task, due to the fact that sometimes the detection of groups[5] can not be based just on spatial cohesion, because also verbal and non-verbal communication among participants (talking, gesticulation, visual contact, body orientation and spatial arrangement) have

[5]Some proposals on automatic detection of groups within a crowd in Leal-Taixe et al. (2011) and Bazzani et al. (2012).

to be considered. It is not our aim to provide a comprehensive discussion of the issues related to analysis and detection of groups by means of automatic or manual techniques. More details on group data collection can be found in Appendix B.

Considering the current state of the research, the validation of the model with respect to groups is a hard problem: despite that, fundamental diagrams on flow and velocity of groups have surely to be in tune with the analysis above provided in Sec. 5.1.1. However we expect an impact of group presence on these results and even a difference between individuals and group members in these scenarios. On the other hand, speed and velocity of single pedestrians and group members are not enough to characterize their dynamics. Mechanisms introduced to represent and manage group interactions are aimed at introducing cohesion. How to measure their effectiveness? As already stated in Sec. 4.2.2 we introduced a metrics to evaluate the dispersion of a pedestrian groups as the ratio between the occupied area and its size. We will use the same metrics to evaluate the behavior of groups in terms of aggregation and dispersion, analyzing the group dispersion on the basis of this method. The variability of this factor will be evaluated according to an increasing from a density viewpoint in order to study if the mechanism works, maintaining a plausible level of cohesion within groups also under the influence of pedestrian density.

5.2 Application of the Model on Benchmark Scenarios

The description on traditional methods for model validation is the starting point to introduce the process of validation we propose. The step of validation was done by means of a tool based on the agent-based model proposed in Chapter 4 and developed by CSAI Research Center, that supports the development of what-if scenarios about pedestrian dynamics with groups within structured environments (see Appendix C for a complete description of the tool).

Benchmark scenarios on which the model was tested are the follows:

- *linear scenarios*, corridors of different size in which an analysis based on fundamental diagrams with a bidirectional flow and the detection of lane formation phenomenon were performed;
- *corner scenario*, in which an analysis based on fundamental diagrams with a unidirectional flow was performed;
- *T-junction scenario*, in which an analysis of fundamental diagrams, trajectories and level of density were performed.

In all the scenarios the impact of groups was evaluated by means of a comparison in terms of fundamental diagrams and an analysis of group dispersion.

5.2.1 Technical Details

Before discussing the results in all the above mentioned scenarios, it is necessary to point out some technical details about the running of the simulations.

Calibration process

The first step in the validation process always consists in a calibration step in which all the components that concur in the definition of pedestrian behavior are analyzed and balanced among them: in particular, in our model, we recall that the movement of agents in the scenario is based on the evaluation of the utility on all the cells in their neighborhood according to the weighted utility function $U(c)$ (Sec. 4.1.5).

From this point of view, we require that all the $k_i \in [0 - 100]$ parameters in $U(c)$ were involved in the calibration process, aiming at finding standard values to set up simulations. The process of calibration was incremental, first focusing on every parameter and then combing them to study the overall dynamics.

Results on several tests generated the following configuration:

- $k_g \in [8 - 12]$ (*goal attraction*): higher values tend to wipe out the other behavioral components and the movement of pedestrians is only influenced by the goal;
- $k_o \in [8 - 10]$ (*obstacle repulsion*);
- $k_s \in [10 - 30]$ (*proxemic separation*): higher values tend to generate block situations in bidirectional flow without generating the effect of lane formation;
- $k_d \in [1 - 2]$ (*previous direction*): for higher values pedestrians tend to exceedingly maintain the previous direction of movement;
- $k_{ov} \in [9 - 13)$ (*overlapping*): for higher values the effectiveness of overlapping method does not influence the flow while for lowest values pedestrian flow becomes too much fluid with respect to level of density;
- $k_c \in [6 - 8]$ (*proxemic group cohesion*): for higher values the dynamics of pedestrians is influence by the tendency of groups to stay too cohesive and to behave like blocks with respect to the overall dynamics;
- $k_{inter} \in [6 - 8]$ (*structured group cohesion*): higher values influence too much the cohesion in structured groups that try to behave as simple groups with a high level of cohesion. Differently for lower values, the cohesion is not relevant with respect to other behavioral components.

The configuration[6] used in all the benchmark scenarios in which the model was validated is the follow: $k_g = 8$, $k_o = 8$, $k_s = 28$, $k_d = 1$ $k_c = 7$, $k_{inter} = 7$ and $k_{ov} = 9.5$.

[6]Unless otherwise noted.

Duration of Simulations

We already introduced the different scenarios in which we want to test and validate the model: from this point of view a first question to build the simulation process is related to the quantity and the duration of the simulations.

For every scenarios and for every level of density we performed a minimum of 3 and a maximum of 8 simulations, according to the degree of variations in the simulation results (an increasing in the variations corresponds to an increasing in the number of experiments): variations were derived from the analysis of standard deviation on results. In particular, large variations were detected approximating the critical density in the fundamental diagram, while for lower and higher level of density variations are smaller. Experiments were first performed with a pedestrian configuration without groups and then replicate with groups.

We define a simulation as a sequence of steps, temporal units in which all the pedestrians in the scenario evaluate the current state of the simulation (both in terms of environment and other pedestrians), choose their next movement and update their position according to the already cited shuffle sequential strategy (Sec. 4.1.3). We previously defined in Sec. 4.1.2 that the duration of the each time step in terms of "simulated" seconds is equal to 3 steps/second.

Every simulation we performed was compose of 1.800 steps that correspond to 10 minutes of simulated flow. The time necessary to complete such as simulations depend on the level of density in the scenario: for the lowest level of density ($0.5\ m^{-2}$) the simulation time is about 5 minutes, while for the highest level of density ($4.0\ m^{-2}$) is about $2:30$ hours[7].

Statistics on Simulations

Output produced by the tool simulation are saved in the end of the simulations and every 180 steps: several statistics data necessary to support the analysis on singles and groups are available allowing a comparison in terms of fundamental diagrams and space utilization diagrams.

With respect to the total duration of a simulation (1.800 steps), we required that the first 100 steps are cut and not considered in the evaluation of statistics: the reason is the fact that we want to avoid the initial condition in which the density in the scenario is not the overall density we are studying because of some agents could not enter yet the scenario. Moreover, we want to avoid the effect of starting waves as presented in Tomoeda et al. (2012). Without this wariness, data in output could present some turbulence and be compromise.

[7] On a Dell Precision 3500, Intel Xeon, Quad Core 2.53GHz. Note that the parallelization of a simulation on the different cores is not supported due to characteristics of the simulation tool that deals with simulation as a unique and indivisible task. However, to optimize the validation process we run parallel simulations exploiting all the four cores of our CPU.

5.2.2 Linear Scenarios

In this section we propose the analysis of corridor scenario in which a bidirectional flow of pedestrians is simulated. More in detail, the analysis of the flow is performed on three different linear scenarios with a variation of size in terms of width and height (Fig. 5.5).

The configurations taken into account are related to a linear corridor with size 2.4 m $\times$ 20 m *(a)*, 3.6 m $\times$ 13.3 m *(b)* and 4.8 m $\times$ 10 *(c)* as shown in Fig. 5.5. Note that the variation in terms of width and height were applied according to the principle to maintain the total area equal to 48 m^2 in every scenario. In particular, between the first and the second configuration the values of width and height were respectively multiplied and divided by 1.5, while between the first and the third configuration the values where respectively multiplied and divided by 2.

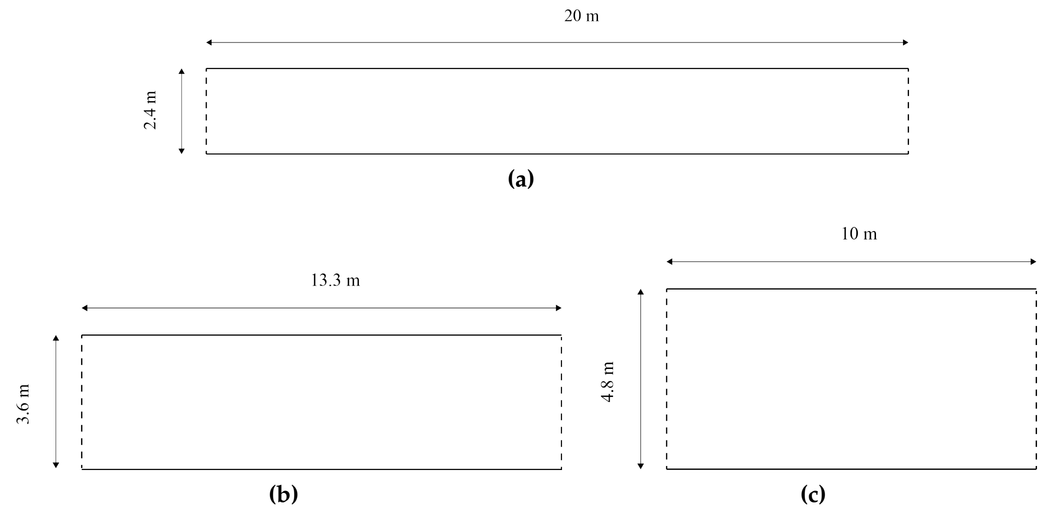


Figure 5.5: *Linear corridors with size* 2.4 *m* $\times$ 20 *m* (a), 3.6 *m* $\times$ 13.3 *m* (b) *and* 4.8 *m* $\times$ 10 *m* (c)

After the definition of the environmental configuration of scenarios, an analysis related to the initialization of the simulations in terms of *¡number of pedestrians-density¿* was done. According to the aim to evaluate how the presence of groups influences the pedestrian flow, in all the scenario simulations with and without groups were done, studying the variation of the flow in both cases. The choice to test the model in bidirectional condition allowed the study of the impact of groups as a negative or a positive elements in solving several points of collisions among pedestrians, surely influenced by the mechanism of group cohesion.

In Table 5.1 the configurations used to initialize the simulations are shown: for each level of density, the total number of pedestrians in the scenario is shown (column two). In case of simulations without groups, the number of the pedestrians in the scenario overlaps with data in column two, while in case of simulations with groups, the number of pedestrians is divided into singles, couples, triples and groups of six (dealt with simple groups). Table 5.1 reports the division of pedestrians in these categories: note that the number of pedestrians is equally divided into the two starting areas on the left and on the right, in order to represent a bidirectional flow equally balance. The overall population of a starting area behaves as a structured group[8], in which a low level of cohesion models the attractiveness among pedestrians and groups that share the same starting area and the same goal[9].

Density	Pedestrians	Singles	Couples	Triples	Groups of six
0.5	30	16	4	2	0
0.8	50	10	8	4	2
1.0	60	20	8	4	2
1.2	70	20	10	6	2
1.3	74	24	10	6	2
1.4	84	30	12	6	2
1.5	90	32	14	6	2
1.6	96	32	14	8	2
1.7	100	36	14	8	2
1.8	104	40	14	8	2
1.9	110	40	14	10	2
2.0	116	42	16	10	2
2.1	122	44	18	10	2
2.2	130	48	20	10	2
2.3	134	48	22	10	2
2.4	138	48	24	10	2
2.5	146	48	22	10	4
2.7	160	52	24	12	4
2.9	170	62	24	12	4
3.2	186	64	28	14	4
3.5	202	74	28	16	4
3.7	214	76	30	18	4
4.0	232	78	32	18	6

Table 5.1: *Configurations used in the simulations according to level of density: values in column two represent the total number of pedestrians in the scenario. All these values are equally distributed with respect to the two starting areas in the scenario*

[8]We applied this configuration in terms of simple and structured group to all the scenarios presented in the validation process.

[9]This method is also comparable with the use of dynamic floor field proposed in Burstedde et al. (2001)

Values in Tab. 5.1 are obtained from an analysis of the relevant literature with respect to the few observations on groups (Moussaïd et al., 2010; Willis et al., 2004; Schultz et al., 2010; Federici et al., 2012). In particular, in the case of simulations with groups the 35% of pedestrians are considered as single while the 65% belong to groups, divided into couples (45%), triples (35%) and groups of six members (20%). The decision to perform the study considering couples, triples and groups of six was done because observations underlined that these are the most common typology of groups that can be identified within a crowd.

Several analysis were made with respect to the results of the simulation: variations in the flow and the velocity of pedestrians with and without groups were evaluated, validating the model and analyzing and discussing the impact of groups on pedestrian flows. Contribution of groups on the basis of their size was also investigated, showing the relationship between the size of a group and its influence on the flow.

In the end, an evaluation of the influence of variation in the width of the scenario will be discussed.

Validation of the Model and Impact of Groups in Linear Scenarios

The first analysis on results of the simulations was performed to validate the model with respect to variation of the flow without groups using fundamental diagrams, in the three different environmental configurations before introduced.

For simplicity, let us introduce the notation we will use in the following:

- corridor with size 2.4 m $\times$ 20 m will be referenced as corridor *A*;
- corridor with size 3.6 m $\times$ 13.3 m will be referenced as corridor *B*;
- corridor with size 4.8 m $\times$ 10 m will be referenced as corridor *C*.

Fig. 5.6, Fig. 5.7 and Fig. 5.8 show three fundamental diagrams, one for each environmental configuration, in which blue and red points respectively represent pedestrian flow without and with groups.

All the diagrams properly represent changes in the flow with respect to the level of density. The range for the critical value of density belongs to the interval $[1.8 - 2.3]$ m^{-2} in the situation without group, in tune with experimental results and data obtained from validated and recognized models in the literature.

About the impact of groups, a variation of flow in case of groups with respect to the case without group has to be analyzed. Considering charts in Fig. 5.6, Fig. 5.7 and Fig. 5.8, it is possible to note that the level of critical density reached by the flow without groups is higher with respect to the flow with groups: in the latter, the value of critical density belongs to the interval $[1.5 - 1.8]$ m^{-2}. This means that the flow without groups increases until values in the interval $[2.0 - 2.2]$ $s^{-1}m^{-1}$ while the flow with groups until value in $[1.5 - 2.0]$ $s^{-1}m^{-1}$.

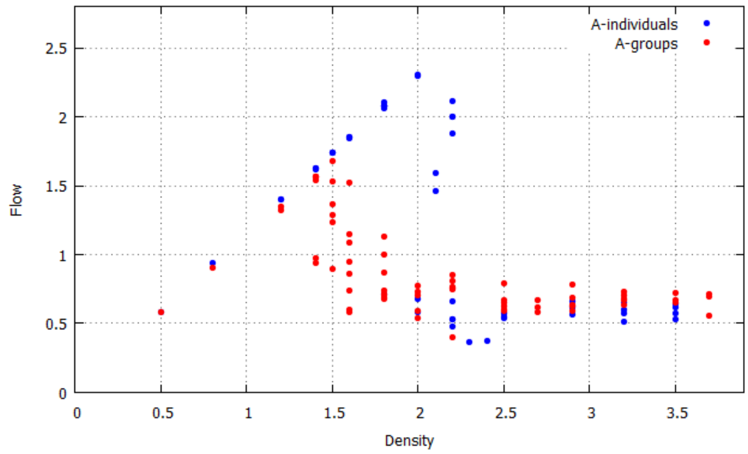


Figure 5.6: *Fundamental diagrams with and without groups in corridor A*

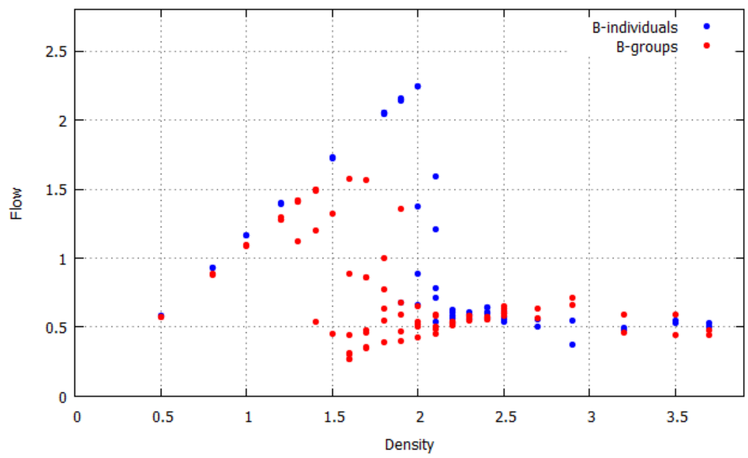


Figure 5.7: *Fundamental diagrams with and without groups in corridor B*

On the basis of these analyses, the presence of groups can be interpreted as a *negative factor* on the flow dynamics. This trend is maintained for a level of density $< 2.5\ m^{-2}$.

