Towards a More Comprehensive Estimation of Social Costs in Pedestrian Facilities

Stefania Bandini, Luca Crociani, Giuseppe Vizzari

CSAI - Complex Systems & Artificial Intelligence Research Center
University of Milano-Bicocca
Viale Sarca 336, 20126, Milano, Italy
`{bandini,luca.crociani,vizzari}@disco.unimib.it`

Abstract. This paper discusses several improvements to the computational model of MakkSim, with the aim of allowing simulation of aged people as well as persons with mobility impairments. In particular, a method for modelling heterogeneity in speed is discussed and two special objects of the environment (i.e., stairs and seats), have been defined; in addition, a proposal for modelling the presence of a caretaker is described as a particular type of group of pedestrians. Finally, the paper presents a way of computing social costs implied by the environment taking into account the characteristics of pedestrians moving throughout the related facilities. The overall objective is to achieve a system usable for the evaluation of the usability and accessibility of planned environments and facilities by means of simulation, by also taking into account this category of people.

Key words: Ageing Society, Crowd simulation, Agent-Based Models.

1 Introduction

Urbanization is currently one of the most significant tendencies of the world population: it has been forecast that by 2025 the 58% of the global population will live in cities and urban agglomerates [1]. This phenomenon becomes even more important if we also take into account two additional tendencies, which are (i) the decrease of the fertility rate and (ii) the increase of life expectancy. Those aspects lead to the well-known phenomenon of the *Ageing Society* [2], which represents one of the main challenges of the more economically developed countries, since the working class will no longer be able to sustain the social and economical costs of aged/not working people.

The concept of *Age-Friendly city*, defined by the World Health Organization [3], describes a framework for the development of cities which encourages the *active ageing* of their citizens, allowing them to maintain an active and productive status in the society, in order to delay the time in which they will become a cost. Mobility represents a key feature of this framework, being significant with respect both to transportation and accessibility and viability comfort inside facilities.

Nowadays, the usage of computer models for simulating the pedestrian dynamics can help designers to perform a deep and dynamical analysis of their projects, allowing them to populate and simulate environments by configuring the so-called *what-if* scenarios. These tests support, therefore, the improving of the overall security and perceived comfort of the plans. Given the importance of this kind of analysis, several commercial simulators have been recently developed and can be currently found on the market[1]. These tools provide simulation frameworks whereby it is possible to configure sufficiently heterogeneous populations of pedestrians (e.g. with a different walking speed) and, in some cases, even to simulate the presence of groups of people (modelled with an attractive force among members, although this feature is generally not systematically documented and evaluated). However, although some significant results have been achieved, the overall issue of simulating large and heterogeneous crowds of pedestrians still presents open challenges, since the crowd is a complex system and all of these mathematical/computational models can be improved for obtaining more microscopic and realistic simulations.

The work described in this paper is focussed on the realization of a computational model specifically tailored to simulate the presence of pedestrians with restricted mobility (elderly people as well as persons with physical impairments), basically characterized by a lower walking speed [4], but with potentially a number of additional requirements for a realistic model definition (they will tend to avoid crowded situations, they will need seats during waiting situations and so on) and the need of a different way to evaluate normal metrics for the evaluation of environments and plans, like travel times.

Finally, in fact, the paper presents a proposal for the calculation of the so-called "social costs"[2] which can emerge by the actual usage of the environment by pedestrians. The presence of *not comfortable* elements (e.g. stairs) or situations (e.g. waiting in a queue) in the navigable space, in fact, can increase stress and fatigue of people and especially fragile ones. In addition to this, this kind of facility and the need to employ it can lead to falls that can have significant negative effects for aged people and, therefore, imply healthcare costs sustained by the society (in a different way according to local policies) therapies.

The paper will, first of all, introduce the modelling approach to show how it can be applied to simulate the presence of particular categories of pedestrians like elderlies and people with mobility impairments, sometimes moving with an accompanying person. Then, a proposal for a comprehensive way to evaluate social costs implied by the plan of an environment will be introduced and discussed.

---

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

[2] Currently, several definitions of the social costs can be found in the literature and they are often built-in commercial simulation platforms, but an extension of this concept with more specific variables for this category of people can be very useful for the designing of more Age-Friendly facilities.

2 Computational Model: Baseline and Improvements

This section aims to explain the improvements introduced in MakkSim, an agent-based model employing a discrete environment and the *floor field* approach [5], in order to allow the simulation of people with restricted mobility. Starting from a description of the baseline model, each proposed additional feature will be discussed.

