Information **2013**, *4*, 75-93; doi:10.3390/info4010075

OPEN ACCESS

information

ISSN 2078-2489

www.mdpi.com/journal/information

Article

Epistemological Levelism and Dynamical Complex Systems: The Case of Crowd Behaviour

Stefania Bandini * and Giuseppe Vizzari

Complex Systems and Artificial Intelligence (CSAI) Research Center, University of Milano-Bicocca, Viale Sarca 336/14, 20126 Milano, Italy; E-Mail: giuseppe.vizzari@disco.unimib.it

* Author to whom correspondence should be addressed; E-Mail: bandini@disco.unimib.it; Tel.: +39-0264487835; Fax: +39-0264487839.

Received: 19 November 2012; in revised form: 13 December 2012 / Accepted: 7 January 2013 / Published: 15 January 2013

Abstract: The main aim of this paper is to show how the design and creation of computational models to study and simulate of the behaviour of dynamical complex systems, and in particular crowds of pedestrian, actually implicitly employs elements of a framework introduced by Luciano Floridi in his paper "The Method of Levels of Abstraction". The example of the computer based simulation of the complex phenomenon of crowd dynamics and the related knowledge requiring different abstract levels and representation will be introduced in order to show how concepts like observables and system behaviour are commonly employed to compare and evaluate simulation models.

Keywords: complex systems; simulation; crowd

---

1. Introduction

In his paper "The Method of Levels of Abstraction" [1] Luciano Floridi introduces arguments in defence of the need of forms of "levelism" to study the reality. As argued in the mentioned paper, "more recently the concept of simulation has been used in computer science to relate levels of abstraction to satisfy the requirement that systems constructed in levels (in order to tame their complexity) function correctly". In accordance with this argument, an increasing interest in the development of discussions about the epistemology of computer simulations is testified by a flourishing of literature on the argument [2]. Advanced computer-based simulation methods and techniques have been developed thanks to the creation of innovative computational models (e.g., cellular automata, agent-based systems) and related powerful distributed technologies (e.g., grid computing) allowing computer-based experiments to be performed. This algorithmic and computational power allowed also for the representation and modelling of complex phenomena not only circumscribed to natural sciences, but also social and economic phenomena, showing novel fields of scientific investigation and epistemological discussions [3–5]. Additional discussions, more on the field of the computer science side of this research effort, include [6–8].

The computer-based simulation of the dynamical behaviour of crowds and pedestrians is a challenging field of research naturally involving knowledge coming from different disciplines, producing interesting results from physics and applied mathematics, to computer science, often in collaboration with anthropological, psychological, sociological studies and the humanities in general. Sometimes, these results allowed also the design and development of commercial software packages, due to the pressure of decision makers and crowd managers of public spaces. (See [9] for a significant although not necessarily comprehensive list of simulation platforms.) Despite the presence of commercial packages, the modelling and simulation of crowd and pedestrians requires much more knowledge and epistemological discussions [10]. In particular, in the following we will show how the notion of *levels of abstraction* can be very useful to clarify what are the actual goals of the simulation effort, what is the object of the analysis and therefore correctly set the research effort in the wide and heterogeneous relevant literature. A level of abstraction formally defines “the scope or granularity of a single mode”; Floridi also introduces the notion of *gradient of abstractions* as “a way of varying the level of abstraction in order to make observations at differing levels of abstractions”. Even though it is possible to observe the crowd phenomenon at different levels of granularity, it is not simple (and possibly not really useful) to put different and heterogeneous models into a hierarchical relation such as one inspired by the notion of gradient of abstraction. Nonetheless, it is important to notice that notions of *observables* and *system behaviours*, instrumental in the definition of the levels and gradients of abstractions, can be very important to describe and discuss the results of simulations and, therefore, to evaluate and compare models. These concepts support the definition of “standard outputs” of models that support their evaluation and also the actual comparison of their effectiveness (in a process of alignment [11] that still represents an open issue despite being well-known in the field).

In the following, we will briefly describe some relevant influences from different areas of the Humanities to this research effort; Section 3 will instead provide a compact review of the current state of the art of the area of pedestrian and crowd modelling and simulation. Section 4 will present and sample model for the simulation of pedestrian movement, while Section 5 will clarify the relevant system behaviours in this area, even beyond the scientific research context, considering the practitioner’s perspective. Conclusions and future developments will end the paper.

2. Elements of an Interdisciplinary Approach

Pedestrian and crowd modelling research context regards events in which a large number of people may be gathered or bound to move in a limited area; this can lead to serious safety and security issues for the participants and the organisers. The understanding of the dynamics of large groups of people is very important in the design and management of any type of public events. In addition to safety and security concerns, also the comfort of event participants is another aim of the organisers and managers of crowd related events. Large people gatherings in public spaces (like pop-rock concerts or religious rites participation) represent scenarios in which crowd dynamics can be quite complex due to different factors (the large number and heterogeneity of participants, their interactions, their relationship with the performing artists and also exogenous factors like dangerous situations and any kind of different stimuli present in the environment [10]). The traditional and current trend in social sciences studying crowds is still characterised by a non-dominant behavioural theory on individuals and crowds dynamics, although it is recognised that a behavioural theory is needed to improve the current state of the art in pedestrian and crowd modelling and simulation [12].

2.1. Proxemics

The term *proxemics* was first introduced by Hall with respect to the study of set of measurable distances between people as they interact [13]. In his studies, Hall carried out analysis of different situations in order to recognise behavioural patterns. These patterns are based on people's culture as they appear at different levels of awareness. In [14] Hall proposed a system for the notation of proxemic behaviour in order to collect data and information on people sharing a common space. Hall defined proxemic behaviour and four types of perceived distances: *intimate distance* for embracing, touching or whispering; *personal distance* for interactions among good friends or family members; *social distance* for interactions among acquaintances; *public distance* used for public speaking. Perceived distances depend on some additional elements that characterise relationships and interactions between people: posture and sex identifiers, sociofugal-sociopetal (SFP) axis, kinesthetic factor, touching code, visual code, thermal code, olfactory code and voice loudness.

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

It must be noted that some recent research effort was aimed at evaluating the impact of proxemics and cultural differences on the fundamental diagram [15], a graph showing how the average velocity of pedestrians in a section of the environment (e.g., one of the ends of a corridor) varies according to the density of the observed environment, a typical way of evaluating both real crowding situations and simulation results that will be more thoroughly described in Section 5. The work has essentially confirmed, better quantified and extended Hall's findings, and together with recent results in nonverbal behaviour studies [16] it has renewed the interest in this kind of observation.

2.2. Crowds: Canetti's Theory

Elias Canetti's work [17] proposes a classification and an ontological description of the crowd; it represents the result of 40 years of empirical observations and studies from psychological and anthropological viewpoints. Elias Canetti can be considered as belonging to the tradition of social studies that refer to the crowd as an entity dominated by uniform moods and feelings. We preferred this work among others dealing with crowds due to its clear semantics and explicit reference to concepts of loss of individuality, crowd uniformity, spatial-temporal dynamics and *discharge* as a triggering entity generating the crowd, which could be fruitfully represented by computationally modelling approaches like MAS.