Differently, for higher densities (from $2.5\ m^{-2}$ to $4.0\ m^{-2}$), the presence of groups has a little impact on pedestrian flow, that can be also considered as positive: in Fig. 5.6 and 5.7 it is possible to note that higher level of flow are assigned to situations with groups with respect to situations without groups.

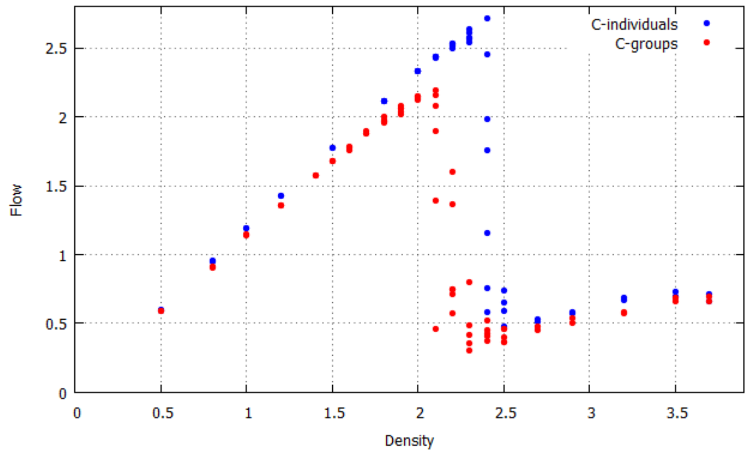


Figure 5.8: *Fundamental diagrams with and without groups in corridor C*

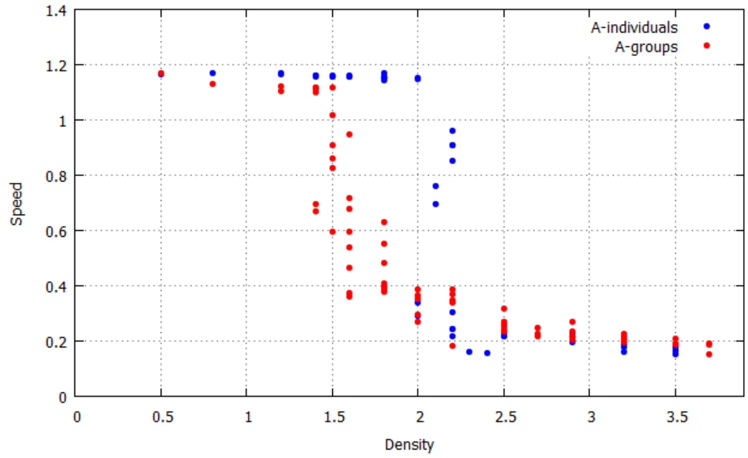
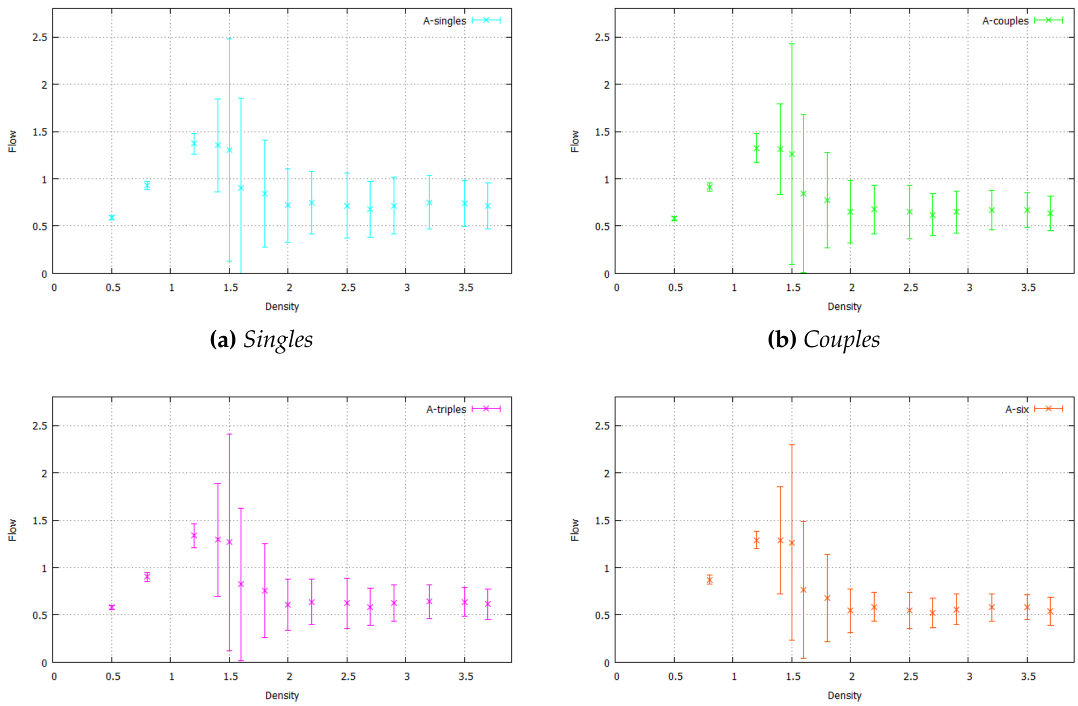


Figure 5.9: *Speed diagram in corridor A*

This phenomenon can be further investigated by means of an analysis of pedestrian speed: Fig. 5.9 shows the speed diagram in corridor A, in which pedestrian speed decreases with respect to the increasing of the density until a certain value. In general, the average speed of pedestrians in a flow without groups is higher with respect to the configuration with groups, while, for values of density $> 2.5\ m^{-2}$, it is possible to note that the speed values are comparable, probably due to the presence of the lane formation phenomenon, that was detected by means of a face validation process on space utilization diagrams. The behavior in terms of speed and the detection of lanes explains the variation in the fundamental diagrams on the overall density interval. Also preliminary analyses on experimental data presented in Nishinari (2012) and Manenti et al. (2011) support this results, that can appear as counterintuitive, showing that the presence of groups and, in particular, of couples, can positively influence the pedestrian flow.



(a) *Singles* **(b)** *Couples*

(c) *Triples* **(d)** *Groups of six*

Figure 5.10: *Fundamental diagrams related to different groups involved in the simulations with the relative standard deviations*

The impact of groups can be analyzed more in detail considering the singular influence of every type of group (according to its size) to the pedestrian flow with the goal to understand if a relationship exists between the size of the group and its (negative) contribution to the overall pedestrian dynamics.

To reach this scope, data related to the different simulated groups were aggregated, and a comparison among the relative fundamental diagrams was performed. In Fig. 5.10 fundamental diagrams on aggregated data related to the different types of groups involved in the simulation are presented, along with the relative standard deviation: Fig 5.10a represents the variation for singles, Fig. 5.10b represents the variation for couples, Fig. 5.10c represents the variation for triples and Fig. 5.10d represent the variation for groups with six members. As summary, Fig. 5.11 represents on the same chart all group contributions.

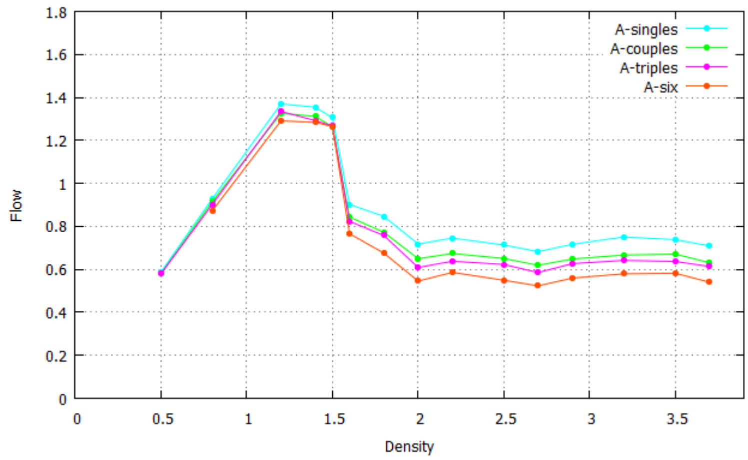


Figure 5.11: *Comparison among fundamental diagrams on aggregate data with respect to groups of different size*

Influence of Corridor Width

The choice of evaluating the influence of groups in different linear scenarios was inspired by Zhang et al. (2011b), in which a comparison in terms of pedestrians flow from experimental data among three corridors of width 1.8 m, 2.4 m and 3.0 m is presented. In this case, authors show that, in conformance with Hankin and Wright (1958), above a certain minimum of about 1.22 m, the maximum flow is directly proportional to the width of the corridors.

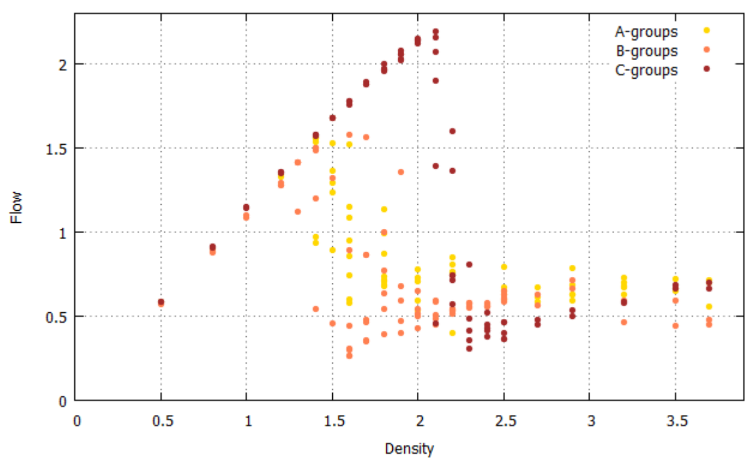


Figure 5.12: *Comparison among corridor widths: fundamental diagrams in case of groups in corridors A, B and C*

We have chosen to expand the width of the corridors considering the comparison among sizes of 2.4 m, 3.6 m and 4.8 m. Figure 5.12 represents the three different fundamental diagrams in case of groups: these results are in tune with the above mentioned theory about the dependency between maximum reachable flow and the width of a corridor. In particular, in the case of corridor C, relevant variations can be detected around the critical density value. After that value, the influence of width on the pedestrian flow seems to be not relevant, probably due to the activation of overlapping extension to deal with high density situation (Sec. 4.1.5) and to the phenomenon of lane formation.

5.2.3 Corner Scenario

The second scenario in which the model was experimented is a corner corridor with size 2.4 m $\times$ 6.4 m. The corner was set up according to Zhang et al. (2011b) and the output of simulation without groups were compared with data collected from authors. Figure 5.13a and 5.13b respectively show the dimension of the scenario and a graphical representations of pedestrians trajectories.

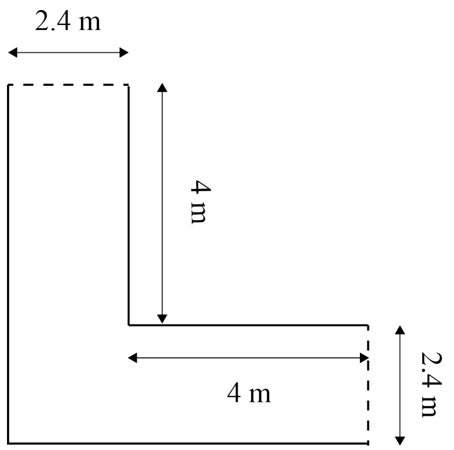
Density	Pedestrians	Singles	Couples	Triples	Groups of six
0.5	15	5	2	2	0
0.8	23	8	2	2	1
1.0	29	10	3	2	1
1.2	35	12	4	3	1
1.5	44	15	7	3	1
1.8	53	19	8	4	1
2.0	59	21	10	4	1
2.5	73	26	10	5	2
3.0	88	31	13	6	2

Table 5.2: *Configurations used in the corner simulations according to the level of density*

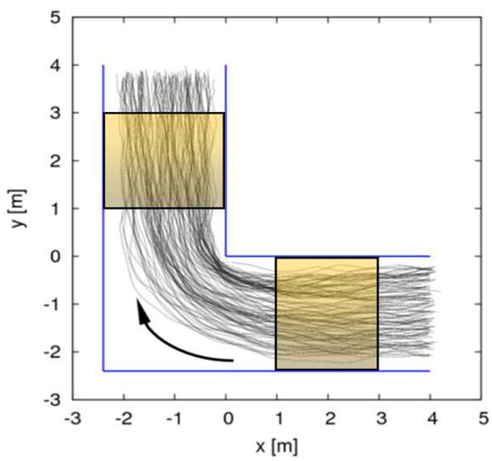
Several simulations with and without groups were conducted: configurations used are shown in Table 5.2. Note that in this scenario, with respect to the linear ones, variation in the unidirectional flow (according to trajectories in Fig. 5.13b) was investigated: for this reason, all the pedestrians in the scenario share the same starting area.

Due to the fact that the flow is just unidirectional, the shape of fundamental diagram differs from the one in case of bidirectional flow. Figure 5.13c represents four sets of experimental data in which the first and the second data set graphically represented by squared points are related to the pedestrian flow in front of turning and behind turning. It can be noted that the flow just increases and that the level of the critical density is not reached[10].

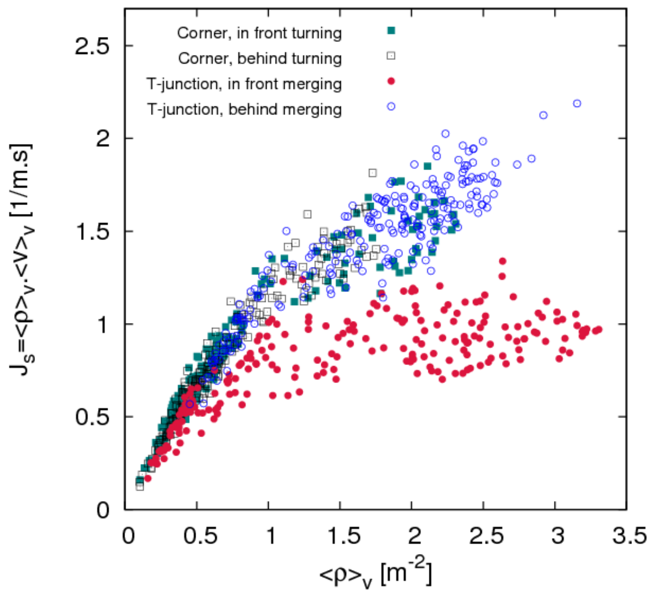
[10]According to Sec. 5.1.1, the critical density value in case of unidirectional flow belongs to the range



(a) *Scenario*



(b) *Trajectories*



(c) *Experimental data*

Figure 5.13: *Graphical representation of corner scenario* (a),*trajectories and experimental data from Zhang et al. (2011b)* (b) *and* (c)

Our model is able to represent the same tendency: in Fig. 5.14 blue line and red line respectively represent the variation of the flow with average data without and with groups. It is clear that groups negatively influence the variation of the flow that does not increase so much in case of pedestrian aggregation.

