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Incorporating Prediction Factor into the Investigation Capability in the Social Force Model: Application on Avoiding Grouped Pedestrians

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Abstract: Incorporating decision making capability into a microscopic crowd dynamic model is an essential factor for introducing a well-representative model for the pedestrian flow. In normal situations, this capability was presented by providing the simulated independent pedestrians in the Social Force Model an investigation ability of their walkways. However, predicting semi-blocked situations by the simulated intelligent pedestrians has not been treated in their investigation. In this paper, the authors describe the investigation capability of independent pedestrians in normal situations. In addition, the prediction aspect is introduced for the simulated independent pedestrians as an extension for the investigation capability to let the model appear more representative of what actually happens in reality. Simulations are performed to validate the work qualitatively by tracing the behavior of the simulated pedestrians and studying the impact of this behavior on their interactions with the grouped pedestrians. Finally, a comparison between the extended model and the original model with regards to the quantitative measurement (the efficiency of motion) is made.

Keywords: Decision making, investigation capability, prediction, grouped pedestrians.

1. Introduction

Over the last few decades, researchers have devoted much attention to pedestrian studies to provide solutions for some challenging problems such as congestion[1]. Microscopic techniques, which are essentially a branch of pedestrian studies, are mainly concerned with the interactions among pedestrians and their effects upon each other [1]. One of the most important models in the microscopic level of pedestrian studies is the Social Force Model. It has been considered by a considerable number of researchers to be the optimal such model [1–3], at least in regards to the self-organization phenomena reproduced by the model. However, the model has attracted significant criticisms from other researchers [3–5]. Most of these criticisms have involved the psychological and social facts that the pedestrians are intelligent people with the ability to make more far-sighted decisions than simply reacting to the immediate surrounding pedestrians. For that reason, decision-making capabilities have begun to be incorporated into the Social Force Model by [3]. Pursuing this intention in [6–10], other aspects of independence have been incorporated into the emergency and non-emergency situations. In this article, to obtain more realistic model, the simulated independent pedestrians are provided with more intelligence by incorporating the ability of predicting the undesirable situation as a factor into their investigation capabilities. This article is organized as follows. In the next section, a brief introduction of the Social Force Model is introduced. The investigation capability (Z-SH model) incorporated into the Social Force Model in [10] is summarized in the third section. In the fourth section, the prediction factor is incorporated as a further extension to (Z-SH model). In the fifth section, a model for grouped pedestrians (which is a popular phenomenon found in many pedestrian areas) is developed. Further description of the qualitative validation of the investigation capability in the extended model

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under normal situations is provided in the simulation section, with regards to the avoidance of obstacles. Here, the obstacles are represented by groups of pilgrims, where the groups with lower velocities than the other pilgrims create moving obstacles. Accordingly, the behavior against fixed obstacles is implicitly included in this study.

2. The Social Force Model

The Social Force Model was developed by Helbing and Molnar [11]. One of the most important features of this model is its representation of pedestrians' motivations in terms of the other objects (pedestrians and obstacles) surrounding him as social forces. The sum of these forces is implemented in a Newtonian equation, which, in turn, determines the acceleration of the pedestrian's motion. An extension by Helbing and his co-workers [12] incorporated the physical forces arising in the case of contact amongst the pedestrians into the model. Some aspects of the model have been modified by Lakoba and his co-workers [3] and Yu and Johansson [13]. The model is characterized by reproducing the self-organized phenomena of pedestrian dynamics in normal and panic situations [12,14]. The main equations of the model are:

$$\frac{d\vec{x}_i(t)}{dt} = \vec{v}_i(t), \tag{1}$$

$$m_i\frac{d\vec{v}_i(t)}{dt} = \vec{f}_i(t)+\varepsilon_i = \vec{f}_i^{pref}(t)+\sum_j \vec{f}_{ij}(t) + \sum_{object}\vec{f}_{i,object}(t)+\varepsilon_i, \tag{2}$$

$$\vec{f}_i^{pref}(t) = \gamma\left(\vec{v}_i^0(t)-\vec{v}_i(t)\right), \tag{3}$$

$$\vec{v}_i^0(t) = \vec{e}_i^0(t)(1+E_i(t))V_i^0 D_i + \langle\vec{v}_j(t)\rangle_i(1-D_i), \tag{4}$$