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

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

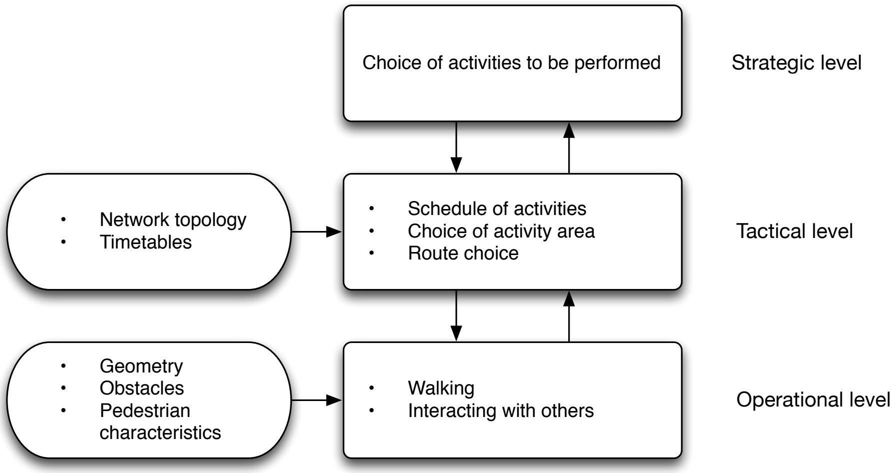
A discharge is a particular event, a situation, a specific context in which this principle is not valid anymore, since pedestrians are willing to accept being very close (within touch distance). Canetti provided an extensive categorization of the conditions, situations in which this happens and he also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

Recent developments aimed at formalizing, embedding and employing Canetti's crowd theory into computer systems (for instance supporting crowd profiling and modelling) can be found in the literature [18,19] and they represent a useful contribution to the present work.

3. Related Works

The movement of pedestrians and crowds in an environment can be considered, analysed and modelled from different perspectives and with different aims. Figure 1, adapted from [10], emphasises the fact that one could try to study high level decisions about tasks involving movement to be performed (*i.e.*, strategic choices), or decisions about how they should be performed: the latter involve choices about the ordering and timing of activities, but also choices about the routing and travel mode in a representation of the environment (generally a graph). Finally, one could focus on the specific fine grained movement decisions of pedestrians at the micro-scale (*i.e.*, operational choices), their trajectories in portions of the build environment like buildings, streets, stations. These different kind of analyses were informally described by researchers and practitioners in this area as different levels of abstraction and even considering Floridi's definition this statement holds: the analyses and models associated to the different levels are about different *observables*, some of which actually represent relevant information for the connected (immediately upper or immediately lower, considering the schema introduced in Figure 1) level. Quite often the analyses focused on one level are carried out in isolation from the other ones, either not considering "low level" details or assuming "high level" choices as sort of input parameters. The above schema has proven to be useful to modellers and practitioners in this area because it provides a framework to clarify the aims and topics of a given modelling effort; it is also the best starting point for an analysis of the possibility to employ the gradient of abstraction notion to more formally analyse the different kind of analyses that can be carried out on the crowd system.

Figure 1. A diagram highlighting different levels of analysis and modelling of the phenomena related to the movement of pedestrians in the environment (adapted from [10]).



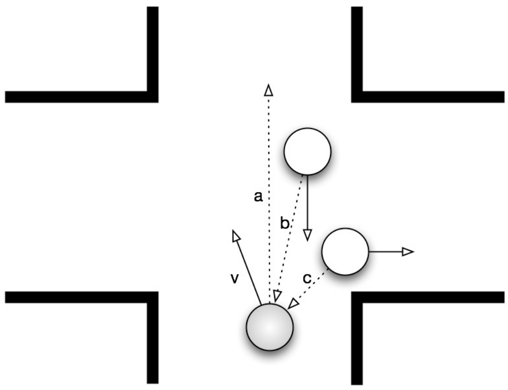
In tune with the above considerations, the literature on these topics is vast and heterogeneous. Even solely focusing on the works discussing the researches on the operational level, it is quite complicated to provide a compact and at the same time comprehensive overview of the different approaches and models for the representation and simulation of pedestrian and crowd dynamics. Dedicated scientific interdisciplinary workshops and conferences are focused on this topic (see, e.g., the proceedings of the first edition of the International Conference on Pedestrian and Evacuation Dynamics [20] and consider that this event has reached the sixth edition in 2012).

Nonetheless, the different approaches can be classified according to the way pedestrians are modelled, and in particular as: (i) *particles subject to forces* of attraction/repulsion, (ii) *states of cells in a Cellular Automata (CA)*, (iii) *autonomous agents*, situated in an environment.

3.1. Particle–Based Approach

The first types of models for pedestrian dynamics adopt an analytical approach, considering the simulated environment as a system of particles and defining its laws of motion. Partial differential equations are set up to represent forces generating the movement of pedestrians, modelling their interaction with the environment (and also among pedestrians themselves, in the case of *active walker* models [21]). Forces of attraction lead the pedestrians/particles towards their destinations (modelling the *goal driven* component of their behaviour), while forces of repulsion are used to represent the tendency to stay at a distance from other points of the environment; Figure 2 shows a sample situation exemplifying this approach. This kind of effect was introduced by a relevant and successful example of this modelling approach: the *social force* model [22]. This approach introduces the notion of social force, representing the tendency of pedestrians to stay at a certain distance one from another. Other relevant approaches take inspiration from fluid-dynamic [23] and magnetic forces [24] for the representation of mechanisms governing flows of pedestrians.

Figure 2. A diagram exemplifying an analytical model for pedestrian movement: 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**).



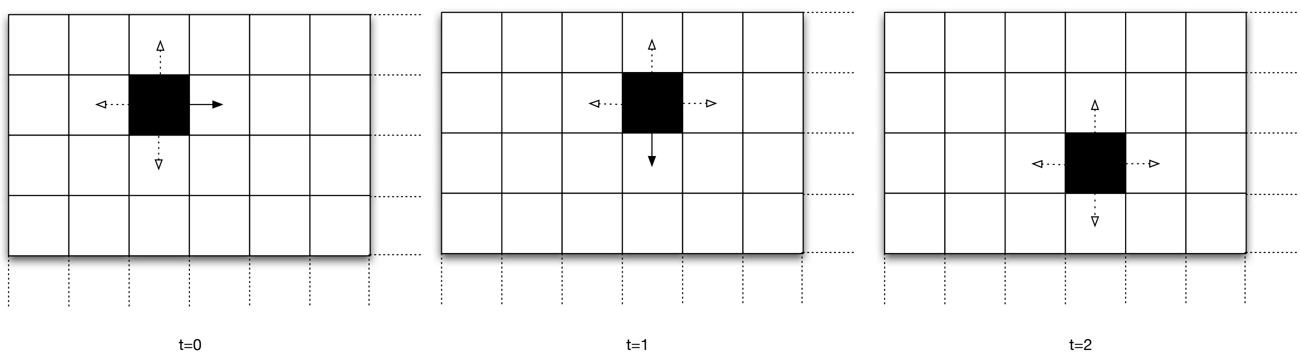
This approach is based on a precise methodology and it has provided significant results. However, its view of pedestrians as mere particles, whose goals, characteristics and interactions must be represented through equations, makes it difficult thus to incorporate heterogeneity and complex pedestrian behaviours in this kind of model. It is worth mentioning, however, that an attempt to represent the influence of groups of pedestrians in this kind of model has been recently proposed [25].