$[4.0 - 8.0]\ m^{-2}$, that is not reached both in experiments of Zhang et al. (2011b) and in our simulations.

Therefore, the analysis related to contribution of the different group typology was done: results agree with the previous analysis in case of linear scenarios. The size of group directly affect the pedestrian flow, and an increasing in the size of group correspond to a decrease in terms of flow.

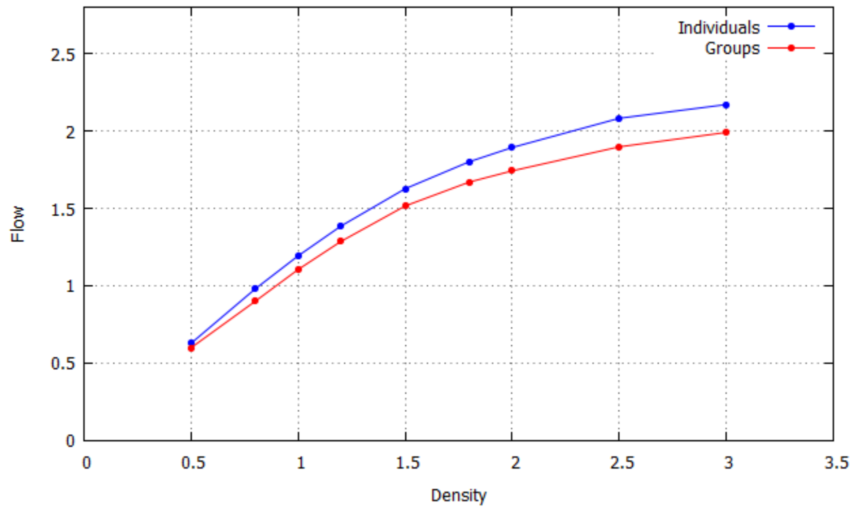


Figure 5.14: *Fundamental diagrams with (in red) and without (in blue) groups in the corner scenario obtained by simulations*

5.2.4 Evaluation on Cohesion Mechanism

Both in the linear and corner scenarios an analysis on the effectiveness of the mechanism to manage group cohesion is required: as previously introduced in Sec. 4.2.3 a balance mechanism regulating the tendency to reach the goal and the tendency to stay cohesive with group members works on a metrics by evaluating group dispersion as ratio between the area occupied by the group and its size.

Fig. 5.15 shows the relationship between the increasing of the density and variation of group dispersion in corridor B. It can be noted that the density does not significantly influence the group cohesion: dispersion in couples belongs to the interval $[0.2 - 0.4]$ m^2, dispersion in triples to $[0.9 - 1.3]$ m^2 and dispersion in groups of six to $[5.0 - 5.6]$ m^2. This means that the mechanism to manage group cohesion works well, decreasing the tendency to reach the goal in favor of group cohesion. Same results were obtained in corridor A and corridor C: figure 5.16 shows the comparison between dispersion values in groups of six in the three different linear scenarios. While in corridor B and C the dispersion of this kind of group is comparable, in corridor A the width definitely impacts on the variability on the dispersion of groups that belong to the interval $[5.1 - 7.1]$ m^2.

Related to the corner scenario, the dispersion of groups is more influenced with respect to the linear ones due to the trajectories that pedestrians follow: groups mainly disperse in turning, occupying a bigger area with respect to linear scenarios. Figure 5.17 shows the behavior for every type of group in the corner scenario: dispersion in couples belongs to the interval $[0.3 - 0.8]\ m^2$, dispersion in triples to $[1.0 - 2.1]\ m^2$ and dispersion in groups of six to $[4.7 - 8.4]\ m^2$.

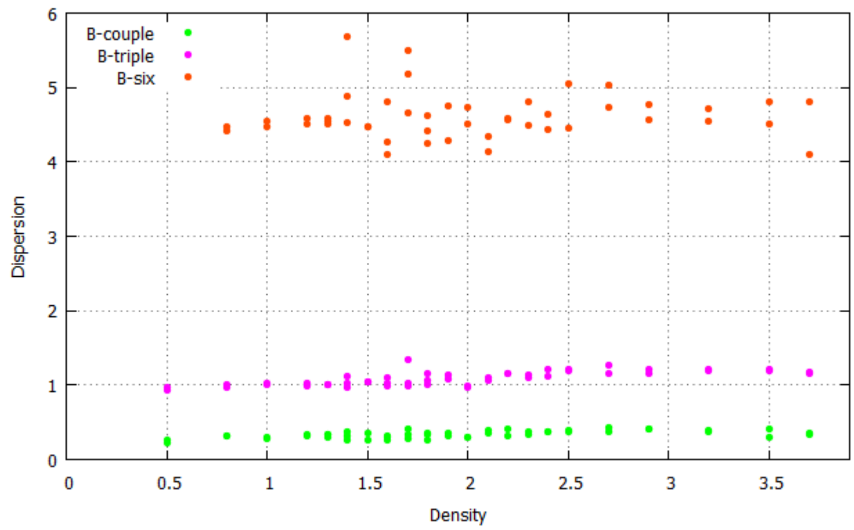


Figure 5.15: *Group dispersion in corridor B*

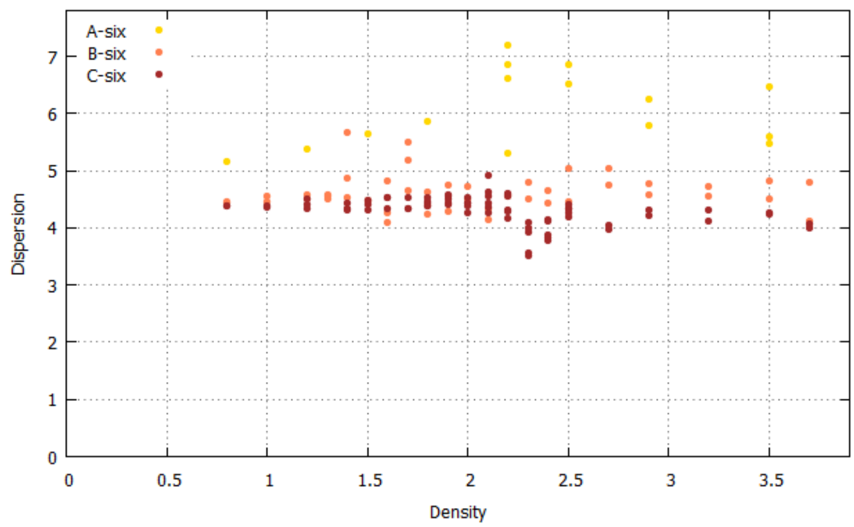


Figure 5.16: *Comparison among group of six members dispersion in corridor A, B and C*

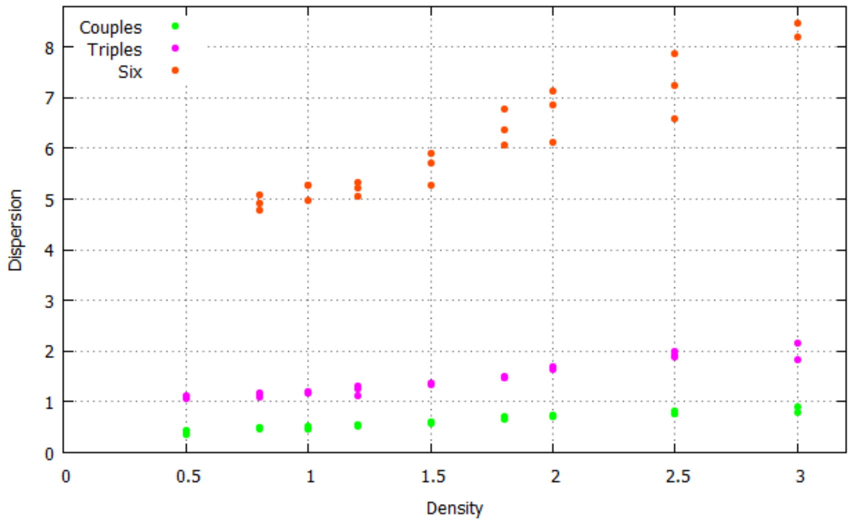


Figure 5.17: *Group dispersion in corner scenario*

5.2.5 T-junction Scenario

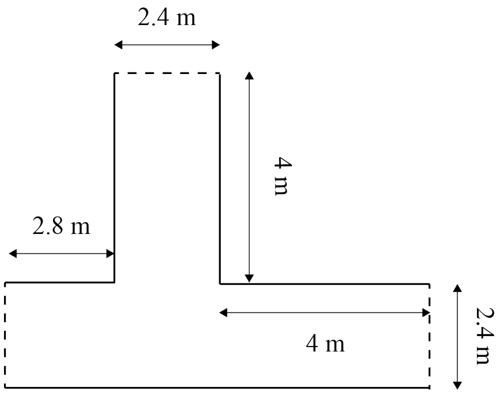
The last scenario in which the model was tested is a so-called T-junction scenario (Fig. 5.18a in which two pedestrian flows share the same destination area according to trajectories shown in Fig. 5.18b. In this scenario both simulations with and without groups were conducted, according to configuration in Table 5.3 where the number of pedestrians are equally divided into the two starting area. Note that with respect to the parameter configurations presented in Sec. 5.2.1 $k_{ov} = 13$: we decreased this parameter to avoid situations in which pedestrian flow is too fluid due to the activation of overlapping.

Fundamental diagrams were compared with data shown in Fig. 5.13c from Zhang et al. (2011b) in which dot points represent the flow in front merging and behind merging in the T-junction scenario.

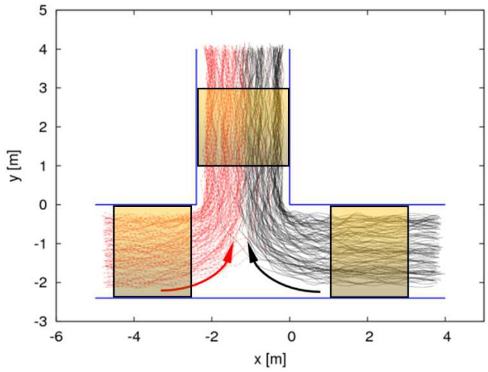
Finally, results on group influence underlined that they have a *negative* impact on the overall flow.

Density	Pedestrians	Singles	Couples	Triples	Groups of six
1.0	45	16	7	3	1
1.5	67	23	10	5	1
2.0	89	31	13	7	2
2.5	112	39	16	8	2
3.0	134	47	20	10	3

Table 5.3: *Configurations used in the T-junction simulations according to the level of density*



(a) *Scenario*

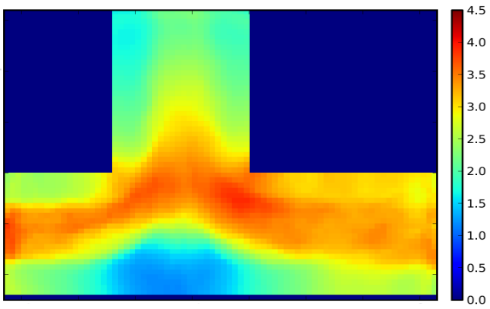


(b) *Trajectories*

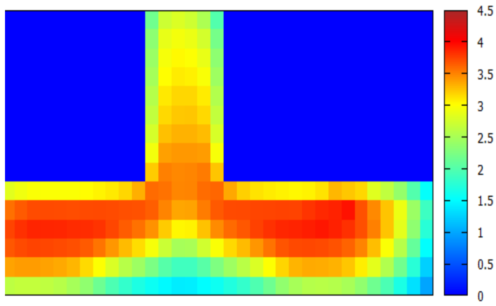
Figure 5.18: *T-junction scenario and trajectories from Zhang et al. (2011a)*

Moreover, an analysis on spatial dynamics of the motion in T-junction scenario was made in Zhang et al. (2011a) by means of topographical information for density profile according to CMD values. The density in the T-junction is not homogeneous (see Fig. 5.19) and a higher density region appears near the junction. The lowest density region is located at a small triangle area, where the left and right branches begin to merge. The density in the branches (near to starting areas) are not uniform and are higher over the inner side. From this point of view, pedestrians prefer to move along the shorter and smoother path.

Our model is able to reproduce the phenomenon: a comparison between the two different density profiles from one run of a simulation with an overall density equal to $2.5\ m^{-2}$ is shown in Fig. 5.19. It can be noted that our model represents well the use of the space by pedestrians and their trajectories. The maximum CMD reaches is the same in the two density profile, and equal to $4.5\ m^{-2}$.



(a)



(b)

Figure 5.19: *Density profile from Zhang et al. (2011a)* (a) *and from our model* (b)

5.3 Conclusions

After the experimentation of the model in benchmark scenarios and the analysis of the data, a discussion on results in order to point out the contribution of the thesis about influence of groups is now propose.

Comparisons based on fundamental diagrams confirm that the model is validated and it is able to correctly represent pedestrian dynamics with respect to benchmark scenarios, both in case of bidirectional and unidirectional flow with and without the presence of groups.

Results also confirm that simple groups *certainly influence pedestrian flow* and, more in detail, that they *negatively influence* the dynamics for density $> 2.5\, m^{-2}$. The behavior for higher densities seems to be different: groups little impact the flow.

As it has been already discussed in Sec. 4.3, due to intrinsic limits of the model based on choices in the representing environment, the model is not able to support it and it is not validated for levels of density $> 4\, m^{-2}$.

Actually, these levels can be detected just in peculiar situations: the circular movements of pedestrians during the Tawaf[11] represents one of this situation, reaching very high level of density and congestion (see Sarmady et al. (2011) for a model representing this situation). Also in emergency situations these levels characterize the situation near the exits, in particular in the case of panic situation.

Related to pedestrian trajectories and their use of space by means of the analysis of space utilization and level of service, our model is able to well represent pedestrian movements: this kind of analysis is useful in case of evaluating strategies for pedestrian management or relevant changes in the configuration of the environment. Simulations allow a comparison among pedestrian management strategies or structural changes in the environment, identifying if they can influence in a positive or negative way the pedestrian flow.

All these results and considerations are related to simple groups: about structured groups a deeply investigation is of course required, such as a more precisely calibration in terms of group cohesion. This process requires sets of data, from observations or empirical experiments, but as we already discussed in Sec. 5.1.3, at now there is a limitation from this point of view. Despite that, the use of structured groups allow to preserve and to replicate the phenomenon of lanes formation in counter flow scenarios.

A real-world situation in which we used the model to perform an evaluation on different strategies and different environmental configurations is presented in Appendix C focusing on the analysis of entry process in the station of Arafat I on Mashaer line in Saudia Arabia in the context of CRYSTALS project.

[11] It is one of the Islamic rituals of pilgrimage. During the pilgrimage towards Mecca, Muslims are to circumambulate the Kaaba (most sacred site in Islam) seven times, in a counterclockwise direction.

6 Conclusions

In this thesis, the issue of modeling groups of pedestrians was dealt with a multidisciplinary approach to investigate the phenomenon of groups as basic elements which a crowd is composed of, and their features in terms of (not only) spatial relationships among members. The starting point for this analysis was the application of Proxemic theory to formally define relationships among pedestrians with respect to inter and intra relationships in groups.

These analyses provided the definition of a general framework for modeling pedestrian groups, in a pedestrian dynamics systems without an explicit declination of space and time of the model.

On the basis of this framework, an agent-based computational model for pedestrian dynamics simulation, explicitly defining the concept of group, was developed, calibrated and validated, adopting the traditional methodologies used in the literature with the goal to study the phenomenon within a crowd, analyzing if their presence influences the dynamics of pedestrian flow and evaluating if their contribution can be interpreted as a positive or a negative factor.