$$\vec{f}_{ij}(t) = \vec{f}_{ij}^{att}(t)+\vec{f}_{ij}^{rep}(t)+\vec{f}_{ij}^{push}(t)+\vec{f}_{ij}^{friction}(t), \tag{5}$$

$$\vec{f}_{i,object}(t) = \vec{f}_{i,object}^{att}(t)+\vec{f}_{i,object}^{rep}(t) + \vec{f}_{i,object}^{push}(t)+\vec{f}_{i,object}^{friction}(t), \tag{6}$$

where $\frac{d\vec{x}_i(t)}{dt}$ is the rate of change in the location of pedestrian i at time t ; $\vec{v}_i(t)$ represents his actual velocity, which is computed numerically by solving Eq. 1 and Eq. 2; $\frac{d\vec{v}_i}{dt}(t)$ is the acceleration of pedestrian i resulting from the sum of the total forces upon him; $\varepsilon_i(t)$ is the fluctuation of individual i; the function $\vec{f}_i^{pref}(t)$ is the preferred force modeled to express the motivation of the pedestrian i to adapt his actual velocity $\vec{v}_i(t)$ to reach another velocity $\vec{v}_i^0(t)$ at which he [1] prefers to walk at time t, called the preferred velocity; $\gamma = {m_i}/{\tau}$, where m_i and τ represent the mass of the pedestrian and the relaxation time, respectively; $\vec{e}_i^0$ is the preferred direction of the preferred velocity; V^0 is the initial preferred velocity; E is the individual's excitement factor modeled in [3], which has a rate of change proportional to the difference between the effective maximum excitement parameter $E_m\left(1-\frac{v}{v_0}\right)$ and the excitement parameter itself; and D is the independence factor that characterizes the independence of the decision makers [3]. In addition, the function $\vec{f}_{ij}(t)$ is the sum of all forces exerted by pedestrian j upon pedestrian i which are of two types. The first type is the social forces, the repulsion force $\vec{f}_{ij}^{rep}(t)$ and the attraction force $\vec{f}_{ij}^{att}(t)$ that represent the model of the repulsive and attractive motivations inside pedestrian i against and towards pedestrian j, respectively [11]; they were modeled as exponential functions with different values of the parameters and opposite directions as follows:

$$\vec{f}_{ij}^{rep}(t) = A^{rep}e^{(R_{ij}-d_{ij}(t))/B^{rep}}\vec{n}_{ij}(t).W(\varphi_{ij}(t)), \tag{7}$$

$$\vec{f}_{ij}^{att}(t) = A^{att}e^{(R_{ij}-d_{ij}(t))/B^{att}}\vec{n}_{ij}(t).W(\varphi_{ij}(t)), \tag{8}$$

$$W(\varphi_{ij}(t)) = \left(\lambda_i+(1-\lambda_i)\frac{1+\cos(\varphi_{ij}(t))}{2}\right), \tag{9}$$

where A^{rep} and B^{rep} are constant parameters that denote the strength and the characteristic repulsive distance of the corresponding force, respectively; A^{att} and B^{att} play the same roles of A^{rep} and B^{rep}, however, their values are larger and the sign of A^{att} is negative. $\vec{n}_{ij}$ is the normalized vector which points from individual j to the pedestrian i; R_{ij} and d_{ij} are the sum of the radius of i and j and the distance between the centers of i and j respectively. The angular parameter $\varphi_{ij}(t)$ denotes the angle between the direction $\vec{e}i(t) = \vec{v}_i(t)/\|\vec{v}_i(t)\|$ of motion and the direction $-\vec{n}_{ij}$, (i.e. $cos\varphi_{ij} = \vec{e}_i.\vec{n}_{ij}$); λ_i is a parameter to model the effect of the perception of individual i to those who are behind him on the magnitude of the force.

According to the values of B^{rep} and the weight function W, each pedestrian has his own perception area in where he becomes aware of the detailed movements of the aforementioned objects inside (microscopic awareness). This area is the source of the effective social forces exerted upon him as depicted in Fig. 1. The second type is the physical forces ($\vec{f}_{ij}^{push}$ and $\vec{f}_{ij}^{friction}$), which were modeled as linear functions in [12], in analogy with the gran-

[1] Here and below, we refer, for brevity of notations, to the pedestrian as he rather than he or she.)