3.2. Cellular Automata Approach

Another significant approach to pedestrian and crowd modelling adopts the Cellular Automata (CA) model, with a discrete representation of spatial and temporal aspects of the system. The cellular space includes both a representation of the environment and an indication of its state, which is the occupancy of the sites it is divided into by obstacles or pedestrians. Transition rules are defined to specify the evolution of every cell's state according to the specific neighbourhood of a cell, a set of cells whose state will be considered in the computation. The transition rule, in this kind of model, generates an apparent idea of movement thanks to a coordinated change of cells state: an atomic step of a pedestrian is realised through the change of state of two cells, the first characterised by an *"occupied"* state that becomes *"vacant"*, and an adjacent one that was previously *"vacant"* and that becomes *"occupied"*; Figure 3 shows a sample situation exemplifying this approach. This kind of application is essentially based on traffic simulation applications of the CA model [26].

The interactions among neighbouring cells are thus the uniform way to render the motion of an individual in the space (and the choice of the destination of every movement step). The iterative application of this rule to the whole cell space may bring to emergent effects and collective behaviours. Relevant examples of crowd collective behaviours that were modelled through CAs are the formation of lanes in bidirectional pedestrian flows [27], the resolution of conflicts in multidirectional crossing pedestrian flows [28]. In this kind of example, different states of the cells represent pedestrians moving towards different exits; this particular state activates a particular branch of the transition rule causing the transition of the related pedestrian to the direction associated to that particular state. Additional branches of the transition rule manage conflicts in the movement of pedestrians, for instance through changes of lanes in case of pedestrians that would occupy the same cell coming from opposite directions.

Figure 3. A diagram showing a sample effect of movement generated through the coordinated change of state of adjacent cells in a CA. The black cell is occupied by a pedestrian that moves to the right in turn 0 and down in turn 1, but these effects are obtained through the contemporary change of state among adjacent cells (previously occupied becoming vacant and vice versa).



It must be noted, however, that the potential need to represent goal driven behaviours (*i.e.*, the desire to reach a certain position in space) has often led to extend the basic CA model to include features and mechanisms breaking the strict locality principle. A relevant example of this kind of development is represented by a CA based approach to pedestrian dynamics in evacuation configurations [29]. In this case, the cellular structure of the environment is also characterised by a predefined desirability level associated to each cell that, combined with more dynamic effects generated by the passage of other pedestrians, guides the transition of states associated to pedestrians. Recent developments of this approach introduce even more sophisticated behavioural elements for pedestrians, considering the anticipation of the movements of other pedestrians, especially in counter flows scenarios [30].

Two recent research efforts that is worth mentioning here are represented by (i) a first attempt to explicitly include proxemic considerations not only as a background element in the motivations a behavioural model is based upon, but rather as a concrete element of the model itself [31] and (ii) a model encompassing a notion of group as a set of pedestrians that are either leaders or followers [32].

3.3. Autonomous Agents Approach

Recent developments in the area of CA approaches (e.g., [33,34]) introduce modifications to the basic approach that are so deep that the resulting models are more similar to agent-based and Multi-Agent Systems (MAS) models employing a cellular space representing agents' environment. An MAS is a system comprising a set of autonomous components interacting according to collaboration or competition schemes and realising an overall behaviour that could not be generated by single entities by themselves. As previously mentioned, MAS models have been successfully applied to the modelling and simulation of several situations characterised by the presence of autonomous entities whose action and interaction determine the evolution of the system, and they are also growingly adopted to model crowds of pedestrians [35–38]. All these approaches are characterised by the fact that the agents encapsulate some form of behaviour inspired by the above described approaches, that is, forms of attractions/repulsion generated by points of interest or reference in the environment but also by other pedestrians.

A different line of research also employing agent based approaches to the modelling of pedestrians and crowds are aimed at providing a realistic 3D visualisation of the simulated dynamics: in this case, the notion of realism includes elements that are considered irrelevant by some of the previous approaches (e.g., visual variety in the clothing of the population of pedestrians), and it does not necessarily require the models to be validated against data observed in real or experimental situations. The approach described in [39], in [40] and in [41] is characterised by a very composite model of pedestrian behaviour, including basic reactive behaviours as well as a cognitive control layer; moreover, actions available to agents are not strictly related to their movement, but they also allow forms of direct interaction among pedestrians and interaction with objects situated in the environment. Other approaches in this area (see, e.g., [42]) also define layered architectures including cognitive models for the coordination of composite actions for the manipulation of objects present in the environment. Another relevant approach, described in [43], is less focused on visual effectiveness of the simulation dynamics, and it supports a flexible definition of the simulation scenario also without requiring the intervention of a computer programmer. However, these virtual reality focused approaches to pedestrian and crowd simulation were not tested in paradigmatic case studies and thoroughly validated against real data.

4. An Agent-Based Proxemic Model

This section introduces an agent-based model including abstractions and mechanisms based on fundamental considerations about proxemics and basic group behaviour in pedestrians. We first defined a very general and simple model for agents, their environment and interaction, then we realised a proof-of-concept prototype to have an immediate idea of the implications of our modelling choices. The present model does not represent an answer to all of the open issues introduced in the previous sections but rather a first step in this line of research already presenting some interesting results; further extensions of the model and its application to more complex scenarios in the context of the Hajj are object of current project activities. The results of this first steps in the modelling and *in-silico* experimentation phase of the project are also discussed in [44].

The simulated environment is based on a simplified real built environment: a corridor with two exits (North and South); different experiments will be described with corridors of different size (10 m wide and 20 m long as well as 5 m wide and 10 m long). We represented this environment as a simple Euclidean bi-dimensional space, which is discrete (meaning that coordinates are integer numbers) but not "discretised" (as in a CA). Pedestrians, in other words, are characterised by a position that is a pair $\langle x, y\rangle$ that does not denote a cell but rather admissible coordinates in an Euclidean space. Movement, the fundamental agent's action is represented as a displacement in this space, *i.e.*, a vector. The approach is essentially based on the Boids model [45], in which rules have been modified to represent the phenomenologies described by the basic theories on pedestrian movement. Boundaries can also be defined: in the example Eastern and Western borders cannot be crossed and the movement of pedestrians is limited by the pedestrian position update function, which is an environmental responsibility. Every agent $a \in A$ (where A is the set of agents representing pedestrians of the modelled scenario) is characterised by a position pos_a represented by a pair of coordinates $\langle x_a, y_a \rangle$. Agent's action is thus represented by a vector $\overline{m}_a = \langle \delta_{x_a}, \delta_{y_a} \rangle$ where $|\overline{m}_a| = \sqrt{\delta_{x_a}^2 + \delta_{y_a}^2} < M$, where M is a parameter depending on the specific scenario representing the maximum displacement per time unit.

More complex environments could be modelled, for instance by means of a set of relevant objects in the scene, like points of interest but also obstacles. These objects could be perceived by agents according to their position and perceptual capabilities, and they could thus have implications on their movement. Objects can in fact (but they do not necessarily have to) be considered as attractive or repulsive by them. The effect of the perception of objects and other pedestrians, however, is part of agents' behavioural specifications. For this specific application, however, the perceptive capability of an agent a are simply defined as the set of other pedestrians that are present at the time of the perception in a circular portion of space or radius r_p centred at the current coordinates of agent a. In particular, each agent $a \in A$ is provided with a perception distance per_a; the set of perceived agents is defined as $P_a = p_1, \ldots, p_i$ where $d(a, i) = \sqrt{(x_a - x_i)^2 + (y_a - y_i)^2} \leq per_a$.