In this thesis we referred as methodology to the 4-step cycle to model complex systems already presented in the Chapter 1, starting from the definition of the main elements of the model towards the development of a computation tool allowing the comparison and the validation of the model on empirical data according to the traditional methods recognized and commonly used in the literature.

Compared with group modeling proposal analyzed in Chapter 2 they usually focus only on little groups from 2 to 4 individuals and they are just partially validated, not considering all the possible methods that have to be considered in the evaluation of a pedestrian dynamics model. Differently, our computational model supports both the definition of simple and structured groups, allowing the management of different levels of cohesion in the same scenario. Our model is not based on the leader-follower paradigm, providing a dynamic changes in the configuration of groups in terms of leadership, useful to characterize situations with high cohesion aspects[1].

[1]Surely, the analysis of the effect of leader-follower mechanism can be one of future developments and investigations starting from the results of the work here presented

Regarding the validation process, the methodologies we used to test the model were seriously approached providing both a quantitative analysis of data and a qualitative representation of movements in terms of trajectories, pedestrians use of space, block situation, density profile and level of service.

Validation process allowed studying the contribution of simple groups on the overall dynamics of a pedestrian system: results showed that they highly impact on flow of pedestrians both under bidirectional and unidirectional conditions.

More in detail, the influence has a negative connotation: impact of simple groups is confirmed as negative both from the results of the model in several benchmark scenarios and from the analysis of data collected during an observation activity. Moreover, results match with the (few) analyses and (scarce) observations on groups presented in the literature, and with the observation we performed at our University. In the latter, results on walking speed in groups showed that, at a low level of density: (i) the more the size of the pedestrian groups is, the lower the walking speed is; (ii) there are no significant differences in walking speed among gender composition and group spatial arrangement; (iii) lane formation phenomenon was easily detected in high density situation during the entrance process to the buildings.

Considering both the observation and the results of our model, one of our main contributions is to confirm the thesis that the phenomenon of groups is relevant in the pedestrian dynamics, and also that it should be considered in the management of crowds and pedestrians: therefore, pedestrian dynamics models should include the possibility to model and define groups of pedestrians. These evaluations are also in tune with results by Moussaïd et al. (2010); Xu and Duh (2010); Sarmady et al. (2009).

From this point of view, our framework and the relative formalization of the phenomenon proposed in Chapter 3 is general enough to be used to support other researchers interesting in to face the problem in the development of pedestrian dynamics models including groups, identifying peculiar elements that should be taken into account in group definition.

More related to group behavior analysis, a definition of different metrics for spatial dispersion can proceed from the approach we used in Chapter 4: this is currently an open issue not only in the pedestrian dynamics field but also in the area of computer science, in which the concept of group can have different shades (e.g. in the graph theory field and for the cluster analysis). Data collected during the validation process and shown on benchmark scenarios in Chapter 5 can be used as starting data set for a comparison among group dispersion metrics.

All these results and considerations are related to simple groups: about structured groups a deeply investigation is of course required, such as a more precisely calibration in terms of group cohesion. This process requires sets of data, from observations or empirical experiments, but as we already discussed in Chapter 5, at now there is a limitation from this point of view. Despite that, the use of structured groups allow to preserve and to replicate the phenomenon of lanes formation in counter flow scenarios.

These analyses on group dispersion - group cohesion mechanism and the formalization of the phenomenon can also positively effect other studies not only in the pedestrian dynamics field: for instance, in the area of computer vision, the detection of individuals is a hard problem with practical results. In fact, problems related to analysis of crowded scenes arise in a variety of contexts, such as surveillance system, event recognition system, density evaluation system (Metaxas et al., 2011). Despite some proposals for detection of single individuals already exist in the literature and are commonly employed, the issue of detected groups of pedestrians appears as more complex: considering spatial distance between two individuals is not a sufficient element to automatically imply their affiliation to a group, because also verbal and non-verbal communication among participants (talking, gesticulation, visual contact, body orientation and spatial arrangement) have to be considered. Early proposals already appeared in the literature (Leal-Taixe et al., 2011; Bazzani et al., 2012), and our work can be applied and used to improve methodologies and to develop algorithms to track groups of pedestrians within a crowd.

Although our model concerns the operational level, trying to solve the problem to determine which will be the precise path that pedestrian will follow reaching his/her goal, a proposal towards the inclusion of tactical and strategic levels can be easily supported by our model. In this case, the focus is on the list of activities to be performed by pedestrians and in which order: an expansion of our model to cover this aspect is presented in Manenti et al. (2012). In this work we show that the use of floor field method to expand information in the environment can be used to support the definition of list of activities, assigned to agents in the beginning of the simulation and defined by means of data gathering and observations on the scenario.

From this point of view, the expansion could be twofold: more related to our work, we could improve our possibilities to extend the model to create more complex scenarios towards the definition of a complete pedestrian dynamics model covering all the aspects (operational level, tactical level, strategic level) defined by Schadschneider et al. (2009). On the other side, a possibility is to include the concept of group just on tactical level: until now and at our knowledge, there are no activity-based models in the literature considering the schedule of activities for groups. The study could be interesting with respect to the case in which group members are in competitions (and not in cooperation) in terms of activities to be performed.

A
MAKKSim: a Tool for Pedestrian Simulation

The aim of this appendix is to introduce MAKKSim, a tool based on the agent-based model proposed in this thesis in Chapter 4 and used for the validation process of the model in Chapter 5. MAKKSim is a software simulation platform developed by CSAI - Complex Systems and Artificial Intelligence Research Center and it supports the development of what-if scenarios about pedestrian dynamics within structured environments and with the presence of structured groups. The tool is one of the results of CRYSTALS project, a multidisciplinary research between the Center of Research Excellence in Hajj and Omrah (Saudi Arabia) and the CSAI Research Center: the main focus of this project was the adoption of an agent-based pedestrian and crowd modeling approach to investigate meaningful relationships between anthropological and sociological characteristics and existing results in the research on crowd dynamics, and to analyze how the presence of heterogeneous pedestrian groups influences emergent dynamics in the context of the Hajj (i.e., the Pilgrimage toward Mecca).

MAKKSim allows end-users to simulate and visualize crowd dynamics in structured spaces. The underlying modeling approach employed by MAKKSim is an agent-based approach, according to which pedestrians and groups of pedestrians within a crowd are represented by individual behavioral and perception rules that drive agents within the environment. MAKKSim agents are able to perceive and avoid spatial elements that represent points of interest or obstacles, and to follow paths throughout these environmental elements. MAKKSim agents are able to perceive other agents and to recognize those that belong to their group and to behave, according to proxemic behavioral rules, by maintaining differently spatial distances inside and outside groups.

Considering the necessity to introduce and describe the environment of the simulation, MAKKSim provides to end-users design tools for the effective and efficient development of what-if scenarios by allowing the import of CAD and 3D files of different formats: the use of these latter allows to simulate populated spaces and the generation of effective 3D visualization of crowd dynamics by means of visual rendering and movies. The integration within 3D formats is supported by the use of Blender[1] as graphical engine: it is an open source, cross platform suite of tools for 3D creation

[1]Blender website: http://www.blender.org/

that can be used for modeling, animating and rendering 3D scenes. Blender provides a Python scripting engine and a set of primitives to support 3D drawing and 2D/3D interactive views.

Currently, MAKKSim is implemented as a script written in Python language that interacts with the graphical engine of Blender to manage simulation process with the definition of the scenario, and to produce graphical output for the visualization of results.

MAKKSim first official exploitation has been within CRYSTALS project, in which MAKKSim has been employed for the development of a set of what-if scenarios within Arafat I railway station to support decisions and operations of organizers and crowd managers devoted to the yearly pilgrimage at Mecca (see Appendix C for an overview on CRYSTALS project and the scenario of Arafat I station on Mashaer rain line).

In this appendix, an overview on the tool will be given. In Sec. A.1 an analysis of the software architecture will be provided, along with the capability of customization of the tool related to the simulation in Sec. A.2 . Output of the simulation and some conclusions about the capability of the tool will be analyzed in Sec. A.3 and Sec. A.4, respectively. Materials here presented is a revised version from Bonomi et al. (2011).

A.1 Software Architecture

In this section an overview on MAKKSim software architecture and an analysis of relevant modules which manage simulations in terms of environment, pedestrians and statistics are presented. The software architecture of MAKKSim is composed by potentially reusable modules to build personalized decision support systems and it can be further extended by means of scripts written in Python language.

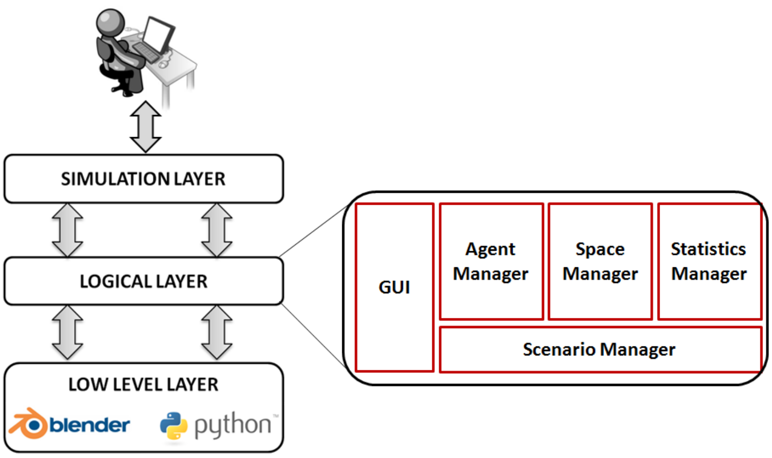


Figure A.1: *The three-level software architecture*

MAKKSim software architecture is based on a three layers (Fig. A.1):

1. *low level layer*, composed by Python virtual machine that runs the project and the Blender 3D environment that is used to produce an easy-to-read visual response;
2. *logical layer*, the core of the project;
3. *simulation layer*, that supports end-users in the creation of simulations, and includes the model of the environment and the configurations of parameters of the simulation (e.g. groups, agents, targets and so on).

These layers are not stand-alone modules: interactions among layers are necessary and allowed in order to exchange information and data from simulation to low level and vice versa.

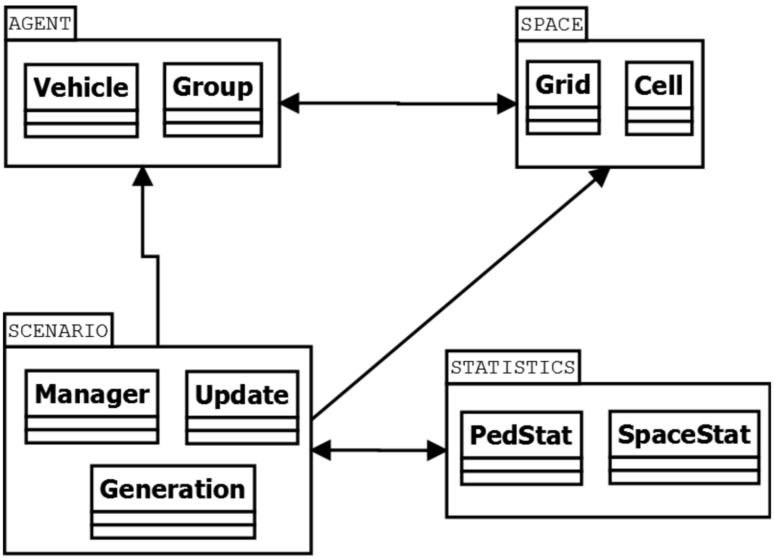


Figure A.2: *UML representation of the principal packages and the relative classes*

The logical layer represents the core of the simulation engine, in which the code of the project where packages and classes are located. Figure A.1 proposes an overview on the packages that compose the logical layer: in particular, the code is organized in four packages, along with a GUI module to realize the graphical user interface between the simulator and the end-user.

More in detail, in Fig. A.2 a high-level UML diagrams shows the packages presented before which connections among them and the main classes contained.

The modules are the follows:

- *scenario manager*, devoted to the management of the entire simulation, working with other modules to support the simulation cycle such as the discretization of the environment, the generation of floor fields, the generation of pedestrians and groups, the implementation of the update procedure according to different update strategies;

- *space manager*, devoted to the management of the space, in particular related to the definition of grids and cells and the management of spatial markers along which the start and destination areas (see Sec. 4.1.1);
- *agent manager*, devoted to the management of pedestrians in terms of agents and groups of agents;
- *statistics manager*, that interacts with the scenario manager in order to produce statistics on the simulation. Several statistics are saved during the simulation in particular related to the following aspects: pedestrian actions, traveling time and space utilization considering blocks and movements among cells, evaluation of the cumulative mean density (CMD) according to the definition in Sec. 4.1.1.

A.2 Simulation Settings

MAKKSim shows a simple and user-friendly interface composed of two main parts: on the left, the definition of the scenario of the simulation is supported by Blender environment with all the tools for drawing and customize objects. All the information related to the simulation that can be modified by the user are manually set by means of the user interface on the right.

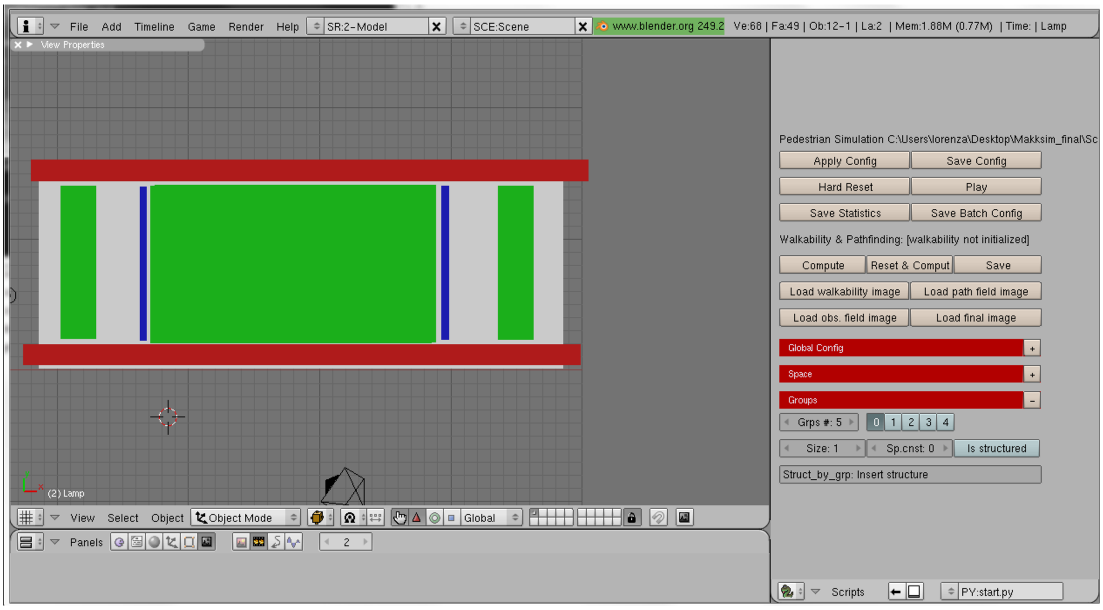


Figure A.3: *MAKKSim overview: on the left, Blender allows the definition of the scenario of the simulation, while on the right the user interface allows the set up of the environment and the configuration of pedestrians in the simulation*

In Fig. A.3 a corridor scenario with size equal to 4.8 m ×10 m is shown (one of the scenario used in the validation process in Chapter 5), drawn by the user using the appropriate tool of drawing. On the right, the complete user interface is shown. In particular, utilities support end-users in tree main steps:

- the *definition of the environment* of the simulation: thanks to the integration with Blender, MAKKSim is able to import 3D files in order to extract and draw the scenario. The end-user can import 3D and 2D file formats of the environment. An annotation and selection of spatial structure is then required in order to identify the main elements of the scenario which have to be considered in the simulation (e.g. the raw geometry of the roads, obstacles, corridors, gateways, and so on). The measure of the scenario can be directly set by the user as shown in Fig. A.4, in particular the width and the height of the simulation plan such as the possibility to assign roles to objects in the environment according to the definition of spatial markers (i.e., start and destination areas, obstacles);

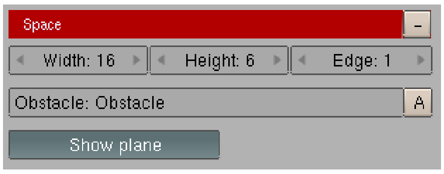


Figure A.4: *User interface dedicated to the definition of simulation plan and spatial markers*

- the *definition of pedestrians and groups*: the user interface (Fig. A.5) allows to define the number of groups of pedestrians involved in the simulation and their features, such as the size and the relative < *start area, destination area* >. Moreover, it is possible to specify if a group is a simple or a structured group, building more complex configurations;

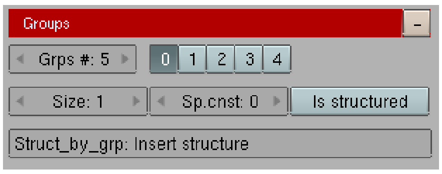


Figure A.5: *User interface dedicated to the definition of pedestrian groups*

- the *definition of parameters* of the simulation: according to the definition of the utility function $U(c)$ presented in Sec. 4.1.5, all the k_i parameters can be set by means of user interface. Figure A.6 shows the possibility to modify all the parameters that play a role in the evaluation of movement choice. User can also decide which kind of update strategy that has to be used[2] and the kind of action

[2] Note that currently just the shuffle sequential update strategy is supported by the tool.

choice mechanism (i.e., stochastic or deterministic approach).

