

## *Agent - based simulation of pedestrian behaviour*

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### **1 Introduction**

Walking is the most sustainable mode of transport, involves 75% of all trips under a kilometre, is the first and last segment of every travel, affects the level of service of important transport infrastructure such as airports and railway stations, is of fundamental importance in fields related to urban planning, emergency, disaster planning. Nevertheless, transportation engineering is traditionally focused on motorized travel and therefore there is a general lack of research and methods to model pedestrian behaviour.

Existing transport pedestrian models can be roughly separated in analytical models and micro-simulations.

The first ones include “before and after” methods, regression analysis models (Older, 1968; Pushkarev, 1971), analogies with fluids, gas kinetics and other physical flow systems (Helbing, 1992; Henderson, 1974), entropy maximization (Butler, 1978), dynamic network analysis with flow models calibrated on the basis of data collected (Di Gangi, 2007), discrete choice model to predict pedestrians’ route choice (Antonini, 2006; Ignaccolo 2006), stochastic queuing and Markovian models (Mitchell, 2001). They use mathematical models to calculate average pedestrian flows along a path, but are not able to include peculiar aspects of pedestrian (human) behaviour.

The second ones simulate the movement of each single pedestrian following a set of pre-determined rules of behaviour, and are applicable to a greater variety of situations, such as closed spatial environments, or unusual demand flows, where local dynamics of individual decision making is strongly affected by geometry, randomness, social preferences, local and collective behaviour of other individuals. Some simulation approaches are based on the concept of “social force”, that include a sort of internal moti-

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variations of the individuals to perform certain actions (movements) and its influence on people's dynamic variables (velocity, acceleration, distance) (Helbing, 1995), others use the cellular automata technique to model the behaviour of single pedestrians by means of a limited set of rules describing its features (Blue, 2001; Sarmady, 2008), or finally perform agents simulations able to treat pedestrians as fully autonomous entities with cognitive and often learning capabilities (Koh, 2008; Batty, 1999). The main feature of agent simulations is that computational algorithms are not used to calculate complex equations as in traditional micro-simulation, but only to describe simple rules that has to be followed by each component during simulation: the consequence is that simulation does not force the system into a preset track, but rather pushes it along an evolving direction, leaving it free, within given limits, to choose which trajectory to follow.

In this paper we perform an agent-based simulation of people moving in a closed spatial environment, using the Castello Ursino in Catania (Italy) as case study. The simulation intend to evaluate if optimal configuration can be found both considering the so called "Carrying Capacity" of the museum, that is the total number of visitors the building can tolerate keeping maximum the level of global satisfaction (see also Garofalo, 2007), and considering the safety of the building, in terms of evacuation strategies and performances. In addition, the case study will be useful to show how an agent-based simulation of pedestrian walking dynamics in a given bounded environment can be important in exploring rising crowd behaviour which can affect, in turn, the level of service and the safety of a closed environment (the safety issues were also analyzed in Camillen et al., 2010, in publication).

## **2 Methodology and case study**

### *2.1 Agent-based simulations: the NetLogo platform*

An agent-based simulation is a computer technique simulating a system whose main components are 'agents', i.e. single mobile entities which are capable of autonomous actions in order to meet their fixed objectives (Woolridge, 2002). Agents can perceive and respond to changes in their environment, can take autonomous decisions to achieve their goals and can interact in a social way with other agents, if useful to realize their objectives (Figure 1).

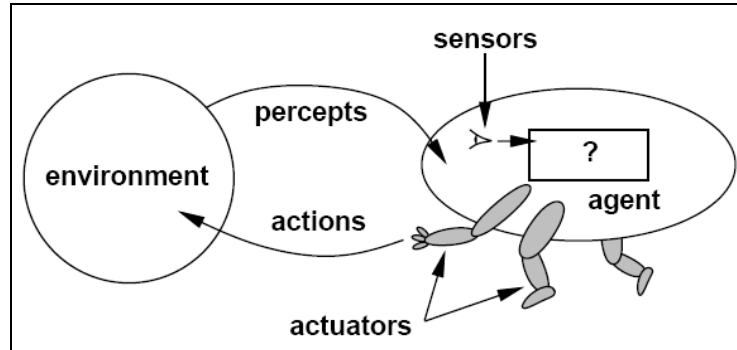


Figure 1– Agent properties

They are called intelligent if they can learn by experience from the environment and adapt to it in the sense that they are provided with “rules to change the rules”.