Pedestrians are modelled as agents situated in an environment, each occupying about 40 cm^2, characterised by a state representing individual properties. Their behaviour has a goal driven component, a preferred direction; in this specific example it does not change over time and according to agent's position in space (agents want to get out of the corridor from one of the exits, whether north or south), but it generally changes according to the position of the agent, generating a path of movement from its starting point to its own destination. The preferred direction is thus generally the result of a stochastic function possibly depending on time and current position of the agent. The goal driven component of the agent behavioural specification, however, is just one the different elements of the agent architectures that must include elements properly capturing elements related to general proxemic tendencies and group influence (at least), and we also added a small random contribution to the overall movement of pedestrians, as suggested by [46]. The actual layering of the modules contributing to the overall is object of current and future work. In the scenario, agents' goal driven behavioural component is instead rather simple: agents heading North (respectively South) have a deliberate contribution to their overall movement $\overline{m}_a^g = \langle 0, M \rangle$ (respectively $\overline{m}_a^g = \langle 0, -M \rangle$).

We realised a simulation scenario in a rapid prototyping framework [47] and we employed it to test the simple behavioural model that will be described in the following. In the realised simulator, the environment is responsible for updating the position of agents, actually triggering their action choice in a sequential way, in order to ensure fairness among agents. In particular, we set the turn duration to 100 ms and the maximum covered distance in one turn is 15 cm (*i.e.*, the maximum velocity for a pedestrian is 1.5 m/s).

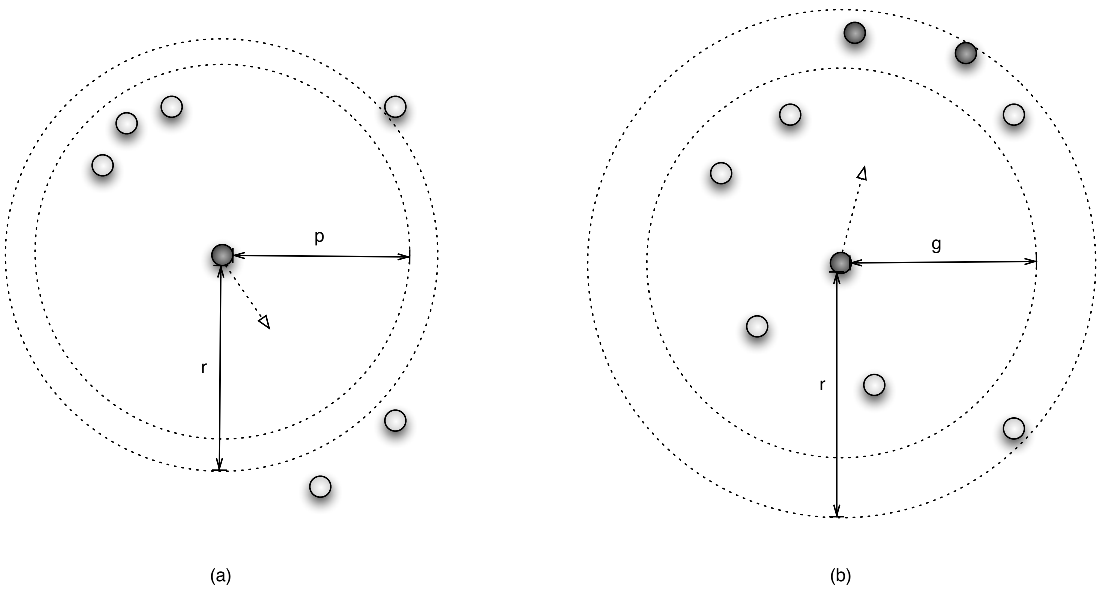
4.1. Basic Proxemic Rules

Every pedestrian is characterised by a culturally defined proxemic distance p; this value is in general related to the specific culture characterising the individual, so the overall system is designed to be potentially heterogeneous. In a normal situation, the pedestrian moves (according to his/her preferred direction) maintaining the minimum distance from the others above this threshold (rule *P1*). More precisely, for a given agent a, this rule defines that the proxemic contribution to the overall agent movement $\overline{m}_a^p = 0$ if $\forall b \in P_a : d(a, b) \geq p$.

However, due to the overall system dynamics, the minimum distance between one pedestrian and another can drop below p. In this case, given a pedestrian a, we have that $\exists b \in P_a : d(a, b) < p$; the proxemic contribution to the overall movement of a will try to restore this condition (rule *P2*) (please notice that pedestrians might have different thresholds, so b might not be in a situation so that his/her *P2* rule is activated). In particular, given $p_1, \ldots, p_k \in P_a : d(a, p_i) < p$ for $1 \leq i \leq k$, given c the centroid of $pos_{p_1}, \ldots, pos_{p_k}$, the proxemic contribution to the overall agent movement $\overline{m}_a^p = -k_p \cdot \overline{c - pos_a}$, where k_a is a parameter determining the intensity of the proxemic influence on the overall behaviour.

These basic considerations, also schematised in Figure 4a, lead to the definition of rules that support a basic proxemic behaviour for pedestrian agents; these agents are not characterised by any particular relationship binding them, with the exception of a shared goal, *i.e.*, they are not a group but rather an unstructured set of pedestrians.

Figure 4. Basic behavioural rules: a basic proxemic rule drives an agent to move away from other agents that entered/are present in his/her own personal space (delimited by the proxemic distance p) (**a**), whereas a member of a group will pursue members of his/her group that have moved/are located beyond a certain distance (g) but within his/her perception radius (r) (**b**).



4.2. Group Dynamic Rules

We extended the behavioural specification of agents by means of an additional contribution representing the tendency of group members to stay close to each other. First of all, every pedestrian may be thus part of a group, that is, a set of pedestrians that mutually recognise their belonging to the same group and that are willing to preserve the group unity. This is clearly a very simplified non-hierarchical notion of group, and in particular it does not account for hierarchical relationships in groups (e.g., leader and followers), but we wanted to start defining basic rules for the simplest form of group.