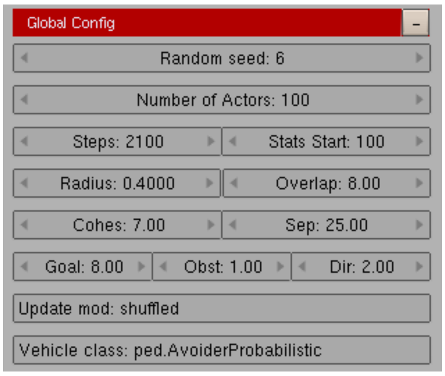


Figure A.6: *User interface dedicated to the definition of simulation parameters*

A.3 Simulation Output

Output produced by MAKKSim during a simulation run is composed of two kinds of results. First, an *instantaneous graphical result* can be used for a *face validation* of the simulation, in order to compare the simulated behavior with the expected behavior that can be directly detected by the user. Moreover, *videos of the simulations* can be produced placing Blender native cameras in different points of the scenario. Figure A.7 shows a frame of simulation in which two pedestrian flows (identified by two different colors, red and cyan) come across in the scenario of Fig. A.3: spatial markers are defined following a specific color identification. Green and blue areas indicate start and destination points, while red areas constrain the scenario representing walls, i.e. the only obstacles and non-walkable area in this particular scenario.

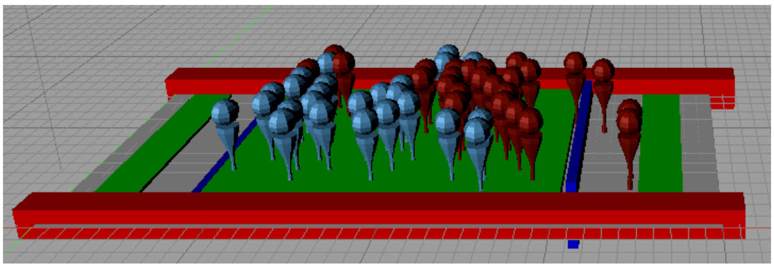


Figure A.7: *An example of instantaneous graphical result of a simulation*

The second kind of results is related to a *collection of statistics* on pedestrians dynamics: data related to positions, actions and movements are saved into *.csv* files and are used to analyze simulations from an analytic point of view by means of mathematical tools. Information on traveling time supports the calculation of pedestrian flow and average speed, while positions and actions of agents are necessary for the evaluation of space utilization. To represent how the space is used by pedestrians, the tool generates .csv files and the relative images in which values of CMD such as block situations are represented in terms of grey or color scales. Figure A.8 shows an image produced starting from a .cvs file as output of a simulation, representing the distribution of the CMD in the scenario of corridor with a global density equal to $3m^{-2}$. Darkest areas represent the cells in which the CMD is highest, according to the scale proposed on the right.

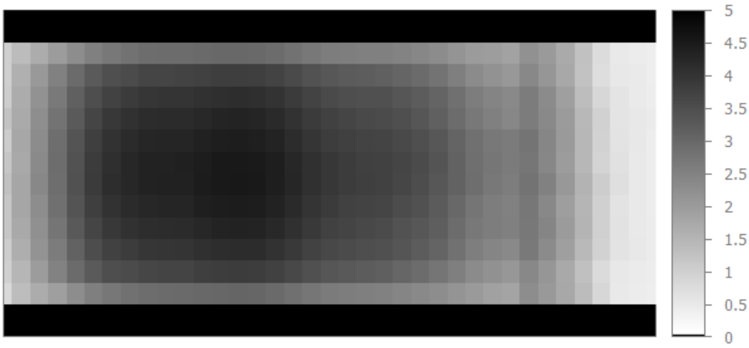


Figure A.8: *Image representing the distribution of the CMD in the case of global density in the scenario equal to* $3m^{-2}$

A.4 Conclusions

Computational models of crowds and simulators are growly investigated in the scientific context, but also adopted by firms and decision makers to support their work in the design of urban and public spaces. MAKKSim is a first effort to realize a tool that can be useful both to researchers and to crowd managers. With the analytic results provided by the tool, a study on pedestrian dynamics and flows can be conducted. The possibility to set the majority of the parameters that influence the simulation allows the study of little modification in the pedestrian behavior and to perform a comparison in situations in which heterogeneous entities share the same space within a crowd.

The tool are an endless on-going work with the aim to add elements to enrich its capability: for instance, some ideas related to the possibility to introduce intermediate points of interest are now under investigation, without modifications with respect to the computational model in Chapter 4.

B

Data Gathering at University of Milano-Bicocca

Thanks to a collaboration with the University Authorities, the CSAI Research Center performed an observation during the admission test to the Faculty of Psychology of the University of Milano-Bicocca, which took place in September 1, 2011.

The aim of the observation was to gather empirical data related to pedestrian and group dynamics in different density conditions, deepen the results achieved from early observations (Moussaïd et al., 2010; Costa, 2010; Willis et al., 2004; Schultz et al., 2010). The survey consisted in collecting data by means of a people counting activity and a video recording of the event. In particular, the pedestrian flow incoming to the admission test was observed during the gathering time before the entrance process in university buildings.

Data collected during this observation are an original contribution with respect to the current literature: the chosen scenario is innovative considering the usual environments used for data collections (e.g. public stations, airports and shopping areas).

In addition, the focus of the survey was on data related to groups: as already discussed in Sec. 5.1.3, scarce data have been collected in this sense considering the whole literature regarding pedestrian dynamics. Adding new data to the literature is a contribution with respect to the current lack on data on groups, due to the fact that the latter are necessary to realize and validate computational models and tools to build simulations, that can have direct applications on the management of crowds and public spaces. Results of the analyses here presented are published in Federici et al. (2012) and Federici et al. (2012, in press).

The Chapter is organized as follow: first, the methodological framework used in the observation will be given in order to provide the context of the study (Sec. B.1), followed by a full analysis of the collected data (Sec. B.2). Chapter ends with a summary and a discussion on results of the analysis in Sec. B.3.

B.1 Methodological Framework

Data gathering was performed during the admission test to the Faculty of Psychology of the University of Milano-Bicocca (Fig. B.1), which was attended by about two thousand persons in September 1, 2011. An analysis of the scenario and an introduction to the methodological approach used in data collection will be now given to contextualize the data gathering activity.

B.1.1 Scenario Analysis

The goal of the survey was to observe the behavior of pedestrians that reached Piazza dell'Ateneo Nuovo before the opening time of the entrance examination, and during the entrance process in Buildings U7 and U6, the locations in which participants had to attend the test.

By means of preliminary inspections regarding the topology of the University of Milano-Bicocca and the Bicocca district, we chose to observe the incoming pedestrian flow according to trajectories shown in Fig. B.2 (i) in reaching Piazza dell'Ateneo Nuovo and (ii) in the entrance process in the building U7 and U6. Actually, participants were divide in two groups, associated to these two buildings: the entrance in the venues were strictly regulated by authorities.

Figure B.1: *The University of Milano-Bicocca was established in 1998, and it is located in an area on the northern outskirts of Milan. In the year 2010/2011 the students enrolled at the University of Milano-Bicocca were 32.000*

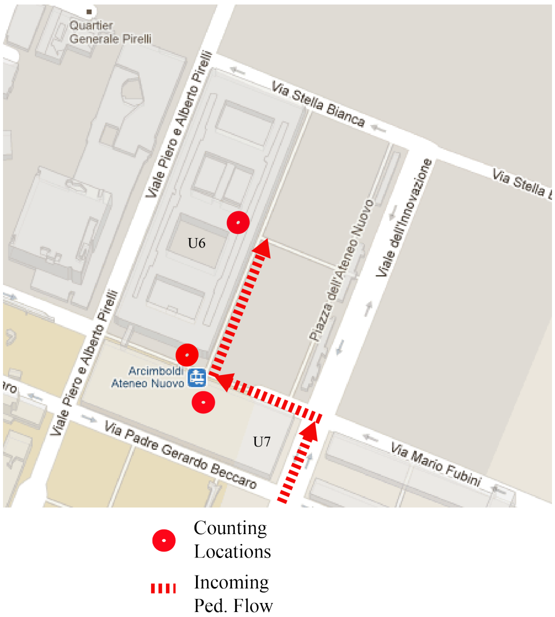


Figure B.2: *The trajectory of pedestrian flow reaching Piazza dell'Ateneo Nuovo (dotted line) and the counting locations in building U6 and U7 (circular points)*

During the on-site inspections, several officers of the University were interviewed, in order to achieve any informal details used in the management of the event, focusing on their past experiences. On the basis of these inspections, three locations for video footage and people counting activity were chosen (*A*, *B* and *C* in Fig. B.3):

- *Location A*: this point was chosen with the aim to video/photo record the entrance process in Piazza dell'Ateneo Nuovo and to count the total flow of people reaching the University of Milano-Bicocca for the admission test. The shooting of the flow and the people counting activity were realized from the mezzanine bridge that connects the Buildings U7 and U6;

- *Location B*: this point was chosen with the aim to video/photo record the queues in front of the entrances with respect to the Building U6, from a zenith point of view. The shooting of the queues at Piazza dell'Ateneo Nuovo were realized from a suitable lecture hall of the Faculty of Psychology - U6 - 3^{rd} floor, and from the first floor of the Building U6. People counting activity was performed from the ground floor of the building, near the entry;

- *Location C*: this point was chosen with the aim to video/photo record the queues in front of the ingress of the Building U7, from a zenith point of view, and to count the people moving towards Building U6. Note that just a portion of the total incoming flow went towards Building U6. The shooting of the queues at the Building U7 such as the people counting activity were performed from the Computer Lab 732 - U7 - 3rd floor.

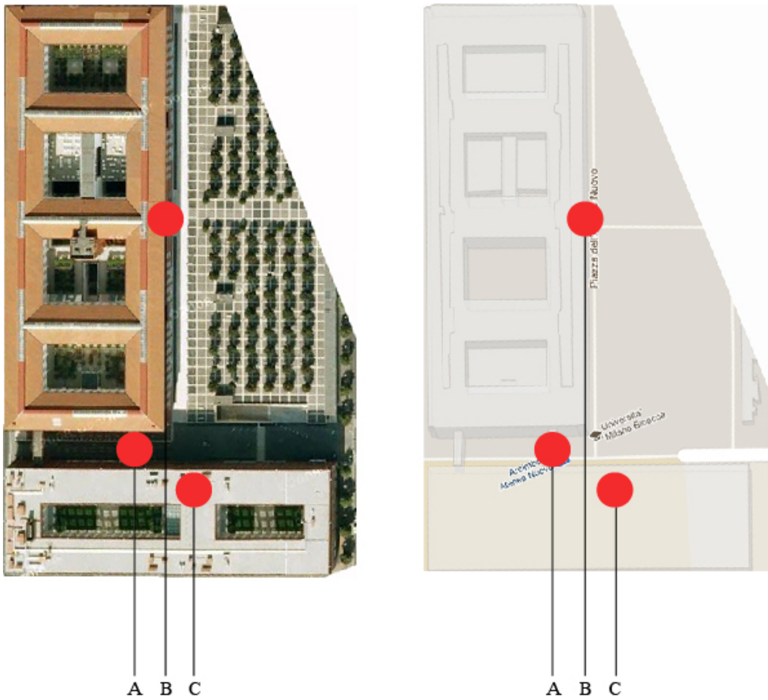


Figure B.3: *Counting locations in Building U6 (locations* A *and* B*) and U7 (location* C*)*

B.1.2 Data Collection Methods

In this survey we adopted a multi-methodological approach to the empirical investigation of pedestrian flows reaching Piazza dell'Ateneo Nuovo, by means of unobtrusive methods of investigation. Therefore, observation and people counting activity were chosen as methods for data collection, because they do not provide manipulation of variables or assignment of subjects to groups, unlike experimental method.

Data collection process was related to the identification of a set of different quantitative values that characterized pedestrian flow, for instance the number of observed people, the frequency and the type of groups along with their spatial arrangement and their walking speed.

The overall observation process started before the beginning of the admission test (7:35) until the end of entrance process into the buildings (10:00). The team was composed of two supervisors and six observers (distributed on the different counting points). Each counter was equipped with: a pre-printed blank table that was necessary to note data, a counting device, a chronograph and a special pass provided by University Authorities.

Existing legislation about privacy was consulted to exceed some ethical issues about the video recording of the event. To ensure more validity to the research, video-recording activities were employed in addition to human counters. With the availability of the University authority, it was possible to access the buildings to support the video-recording equipment localization. The equipment consisted of several full HD video cameras with stands, and several photo-cameras for mobile footage and time lapse pictures, in order to monitor the evolution of pedestrian dynamics and estimate the density. Unobtrusive locations were chosen for video recording, trying not to hinder the activities of the organizers and not to influence the behavior of observed subjects.

B.2 Data Analysis

The starting point of data analysis consisted of a preliminary investigation about data collected by the counters. Then, a manual post-process analysis of the video-recorded images was performed by two independent persons to perform a cross-checking of their conclusions.

A preliminary comparison on the results obtained by the two techniques (head-counting and video footage) showed that the video analysis, although time consuming, is a useful technique to reduce errors in counting, ensuring more validity to the research. Even if expert counters were employed during the activities, the video footage analysis highlighted the presence of an over estimation error in determining the composition of pedestrians flow with respect to total number of pedestrians (around 4%) and their organization in groups (around 10%) in the incoming flow. For this reason we decided to rely on the video materials to perform the further data analyses.

In the following, the results of several analyses about (i) pedestrian flow composition, (ii) level of service, (iii) walking speed and (iv) entrance process will be given.