The overall output of these micro-level properties can lead to the emergence of a collective behavioural pattern, as the result of a trade-off between competitive and cooperative individual choices. The typical case is when local pedestrian movements towards some goal can lead to undesired crowded situations while the tendency to follow what others are doing (herding effect) can favour congestion and panic. In other words, these simulation techniques are able to capture and explore rising crowd behaviours which cannot be described as simple aggregations of individual movements and that often are very far from intuition and hardly foreseeable by experience and common sense (Kitazawa, 2004; Kitazawa, 2003; Osaragi, 2004).

We use NetLogo (Wilensky, 1999) as multi-agent simulation both to create the virtual world environment and an interface for commands and procedures to be activated by the user of the software. The spatial environment in NetLogo is represented by a two dimensional grid (World) of discrete cells, called ‘patches’, whose topology can be chosen among square/rectangular (with closed boundary conditions), cylindrical (with open boundary conditions on one direction) or toroidal (with open boundary conditions on both directions). Unlike pixels in a picture, patches are active motionless elements, since they can possess several features (coordinates, colours and other user-variables) and can be able to interact with moving agents which pass over them. We will give some more details on the Netlogo environment in the next section.

## 2.2 The Castello Ursino Museum

Using Netlogo, we apply the agent-based approach to study pedestrian

behaviour inside a complex old building, the Castello Ursino (Figure 2). It is a square compact building, with four towers and ten rooms placed around a central courtyard, useful for the evacuation plan.

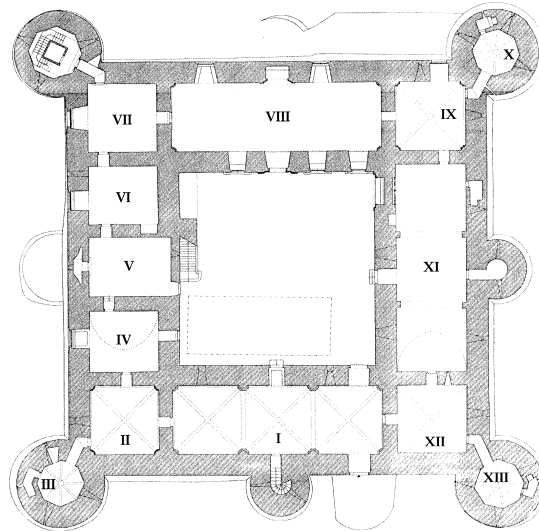


Figure 2– Real Planimetry of Castello Ursino

This building represents a good environment to test the complex emerging behaviour of a great number of visitors walking along its rooms full of paintings, sculptures and other works of art, trying to maximize their personal satisfaction during the visit experience, while interacting each other and with the environment. There is only one main entrance/exit door but many rooms which contain different paintings and artworks, thus providing different levels of interest to visitors. The simulation will be used to evaluate what is the optimal number of people simultaneously visiting the museum, in terms of level of overall satisfaction experimented. This practical problem recalls the concept of “carrying capacity” of a biological species in an environment, as the population size of the species that the environment can sustain indefinitely, given the food, habitat, water and other necessities available. Usually studied with well known predator-prey mathematical logistics relationships, they can be hardly applied when moving from the wild to more complex human behaviour and environments. The concept of carrying capacity as the maximum number of visitors to be accepted into the museum has been used to measure the performance of the system simulated under normal fruition dynamics, as explained in section 3.1.

As most of the building belonging to historical heritage, Castello Ursino

shows some concerns about safety management. Therefore an emergency dynamics will be also simulated, to measure the safety performances in terms of evacuation times for different layout of the buildings, safety procedures and crowding scenarios, as described in section 3.2.

Results are averaged over 100 different simulation runs, performed with the same parameters.

### 3 Implementation of the agent-based model and simulation results

#### 3.1 Normal fruition dynamics

The planimetry of the ground floor of Castello Ursino museum has been reproduced within the NetLogo interface preserving the real scale (Figure 3).