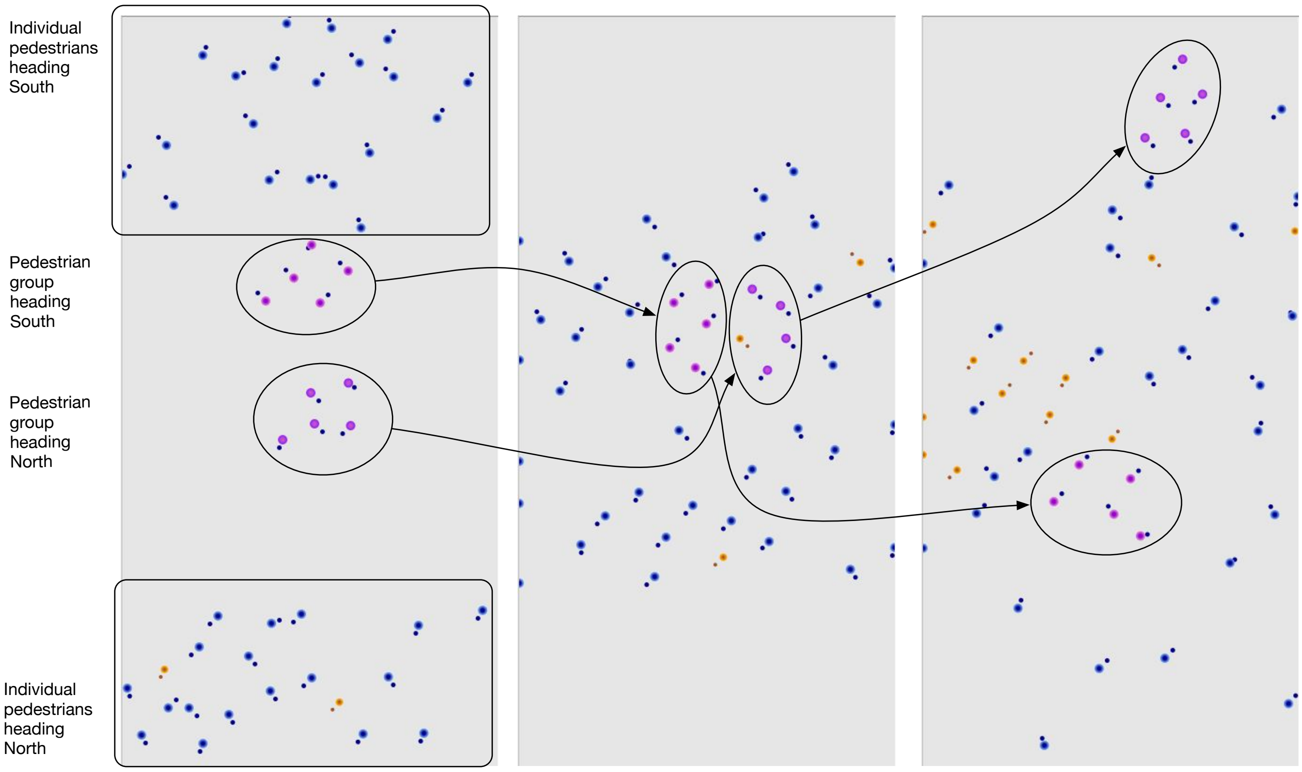
Every pedestrian is thus also characterised by a culturally defined proxemic distance g determining the way the pedestrian interprets the minimum distance from any other group member. In particular, in a normal situation a pedestrian moves (according to his/her preferred direction and also considering the basic proxemic rules) keeping the maximum distance from the other members of the group below g (Rule *G1*). More precisely, for a given agent a, member of a group G, this rule defines that the group dynamic contribution to the overall agent movement $\overline{m}_a^g = 0$ if $\forall b \in (P_a \cap (G - \{a\})) : d(a, b) < g$.

However, due to the overall system dynamics, the maximum distance between one pedestrian and other members of his group can exceed g. In this case, the pedestrian will try to restore this condition by moving towards the group members he/she is able to perceive (rule *G2*). In particular, given $p_1, \ldots, p_k \in (P_a \cap (G - \{a\})) : d(a, p_i) \geq g$ for $1 \leq i \leq k$, given c the centroid of $pos_{p_1}, \ldots, pos_{p_k}$, the proxemic contribution to the overall agent movement $\overline{m}_a^g = k_g \cdot \overline{c - pos_a}$, where k_a is a parameter determining the intensity of the group dynamic influence on the overall behaviour.

This basic idea of group influence on pedestrian dynamics, also schematised in Figure 4b, lead to the extension of the basic proxemic behaviour for pedestrian agents of the previous example. We tested the newly defined rules in a similar scenario but including groups of pedestrians. In particular, two scenarios were analysed. In the first one, we simply substituted 4 individual pedestrians in the previous scenario with a group of 4 pedestrians. The group was able to preserve its unity in all the tests we conducted, but the average travel time for the group members actually increased. Individuals, in other words, trade some of their potential speed to preserve the unity of the group. In a different scenario, we included 10 pedestrians and a group of 4 pedestrians heading north, 10 pedestrians and a group of 4 pedestrians heading south. In these circumstances, the two groups sometimes face and they are generally able to find a way to form two lanes, actually avoiding each other. However, the overall travel time for group members actually increases in many of the simulations we conducted.

Figure 5 shows two screenshots of the prototype of the simulation system that was briefly introduced here. Individual agents that are not part of a group are depicted in blue, but those for which rule P2 is activated (they are afraid to be touched) are in orange to highlight the invasion of their personal space. Members of groups are depicted in violet and pink. The two screenshots show how two groups directly facing each other must manage to “turn around” each other to preserve their unity but at the same time advance towards their destination.

Figure 5. Screenshots of the prototype of the simulation system.



5. Observable Behaviours in Crowd Simulation Models

After introducing a sample pedestrian and crowd model, it is now possible to introduce in a more systematic way those relevant measurements and analyses of the simulation results that represent the *effectiveness* side of the way to evaluate a simulation model (the *efficiency* dimension of this kind of research effort is out of the scope of this section). In Floridi's framework, these measurements and analyses would be called *system behaviours*.

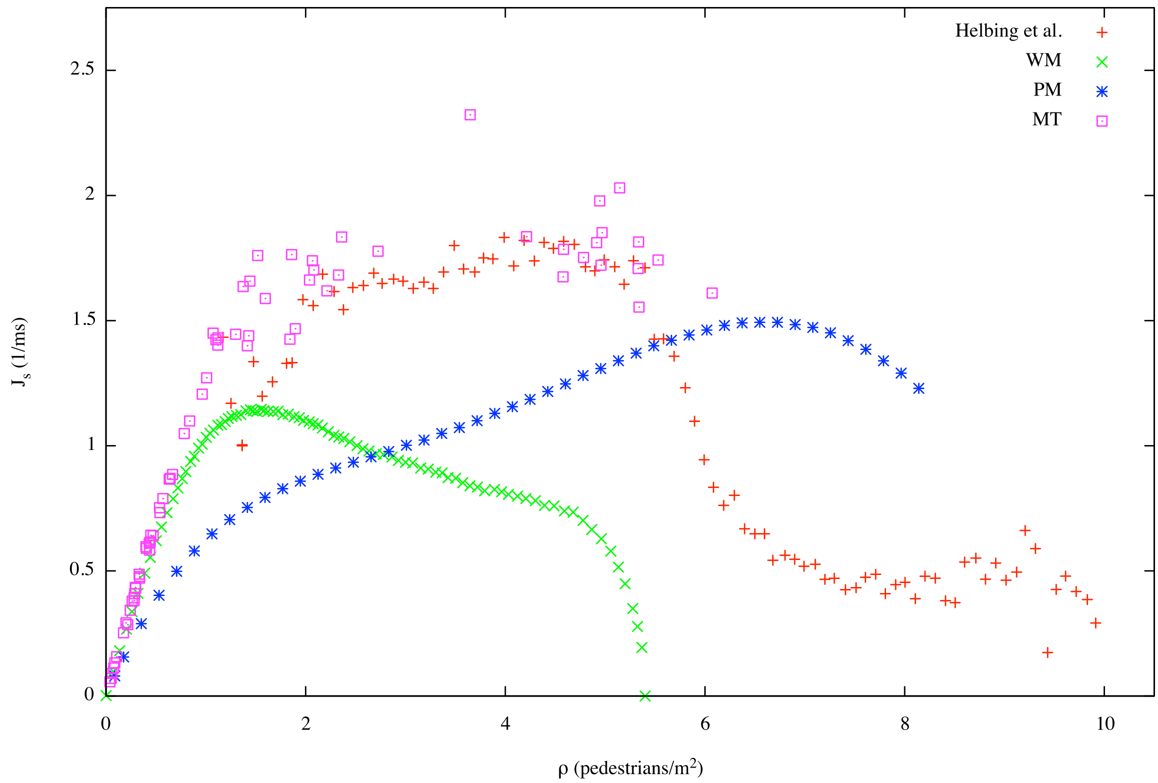
Once a model has been defined and a simulation system implementing it has been realised, it is possible to execute such system and to analyse its results. First of all, this can be done to understand if the model and the simulator implementing it produce dynamics that match, to a certain extent, those that can be observed in reality (at least when the simulated scenario does represent a real situation, not, for instance, a designed or planned one). After the model has proven its merits in a sufficiently representative set of scenarios, it can be used for the sake of explanation or prediction. Leaving aside the issues related to the usage of simulation as a method for scientific investigation (for a more comprehensive discussion on these topics please consider [6] or [8] in the specific context of agent-based approaches), we are now going to focus on the nature of the "results" of a pedestrians or crowd simulation.