B.2.1 Pedestrian Flow Composition

In this section an analysis about the composition of the incoming flow to the admission test is proposed. The counting is related to the total number of individuals, divided into singles, couples, triples and groups with four members. The identification of groups in the streaming of passers-by was assessed considering verbal and non verbal communication indicators: talking, gesticulation, visual contact, body orientation and, in particular, on spatial arrangement and cohesion of group members (in reference to typical proxemic patterns, see Sec. 2.2 for a complete explanation about group features and proxemic aspects).

During the survey design, a preliminary quantitative analysis of subscription list to the admission test were performed considering the university authority information: the official number of participants to the test was 2094, including 437 males (29%), and 1657 females (79%), on average 19 years old. The incoming process is shown in Fig. B.4 considering the percentage for every minute. Actually, the counting activity that was performed from location A detected the presence of 1897 students. The difference between the expected value and the measured value can derive from the fact that a portion of registered participants did not take part in the admission test; moreover, some participants reached the venues by car, using other ways to approach the buildings.

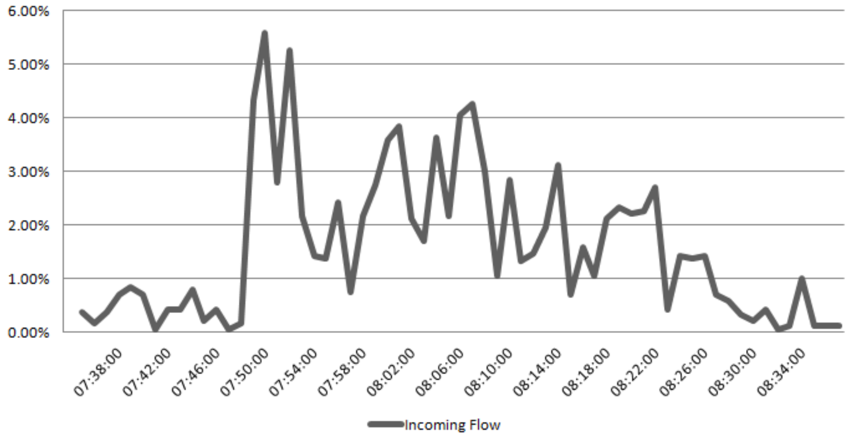


Figure B.4: *Incoming process considering percentage of pedestrians reaching Piazza dell'Ateneo Nuovo in every minute from 7:35 to 8:40*

Related to the composition of the incoming flow, it is possible to detect that the 34% of pedestrians arrived alone, while the majority of the people (66%) arrived in groups divided into couples, triples and groups of 4 members (Fig. B.5a). Related to the different types of groups, 77% of pedestrians arrived in couples, 19% in triples and the 4% in larger groups (Fig. B.5b).

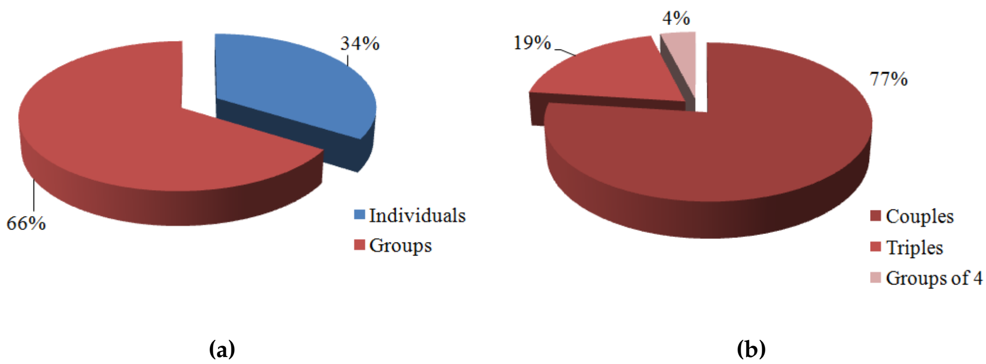


Figure B.5: *Charts related to* (a) *the percentages of individuals and groups in the incoming flow and* (b) *the percentages of the different types of groups according to the size*

An interesting analysis related to crowd composition can be made considering the percentage of different pedestrian patterns for each time interval: individuals, couples and triples are constant patterns, while larger groups sometimes are not detected. This consideration agrees with references in the literature, stated that couples and triples are most commonly detected groups in crowded situations (Moussaïd et al., 2009).

Spatial arrangements were also evaluated in the analysis of incoming flow. Results are in tune with previous observations on groups (Costa, 2010). An overview on different spatial arrangements for couples, triples and groups with four members is shown in Table B.1. In summary, the following patterns were detected:

- 97% of couples is characterized by line-abreast pattern, 3% by river-like pattern;
- 66% of triples is characterized by line-abreast pattern, 33% by V-like pattern, and 1% by river-like pattern;
- groups with four members were usually split into sub-units of dyads, triads, and single individuals: 30% of four-person groups is characterized by rhombus-like pattern (one person heading the group, followed by a dyad and ended by an another single person), 21% of the groups splits into two dyads, 21% line-abreast pattern; 14% triad followed by a single person, 7% single individual followed by a triad, 7% by V-like pattern.

	Couples	Triples	Four Person Groups
Line abreast pattern	97%	66%	21%
River-like pattern	3%	1%	
V-like pattern		33%	7%
Rhombus-like pattern			30%
Two-dyad pattern			21%
Triad + single pattern			14%
Single + triad pattern			7%

Table B.1: *Percentages related to the spatial patterns of walking groups detected in the incoming flow*

B.2.2 Level of Service

In this section an analysis about a selected portion of the incoming pedestrian flow is presented, focusing on level of density and level of service (LOS) with respect to the standard used in the literature and already introduced in Sec. 5.1.2.

In this context, the analysis was focused on the portion of pedestrian flow that reached Building U6 (considering flow trajectory in Fig. B.2), between 7:52 and 8:15, the interval in which the majority of pedestrians reached the venues. The area in which measurements on LOS was performed is shown in red in Fig. B.6, for a total area of $146.4\ m^2$. Considering the configuration of the scenario, we applied the LOS for walkways (see Fig. 5.3).

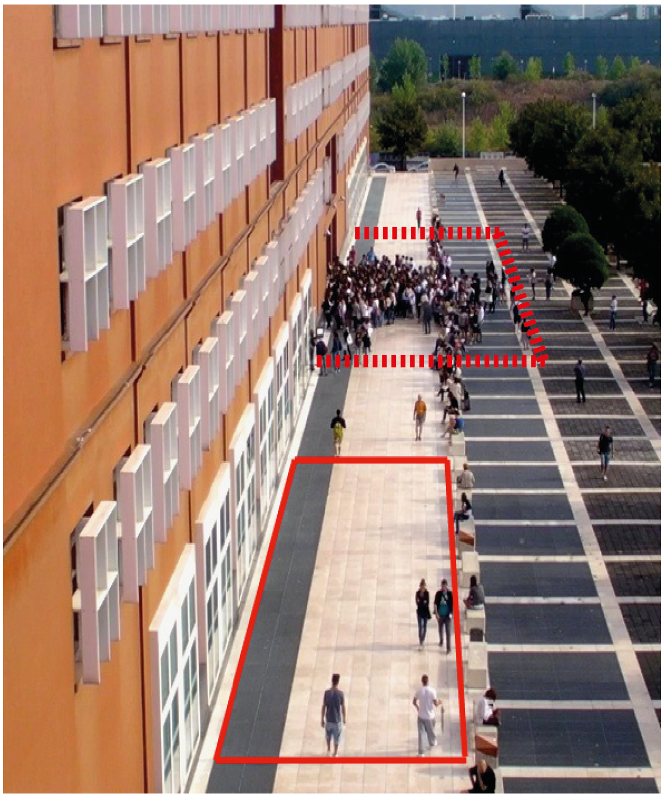


Figure B.6: *In red (solid line) the area in which measurements for the LOS analysis*

The analysis of the selected portion of the pedestrian flow detected the presence of 745 pedestrians (39% with respect to the total incoming flow). According to Fruin (1992) the flow rate was measured as the relationship among pedestrian/minute/meter (Table B.2): the average flow rate (5.09 ped/min/m) belongs to A-level (≤ 7), while several time intervals belong to B-level (> 7, ≤ 23).

B.2.3 Walking Speed Analysis

In order to perform an analysis related to the walking speed of groups, we chose a subset of the intervals interested in the LOS analysis, focusing on the ones with the highest flow rate values (highlighted in Tab. B.2).

The analysis was focused on the walking speed of pedestrians, in order to evaluate if a statistic relevant difference can be detected between the velocity of single pedestrians and the velocity of groups of pedestrians.

Time	Incoming	Outcoming	Total Flow	Flow Rate	LOS
07:52	6	1	7	1.15	A
07:53	23	1	24	3.93	A
07:54	27	4	31	5.08	A
07:55	40	0	40	6.56	A
07:56	64	5	69	11.31	B
07:57	19	5	24	3.93	A
07:58	25	3	28	4.59	A
07:59	19	5	24	3.93	A
08:00	15	0	15	2.46	A
08:01	12	5	17	2.79	A
08:02	16	0	16	2.62	A
08:03	25	1	26	4.26	A
08:04	35	3	38	6.23	A
08:05	52	3	55	9.02	B
08:06	27	0	27	4.43	A
08:07	35	2	37	6.07	A
08:08	32	1	33	5.41	A
08:09	50	2	52	8.52	B
08:10	4	7	50	8.2	B
08:11	34	0	34	5.57	A
08:12	15	4	19	3.11	A
08:13	35	1	36	5.9	A
08:14	15	2	17	2.79	A
08:15	22	4	26	4.26	A
	686	**59**	**745**	**5.09**	

Table B.2: *Analysis of the flow rate variation and the relative LOS: intervals in which flow rates are higher than the average value are highlighted*

The sample we analyzed was composed of 201 pedestrians (27% of the U6 incoming flow): 50 singles (25%), 50 couples (50%), and 17 triples (25%). Moreover, we focused on the relationship between the level of social density and the walking speed, taking into account the influence of gender, group size and group spatial arrangement. Larger groups were not regularly detected: for this reason, we just worked on singles, couples and triples.

The average social density observed was equal to $0.18\ m^{-2}$, in agreement with the LOS previously identified. A preliminary analysis on walking speed identified the following average values with the relative standard deviation: singles $M = 1.38\ ms^{-1}$, $\sigma = 0.162$; couples $M = 1.30\ ms^{-1}$, $\sigma = 0.146$; triples $M = 1.21\ ms^{-1}$, $\sigma = 0.117$.

Variable	Walking Speed (ms^{-1})					
	Mean	**Median**	**Standard Dev**	**Minimum**	**Maximum**	**Total**
Female	1.30	1.29	0.16	0.97	1.83	134
Male	1.31	1.29	0.15	1.03	1.76	67
Singles	1.39	1.38	0.16	0.97	1.80	50
Couples	1.30	1.28	0.15	1.00	1.83	50
Triples	1.21	1.22	0.12	1.03	1.38	17
Female (alone)	1.38	1.39	0.16	0.97	1.80	30
Male (alone)	1.39	1,37	0.17	1.08	1.76	20
M+M	1.27	1.28	0.09	1.14	1.41	6
F+F	1.29	1.25	0.17	1.00	1.83	24
Mixed couples	1.32	1,30	0.13	1.07	1.56	20
M+M+M	1.19	1.19	0	1.19	1.19	1
F+F+F	1.21	1.22	0.12	1.07	1.36	7
Mixed triples	1.16	1,14	0.11	1.03	1.29	9
Couples Line	1.30	1.28	0.15	1.00	1.83	50
Triples Line	1.25	1.30	0.11	1.07	1.38	11
Triples V-shape	1.14	1.13	0.10	1.03	1.03	6

Table B.3: *A complete overview on walking speed for every variable involved in the analysis (size of group, gender and spatial arrangement)*

Table B.3 shows a complete overview in which average, median, standard deviation such as minimum and maximum value are presented for every variable (size of group, gender and spatial arrangement) involved in the analysis.

On these results we applied the *one-way analysis of variance*, also called ANOVA, in order to evaluate if the difference in walking speed among singles, couples and triples is statistically relevant with respect to the size of groups, gender composition and spatial arrangement (Fig. B.7). We adopted SPSS[1] as statistic analysis tool.

Regarding the first variable, results of ANOVA show a significant group size composition effect ($p < 0.05$) with respect to the walking speed. More in detail, the differences in walking speed between singles and couples, singles and triples, couple and triples, were also investigated with a T-test, which confirmed a significant group size effect ($p < 0.01$). In summary, the results show that, at a low level of density, the more the size of the pedestrian groups is, the lower the walking speed is.

Differently, in relation to the group gender composition, T-test analyses show no significant differences ($p > 0.05$) between the average walking speed of (i) females

[1] http://www-01.ibm.com/software/analytics/spss/

ANOVA

Walking_Speed

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	,435	2	,218	9,678	,000
Within Groups	2,563	114	,022		
Total	2,998	116			

Post Hoc Tests

Multiple Comparisons

Walking_Speed
LSD

(I) N_people	(J) N_people	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	2	,08660*	,02999	,005	,0272	,1460
	3	,17386*	,04210	,000	,0905	,2573
2	1	-,08660*	,02999	,005	-,1460	-,0272
	3	,08726*	,04210	,040	,0039	,1707
3	1	-,17386*	,04210	,000	-,2573	-,0905
	2	-,08726*	,04210	,040	-,1707	-,0039

*. The mean difference is significant at the 0.05 level.

Figure B.7: *Results on ANOVA produced by SPSS*

and males walking alone, (ii) same and mixed-gender couples and (iii) same and mixed-gender triples.

Moreover, considering the different spatial arrangement, a T-test analysis shows that the difference between the average walking speed of line-abreast and V-like patterns is not significant ($p > 0.05$).

B.2.4 Entrance Process

The last part of the analysis work was focused on the entrance process in building U6, focusing on the density nearest the doors and on the relative LOS.

As already introduced, every participant had to attend the test in a precise classroom: after reaching the building, participant had to wait outside for a call based on classroom number. For every call, a variable number of pedestrians (between 10 and 30) entered the building and were accompanied to their classroom. The calls were done randomly with waiting intervals among them. Figure B.8a represents the area in which participants waited for the calls: the situation is shown in Fig. B.8b.

Measurements related to the level of density were focused on the area in front of door *B* with size 6.54 m $\times 4.7$ m $= 30.7$ m^2. Calls started at 9:12 and ended at 10:02. The level of density in this area was measured every five minutes: chart in Fig. B.8c shows the variation from the opening hour. The maximum level of density equal to $4.43\ m^{-2}$ was reached around 9:22. In such a level of density, the identification of groups is not possible: spatial patterns are not recognizable and the non-verbal interactions can not be detected. For this reason, we decided to perform a different analysis based on LOS and the detection of lane formation phenomenon.