2.1 Baseline

Baseline model is described through discussion of its main features: *environment*, *time*, *agents* and *social interactions.*

2.1.1 Environment The environment is modelled in a discrete way and represented as a grid of squared cells with 40 cm^2 size (according to the average area occupied by a pedestrian [6]). Cells have a state indicating that they are either vacant or occupied by obstacles or pedestrians. In order to manage overcrowded situations[3], we introduced the possibility that each cell can be occupied also by two pedestrians.

The information related to the scenario[4] of the simulation is represented by means of *spatial markers*, special sets of cells that describe relevant elements in the environment. The model baseline contains three kinds of spatial markers: (i) *start* areas, that are, generation points of agents in the scenario; (ii) *destination* areas, possible targets of the pedestrians in the environment; (iii) *obstacles*.

A *floor field*-like approach[5] is used for managing the navigation through the environment, by using a set of superimposed grids (similar to the grid of the environment) starting from the scenario configuration. Floor field values are spread on the grid as a discrete gradient and they are used to support pedestrians in the navigation of the environment, representing their interactions with static object (i.e., destination areas and obstacles) or with other pedestrians. Moreover, floor fields can be *static* (created at the beginning and not changed during the simulation) or *dynamic* (updated during the simulation). Three kinds of floor fields are defined in our model:

- *path field*, that indicates for every cell the distance from one destination area, acting as a potential field that drives pedestrians towards it (static). One path field for each destination point is generated in each scenario;
- *obstacles field*, that indicates for every cell the distance from neighbour obstacles or walls (static). Only one obstacles field is generated in each simulation scenario;

---

[3] in which the density is higher than 6.25 m^2 (i.e. the maximum density reachable by our discetisation).

[4] It represents both the structure of the environment and all the information required for the realization of a specific simulation, such as crowd management demands (pedestrians generation profile, origin-destination matrices) and spatial constraints.

- *density field*, that indicates for each cell the pedestrian density in the surroundings at the current time-step (dynamic). Like the previous one, the density field is unique for each scenario.

Chessboard metric with $\sqrt{2}$ variation over corners [7] is used to produce the spreading of the information in the path and obstacle fields. Moreover, pedestrians cause a modification to the density field by adding a value $v = \frac{1}{d^2}$ to nearby cells whose distance d from their current position is below a given threshold, while value 1 is added to the cell where they are situated. Agents are able to perceive floor fields values in their neighbourhood by means of a function $Val(f, c)$ (f represents the field type and c is the perceived cell). This approach to the definition of a perception model moves the burden of its management from agents to the environment, which would need to monitor agents anyway in order to produce some of the simulation results.

2.1.2 Time and Update Mechanism In the baseline model, time is also discrete, employing steps of 0.3 seconds. This choice, along with the adoption of a Moore neighbourhood with radius equal to 1 cell, generates a linear pedestrian speed of about 1.31 ms^{-1}, which is comparable with the data from the literature representing observations of crowd in normal conditions [6].

Regarding the update mechanism, three different strategies are usually applied in this context [8]: *ordered sequential*, *shuffled sequential* and *parallel* update. The first two strategies are based on a sequential update of agents, respectively managed according to a *static* list of priorities that reflects their order of generation or a *dynamic* one, shuffled at each time step. On the contrary, the parallel update calculates the choice of movement of all the pedestrians at the same time, actuating choices and managing conflicts in a latter stage. The two sequential strategies, instead, imply a simpler operational management, due to an a-priori resolution of conflicts between pedestrians.

In the baseline model we chose to adopt the shuffled sequential strategy, updating the list of agents using a dynamic list of priority that is randomly generated every step.

2.1.3 Pedestrians and Movement Formally, our agents are defined by the following triple:

$$Ped : \langle Id,\ Group,\ State \rangle; \quad State : \langle position,\ oldDir,\ Dest \rangle$$

with their own numerical identifier, their group (if any) and their internal state, that defines the current position of the agent, the previous movement and the final destination, associated to the relative path field.

Before describing agent behavioural specification, it is necessary to introduce the formal representation of the nature and structure of the groups they can belong to, since this is an influential factor for movement decisions.