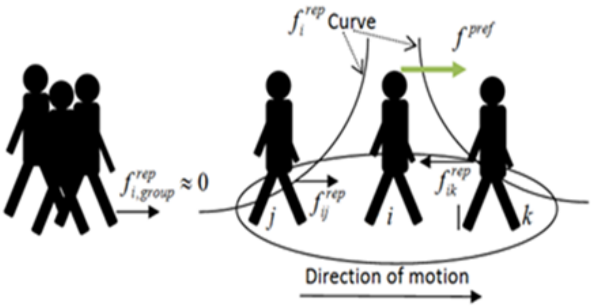

Figure 1 The perception of a pedestrian is represented as a circle centered at the location of the pedestrian himself. The radius of this area and the effects of the inside elements vary according to both the magnitude of B^{rep} and the weight function W, modeled in Eq. 7.

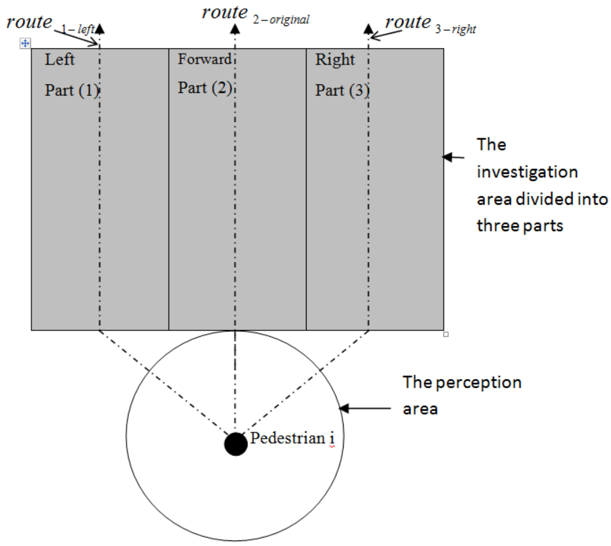

Figure 2 The perception area represented by a circle and the investigation area represented by three rectangular parts, each part includes a representative route.

ular forces; and their effect emerges in case of contact situation. The function $\overrightarrow{f}_{i,object}$ is analogous with $\overrightarrow{f}_{ij}$ but with regarding objects such as walls and columns.

3. THE INVESTIGATION CAPABILITY (Z-SH MODEL)

The investigation capability as an aspect for the independent pedestrians in normal situation was incorporated into the Social Force Model by Zainuddin and Shuaib in [10], to solve the counterintuitive behavior which emerged while performing large-scale simulations based on the Social Force Model. The simulated pedestrians who become excited $(E > 0)$ are short-sighted to avoid some anticipated blocked situations which are reasons for their undesirable situations [10]. In other words, the pedestrian in the Social Force Model has limited perception, and accordingly, he cannot take a decision to avoid blocked situations resulting from several reasons such as the presence of obstacles, bottlenecks, grouped pedestrian sets.

The investigating capability is represented by the feature of understanding the functionality of the density factor by the pedestrians in determining their intermediate points for their walking, accordingly changing their routes, and consequently overtaking the encountered blocked situations. The model of this capability, as introduced in [10], includes three essential parts: firstly, the investigation area model in which the pedestrian is provided with more intelligence and more options. This area is located beyond the perception area of the concerned pedestrian (see Fig. 2) and is divided into parts (in front, left and right parts) corresponding to his intuitive investigation which is performed by glances to the left and right of his original route, looking for an attractive area that could relieve the pressure. These parts are associated with the possible routes of pedestrian i to reach his destination (in front, left and right routes).

It is worth to note here that the aforementioned shape of the investigation area is an approximate shape chosen based on the intuitive investigation mentioned above. It can be presented as a circular or oval shape in which the pedestrian and his perception area are included. Indeed, several factors govern the shape and dimensions, such as the density and the height of the pedestrians [15]. However, incorporating such factors into the model of this area is a future work.