One of the first type of relevant data that can be generated by a pedestrian simulation system is represented by the time that is necessary for a simulated pedestrian to complete a certain specific type of composite path in the environment: questions like "considering this arrangement of the environment and these crowding conditions, how long does it take to move from point A to point B?" represent a significant motivation behind the whole modelling and simulation effort. Considering the specific nature of the involved models, but also the nature of the simulated reality, it is more appropriate to talk about average travel time associated with a given path (and sometimes to a given type of pedestrian, whenever the model can deal with different types of agents in the simulated scenario). Some of the considerations introduced in [48], in fact, effectively highlight the potential limits of pedestrian models: in the cited paper, a well known and widely adopted model [49], which is able to generate plausible and realistic dynamics from both qualitative and quantitative perspectives (e.g., formation of lanes, patterns at intersections and bottlenecks), does not faithfully reproduce a pedestrian avoidance pattern among just two individuals. Results of pedestrian and crowd models should therefore be considered and analysed at an aggregate level.

A different kind of analysis of simulation results that represents a further step in the above direction is represented by the so-called *fundamental diagram* [10]: this graph shows how the average velocity of pedestrians in a section of the environment (e.g., one of the ends of a corridor) varies according to the density of the observed environment. Since the flow of pedestrians is directly proportional to their velocity, this diagram is sometimes presented in an equivalent form that shows the variation of flow according to the density. In general, we expect to have 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. Despite being of great relevance, different experiments gathered different values of empirical data. Consensus on the shape of the function is wide, but the range of the possible values has even big differences from different versions, as one can see from the set of different diagrams in Figure 6 where both lines are related to design manuals ([50,51]) and also data points are related to experimental measurements (respectively carried out in the context of the Hajj in Saudi Arabia by [52] and in the city of Osaka, in Japan, by [53]). The maximum possible value for density before congestions arise is also disputed. In the several versions of the fundamental diagram presented, this value ranges between 3.8 m^2 and 10 m^2, which is more than double. In [54], the authors report densities of 8 m^{-2} during the Tawaf, one of the Islamic rituals of pilgrimage, and in general values higher than 6.25 m^{-2} (the limit of several CA-based models) are reported to be found. Nonetheless, the capability of a model to generate a plausible fundamental diagram represents a sort of necessary condition for the possibility of actually reproducing in a faithful way pedestrian dynamics in more complex situations than a single corridor or section of a larger scenario.

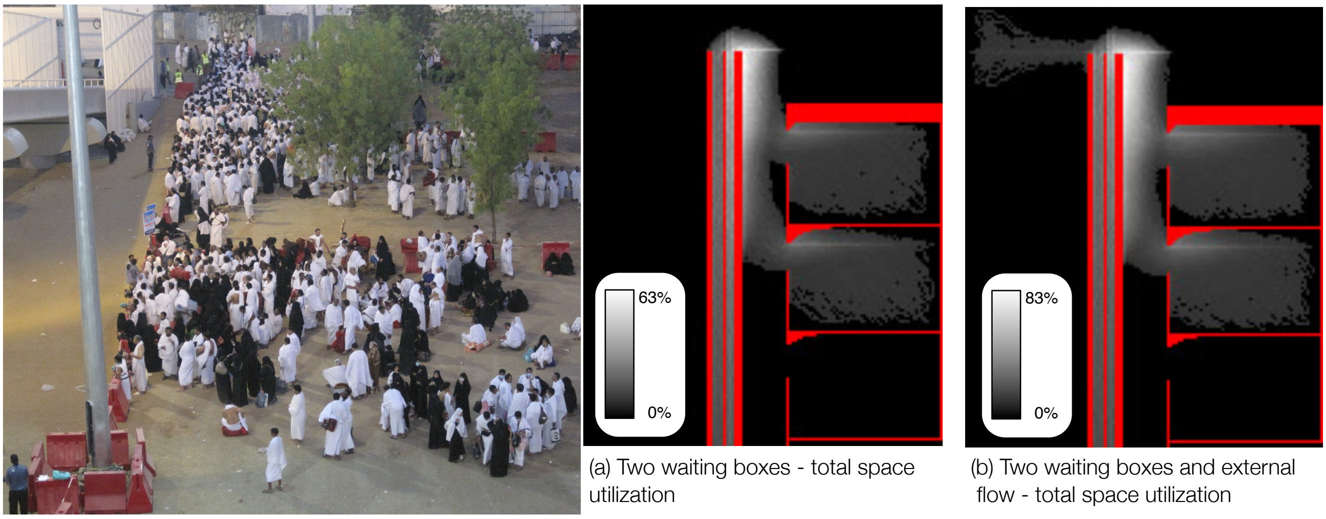
Finally, one of the most interesting possibilities offered by pedestrian simulation system is the chance to actually visualise the plausible utilisation of space in the actual map of the environment in order to identify potentially problematic situations. This measure is essentially related to the frequency of occupation of a "spot" of the simulated environment by a pedestrian on the overall simulated time; this value is essentially related to the geometry of the environment and the planned flows, and it is strongly related to local average density of pedestrians (relating to the so-called "level of service" for pedestrian facilities [55]). Figure 7 shows an sample situation in the context of the Hajj, more thoroughly described in [56]: in this scenario, each pilgrim moves from a waiting area towards a ramp to reach a train station. The overall process of arrival of pilgrims to the station must be organised in order to avoid congestion and a simulation system can help in understanding how different crowd management schemes perform from this perspective. The diagrams of Figure 7 respectively show the level of space utilisation (a) in the simultaneous arrival of pilgrims from two waiting areas and (b) when a group of pilgrims move directly to the ramp in addition to the pilgrims moving from the previous two waiting areas.

Figure 6. Empirical fundamental diagrams for pedestrian movement in planar facilities as reported by design manuals design manuals [50,51] and also data points related to experimental measurements (respectively carried out in the context of the Hajj in Saudi Arabia by Helbing [52] and in the city of Osaka, in Japan, by [53]).



It must be emphasised that the substantial number, variety and level of formalisation of relevant system behaviour are actually an important factor supporting the possibility to evaluate and compare the results of a modelling approach. In fact, given the heterogeneity in the modelling approaches, briefly introduced in Section 3, it might be difficult to put them in relation in terms of different levels of abstractions, in Floridi's sense. Nonetheless, it is generally quite simple to achieve the necessary information from the model to analyse its results in terms of the above system behaviours and therefore to actually compare the performance of models on the basis of the outcomes of their application, as shown in Figure 8: the analysis described in [57], for instance, shows how different (commercial) simulation platforms, working respectively with a discrete and a continuous spatial representation of the environment, can actually produce comparable results in terms of analysis of the "level of service".