Social Interactions – In order to deeper model social relationships, two kinds of groups have been defined in the model: the *simple group*, that indicates a family or a restricted group of friends, or any other small group in which there are a strong and simply recognizable cohesion; the *structured group*, generally a big one (e.g. a group of team supporters or a touristic group), that shows a slight cohesion and a natural fragmentation into subgroups, in which the cohesion gets stronger. In particular, between members of a simple group like a family it is possible to identify an evident tendency to stay quite close, in order to guarantee the possibility to perform interactions by means of verbal or non-verbal communication [9]. On the contrary, in large groups people are mostly linked by the sharing of a common goal, and the overall group tends to maintain only a week compactness, with a following behaviour between members. In order to model these two typologies, the formal representation of a group is described by the following:

$$Group : \langle Id, [SubGroup_1, \ldots, SubGroup_m], [Ped_1, \cdots, Ped_n] \rangle$$

In particular, if the group is simple, it will have an empty set of subgroups, otherwise it will not contain any direct references to pedestrians inside it, which will be stored in the respective leafs of its three structure. Differences on the modelled behavioural mechanism in simple/structured groups will be analysed in the following section, with the description of the utility function.

Agent Behaviour – In order to perform the agent behaviour, its life-cycle has been defined on four steps: *perception, utility calculation, action choice* and *movement*. The *perception* step provides all the information needed for choosing its destination cell to the agent. In particular, if an agent does not belong to a group (hereafter *individual*), in this phase it will only extract values from the floor fields, while in the other case it will perceive also the positions of the other group members within a configurable distance, for the calculation of the *cohesion* parameter. The choice of each action is based on an utility value, that is assigned to every possible movement according to the following function:

$$U(c) = \frac{\kappa_g G(c) + \kappa_{ob} Ob(c) + \kappa_s S(c) + \kappa_c C(c) + \kappa_i I(c) + \kappa_d D(c) + \kappa_{ov} Ov(c)}{d}$$

Function $U(c)$ takes into account the behavioural component considered relevant for pedestrian movement. For each function has been introduced a κ coefficient for its calibration. The purpose of d is to constrain the diagonal movements, in which the agents cover a greater distance ($0.4 * \sqrt{2}$ instead of 0.4) and assume an higher speed than the non-diagonal ones.

The first three functions combine information derived by local floor fields and they model the basic factors considered in the pedestrian behaviour: goal attraction (i), geometric (ii) and social repulsion (iii). The fourth and fifth elements aggregate the perceived positions of members of agent group, both simple (iv) and structured (v), to calculate the level of attractiveness of each neighbour cell, relating to cohesion phenomenon. Moreover, two factors represent preferences with respect to movement, helping the model to reproduce more realistic simulations both in qualitative and quantitative perspective: (vi) adds a bonus to the utility of the cell next to the agent according to his/her previous direction, while (vii) describes the *overlapping* mechanism, a method used to allow our model the possibility to treat high density situations, allowing two pedestrians temporarily occupying the same cell at the same step.

As previously explained, the main difference between simple and structured groups resides in the cohesion intensity, which is significantly stronger in the simple ones. Functions $C(c)$ and $I(c)$ have been defined to correctly model this difference. Nonetheless, various preliminary tests on benchmark scenarios show us that, used singularly, function $C(c)$ is not able to reproduce realistic simulations. Human behaviour, in fact, is very complex and people can react differently even in simple situation, for example by allowing temporary fragmentation of simple groups in front of several constraints (obstacles or opposite flows). Acting statically on the calibration weight, it is not possible to configure this dynamic behaviour: with a small cohesion parameter several permanent fragmentations have been reproduced, while with an increase of it we obtained no group dispersions, but also an excessive and unrealistic compactness of them.

In order to face this issue, another function has been introduced in the model, with the aim to balance the calibration weight of the three attractive behavioural elements, depending from the fragmentation level of simple groups:

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

$$DispBalance = tanh\left(\frac{Disp(Group)}{\delta}\right); \quad Disp(Group) = \frac{Area(Group)}{|Group|}$$

where k_i, k_g and k_c are the weighted parameters of $U(c)$, δ is the calibration parameter of this mechanism and $Area(Group)$ calculates the area of the convex hull defined using positions of the group members. As we will see in next section, a dynamic and adaptive behaviour of groups has been obtained with this mechanism, which relaxes the cohesion if members are sufficiently compact and intensifies it with the growing of dispersion.

After the utility evaluation for all the cells in the neighbourhood, the choice of action is stochastic, with the probability to move in each cell c as (N is the normalization factor):

$$P(c) = N \cdot e^{U(c)}$$

On the basis of $P(c)$, agents move in the resulted cell according to their set of possible actions, defined as list of the eight possible movements in the Moore neighbourhood, plus the action to keep the position (indicated as X): $A = \{NW, N, NE, W, X, E, SW, S, SE\}$.