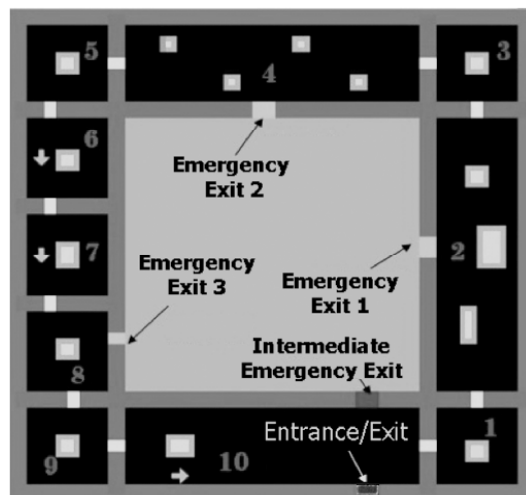


Figure 3 – Planimetry of Castello Ursino, realized on the NetLogo spatial grid

The grain of resolution is a square patch  $60 \times 60 \text{ cm}^2$ , able to carry one visitor at a time. The different patch's colours of the spatial environment (here reported in gray scale, but coloured in the real interface) allow the agents to recognize and properly interact with objects with different "physical property", i.e. internal and external walls, external entrance/exit door (on the bottom), internal doors, three emergency exits from rooms 2, 4 and 8 to the internal courtyard, one intermediate emergency exit from the courtyard to room 10, artworks (rectangular areas inside the rooms), fruition spaces around the artworks and free space (in black). Arrows in rooms

6, 7 and 10 represents emergency signs indicating the closer exit direction.

In the normal fruition dynamics, visitors access the museum in groups of randomly selected sizes  $S$  (between 1 and  $S_{MAX}$ ) separated by random intervals of time uniformly distributed around the quantity  $\Delta T$  (inter-arrival time); they move counter-clockwise along one patch in one time-step (=1sec), so they have an average velocity of 0.60 m/sec, little less than the normal pace (0.75 m/sec). Though constrained by the colour of the patches, the motion of the visitors is not predetermined and follows a few intuitive rules: each agent possesses a radius of vision and is attracted by doors or artworks around him; when no obstacles are present, he moves towards his target, doors or artworks, which are dynamically stored in an individual memory so that he will not pass twice through the same door and will not attend twice the same artwork; in presence of obstacles, walls or other people, he tries to avoid them going around. For each artwork, each agent has a different random interest, i.e. the time he is willing to spend enjoying that artwork, and a different random patience, i.e. the time he is willing to spend waiting for free space in the fruition area around that artwork. As a function of patience and interest it is possible to calculate in real time the level of satisfaction of each visitor: in particular, individual satisfaction increases with the number of artworks really visited (proportionally to the interest) and decreases with the time spent in the fruition area for every artwork (proportionally to the patience), which in turn is affected by the presence of the other visitors. Once the visit is over, visitors exit from the only external door in room 10, which is the same used to access the museum, then they make their final satisfaction to be added to a global variable, called 'total satisfaction' (which is also divided by the number of visitors, to calculate the 'average satisfaction').

For evaluating the carrying capacity of the museum, we firstly plot in Figure 4 the number of visitors simultaneously present inside the museum (averaged over ten simulation runs) as a function of the inter-arrival time  $\Delta T$  and for three different entering group sizes  $S_{MAX}$ . Of course such a number decreases with  $\Delta T$  and increases with  $S_{MAX}$ : therefore, studying the normal fruition dynamics, we will fix  $S_{MAX}=30$  and  $\Delta T=20s$  in order to be able to change the total number of agents visiting the museum from 20 to 200 and to evaluate, for each value, their total visit time and their satisfaction.

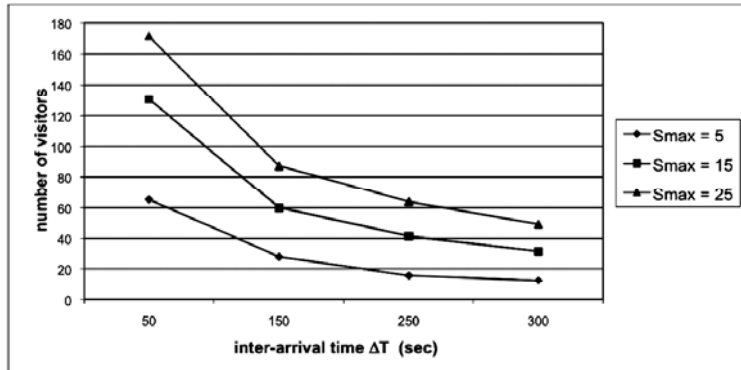


Figure 4 – Average number of visitors inside the museum for different arrival pattern ( $S_{MAX}=30$  and  $\Delta T=20s$ )

The graphics of Figure 5 present the output of the visit time and both of the average satisfaction and the total satisfaction as a function of the visitor load of the museum. All the curves have been normalized to their maximum values.