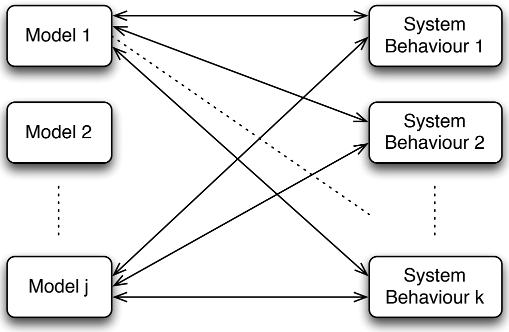
Figure 7. A portion of a simulated scenario on the left and two schematic representations of the level of space utilisation on the right.



(a) Two waiting boxes - total space utilization

(b) Two waiting boxes and external flow - total space utilization

Figure 8. A mapping scheme between models and relevant system behaviours.



6. Conclusions and Future Works

The paper has discussed the relationships between concepts and notions defined by Luciano Floridi's epistemological levelism [1] and the area of pedestrian and crowd modelling and simulation, an area of application of dynamical complex systems. In particular, we showed that the notion of levels of abstractions is important to clarify and focus the specific object of analysis of a research effort in this area. Moreover, we also discussed the difficulties in arranging different modelling approaches into a gradient of abstractions, given the heterogeneity of approaches and the related concepts and mechanisms; however, we clarified how precise and generally recognised system behaviours have emerged as means of comparison of model results. Future works may explore the relationships between models, results and theories coming from different disciplinary researches that, to a different extent, influenced the definition of pedestrian and crowd models in the epistemological levelism framework.

References

1. Floridi, L. The Method of Levels of Abstraction. *Mind. Mach.* **2008**, *18*, 303–329.

2. Grüne-Yanoff, T.; Weirich, P. The Philosophy and Epistemology of Simulation: A Review. *Simul. Gaming* **2010**, *41*, 20–50.
3. Winsberg, E. Simulations, Models, and Theories: Complex Physical Systems and Their Representations. *Proc. Philos. Sci. Assoc.* **2001**, *2001*, 442–454.
4. Winsberg, E. Simulated Experiments: Methodology for a Virtual World. *Philos. Sci.* **2003**, *70*, 105–125.
5. Varenne, F. Framework for M&S with Agents in regard to Agent Simulations in Social Sciences: Emulation and Simulation. In *Activity-Based Modeling and Simulation*; Muzy, A., Hill, D.R.C., Zeigler, B.P., Eds.; Presses Universitaires Blaise Pascal: Clermont-Ferrand, France, 2010; pp. 53–84.
6. Gilbert, N.; Troitzsch, K.G. *Simulation for the Social Scientist*, 2nd ed.; Open University Press: Maidenhead, UK, 2005.
7. Edmonds, B. The Use of Models—Making MABS More Informative. In *Multi-Agent-Based Simulation, Second International Workshop, MABS 2000*, Boston, MA, USA, July 2000; Springer–Verlag: Heidelberg, Germany, 2001; Volume 1979, pp. 15–32.
8. Bandini, S.; Manzoni, S.; Vizzari, G. Agent Based Modeling and Simulation: An Informatics Perspective. Available online: http://jasss.soc.surrey.ac.uk/12/4/4.html (accessed on 14 January 2013).
9. Evacmod.net. Available online: http://www.evacmod.net/?q=node/5 (accessed on 1 January 2013).
10. Schadschneider, A.; Klingsch, W.; Klüpfel, H.; Kretz, T.; Rogsch, C.; Seyfried, A. Evacuation Dynamics: Empirical Results, Modeling and Applications. In *Encyclopedia of Complexity and Systems Science*; Meyers, R.A., Ed.; Springer: Heidelberg, Germany, 2009; pp. 3142–3176.
11. Axtell, R.; Axelrod, R.; Epstein, J.M.; Cohen, M.D. Aligning Simulation Models: A Case Study and Results. *Comput. Math. Organ. Theor.* **1996**, *1*, 123–141.
12. Kuligowski, E.D.; Gwynne, S.M.V. *Pedestrian and Evacuation Dynamics 2008*; Springer: Heidelberg, Germany, 2010; pp. 721–732.
13. Hall, E.T. *The Hidden Dimension*; Anchor Books: New York, NY, USA, 1966.
14. Hall, E.T. A System for the Notation of Proxemic Behavior. *Am. Anthropol.* **1963**, *65*, 1003–1026.
15. Chattaraj, U.; Seyfried, A.; Chakroborty, P. Comparison of Pedestrian Fundamental Diagram Across Cultures. *Adv. Complex Syst.* **2009**, *12*, 393–405.
16. Costa, M. Interpersonal Distances in Group Walking. *J. Nonverbal Behav.* **2010**, *34*, 15–26.
17. Canetti, E. *Crowds and Power*; Farrar, Straus and Giroux: New York, NY, USA, 1984.
18. Bandini, S.; Manzoni, S.; Redaelli, S. *Towards an Ontology for Crowds Description: A Proposal Based on Description Logic*; Umeo, H., Morishita, S., Nishinari, K., Komatsuzaki, T., Bandini, S., Eds.; Springer: Heidelberg, Germany, 2008; Volume 5191, pp. 538–541.
19. Bandini, S.; Manenti, L.; Manzoni, S.; Sartori, F. A Knowledge-Based Approach to Crowd Classification. In *Proceedings of the The 5th International Conference on Pedestrian and Evacuation Dynamics*, Gaithersburg, MD, USA, 8–10 March 2010.
20. Schreckenberg, M.; Sharma, S.D. *Pedestrian and Evacuation Dynamics*; Springer–Verlag: Heidelberg, Germany, 2001.