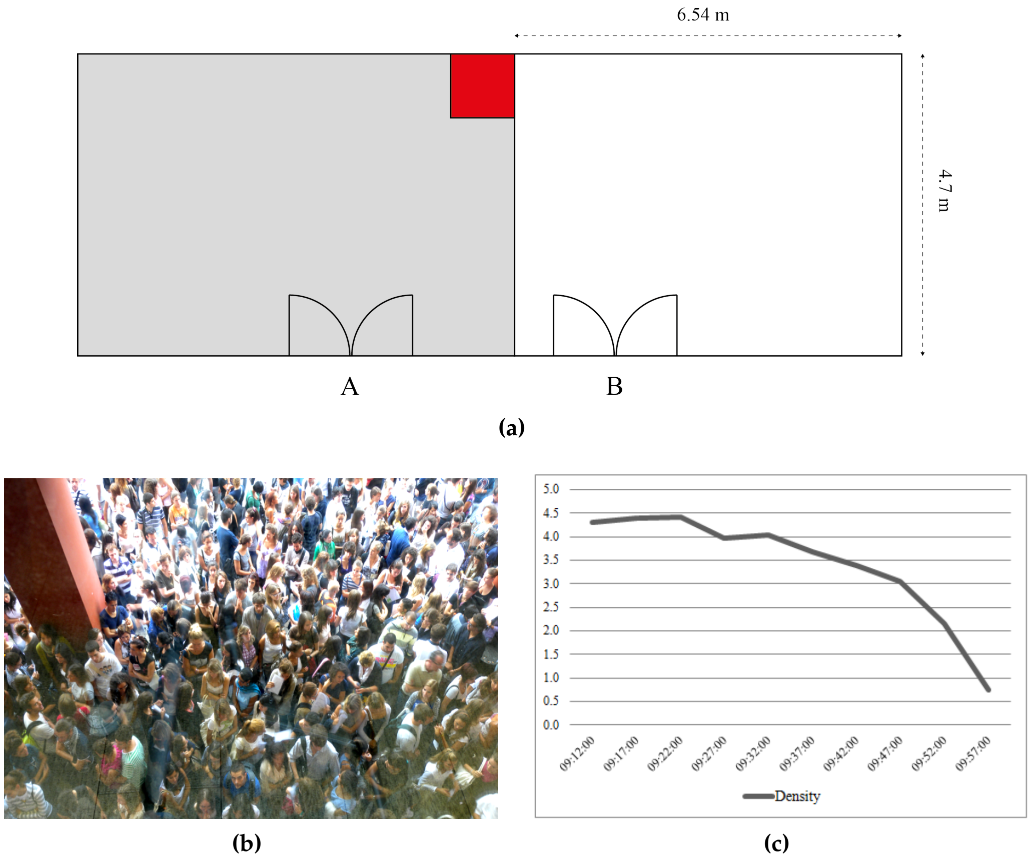


Figure B.8: *Graphical representation of the entrance in building U6* (a) *and a screenshot from video footage* (b)*: measurements for the levels of density* (c) *was focused in the area in front of door* B

Moreover, we evaluated the LOS considering the entrance flow both from door A and door B: two observers detected the number of pedestrians for every door in every minute. We applied here the LOS scale for walkways because the flow on the doors was a free flow and people entering the building did not assume a queue configuration.

Table B.4 shows, for every time interval in which pedestrians were allowed to enter the building, the number of incoming people, the relative flow rate and the LOS evaluation as previously defined in Sec. B.2.2. It is clear that, due to the fact that we are dealt with a high-density situation, the LOS here calculated are worst with respect to the ones in Sec. B.2.2. Time intervals that are not explicitly indicated in Table B.4 correspond to waiting moments in which organizers accompanied participants to their own classrooms inside the building.

Starting Time	Ending Time	Incoming	Total	Flow Rate	LOS
09:10:00	09:15:00	70	70	11.20	B
09:18:00	09:20:00	37	107	14.80	B
09:22:30	09:25:00	54	161	17.28	B
09:25:00	09:27:00	67	228	26.80	C
09:30:00	09:31:00	25	253	20.00	B
09:32:40	09:33:26	33	286	34.43	D
09:34:00	09:34:30	28	314	44.80	D
09:36:30	09:37:00	30	344	48.00	D
09:39:00	09:39:40	31	375	37.20	D
09:41:00	09:41:30	7	382	11.20	B
09:42:40	09:43:10	14	396	22.40	B
09:43:30	09:43:45	13	409	41.60	D
09:45:00	09:46:00	27	436	21.60	B
09:46:30	09:47:00	22	458	35.20	D
09:48:30	09:49:40	78	536	53.49	E
09:50:20	09:51:30	37	573	25.37	C
09:53:00	09:54:00	25	598	20.00	B
09:54:40	09:55:15	17	615	23.31	C
09:56:00	09:56:10	7	622	33.60	D
09:57:00	09:57:10	13	635	62.40	E
09:58:20	09:58:40	6	641	14.40	B
10:00:00	10:02:00	22	663	8.80	B
			663	**28.54**	

Table B.4: *Analysis on flow rate variation and the relative LOS during the opening time: intervals in which flow rates are highest are highlighted*

In this context, the analysis of video footage showed the presence of lane formation phenomenon: it was possible to investigate the composition of lanes with an evaluation of the level of density in which they can be detected and their composition in terms of number of pedestrians and their duration.

Table B.5 resumes all these features for the six lanes that we identified: note that the phenomenon appeared in the intervals with the highest levels of density considering the overall entrance process.

B.3 Conclusions

A summary of the results achieved with this survey is now proposed.

About the composition of pedestrian flow, the analysis identified that the majority

Lane	Density (m^{-2})	Pedestrians	Duration
1	4.30	26	0:44
2	4.30	39	1:27
3	4.40	26	1:16
4	4.40	9	0:15
5	4.43	9	0:28
6	4.43	14	0:54

Table B.5: *Analysis of lanes detected during the analysis of video footage with the relative level of density and their composition and duration*

of pedestrians arrived in groups (66% vs 34%): on the size of groups, couples and triples were the dominant types of group, always detected in the scenario.

The collected results can be compared to others similar observations (Costa, 2010; Willis et al., 2004; Schultz et al., 2010), taking into account the different context where the observations took place. Although the admission test is an individual event, we detected a pervasive presence of groups: this confirms that groups can be considered as a basic constitutive element of a crowd.

Results on walking speed in groups showed that, at a low level of density: (i) the more the size of the pedestrian groups is, the lower the walking speed is; (ii) there are no significant differences in walking speed among gender composition and group spatial arrangement; (iii) lane formation phenomenon was easily detected in high density situation during the entrance process to the buildings.

These results, along with the analysis of the LOS, will support the definition of a set of recommendations aimed at achieving a more efficient management of people who attend every year the admission test (e.g. reduction of waiting times, better organization of queues and guidance information to the attendees), with specific reference to pedestrian circulation dynamics and physical layout of the environment.

C

Groups in a Real-world Scenario: the Case of Arafat I Station

Thanks to the participation within the CRYSTALS project, which is a multidisciplinary research between the *Center of Research Excellence in Hajj and Omrah* (Umm Al Qura University, Saudi Arabia) and the *CSAI Research Center* (University of Milano-Bicocca, Italy), we had the possibility to apply the model presented in Chapter 4 in a real-world scenario. One of the main aims of the project was the study of the presence of heterogeneous[1] groups of pilgrims, evaluating their influence on pedestrian dynamics in the context of the Hajj (i.e., the Pilgrimage towards Mecca) with particular reference to Arafat I station.

In the following, an analysis of the scenario referring to Mashaer line and Arafat I station in the context of Hajj will be given in Sec. C.1. Simulations on crowd management strategy and on structural changes in the environment of the station will be presented in Sec. C.2. In the end, some conclusions about the modeling results will be discussed in Sec. C.3.

C.1 Scenario Analysis

The Hajj is the pilgrimage to Mecca: the performance of Hajj is obligatory at least once in a lifetime for every Muslim, male or female, who is mentally, financially and physically fit. The Hajj takes place on five specified days every year between the 8^{th} and the 12^{th} day (optionally the 13^{th}) of the twelfth month of the Islamic calendar.

The pilgrimage comprises a precise sequence of rituals conducted at various Holy Sites: Arafat, Muzdalifah and Mina. The latter are respectively situated 20, 13 and 6 Km from the Grand Mosque in Mecca. The planning of the Hajj must take into account a complex spatial-temporal-ritual phenomena that involve moving a large numbers of people (and organizing the services they need) to multiple sites at different times, but in a very compact time frame. It is one of the largest and structured pilgrimages in the world and it involves over 2 millions of people coming from over 150 countries.

[1] From a cultural point of view.

C.1.1 Innovations in Pilgrim Crowd Management

From 1990s, a new infrastructural plan called *Makkah Structural Plan* provided a framework to ensure the future construction, land use and transportation infrastructure necessary to support the organization and the management of pilgrim crowd.

A significant example of the actions carried out as a consequence of the definition of the Makkah Structural Plan is the construction of the Mashaer rail line. Before this development the pilgrims moved on buses and foot, and this created of course a traffic jam of massive proportions.

The newly developed Mashaer rail line is a rapid rail transit system that connects the Holy sites of Mina, Muzdalifah and Arafat (Fig. C.1); it is aimed at drastically reducing traffic congestion at the Holy Sites. It is designed to help accommodate the continuously growing number of pilgrims and to improve their comfort. In 2010, the year of its opening, it operated at about 35% of the full capacity but already replacing about 4000 buses previously used to transport about 150.000 pilgrims.

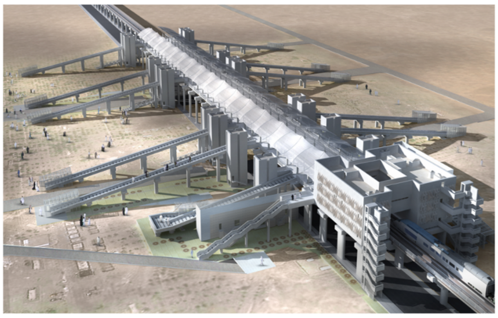
The line and the comprised stations are involved in very different types of transport movements in different days of the Hajj. The line includes 9 stations: 3 in Mina, 3 in Muzdalifah and 3 in Arafat.

Figure C.1: *Mashaer line and the different holy sites, from Kaysi and Darwish (2010)*

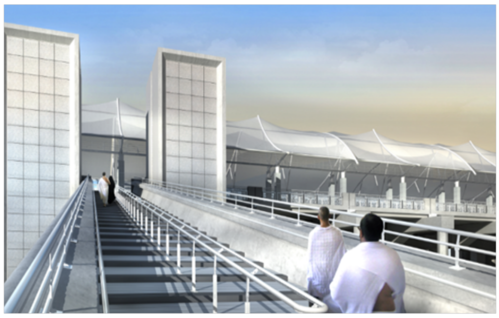
C.1.2 Arafat I Station

In the context of CRYSTAL project we chose to deepen the analysis of Arafat I station due to the fact that it is not located too close to holy spaces, allowing to perform observation activities also to non-muslin persons. The Arafat I station is the farthest from central Mecca in the whole Mashaer line; the station lies very close to the southwestern border of the Arafat plain. Figure C.2 shows some renders of Arafat I station (Kaysi and Darwish, 2010).

Figure C.3 proposes a schematic view of the Arafat I station with the possible flows of pedestrians from outside the station towards the platforms. More in detail, 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 *principle of waiting-boxes*: pilgrims are subdivided into groups of about 250 persons on the basis



(a)



(b)

Figure C.2: *Some renders of Arafat I station and the surrounding area from Kaysi and Darwish (2010)*

of their nationality and their native language, that are led by specific leaders (generally carrying a pole with signs supporting group identification by pilgrims). The groups start from the tents area and flow into these fenced located in immediately outside the station, between the access ramps and the elevators (Fig. C.4).

Groups of pilgrims wait in these areas for an authorization by the station agents to move towards the ramps or elevators. In this way it is possible to stop the flow

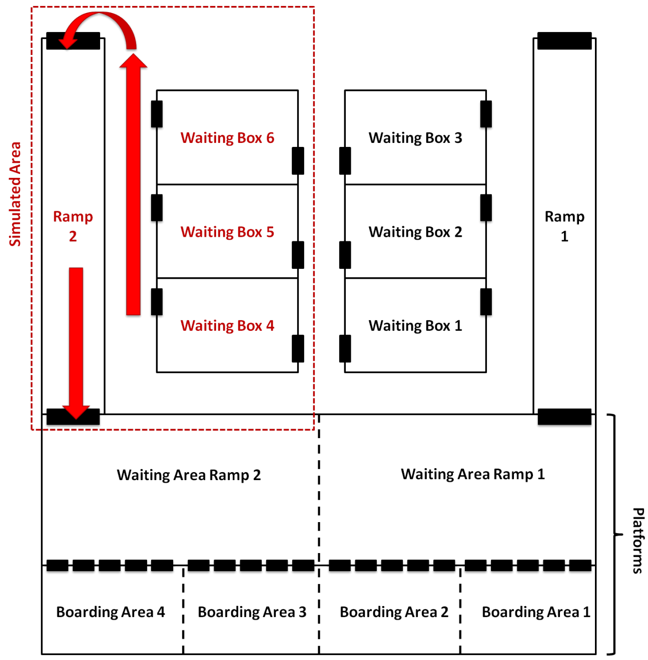
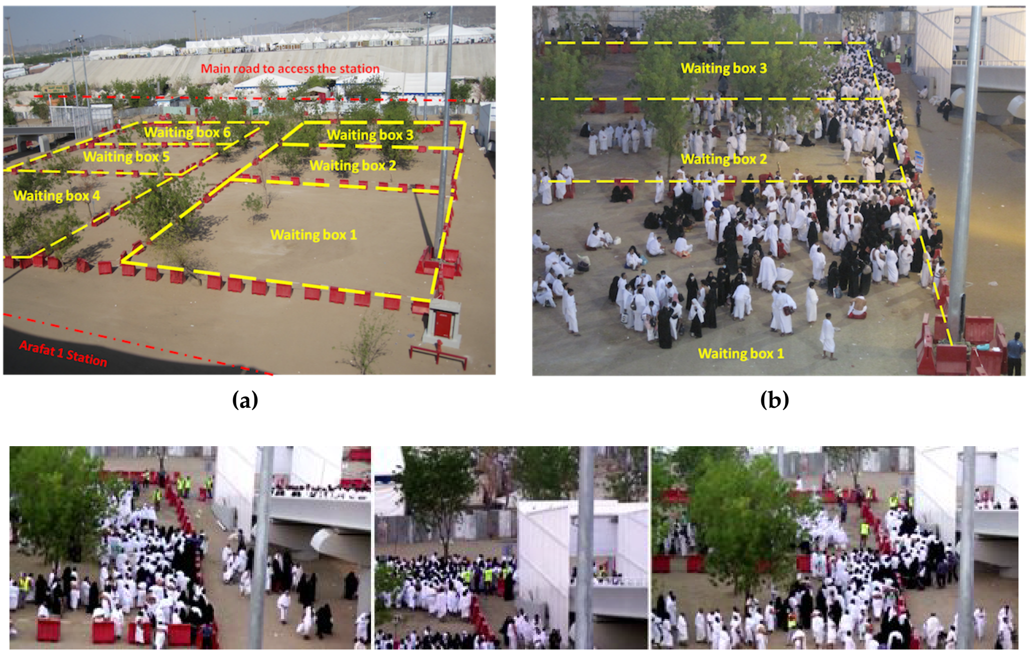


Figure C.3: *Schematic view of Arafat I station with the pedestrian flow from waiting boxes towards the ramp* of pilgrims whenever the number of persons on the platforms (or on their way to reach it using the ramps or elevators) is equal to the train capacity, supporting thus a smooth boarding operation. Actually, 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.

During the observations carried out in the context of Hajj 2010, in one case a group of pilgrims moved directly from the tents area towards one of the ramps. At the same time, another group from a waiting area was already approaching the ramp. This conflict caused a longer than average waiting time of other groups, due to the fact that more pilgrims than usual were climbing the ramp (or waiting to do that). Moreover, during the observations, elevators were not operative and they were not reserved to groups including people with disabilities or walking problems, like aged people: this leads to longer waiting times that could represent an issue in very hot days.



(a) (b) (c)

Figure C.4: *The management of pilgrims based on the waiting box principle*

C.2 Simulations on Arafat I

Starting from the observations performed in October 2010, and in tune with one of the scope of CRYSTALS project, we simulated the scenario of Arafat I by means of

MAKKSim tool[2], a pedestrian dynamics simulation platform based on the computational model presented in Chapter 4.