2.2 Improvements

This section will focus on the improvements proposed for the model, in order to obtain a simulated pedestrian behaviour similar to one of a person with restricted mobility. In particular, several elements have been taken into consideration: his/her lower speed, the possible presence of a *caretaker* or an accompanying person, defining a special case of group (i.e. the two persons will walk strictly together, maintaining a constant speed) and other details of their behaviour like the general need of the handrail in the stairs. As it will be described in the following, several of them have already been developed in the simulator and are under validation, while other ones are still in the developing phase.

Each new feature will be discussed with the next subsections, starting from a preliminary yet significant work about the agents update strategy and following with the ones which directly regard the aims of this work.

2.2.1 Parallel update A preliminary work to improve the expressiveness of the model has regarded the development of the parallel update strategy. This mechanism, in fact, describes a parallel choice of movement by the agents and leads to the generation of conflicts, considered as another important aspect of the crowd dynamics[10, 11].

With the new update strategy, the agents life-cycle does not change, but the *movement* execution becomes dependent from the additional conflict resolution rules of the model. The model overall activity flow, in fact, has been modified with the following three step procedure:

- *update of choices* and *conflicts detection* for each agent of the simulation;
- *conflicts resolution*, that is the resolution of the detected conflicts between agent intentions, solved employing new rules in the model;
- *agents movement*, that is the update of agent positions exploiting the previous conflicts resolution, and *field update*, that is the recalculation of the density field according to the new positions of the agents.

Since it is not the principal object of this paper, a thorough description of the rules introduced for the management and resolution of conflicts will not be performed. However, it is mandatory to explain that our rules describe a stochastic resolution with three possibilities: only one agent moves, two agents move (overlapping) or no-one moves (friction). Two parameters have been introduced for managing the calibration of this mechanism. In addition, when a conflict is arisen between more than two pedestrians, the situation is simplified by extracting two agents, which will be able to move according to conflict resolution rules, and imposing non-movement to the others.

2.2.2 Heterogeneous Speed Profiles This feature represents the experimental and innovative part of this work since, in the current literature, discrete models for pedestrian dynamics generally assume only one speed profile for all the population. This is also considered one of the main criticism to this approach.

We evaluated several ways to improve the expressiveness of our computational model for this purpose, some of them taken by the literature[12]:

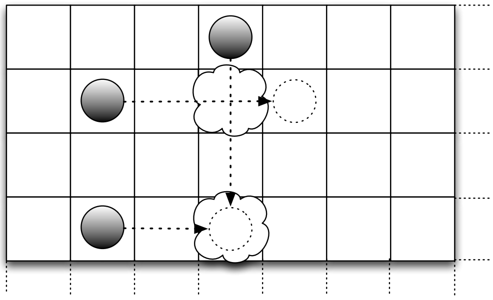

Fig. 1. Set of possibly arising conflicts by allowing agents more than 1 movement per step. Picture inspired by [12].

1. By improving agents movement capabilities (i.e. they can perform more than 1 movement per time step), according to its *desired* speed (his/her configured speed profile). In this way, given k the side of cells of the discrete grid, its possible to obtain speed profiles equal to $n \cdot k$ m/step, with $n \in \mathbb{N}$.
2. By improving movement capabilities of the agents and modifying the current space discretization towards a finer grain, described by a lower size of cells. Thanks to this method, by fixing a maximum speed of pedestrians, it is possible to obtain a greater set of possible speed profiles.
3. By modifying the current time scale, so defining an higher maximum speed profile of the pedestrians and rescaling the other speed profiles of each agent in a *stochastic* way, that is, by means of a probability to not execute the movement at a given step of the simulation.
4. By refining the space discretization and also the time-scale, leaving agents movement capabilities located in the cells surrounding the ones where they are located. As for the previous one, also in this way the desired speed of each pedestrian is obtained in a stochastic way.

The first two methods can be effective (especially the second one), but they both lead to complications and increases of computational costs for managing micro-interactions and conflicts, as shown in Fig. 1, therefore they have not been chosen as a solution. The fourth method also suffers for the increasing of computational times of the simulations, which increases proportionally to the ratio S_o/S_n, with S_o and S_n respectively equal to the old and new size of cells (e.g. if the size is half-divided, for performing the same space agents will need a number of update cycles at least doubled). These reasons led to undertake the third method, since it does not affect computational complexity in a relevant way and it is the simplest one to develop.