21. Helbing, D.; Schweitzer, F.; Keltsch, J.; Molnár, P. Active Walker Model for the Formation of Human and Animal Trail Systems. *Phys. Rev. E* **1997**, *56*, 2527–2539.
22. Helbing, D.; Molnár, P. Social force model for pedestrian dynamics. *Phys. Rev. E* **1995**, *51*, 4282–4286.
23. Helbing, D. A Fluid–Dynamic Model for the Movement of Pedestrians. *Complex Syst.* **1992**, *6*, 391–415.
24. Okazaki, S. A Study of Pedestrian Movement in Architectural Space, Part 1: Pedestrian Movement by the Application of Magnetic Models. *Trans. AIJ* **1979**, 111–119.
25. Moussaïd, M.; Perozo, N.; Garnier, S.; Helbing, D.; Theraulaz, G. The Walking Behaviour of Pedestrian Social Groups and Its Impact on Crowd Dynamics. *PLoS ONE* **2010**, *5*, e10047.
26. Nagel, K.; Schreckenberg, M. A cellular automaton model for freeway traffic. *J. Phys. I Fr.* **1992**, *2*, 222–235.
27. Blue, V.J.; Adler, J.L. Cellular Automata Microsimulation of Bi-Directional Pedestrian Flows. *Transport. Res. Rec.* **1999**, *1678*, 135–141.
28. Blue, V.J.; Adler, J.L. Modeling Four-Directional Pedestrian Flows. *Transport. Res. Rec.* **2000**, *1710*, 20–27.
29. Schadschneider, A.; Kirchner, A.; Nishinari, K. CA Approach to Collective Phenomena in Pedestrian Dynamics. In *Cellular Automata, 5th International Conference on Cellular Automata for Research and Industry, ACRI 2002*; Bandini, S., Chopard, B., Tomassini, M., Eds.; Springer: Heidelberg, Germany, 2002; Volume 2493, pp. 239–248.
30. Nishinari, K.; Suma, Y.; Yanagisawa, D.; Tomoeda, A.; Kimura, A.; Nishi, R., In *Pedestrian and Evacuation Dynamics 2008*; Springer: Heidelberg, Germany, 2008; pp. 293–308.
31. Was, J. Crowd Dynamics Modeling in the Light of Proxemic Theories. In *ICAISC (2)*; Rutkowski, L., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M., Eds.; Springer: Heidelberg, Germany, 2010; Volume 6114, pp. 683–688.
32. Sarmady, S.; Haron, F.; Talib, A.Z.H. Modeling Groups of Pedestrians in Least Effort Crowd Movements Using Cellular Automata. In *Asia International Conference on Modelling and Simulation*; Al-Dabass, D., Triweko, R., Susanto, S., Abraham, A., Eds.; IEEE: Washington, DC, USA, 2009; pp. 520–525.
33. Henein, C.M.; White, T. Agent-Based Modelling of Forces in Crowds. In *Multi-Agent and Multi-Agent-Based Simulation, Joint Workshop MABS 2004*; Davidsson, P., Logan, B., Takadama, K., Eds.; Springer–Verlag: Heidelberg, Germany, 2005; Volume 3415, pp. 173–184.
34. Dijkstra, J.; Jessurun, J.; de Vries, B.; Timmermans, H.J.P. Agent Architecture for Simulating Pedestrians in the Built Environment. *International Workshop on Agents in Traffic and Transportation*, Hakodate, Japan, 2006; pp. 8–15.
35. Batty, M. Agent Based Pedestrian Modeling (editorial). *Environ. Plan. B Plan. Des.* **2001**, *28*, 321–326.
36. Gloor, C.; Stucki, P.; Nagel, K. Hybrid Techniques for Pedestrian Simulations. In *Cellular Automata, 6th International Conference on Cellular Automata for Research and Industry, ACRI 2004*; Sloot, P.M.A., Chopard, B., Hoekstra, A.G., Eds.; Springer: Heidelberg, Germany, 2004; Volume 3305, pp. 581–590.

37. Toyama, M.C.; Bazzan, A.L.C.; da Silva, R. An agent-based simulation of pedestrian dynamics: from lane formation to auditorium evacuation. *5th International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2006)*; Nakashima, H., Wellman, M.P., Weiss, G., Stone, P., Eds.; ACM: New York, NY, USA, 2006, pp. 108–110.
38. Bandini, S.; Federici, M.L.; Vizzari, G. Situated Cellular Agents Approach to Crowd Modeling and Simulation. *Cybern. Syst.* **2007**, *38*, 729–753.
39. Musse, S.R.; Thalmann, D. Hierarchical Model for Real Time Simulation of Virtual Human Crowds. *IEEE Trans. Vis. Comput. Graph.* **2001**, *7*, 152–164.
40. Curtis, S.; Guy, S.J.; Zafar, B.; Manocha, D. Virtual Tawaf: A case study in simulating the behavior of dense, heterogeneous crowds. *ICCV Workshops*; IEEE: Washington, DC, USA, 2011; pp. 128–135.
41. Shao, W.; Terzopoulos, D. Autonomous pedestrians. *Graph. Model.* **2007**, *69*, 246–274.
42. Paris, S.; Donikian, S. Activity-Driven Populace: A Cognitive Approach to Crowd Simulation. *IEEE Comput. Graph. Appl.* **2009**, *29*, 34–43.
43. Murakami, Y.; Ishida, T.; Kawasoe, T.; Hishiyama, R. *Scenario Description for Multi-agent Simulation*. AAMAS, ACM: New York, NY, USA, 2003; pp. 369–376.
44. Manenti, L.; Manzoni, S.; Vizzari, G.; Ohtsuka, K.; Shimura, K. *An Agent-Based Proxemic Model for Pedestrian and Group Dynamics: Motivations and First Experiments*; Villatoro, D., Sabater-Mir, J., Sichman, J.S., Eds.; Springer: Heidelberg, Germany, 2011; Volume 7124, pp. 74–89.
45. Reynolds, C.W. Flocks, herds and schools: A distributed behavioral model. *SIGGRAPH '87: Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques*; ACM: New York, NY, USA, 1987; pp. 25–34.
46. Batty, M. *Advanced Spatial Analysis: The CASA Book of GIS*; Esri Press: Aylesbury, UK, 2003; pp. 81–106.
47. Nodebox. Available online: http://www.nodebox.org (assessed on 7 January 2013).
48. Pettré, J.; Ondřej, J.; Olivier, A.H.; Cretual, A.; Donikian, S. Experiment-based modeling, simulation and validation of interactions between virtual walkers. In *Proceedings of the 2009 ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA '09)*; ACM: New York, NY, USA, 2009; pp. 189–198.
49. Helbing, D.; Farkas, I.J.; Molnár, P.; Vicsek, T. *Pedestrian and Evacuation Dynamics*; Springer: Heidelberg, Germany, 2001; pp. 21–58.
50. Weidmann, U. Transporttechnik der Fussgänger—Transporttechnische Eigenschaftendes Fussgängerverkehrs (Literaturstudie). Literature Research 90, Institut füer Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau IVT an der ETH Zürich, Zürich, Switzerland, 1993.
51. Predtechenskii, V.; Milinskiĭ. *Planning for Foot Traffic Flow in Buildings*; Amerind Publishing: New York, NY, USA, 1978.
52. Helbing, D.; Johansson, A.; Al-Abideen, H.Z. The Dynamics of Crowd Disasters: An Empirical Study. *Phys. Rev. E* **2007**, *75*, doi: 10.1103/PhysRevE.75.046109.
53. Mori, M.; Tsukaguchi, H. A new method for evaluation of level of service in pedestrian facilities. *Trans. Res. A* **1987**, *21*, 223–234.

54. Zafar, B. *Analysis of the Mataf—Ramadan 1432 AH*; Technical Report; Hajj Research Institute, Umm al-Qura University, Saudi Arabia, 2011.
55. Fruin, J.J. *Pedestrian planning and design*; Metropolitan Association of Urban Designers and Environmental Planners: New York, NY, USA, 1971.
56. Vizzari, G.; Manenti, L.; Ohtsuka, K.; Shimura, K. An Agent-Based Approach to Pedestrian and Group Dynamics: Experimental and Real World Scenarios. In *Proceedings of the 7th International Workshop on Agents in Traffic and Transportation*, Valencia, Spain, 2012.
57. Castle, C.; Waterson, N.; Pellissier, E.; Bail, S. A Comparison of Grid-based and Continuous Space Pedestrian Modelling Software: Analysis of Two UK Train Stations. In *Pedestrian and Evacuation Dynamics*; Peacock, R.D., Kuligowski, E.D., Averill, J.D., Eds.; Springer: Heidelberg, Germany, 2011; pp. 433–446.