Secondly, the investigation process model which is based on the assumption that the pedestrian possesses his own awareness of the macroscopic behavior of the other pedestrians inside his investigation area, which may influence his choice of the route toward his destination. In other words, the pedestrian explores the repulsive characteristics of the parts (which are inherited to the included routes) of his investigation area, such as the density of the pedestrian crowd inside each part. Thus, the model for the repulsion of the alternative routes for pedestrian who becomes engaged with this process (i.e. $Inv_{i=1}$) because of being excited $(E > 0)$ is

$$rep_{route_{i,j}}(t) = a.\sigma_{part_{i,j}}(t), \tag{10}$$

where $rep_{route_{i,j}}$ is the repulsive effect of route j included in part j, and j here has the following values:1, 2, and 3 corresponding to the aforementioned choices: left, in front and right, respectively; the constant a is the proportionality factor to determine the proportional relationship between the density of an area and its repulsion. The index of the route with the minimum repulsion is determined by comparison between the computed repulsions of the alternative routes and selecting the minimum repulsive route

$$new, i = index\{\min_j(rep_{route_{i,j}}(t)) | j \in \{1,2,3\}\}. \quad (11)$$

Finally, the decision making model where the pedestrian makes a decision to direct his motion toward a new area which contains the route that has the minimum repulsion $rep_{new_{i,j}}$. Changing decision from the current route to a new route is made if the new route provides a utility to the pedestrian with worthwhile magnitude (the threshold of this utility is denoted by E^{th}). In this case, the decision factor of the pedestrian (denoted by DC) is equal to one. The preferred direction of the pedestrian in Eq. 4 is replaced by $\vec{e}^{\,0}_{curr,i}$, and Eq. 4 becomes

$$\vec{v}^{\,0}_i = \vec{e}^{\,0}_{curr,i}(1+E_i)V^0_i D_i + \langle \vec{v}_j \rangle_i (1-D_i), \quad (12)$$

where

$$\vec{e}^{\,0}_{curr,i}(t) = \begin{cases} \vec{e}^{\,0}_{new,i} & DC_i = 1 \\ \vec{e}^{\,0}_{curr,i} & DC_i = 0 \end{cases}. \quad (13)$$

The pedestrian continues investigating the situation, except in the case when he is directly walking toward his destination and his excitement factor is equal to zero.

4. THE PREDICTION FACTOR

The independent pedestrian, in real situation, may have previously launched the investigation process as a result of the prediction of such discomforting situations in his forward sighted area, although his excitement factor is not greater than zero. This is directly associated with his full consciousness of his trip, where he is continuously motivated to investigate his forward area. Pedestrians with time constraint to reach their destination are examples of those who usually investigate the situation along their trip. Another example is people jogging in walkways occupied with walking pedestrians, as shown in Fig. 3(a).

This attribute is denoted with discomfort-prediction factor ($pred$) which has the following model:

$$pred_i = \begin{cases} 1 & he\ has\ prediction\ characteristic \\ 0 & no-prediction \end{cases} \quad (14)$$

For pedestrians with discomfort-prediction factor ($pred = 1$), $E^{forward}_i$ denotes the predicted excitement factor of pedestrian i considering himself as walking in his forward area (the in front part of the investigation area).

This value is computed by using the original equation of excitement factor but by replacing his actual speed with the average speed of the in front part. It is worthy to note that $E^{forward}_i$ vanishes as E_i becomes of significant magnitude (i.e.$E_i > E^{forward}_i$).

Figure 3 In (a) some Muslims while performing their rituals (Al-Sae'e) are characterized with higher velocities than others (one ritual behavior which is performed by the minority of pilgrims, such as those shown with arrows, is to run in the specific area apparent in (a)). To conserve their velocities, they mostly follow routes with less interaction with other people such as the sides of their walkway. Furthermore, they may walk in impermissible routes to satisfy their desire such as those shown with arrows. In (b), a group of pilgrims can be easily recognized according to the physical appearance.

$$E_i = \begin{cases} E^{forward}_i & E_i \leq E^{forwared}\ and\ pred_i = 1. \\ E_i & otherwise \end{cases} \quad (15)$$

According to the latter equations, the independent pedestrians in the extended model are classified into two groups: first, the group of pedestrians who have prediction characteristic, thereby, they launch their investigation process before being in contact with discomforting situation as they predict such a situation in their forward areas; second, the group of pedestrians who launch their investigation process when they join such discomforting situations.