The computational model has been modified in several parts. Each agent has a new parameter $Speed_d$ in its $State$, describing its desired speed. For the overall simulation scenario, a parameter $Speed_m$ is introduced for indicating the maximum speed of the pedestrian in the simulation (describing, therefore, the

Algorithm 1 Life-cycle update with heterogeneous speed

```
if $Random() \leq \alpha/\beta$ then
    $updatePosition()$
    $\alpha \leftarrow \alpha - 1$
end if
$\beta \leftarrow \beta - 1$
if $\beta == 0$ then
    $(\alpha, \beta) = Frac(\rho)$
end if
```

assumed time scale). In order to obtain the desired speed of each pedestrian during the simulation, the agent life-cycle is then *activated* according to the probability $\rho = \frac{Speed_d}{Speed_m}$.

By using this method, the speed profile of each pedestrian is modelled in a fully probabilistic way and, in a sufficiently high number of step, their effective speed will be equal to the desired one. But it must be noted that in a lot of cases the speed has to be rendered in a small window of time and in a small portion of space (think about speed decreasing on stairs). In order to overtake this issue, we chose to manage this variable as an *extraction without remission*, updating the probability ρ with *moved* or *not moved* events. The mechanism can be formalized as the following.

- Let $Frac(r) : \mathbb{R} \rightarrow \mathbb{N}^2$ be a function which returns the minimal couple $(i, j) : \frac{i}{j} = r$.
- Let *Random* be a pseudo-random number generator.
- Given ρ the probability to activate the life-cycle of an arbitrary agent, according to its own desired speed and the maximum speed configured for the simulation scenario. Given (α, β) be the result of $Frac(\rho)$, the update procedure for each agent is described by the pseudo-code of Alg. 1. The method *updateChoices*() describes the choice of movement by the agent[5].

This mechanism can be considered consistently better than using only the probability ρ, because it allows the synchronization between the effective speed of an arbitrary agent and its desired one in maximum $Speed_m \cdot 10^{\iota}$ step, where ι describes the number of decimal positions of $Speed_d$ (e.g. if the desired speed is fixed at 1.3 m/sec and the maximum one at 2.0 m/sec, the resulting $Frac(\rho) = \frac{13}{20}$, therefore the agent will effectively simulate its desired speed after 20 steps). Results of the application of this approach in terms of the achieved fundamental diagram[6], have shown a good reproduction of average flows at different densities,

---

[5] Remember that with the parallel update movement executions are performed a-posteriori of the conflict resolution phase.

[6] It is used for analysing average pedestrian flows and velocities, at different values of densities. Since a sufficient amount of data can be found in the literature[13], the fundamental diagram is actually the most important instrument for the quantitative validation of the simulation model.

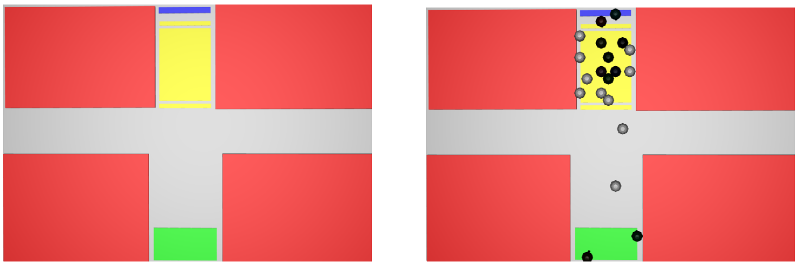
(a) (b)

Fig. 2. A scenario with a marker of type *Stairs* (a) and its effects on the behaviour of agents (b): the white ones, representing aged people, are attracted also by the walls, for simulating the use of handrails.

by simulating a corridor of width 3.6 m and length 20 m with bidirectional flow (see [14] for more information about the experimental setting and achieved results omitted here for sake of space).

2.2.3 Special Objects of the Environment In order to evaluate the accessibility and usability of an arbitrary environment by means of simulations, the computational model must be enriched also in the *Environment* component, with special objects which act on the overall perceived comfort. Obviously, until now it is only possible to make assumption since there are no consistent empirical data about this issue, but it is possible to retain that element like stairs are inconvenient and they increase the social costs, while other elements such as the presence of seats can reduce them in areas where it is necessary to wait.

Firstly, the **stairs** have been considered for this purpose, whose presence in the environment has been modelled by means of an additional type of spatial marker (*Stairs*). In particular, in order to recognize and differentiate the direction of movement (i.e., if agents are going upstairs or downstairs), the extremes of the marker on the top and bottom sides are signed in a special way, as shown in Fig. 2 (a).