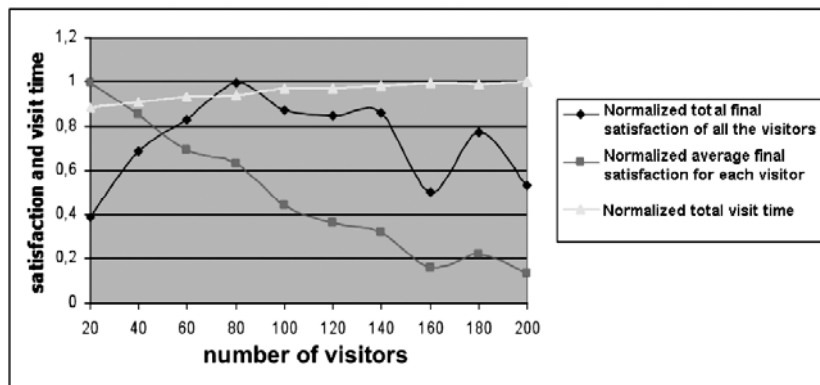


Figure 5 – Normalized values of total visit time and of total and average satisfaction.

The total visit time (light triangles) shows a moderate growth with the number of visitors, probably because the satisfaction depreciation caused by a greater number of visitors does not lead to a proportional longer visit, being its duration conditioned by the degree of patience. As expectable, the average final satisfaction (gray squares) is strongly affected by crowding: it presents its maximum value for the minimum load and tends to zero as the number of visitors overcome 200 units. On the other hand, quite surprisingly, it finds out that the curve of the total final satisfaction of all the visi-

tors at the end of their tour (dark diamonds) is not monotonic but has a maximum at about 80 agents: such a result was a-priori unpredictable and allow us to interpret the number of 80 visitors as a possible value for the carrying capacity of the museum, being it also compatible with a quite good total visit time (intermediate between the minimum and the maximum values).

### 3.2 Emergency dynamics: simulation results

Now we will focus on what happen when, after a transient regime of normal fruition of the museum, an alarm situation suddenly arises. In such a situation, of course, the behaviour dynamics of the agents changes as well as their average speed: in order to take into account the faster pace typical of an alarm situation, we rescaled the time by dividing it for a factor 1.66, thus obtaining an average velocity of 1m/s. We firstly consider the existing configuration of three internal emergency exits.

As it will be shown in the following, agent simulation has allowed an holistic approach, where configurational aspects (number and location of exits), environmental (spatial geometry), behavioral (rules of agents) and procedural aspects (emergency signs) of the evacuation process have been simultaneously modeled, according with the scheme of Figure 6.

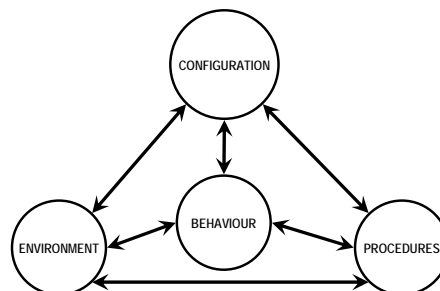


Figure 6 – Scheme of the evacuation process

Actually, as soon as an emergency alarm randomly goes off, each visitors checks if there is one of the three emergency exits overlooking the central courtyard within his radius of vision. If yes, he moves towards that direction, otherwise, if emergency signs are present and visible to him, he follows them; if not, he goes backward following the same path where he came from, until the external entrance/exit door is found. Visitors collected in the courtyard, converge towards the intermediate emergency exit then, finally, they reach the exit door (see the flowchart in Figure 7).

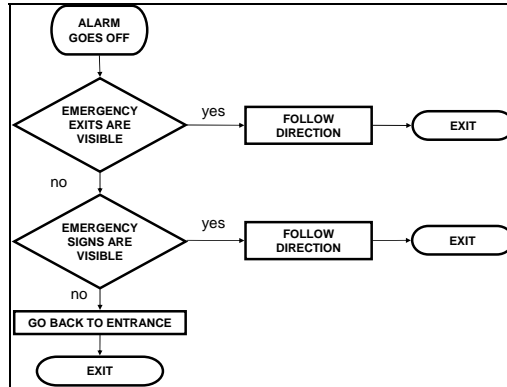


Figure 7 – Flowchart of Emergency dynamics.