5. MODELING GROUPED PEDESTRIANS AS MOVING OBSTACLES

Grouped pedestrians are popular phenomena found in many pedestrian areas. Extreme cases could be found in festivals, ritual areas and so forth. A good representation of such phenomena and the effects on pedestrian flow could be observed in Al-tawaf, Al-sa'e and stoning rituals in the Al-hajj area, where millions of Muslim pilgrims yearly perform their religious rituals in Maka'a in Saudi Arabia (see Fig. 3-b and Fig. 4). Most pilgrims who come from different countries form groups, which may easily be distinguished by certain physical characteristics such as physical contact, uniform clothing (see Fig. 3) ets.

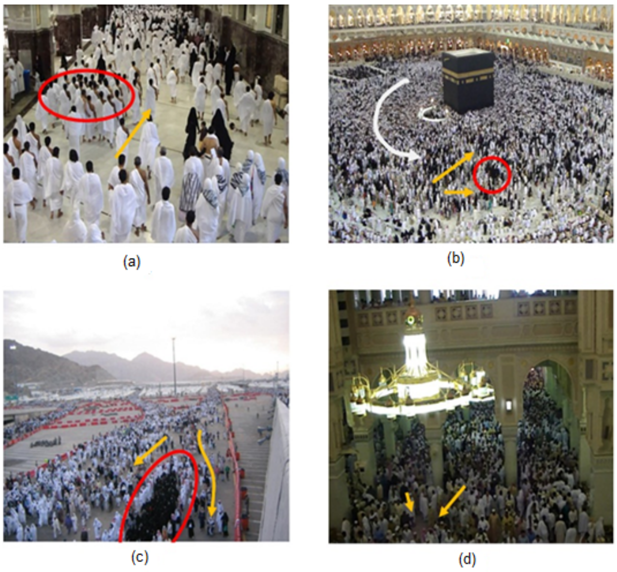

Figure 4 Decision making aspects to avoid groups. Performing Al-Sa'e and Al-Tawaf rituals inside the sanctuary Mosque in Makkah are shown in snapshots (a) and (b). In (c), the pilgrims are walking towards the stoning area in Mena to perform the stoning ritual. In snapshot (d), the people are going outside the Sanctuary Mosque in Makkah after performing their prayers. In (a), (b) and (c), a group of pilgrims can be easily recognized according to the characteristics posed in this section. Penetrating such groups will be the last choice to the other pilgrims, who want to overtake these groups, in case no other choices are available and their excitement are very high. The yellow arrows show the behaviour of the pilgrims who are making decisions to avoid obstacles by directing their motions towards the left or right side of these groups.

Generally speaking, recognizing any grouped pedestrians from other pedestrians depends on several characteristics which members of the group have in common [16,17]. Such these characteristics are mostly resulting from social interactions [18]. Among these characteristics, those which are of major concern in the simulation presented in this section are the following: first, the pedestrians of a particular group must have the same destination and move with nearly the same velocity; second, the pedestrians are close to each other; and finally, the density of the area occupied by the group must be higher than the surrounding area.

Grouped pedestrians could be an attractive source to those who move towards the same direction but with less velocity or those seeking for guidance to their destinations. Therefore, the focal group may be followed by other pedestrians as temporary destinations. This aspect has been modeled in [8] in evacuation situations. Conversely, a group could become a repulsive source to those moving with higher velocity or towards different direction from that of the group itself. The group becomes a repulsive source because of the impenetrable barrier it constitutes, which in certain extreme situations, could function as a moving obstacle as shown in Fig. 4. Quite reasonably, in the latter case, the expected behavior from independent pedestrians (intelligent pedestrians) with investigation ability is to make the decision to avoid such moving obstacles, before coming into contact with them, to avoid delays and other inconveniences to their motion. Such decisions are supported by the observations shown in Fig. 4.

For the examination of validity of the extended model in comparison with the original model in regards to avoiding obstacles such as grouped pedestrians, a simple model of a realistic representation of the motion of a group in normal situation is sufficient for this purpose. The model is inspired from the idea developed in [9] that we can classify the pedestrians of a group into independent pedestrians (the leaders of this group) and dependent pedestrians (the followers) where the latter are adhering to the former pedestrians and following their locations. Examples of those are the families and children who totally depend on their close relatives, such as parents, with whom they are walking. Others that the pedestrians rely on are those who appear as leaders and trustworthy (informed pedestrians), especially, when the formers do not have any knowledge or familiarity of the current environment (uninformed pedestrians) [19]. Figs. 3 and 4 (taken from the empirical data collected by the authors) are good examples of this situation where the leader would mostly be an individual and position in front of the group. This conclusion is matching the conclusion stated in the psychological study [20] that an individual in a front position can lead effectively the group to their destination. To model this behavior, the simulated leaders are considered as destinations for the dependent pedestrians, and instantaneously, they acquire the attribute of being independent. Hence, summarizing the behavior of the dependent pedestrians (the followers), if they have an identified leader (this is the case in this article) then they would keep following their leader. Otherwise, they would continue with the average speed and direction of the others who surround them as modeled in [3] given by Eq. 4.