According to empirical data from the literature [15], the agents inside the *Stairs* marker fix their desired speed to 0.5 (0.4 for elderly people) m/sec, if they are going up, or to 0.7 (0.6 for elderly people) m/sec if they are going downstairs, until they reach the end of it.

For modelling the usage of the **handrail** by elderly persons, we used the *obstacles field* in the reverse way inside the marker, in order to get this kind of agents attracted towards the walls surrounding the stairs. Therefore, agents of type “elderly” are changing the sign of their κ_{ob} during the usage of stairs. Effects are qualitatively displayed in Fig. 2 (b).

The second special object that has been considered with this work are the **seats**, whose introduction described more additional elements for the model:

(a) (b)

Fig. 3. Two groups formed by an aged person and a caretaker. Their walking path will be practically the same.

stairs can be placed in the environment by means of another spatial marker (*Seats*) and, in order to design its possible perception by nearby agents, another *dynamical* floor field has to be introduced. This field is quite similar to the *density field*, with differences residing in values update: their values are spread within a fixed radius of distance from each *Seats* cell, which defines exactly one seat, but only when this ones are free. If an agent temporary occupies one of them, the others must not be able to perceive it.

However, this feature has not yet been completely developed in the simulator, since it is necessary to define also the particular behaviour of the pedestrian, that is, when he/she starts feeling the need of a seat, either in a normal situation or in a waiting situation, where additional improvements are needed even in the *environment* section of the model. This will regard part of the future work.

2.2.4 Presence of a Caretaker Another relevant aspect which can characterize a person with moving disabilities can be the presence of an accompanying person, which drives him/her through the environment. This situation clearly describes a group of type *simple*, but also a special case of it, since they will walk strictly together (see Fig.3), like they were a single entity.

In order to model this phenomenon, a first proposal meant to use the function *Balance* (which adapts the behaviour of group members regarding their dispersion, see Sec.2.1.3) particularly and in a very strict way for this special group, for not allowing fragmentation. The δ parameter of *DispBalance* function, therefore, was fixed to values lower than 1, in order to explore how strong the effects of this function can be. Results of this tests have shown that this method is not suitable for a good simulation of the interested phenomenon: since the probability to have a distance greater to one cell cannot be set to 0 with this mechanism, an high cohesion of the simulated group has been achieved in this way, but in several situations the simulated couple has fragmented itself anyway, even if in a very light way (around 1 meter of distance).

Since the walking path of the two persons in analysis will be practically the same, because the aged person in this situation cannot walk by him/herself, an alternative and more effective method can be to abstract this situation by representing the couple with a single, special, agent whose shape occupies 2 cells. Naturally, this modelling assumption leads to complications in the computational model, since new rules for managing its behaviour and its interactions with other entities. A first proposal for this method is described by the following rules:

1. the agent chooses its preferred movement according to the utility function, evaluating all the cells surrounding its shape[7];
2. according to the chosen direction:
    (a) if the two cells next to the agent position are free, then update its position in them;
    (b) if only one cell is free, then move only the most fair cell of the agent shape (this will cause a *rotation*).

Since this method is still under development, no tests have suggested if the simulated behaviour of the group is acceptable. Therefore, even this aspect represents part of the future works.

3 A Proposal for Social Costs Analysis

The model features presented until now represent a viable approach for the simulation of the behaviour of aged people, whose presence in our society is becoming more and more important. The basic simulation outputs can already give information to decision makers about what is the *perceived comfort* of the planned environment: *space utilisation* and *cumulative mean density* maps are well suited for identifying critical zones of the scenario, while statistics about average travelling times and flows are able to describe their impact in its overall security, by also granting an estimation of the evacuation times.

Notwithstanding, the definition of additional microscopic outputs in the simulator (e.g. length of stair travelled, waiting times in queues) can be useful for understanding the *usability* of the environment from the perspective of its "users". These additional indicators must actually be considered in a different way for young, healthy adults and elderlies or persons with restricted mobility or other disabilities. The definition of parameters for estimating probabilities of injuries on one hand, like falls or faints due to stress and excessive fatigue, and for obtaining an indicator of the overall perceived comfort of the environment on the other, can be exploited for the calculation of these *social costs*. By analysing these costs, users and decision makers will be able to act on the planned environment in order to find solutions which can lead to either less expenses, more benefits, or both. For giving an example, the application of heating systems for the snow removal in side-walks is able to maintain the street clean and to allow

---

[7] This set of cells is calculated by the union of Moore neighbourhood of each cell of its shape.

persons, especially aged ones, to easily use them. In this way, possible falls are prevented, directly decreasing social expenses (for public healthcare system or for families); in addition, the accessibility of the city areas is improved, allowing aged people to normally move themselves inside the city and to maintain an active status, which implies benefits also for the local economy (in addition to being a useful action in the direction of an implementation of active ageing policies, which in turn also aim at reducing social costs in the long run).