A snapshot of a possible situation created by such a dynamics after an alarm event is shown, just to give an example, in Figure 8, where the existing configuration of three emergency exits, without emergency signs, is reported.

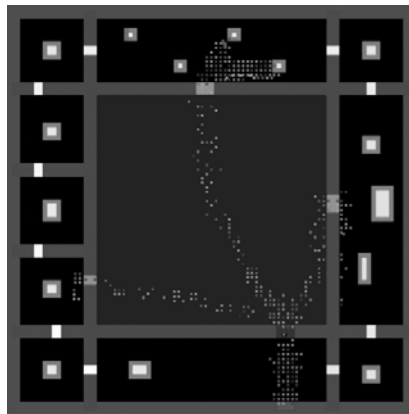


Figure 8 – An example of evacuation through the courtyard in the existing configuration of three emergency exits without emergency signs (see text).

Now imagine that, in a situation like the one just presented, an emergency alarm randomly goes off when, for a given  $S_{MAX}$  and  $\Delta T$ , the net number of visitors inside the museum becomes stationary.

In Figure 9 we report the distribution of the evacuation times for three different group sizes ( $S_{MAX}= 5, 15, 25$ ) and for an inter-arrival time of  $\Delta T=150s$ , in correspondence of two emergency configurations: the existing one without emergency signs (upper panel) and a variant with the introduction of emergency signs (lower panel). The vertical axis of both the plots

measures how many visitors reach the external entrance/exit within the time indicated in the horizontal axis. In the upper panel we observe that the distribution is bimodal (i.e. with two peaks), probably because of the small number of visitors closer to the entrance that rapidly evacuate the museum, coming back and going out from there in a few seconds, while visitors far from the entrance need a longer time to evacuate, both for a longer distance to run (which includes also the internal courtyard path) and for the crowding around the emergency exits. Distribution stays quite similar varying the group size; the only difference, as expected, is a shift towards higher evacuation time when group size increases. The lower panel of Figure 9 shows that the introduction of emergency signs (the arrows in rooms 6, 7 and 10 of Figure 3) slightly reduces the average value of the evacuation times. In this case the distributions have a third small peak around 10 seconds, due to the contribution of visitors situated in the last rooms which, instead of coming back to the entrance, follow the emergency signs then reducing their evacuation time.

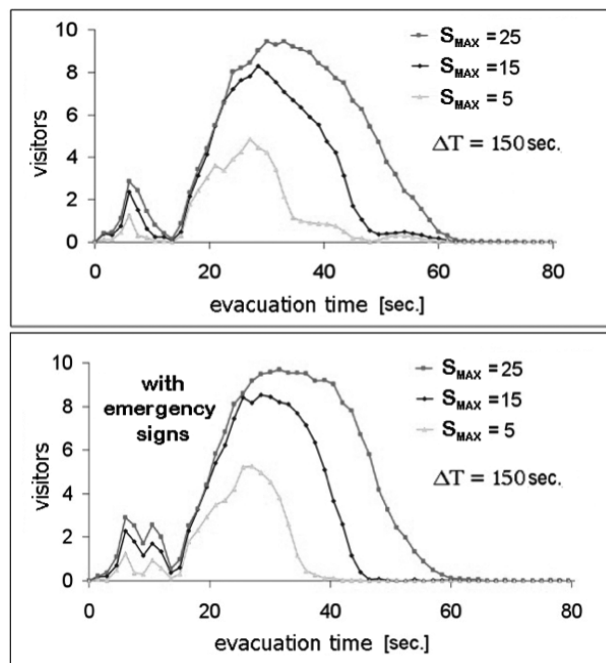


Figure 9 – Alarm dynamic simulation. Distribution of the evacuation times for different group sizes in the existing configuration of three internal emergency exits, in absence of emergency signs (upper panel) and in presence of emergency signs (lower panel).