Equation 4 or Eq. 12, therefore, becomes

$$\begin{aligned}\vec{v}_i^{\,0}(t) = {} & \vec{e}_i^{\,0}(t)(1+E_i(t))V_i^0 D_i \\ & + \left(\langle \vec{v}_j(t)\rangle_i\,(1-led_i) + (v_{i,l}(t)\vec{e}_{i,l})led_i\right) \\ & \times(1-D_i),\end{aligned} \tag{16}$$

$$v_{i,l}(t) = \begin{cases} v_l(t) & d_{i,l} < a_{i,l} \\ v_i^{\max} & otherwise \end{cases}, \tag{17}$$

where led_i is the leader factor attributed to those who are dependent and have leaders $(led_i = 1)$; v_i^{max} is the maximum speed of the dependent pedestrian i with direction $\vec{e}_{i,l}$ towards the area which surrounds his leader l with radius $a_{i,l}$; $d_{i,l}$ is the distance between the location of pedestrian i and his leader; v_l is the velocity of the corresponding leader of pedestrian i. With regards to the last model,

Table 1 The description and values of the parameters used in the simulation.

The pedestrians' parameters:	
$m = [77 - 83]kg$	The pedestrians' mass: uniformly distributed within the range [77 - 83] *kg*
$r = [0.25 - 0.30]m$	The pedestrians' radius: uniformly distributed within the range [0.25- 0.30] *m*
The parameters of the social repulsive force:	
$A^{rep} = 2000N$	The strength of the repulsive social force
$B^{rep} = 0.25$	The repulsive distance of the repulsive force used in the third simulation
$B^{rep} = 0.4$	The repulsive distance of the repulsive force used in the fourth simulation
$\tau = 0.5s$	The pedestrian reaction time
$\varepsilon \in [0\,,\, 0.05 * v^0/\tau\,]$	The fluctuation source of the pedestrian's acceleration is randomly assigned to each individual.
The extended model parameters:	
$U^{th} = 0.2 * rep_{curr}$	The threshold of utility to make a decision
$a = 1.1$	The proportionality factor to determine the proportional relationship between the density of an area and its repulsion

the dependent pedestrian who has a leader will move with his maximum velocity to reach his leader (it is enough here to enter the area with radius $a_{i,l}$ to feel safe so as not to lose his leader), and then would keep moving with the leader's velocity to the destination. It is worthy to note here that $a_{i,l}$ plays a major role in determining the relationship between the leaders and their followers. Indeed, there are other factors such as the density and the social interaction among the group's individuals [20] determine this relationship, and accordingly, govern the shape and dimensions of the area occupied by the pedestrians of a group. However, incorporating such factors into the model of this area is a future work.

6. SIMULATIONS AND DISCUSSION

6.1. Simulations

To examine further the validity of the investigation capability (Z-SH model) in comparison with the original model in accordance with the observations shown in Fig. 4, and to study the effect of incorporating the prediction factor in Z-SH model (the extended model), four simulations are conducted: the first is based on the original model where there is no investigation capability, and the other three simulations are based on the Z-SH model and the extended model as follows. In the second simulation, the independent pedestrians who investigate the situation have no prediction factor, whereas, in the third and fourth simulations, they are granted this factor but with varied perception (this is obtained by governing the values of parameters of the social repulsive force B^{rep}), where the radius of the perception in the third simulation is approximately equal to 2m, and in the fourth simulation is 4m. The physical environment is set up according to the following assumption: a unidirectional walkway which is long enough such that the preferred direction seems to be horizontal towards the left side. Such this environment is numerously available in the Hajj area which has received significant attention from many researchers [10,13,22,23]. Two groups of pedestrians are initialized in each simulation, with identical locations and preferred velocities with mean equals to 1.34 m/s. The other simulated pedestrians are independent ($D = 1$) and have higher velocity equal to 2.5 m/s and are randomly generated in the walkway area. In view of this, the aspects being examined are the interaction between the simulated individual pedestrians and the simulated grouped pedestrians, and the effect of the prediction factor on establishing more comfortable and efficient walking. The pedestrians' parameters, the parameters of the social repulsive force and the new parameters are chosen to have the values shown in Table 1.