The overall objective of this section is to sketch a general indicator that can describe these average expenses paid by the society for the treatment of injuries happened inside pedestrian facilities, or to pedestrian in general, but also the implications of uncomfortable and non-accessible environments on the reduced activities of elderlies, which might be deciding not to go to certain places to carry out their tasks because of perceived unpleasant conditions in the environment. Two elements are composing the indicator, both dependent from the overall comfortability of the space: bad settings or situations leads to accidents, directly causing social expenses, while perceived discomfort during the navigation of the setting can lead fragile types of people to avoid its usage. The idea is to calculate them with a two steps method, firstly calculating the different social costs and then grouping them for obtaining an overall index of the space comfort, which can be used for estimating the lack of incomes due to a reduction of potential customers of the space.

Regarding the first step, that is, *social cost estimation*, we must consider that accidents can naturally occur with different probabilities regarding different situations (walking in stairs, walking outside, etc.), different configurations (e.g. temperature) and different types of pedestrian (i.e., younger ones will have a lower probability). Provided that statistics about these accidents were available[8], the overall cost can be estimated by means of microscopic simulation with our model.

Formally, the method for the social costs analysis must consider the expenses for each type of agent and single situation/activity performed in the scenario navigation. This concept can be described as the following:

$$SocialCosts = \sum_{a \in \overline{P}} \sum_{C_i \in \overline{S}} C_i(a), \qquad \overline{S} = \{C_0, \cdots, C_n\}$$

with $\overline{S}$ the set of all situations considered for the social costs calculation. Each of these ones are described by an additional function able to quantify the single element:

$$C_i(a) = \tau_{a,i} \cdot AvgCost_{a,i}$$

---

[8] It is mandatory to say that studies and data actually present in the literature refer only to particular cases: for example, in [16] useful data about accidents in stairs are shown. Actually, commercial tools for pedestrian simulation are trying to fill this gap by means of several local standards provided, for instance, by transportation authorities (e.g. the London Underground Standard), but their scientific validity is not always demonstrated. Additional studies and surveys are, therefore, needed in order to give a plausible and precise estimation of social costs.

where $\tau_{a,i}$ describes the quantity, in the respective measurement unit, of the condition i (e.g. time passed in the queue) in the simulation for the agent a. $AvgCost_{a,i}$ represents the average cost estimation[9] generated per each unit and for the category the agent a belongs to.

By means of this function, each pedestrian travel can be evaluated regarding elementary situations given by interesting components of the environment: stairs, elements which usually generate queues (e.g. ticket machines), parts of the floor which are usually wet and so on. In particular, for evaluating parts of the environment $\tau_{a,i}$ will represent the covered space, while for situations like queues the measurement unit will be the time. On the other hand, complex situations can be evaluated by splitting them into simpler ones, until they reach an elementary level: for instance, waiting areas where the presence of a sufficient number of seats can be significant, it is necessary to divide the costs evaluation regarding the time passed stood up and seated down. In addition, an extension of the analysis to crowded zones in the scenario can be very important, since they are uncomfortable and can also cause faints, especially to elderly people. A thorough costs analysis has to consider the time passed in them, weighted by means of average local density in that part of the environment.

In order to estimate the *benefit of reducing social costs*, we must have an approximate evaluation of missing economical activities due to avoiding of environment usage by people: a more macroscopic analysis has to be done, once calculated an index of *comfort* of the facility by means of the obtained social costs. Similarly to the *Level of Services* calculation[15], the social costs can be grouped into different classes for having an idea of the overall comfort and walkability of the environment. Comfort is a fuzzy concept and defining an indicator could be not simple task, but studies from urban planners like White [17] can be exploited for this purpose. In addition, the execution of surveys and interviews to customers of different environments, in order to obtain additional data about comfort of their components, can help the final definition of a comfort index. This parameter can be, then, used with statistics about the local population composition, regarding to age and walking impairments, to evaluate the possible lack of incomes regarding this aspect.