Simulation scenario was built starting from a CAD file of the station provided by Saudi Arabia government.

Two different kinds of study were done: the first took inspiration from the unexpected situation detected during the observation in 2010 about the conflict between the group that moved from the waiting box towards one ramp and the external flow that directly moved towards the same ramp. Situations in which the waiting-box principle is respect and the opposite case were compared to understand the effectiveness of pedestrian management.

The second study is related to an improvement in the structural configuration of the area outside the station, trying to evaluate if a change in the geometry of the ramp can have a positive influence with respect to the current situation.

Considering Fig. C.3, the area involved in the simulations is shown as a red rectangular. In this area, four different scenarios were realized:

- scenario *a*, focused on the simultaneous flow of two groups from two different waiting boxes to the same ramp;
- scenario *b*, focused on the simultaneous flow of three groups of pilgrims, two from two different waiting boxes and one coming directly from the tents area;
- scenario *c*, similar to *a*, with structural change in the geometry of the structure of the ramp;
- scenario *d*, similar to *b*, with structural change in the geometry of the structure of the ramp.

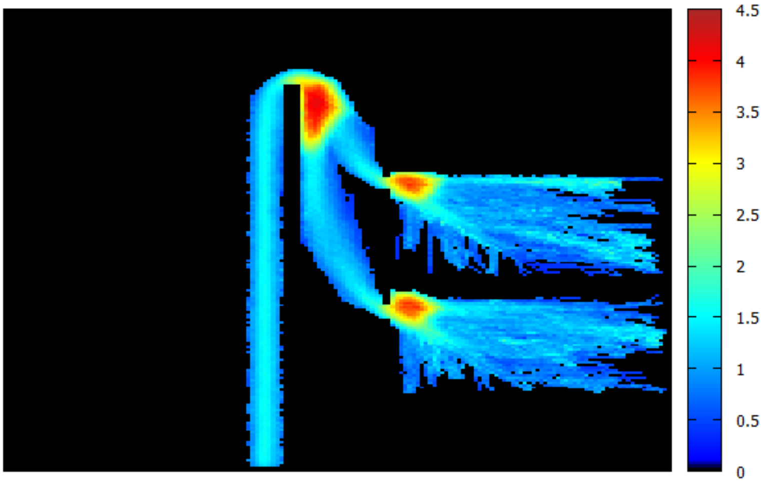
The analysis will be discussed by means of an evaluation in terms of density profile derived from the analysis of cumulative mean density[3] (CMD) as the density experienced by pedestrians in a cell and also referring to the level of service[4] (LOS) in the scenario.

C.2.1 Evaluation on Crowd Management Strategy

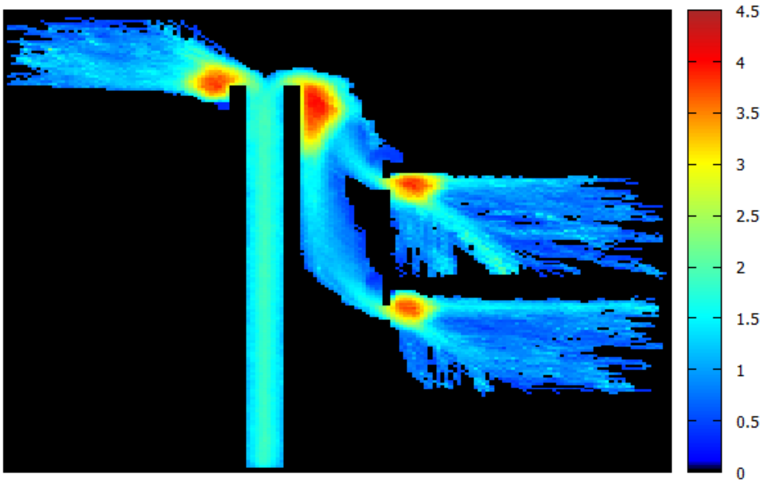
As already introduced, the first study is related to an evaluation on waiting-box principle on the basis of which pilgrims are organized in entering the station, with the goal to evaluate the use of space by pilgrims when the waiting box principle is not respected (Vizzari and Manenti, 2012).

Figures C.5a and C.5b, and C.6a and C.6b report the situation in *a* and *b* with respect to CMD and LOS. The graphical metrics is the follows: the background of the

[2]See Appendix A for a complete explanation on MAKKSim.
[3]See Sec. 4.1.1 for a more detail definition of this concept and for the method we used for its calculation.
[4]See Sec. 5.1.2 for a complete explanation of the concept.



(a)

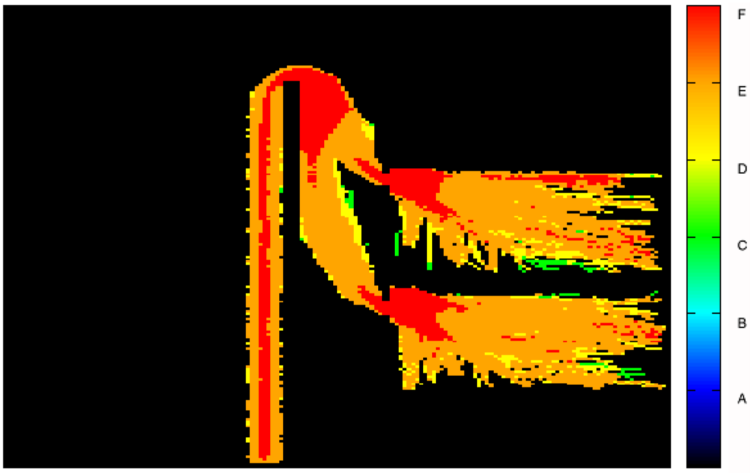


(b)

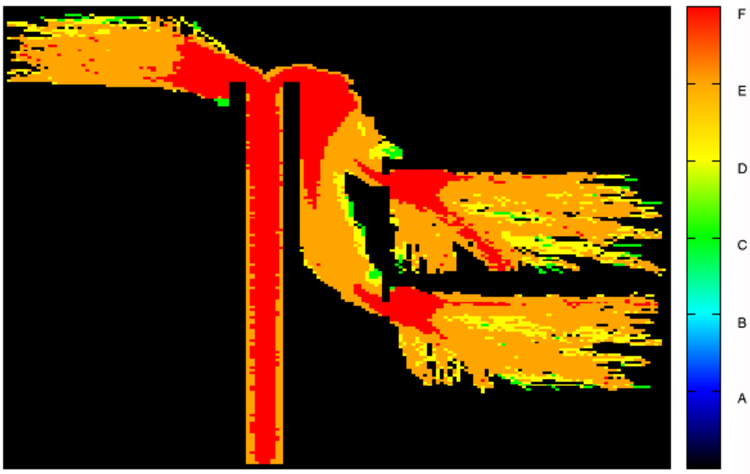
Figure C.5: *Diagrams on density profiles in scenario* a *and scenario* b*, respectively*

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 color scale. 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 they can be easily identified considering Fig. C.3 and C.4.

In particular, in the CMD representation, density profile is shown according to the color scale (from 0 to $4.5\ m^{-2}$) already applied to the validation process of the model



(a)



(b)

Figure C.6: *Diagrams on level of services in scenario* a *and scenario* b*, respectively*

on the T-junction scenario in Sec. 5.2.5. It can be noted that the density on the ramp is higher in scenario *b* with respect to scenario *a*.

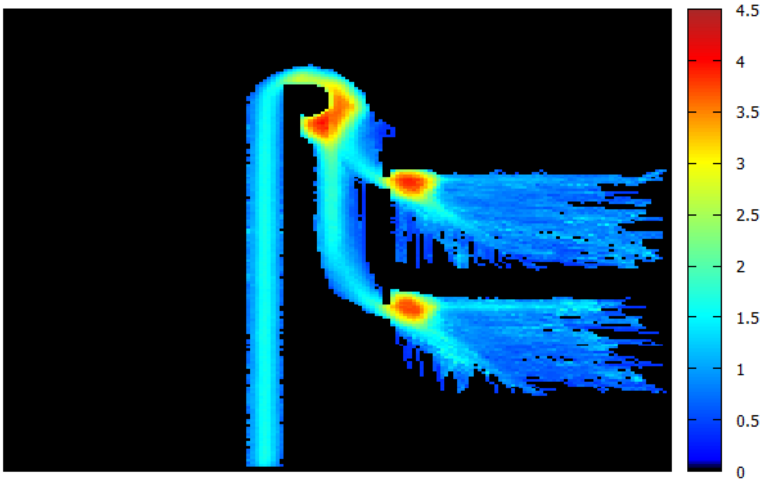
Scenario *b* is also characterized by a noticeably worse performance not only from the perspective of the size of the area characterized by a medium-high space utilization ($\geq 3\ m^{-2}$), but also from the perspective of the highest value of space utilization.

This analysis is also confirmed by the LOS[5] diagrams in Fig. C.6: it can be seen that

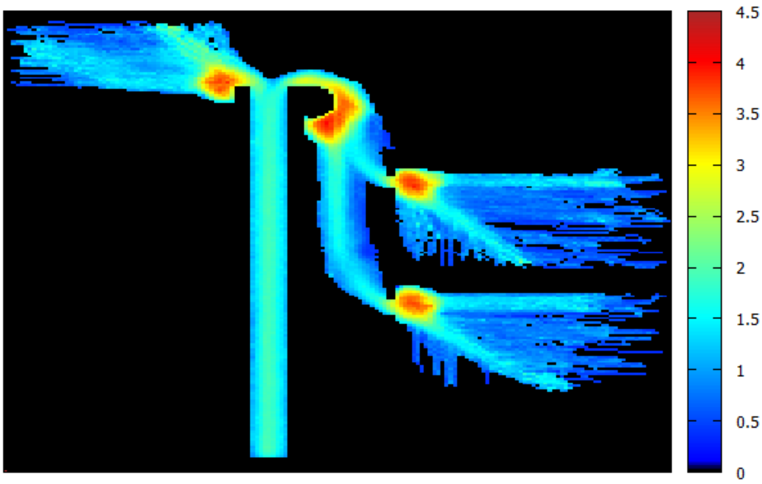
[5]Note that we here applied the LOS for walkways for all the environment: due to a limit of the model, we are not able to include different speeds, modeling the natural slowing down of pedestrians on the ramp, so we decided to proceed with the LOS for walkways instead of the LOS for queuing (that actually

areas belonging to F-level increase in b.

Results therefore confirm that increasing the number of pilgrims that are simultaneously allowed moving 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, under unexpected situations, the whole side of the ramp becomes essentially a queue of pilgrims waiting to move towards the ramp.



(a)



(b)

Figure C.7: *Diagrams on density profiles in scenario* c *and scenario* d, *respectively*

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should be applied in such a scenario).

C.2.2 Evaluation on Environmental Structures

The second study performed by means of simulations of the environment is related to the analysis of structural changes in the environment of the station. The idea started from Yanagisawa et al. (2009) and Yanagisawa et al. (2010) in which authors compared velocity and flow of pedestrians in bottleneck positioning an obstacles before the merging point. They collected data with experiments, and developed a CA-based model to reproduce and study the phenomenon: results show that pedestrian flow increases when they put an obstacle in front of an exit in real experiments due to the fact that it decreases the average number of pedestrians involved in the conflicts, usually detected in bottleneck scenario.

From the previous analysis on Arafat I station, it is clear that the transition from the space between the waiting-boxes and the ramp is the most critical congestion point in the scenario. We tried to improve the situation hypnotizing to change the shape of the ramp adding a round obstacle near the bend.

Results in *c* and *d* are shown in Fig. C.7a and C.7b, in which the influence of the structural modification is represented in terms of density profile: the presence of the circular obstacle positively influences the pedestrian flow, reaching lower levels of density respect to *a* and *b*.

Regarding the LOS analysis, Fig. C.8a and Fig. C.8b present the variation in the LOS: no particular improvement can be detected with respect to Fig. C.6. The reason is that the trajectories of pedestrians reveal some differences in the area between waiting boxes and the ramp: agents stay farther from the ramp, reaching a *F*-LOS shortly before.

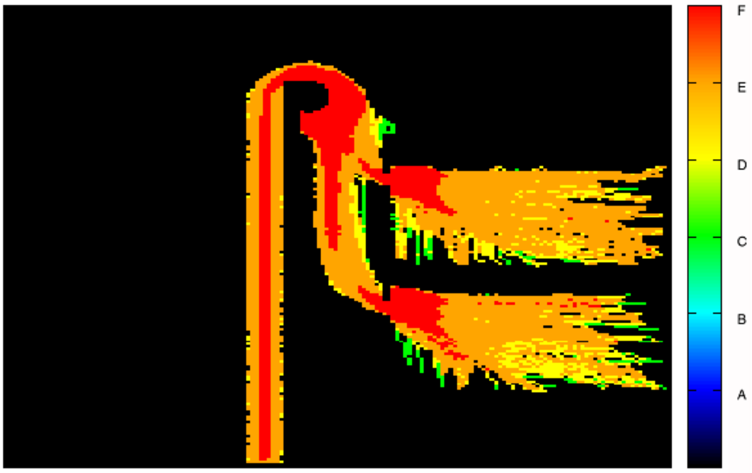
In general, considering the average traveling time of the pedestrian flow in scenario *b* and *d*, an improvement is detected in the latter: pilgrims are able to enter the station more quickly. The improvement in *c* in terms of average time travel is about 3% with respect to *a*.

Results are in line with empirical and simulated experiments in Yanagisawa et al. (2009) and Yanagisawa et al. (2010): actually, the perceived density from pedestrians is in general lowest compared with the scenario without obstacle. The reason could be that pedestrians try to occupy and distribute themselves on all the perimeter of the circular obstacle, using also that space to solve spatial conflicts.

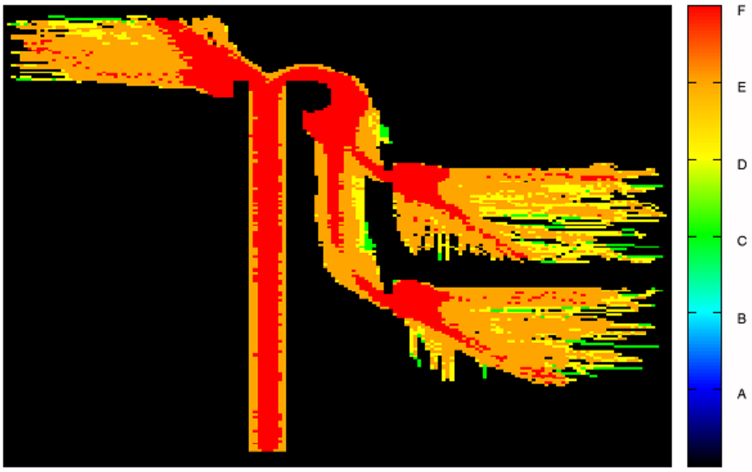
C.3 Conclusions

According to the analysis here explained and the results we obtained, 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.

Moreover, changing the geometry of the ramp positioning a round obstacle before the bend of the ramp can easily avoid and decrease the perception of overcrowding by pilgrims (sometimes it can be the reason for panic attacks or emergency situations) and cut the time necessary to enter the station. In particular the latter is an important aspect



(a)



(b)

Figure C.8: *Diagrams on level of services in scenario* c *and scenario* d*, respectively*

to be considered: there are strictly temporal constraints in the transportation activity of pilgrims. All the pilgrims have to leave Arafat towards Muzdalifah after the sunset and before midnight of the second day of the Hajj. Trains must continuously load pilgrims at Arafat, carry them to Muzdalifah, and come back empty to transport other pilgrims. From this point of view, every improvement to speed up the transportation of pilgrims and to grow their comfort may significantly impress the overall management of the pilgrimage.

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