Let us now focus on the maximum evacuation time, i.e. the total time

needed for all the visitors leaving the museum after an alarm signal: in Figure 10 we evaluate how such a quantity (rescaled to its maximum value) is affected by the total number of visitors present inside the museum when different configurations of available emergency exits are considered. In particular we consider only one exit (only exit n.2, in room 4), two exits (n.1 and n.2) or three exits (n.1, n.2 and n.3). As in Figure 5, we fix  $S_{MAX}=30$  and  $\Delta T=20s$  and we increase the total number of agents visiting the museum from 20 to 200: for each value we let the alarm going off at around the 60% of the total visit time shown in Figure 4 in order to have all the visitors simultaneously present and homogeneously distributed over all the rooms of the museum. Looking at Figure 10, we see that the maximum evacuation time increases with the number of visitors, then saturating for high values, but unexpectedly the emergency exits configuration (using 1, 2 or 3 exits) does not seem to influence it so much the evacuation time. This is probably due to the fact that the three emergency exits give access to the internal courtyard, where all the people will converge towards the intermediate emergency exit, before accessing room 10 and leaving the building by the external entrance/exit: evidently the time spent flowing down the intermediate emergency exit of the courtyard dominates, for any number of visitors, with respect to the time spent by the crowd behind the internal emergency exits, whatever configuration is considered.

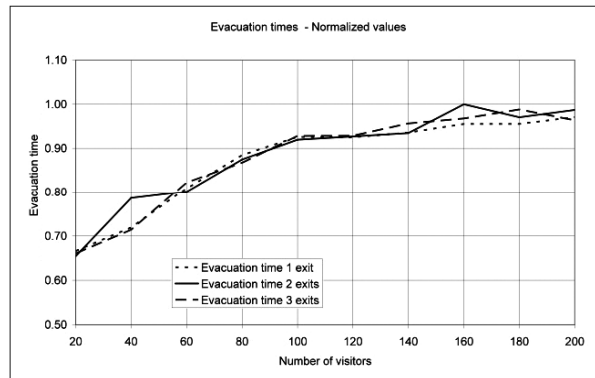


Figure 10 – Alarm dynamic simulation. Maximum evacuation times for three different emergency configurations.

Finally, comparing with the total satisfaction curve found in the fruition regime and the total evacuation time curve found in the emergency regime, averaged over the three exits configurations of Figure 10, we see (Figure 11) that the global maximum in the satisfaction is compatible with a good level of safety, i.e. with a reasonable evacuation time (intermediate between

the minimum and the saturation value). Therefore we can definitively claim that a number of about 80 visitors, representing the best compromise between satisfaction and safety constraints, can be reliably considered as the true carrying capacity of the Castello Ursino museum.

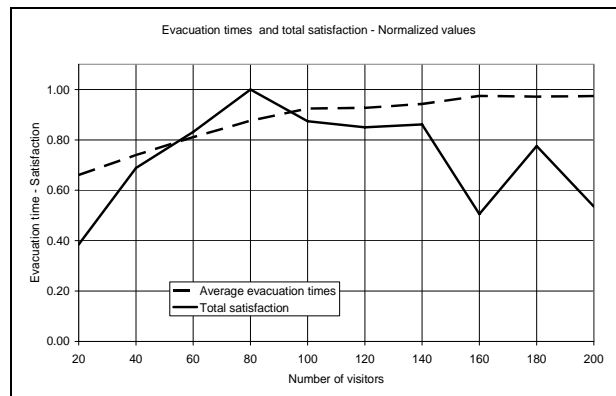


Figure 11 – Global satisfaction and evacuation time.

#### 4 Conclusions

Agent-based simulations show their potential in many context of transport management in presence of unusual demand. We illustrated these ideas with an example based on the simulation of people visiting and evacuating a museum, which offers an excellent test environment for simulating a collective behavior emerging from local movements in a closed space. In the normal fruition regime we found the optimal number of visitors ensuring a maximum in the global satisfaction (carrying capacity of the museum), while in the alarm regime we tested the existing emergency plan for different demand patterns.

Results confirm the convenience and the effectiveness of agent simulations in the design and analysis of complex social systems, fully supporting more traditional strategies already available to the engineers. They show their potential in many context of transport management in presence of unusual demand and in situation where direct observations of human behaviour are not possible or not ethical, such as panic and emergency.

Agent-based simulation can be easily extended to other pedestrian “transportation environment”, such as airports, ships, railway stations or urban areas and several tasks can be performed, such as analysis of pedestrian safety, comfort and walkability, analysis of congestions, bottlenecks and level of service, feasibility studies of urban spaces.

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