4 Conclusions and Future Works

This paper has discussed several improvements to the computational model of MakkSim, with the aim of allowing simulation of aged people as well as persons with mobility impairments. The overall objective is to make the system usable for evaluating planned environment by taking them into consideration, in order to understand also their fatigue assumed through the navigation of the environment, knowing if something could be done to make it more *age-friendly*.

In addition, an experimental method for the estimation of *social costs* has been proposed. This kind of analysis allows to understand the entity of the costs

---

[9] It must refer to statistics about the average number of accidents, with respect to the measurement unit of $\tau_{a,i}$ and their average cost.

for the healthcare of accidents like falls or faints which can be generated by the configuration the environment, as well as lack of incomes derived by people who are not using environment for excessive discomfort.

Future works are aimed, on one hand, at improving the expressiveness of the computational model in order to consider more elements of the behaviour and more elements of the environment. On the other one, a precise and feasible estimation of social costs can be done only once having enough statistical data about accidents and perceived discomfort in the environmental setting, therefore additional studies must be performed in this direction. This line of work must also try to integrate existing approaches and results of the so called *walkability* analysis of the built environment [18].

References

1. United Nations: World Urbanisation Prospect - The 2011 Revision. (2011)
2. United Nations, Dep. of Economic and Social Affairs - Population Division: World Population Ageing: 1950-2050. (2002)
3. World Health Organization: Global Age-Friendly cities: A Guide. (2007)
4. Willis, A., Gjersoe, N., Havard, C., Kerridge, J., Kukla, R.: Human movement behaviour in urban spaces: implications for the design and modelling of effective pedestrian environments. Environment and Planning B: Planning and Design **31** (2004) 805–828
5. Burstedde, C., Klauck, K., Schadschneider, A., Zittartz, J.: Simulation of pedestrian dynamics using a two-dimensional cellular automaton. Physica A: Statistical Mechanics and its Applications **295** (2001) 507 – 525
6. Weidmann, U.: Transporttechnik der fussgãnger: transporttechnische eigenschaften des fussgãngerverkehrs (literaturauswertung). (1993)
7. Kretz, T., Bönisch, C., Vortisch, P.: Comparison of various methods for the calculation of the distance potential field. In Klingsch, W.W.F., Rogsch, C., Schadschneider, A., Schreckenberg, M., eds.: Pedestrian and Evacuation Dynamics 2008. Springer Berlin Heidelberg (2010) 335–346
8. Klüpfel, H.: A Cellular Automaton Model for Crowd Movement and Egress Simulation. PhD thesis, University Duisburg-Essen (2003)
9. Costa, M.: Interpersonal distances in group walking. Journal of Nonverbal Behavior **34** (2010) 15–26 10.1007/s10919-009-0077-y.
10. Kirchner, A., Namazi, A., Nishinari, K., Schadschneider, A.: Role of Conflicts in the Floor Field Cellular Automaton Model for Pedestrian Dynamics. (2003)
11. Kirchner, A., Nishinari, K., Schadschneider, A.: Friction effects and clogging in a cellular automaton model for pedestrian dynamics. Phys. Rev. E **67** (2003) 056122
12. Kirchner, A., Klüpfel, H., Nishinari, K., Schadschneider, A., Schreckenberg, M.: Discretization effects and the influence of walking speed in cellular automata models for pedestrian dynamics. Journal of Statistical Mechanics: Theory and Experiment **2004** (2004) P10011
13. Zhang, J., Klingsch, W., Schadschneider, A., Seyfried, A.: Ordering in bidirectional pedestrian flows and its influence on the fundamental diagram. Journal of Statistical Mechanics: Theory and Experiment **2012** (2012) P02002
14. Bandini, S., Crociani, L., Vizzari, G.: Heterogeneous speed profiles in discrete models for pedestrian simulation. In: Proceedings of the 93rd Transportation Research Board annual meeting. (2014)

15. Fruin, J.J.: Pedestrian planning and design. Metropolitan Association of Urban Designers and Environmental Planners (1971)
16. Health Education Authority: Older People and Accidents. (1999)
17. Whyte, W., Underhill, P.: City: Rediscovering the Center. University of Pennsylvania Press, Incorporated (2009)
18. Gori, S., Petrelli, M.N.M.: Walkability indicators for pedestrian friendly design walkability indicators for pedestrian friendly design walkability indicators for pedestrian friendly design. In: Proceedings of the 93rd Transportation Research Board annual meeting. (2014)