6.2. Discussion

Four snapshots captured from the corresponding four simulations after a specific period of time, estimated as 8 seconds from the beginning of the simulations, are shown in Fig. 5(a, b, c & d) below. By comparing these snapshots with the observations in Fig. 4, counterintuitive behaviors from the simulated pedestrians emerged in Fig. 5(a& b), whereas certain important aspects are visible in Fig. 5(c& d).

Firstly, it is obvious that the areas immediately behind the grouped pedestrians are occupied with other pedestrians which are on contrary of what shown in Fig. 4. However, the number of simulated pedestrians directly following the groups was less in snapshot (b) than in snapshot (a), and accordingly, these areas in snapshot (b) are less dense than in snapshot (a), which indicates the effect of the investigation capability incorporated in the corresponding model. That is, the simulated pedestrians in (b) made their decisions to deviate left or right after joining the grouped pedestrians which, in turn, reduce the clogging caused by this joining. The simulated pedestrians, in snapshot (a),

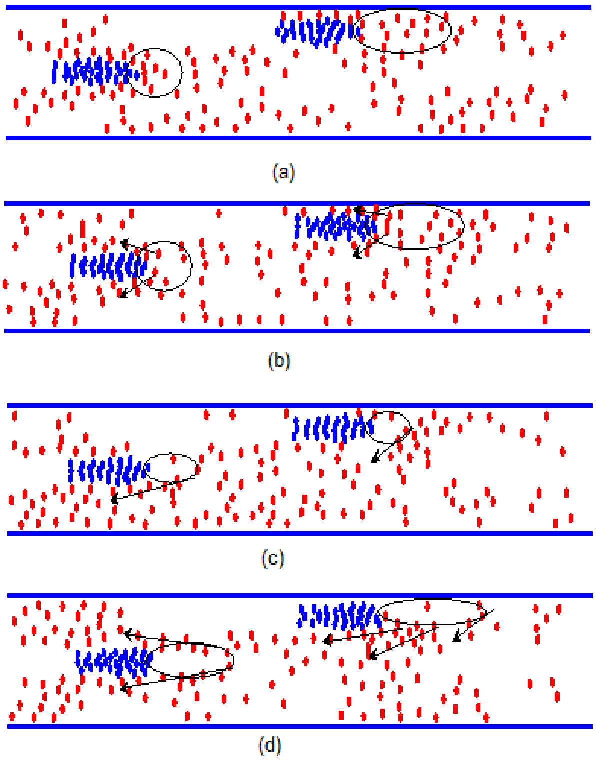

Figure 5 Four snapshots taken from four simulations of the original and the extended model for the comparison with regards to avoiding groups, after 10 seconds from starting the motion of the simulated pedestrians. Snapshot (a) was based on the original model; snapshot (b) was based on the extended model without prediction factor; and snapshots (c) and (d) have been taken from the simulations based on the extended model, with prediction factor and radius of perception equal to 2m and 4m respectively.

avoid this clogging by the effect of the social forces exerted in their perception areas.

In snapshots (c& d), pedestrians' motion forms smooth streams in the lower and upper sides of the groups. This aspect results from the decisions made by the simulated pedestrians, before contact situations with the groups (the simulated pedestrians become aware of the reasons of semi-blocked situations as the presence of such situations in their investigation areas and before entering their perception areas). As a consequence, empty areas immediately behind the groups were formed similar to the real situations shown in Fig. 4. This behavior did not appear in the second simulation, although the involvement of the investigation process, due to the lack of prediction ability of the simulated pedestrians in the second simulation to the undesirable situations in case they continue their walking toward the simulated groups.

In addition, the majority of the simulated pedestrians in snapshot (c& d) chose the lower side because of the higher utility established than the upper side. However, comparing snapshot (c) with (d), it is shown that the empty areas (ellipses) in (d) are larger than the corresponding areas in (c) due to the higher perception owned by the simulated pedestrians walking in snapshot (d).

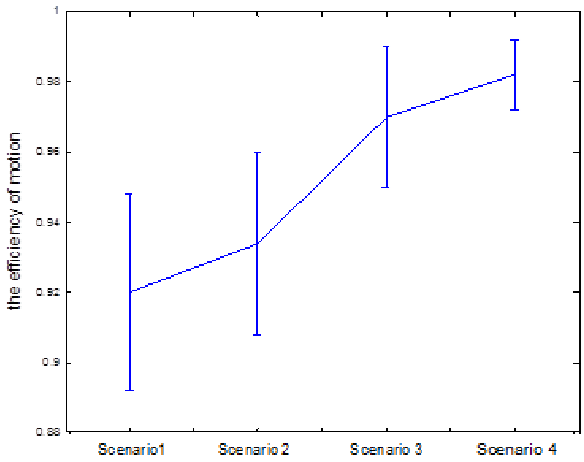

Figure 6 Error bars show the means and deviations of the efficiency of motion for four scenarios: the original model, the (Z-SH) model, the (Z-SH) model with prediction factor and $B = 0.23$, and the (Z-SH) model with prediction factor and $B = 0.4$, respectively.

For further comparison, four scenarios were conducted. Each scenario includes five simulations with the same specification mentioned in the beginning of the sixth section of this article. In each scenario, the mean and deviation of the efficiency of motion for the whole pedestrians were calculated and shown in Fig. 6.

The measurement was used by Helbing and Molnar in [21], on the basis of the Social Force Model. It is denoted by E_{eff} and has the following formula:

$$E_{eff} = \frac{1}{T}\sum_{t=t_0}^{t_{end}}\left(\frac{1}{N_t}\sum_{i=1}^{N_t}\frac{\vec{v_i}\cdot\vec{e}_i^{\,0}}{v_i^0}\right) \qquad (18)$$

where N_t is the number of pedestrians existing in the measured area at each time step t; $T = [t_{end} - t_0]$ is the total time to measure the efficiency of motion E_{eff}. This measurement helps optimize the pedestrian facilities, whether the pedestrians are walking conveniently in the considered facility or not.

According to Fig. 6, firstly, the prediction factor has increased the efficiency of motion of the simulated pedestrians in the third and fourth simulations compared with the first and second simulations. secondly, increasing the perception of the simulated pedestrians in the fourth simulation has increased the efficiency of motion compared with the third simulation. It is worth to note that the results are consistent with the varying qualitative behaviors in the four simulations demonstrated above.

7. CONCLUSION

In this article, further validity of the investigation capability (Z-SH model) was introduced by showing the intuitive realistic behaviors of the simulated pedestrians (obstacles-avoiding behavior), while interacting with groups of other pedestrians. A comparison between the original model, Z-SH model, and Z-SH model with the prediction factor (the extended model) has been made with regards to qualitative and quantitative measurements. The main reason for the new behavior emerged in simulations based on the extended model compared with the Z-SH model and the original model was the role of the prediction factor in determining the appropriate time for making decisions by the pedestrians and, in turn, achieving more comfortable walkway. It is found that the prediction of semi-blocked situations plays a major role in exhibiting the obstacles-avoiding behavior in the relevant simulations by eliminating the contact between the pedestrians and those situations. Consequently, the factor helps in the emergence of smooth motion and the increase of the efficiency of this motion.

It is hoped that this work would benefit, especially those involved in the applications of microscopic studies. Under normal situations, this work could easily be extended to involve many aspects of pedestrian flow by considering multi-directional flow and considering other aspects of interactions such as the behavior of groups to avoid obstacles and other groups. These aspects of interactions are vital phenomena emerged in the Hajj area such as the Al-Sa'e and Al-Tawaf rituals inside the sanctuary Mosque in Makkah, and walking towards the stoning area in Mena to perform the stoning ritual, as well. Regarding these aspects, the dynamic change in the shape of areas constituted by groups should be considered, and the factors such as the social interaction, gender, and other cultural factors which play major role in determining the inter-distances between the individual of a group and the resulting group's density should be incorporated. Finally, it is expected that the prediction factor would play an essential role for determining several aspects of the self-organization Phenomena such as lane-formation phenomenon which could not be obtained by the original model in some cases which involve extreme crowd.

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