*Acta Polytechnica CTU Proceedings* **57**:357–363, 2026
https://doi.org/10.14311/APP.2026.57.0357

Published by the Czech Technical University in Prague

# SHIELDING MODEL FOR LARGE PEDESTRIAN GROUP BEHAVIOUR

Francesco Zanlungo[a, b, *], Zeynep Yücel[b, c]

[a] Palermo University, Department of Physics and Chemistry, 90128, Viale delle Scienze 18, Palermo, Italy
[b] ATR, 619-0237, 2-2-2 Hikaridai, Seika, Soraku, Kyoto, Japan
[c] Ca' Foscari University, Department of Environmental Sciences, Informatics and Statistics, 30172 Via Torino 155, Venezia Mestre, Italy
[*] corresponding author: francesco.zanlungo@unipa.it

Abstract. We propose a mathematical framework to turn a cost function able to reproduce the dynamics of a social group composed of two pedestrians walking under low to medium density conditions into a cost function that may reproduce the dynamics of a group of arbitrary size. We first show that simply extending the two pedestrians cost function to a pair-wise $n$-body one produces completely unrealistic behaviour, while using it as the basis for a first-neighbour one produces more realistic U formations, which are actually observed in human crowds. Nevertheless, for $n > 3$ these formations are unstable in real crowds, and large groups tend to split into 2 and 3 people sub-groups. We finally show that this more realistic behaviour can be reproduced if we assume that the interaction with the closest partner effectively shields the interaction with the other members of the group.

Keywords: Pedestrian group dynamics, crowd simulation.

## 1. Introduction

Pedestrian social groups [1], i.e., groups of pedestrians that have a pre-existing social bond, and that move together towards a shared goal, often while being engaged in some sort of social interaction (e.g., conversation), represent an important component of crowds [2].

Although the effect of groups had been mostly ignored in the early crowd dynamics research, nowadays there is a large literature on the subject, including works on group size distribution [2, 3], group formation [3, 4], models of group dynamics [5, 6], how groups are affected by crowd density [7], the dependence of group dynamics on group composition [8, 9], group collision avoidance and path choice [10, 11], group synchronisation [12], and the effect of groups on crowd dynamics [13].

Nevertheless, groups are still often ignored in crowd simulators. One of the main reasons is probably that data concerning the behaviour of pedestrian groups are difficult to collect. Although the number of works using ecological data has been increasing [14], research on crowd dynamics, and in particular works concerning egress phenomena, has traditionally relied on controlled experiments [15]. Nevertheless, while it may be expected that, to some extent, the collision avoidance in controlled settings resembles how humans act in similar situations, natural social behaviour is arguably harder to attain in artificial settings [3]. At the same time, while advances in sensor technology and tracking algorithms allow nowadays for improved collection of ecological data of individual pedestrians [16], the recognition of social bonds is still challenging [17, 18].

It is in particular hard to recognise *large social groups*, i.e., groups composed of 4 or more pedestrians. Indeed [19] reports, based on combining sensor-based pedestrian tracking with human observation of social behaviours, that large groups tend to split in smaller units, composed of two (dyads) or three (triads) pedestrians, making their detection considerably difficult. Nevertheless it may be argued that this phenomenon is extremely relevant both from the view point of a proper understanding of crowd dynamics, and in order to reproduce such dynamics in simulators, since the effect that large groups would have on crowd flow if they were keeping large formations would be very different from the one they have splitting in smaller units.

This work provides a theoretical contribution in the direction of understanding large groups, by showing a recipe to turn any model able to reproduce the dynamics of dyads into a model for the behaviour of large groups, that properly describes the splitting phenomenon.

## 2. Pairwise (dyad) model

### 2.1. Theory

Although pedestrian models largely differ in the details of their implementation, all microscopic models reproducing individual movements may be formulated using a cost function framework [20].

Namely, each pedestrian $i$ attempts to optimise a function $\mathcal{F}_i$ depending at least on the position and velocity of all the pedestrians and obstacles in their neighbourhood, on their own goal and other features of the surrounding environment. If pedestrian $i$ is part of a social group, it is natural to assume that $\mathcal{F}_i$ includes a corresponding group interaction term,

$$\mathcal{F}_i = \ldots + \mathcal{G}_i + \ldots, \tag{1}$$

where the dots represent the remaining non-group terms in the cost function.

If we denote the partners of $i$ with indices $j$, we may write $\mathcal{G}_i$ as a sum of terms $U_{j,i}$ representing the interactions with each partner.

While in general to reproduce interaction between pedestrians it is needed to include also relative velocity, since groups often move together towards common goals relative velocity may be ignored in a first approximation, and the term $\mathcal{G}_i$ for a pedestrian $i$ in an $n$-people social group assumes the form

$$\mathcal{G}_i = \sum_{j \neq i}^{n} U_{j,i}(\mathbf{r}_{ji}), \tag{2}$$

where $\mathbf{r}_{ji}$ is the relative position vector between the pedestrians,

$$\mathbf{r}_{ji} \equiv \mathbf{r}_j - \mathbf{r}_i.$$

Although in Eq. 2 we write the group interaction term of the cost function as the sum of the interaction terms with the various partners, we take in consideration the possibility that the functional form of $U_{j,i}$ is modified by the presence of the other partners $k$ with $k \neq j$, $k \neq i$, although this dependence is not shown to simplify the notation.

We thus do not necessarily assume that group interaction satisfies a superposition principle.

This obviously does not apply the case of a dyad, in which the $ji$ dependence of the group cost function may be omitted, obtaining

$$\mathcal{G}_i = U(\mathbf{r}_{ji}). \tag{3}$$

### 2.2. A specific model

It may be useful to consider a specific model as a guiding light in our discussion. [5] assumes that by using a polar coordinates reference frame in which $\theta$ is the angle between the relative position vector $\mathbf{r}_{ij} = -\mathbf{r}_{ji}$ and the direction given by a unit vector $\mathbf{g}$ pointing to the local goal (Figure 1), the cost function may be written as the sum of a radial and an angular term,

$$U(\mathbf{r}) = U(r, \theta) = C_r R(r) + C_\theta \Theta(\theta), \tag{4}$$

with $r = ||\mathbf{r}||$,

$$R(r) = \frac{r}{r_0} + \frac{r_0}{r}, \tag{5}$$

where $r_0$ represents the most comfortable distance between the pedestrians, and

$$\Theta^\eta(\theta) = (1+\eta)\theta^2 + (1-\eta)\psi^2. \tag{6}$$

Here

$$\psi = \theta - \operatorname{sgn}(\theta)\pi$$

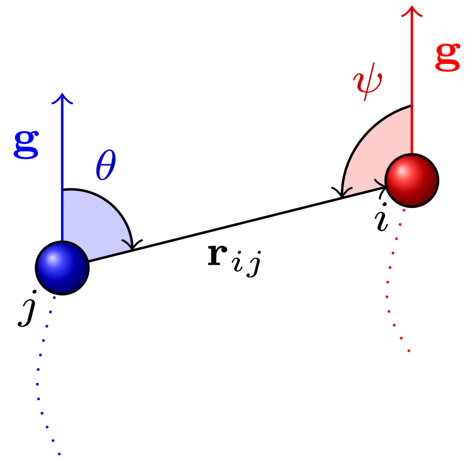


Figure 1. Reference frame and useful variables for the definition of the group model of [5].

represents the angle that the gaze of $i$ has to span between the direction to the goal and the position of $j$ (while $\theta$ represents the corresponding angle for $j$), and

$$-1 \leq \eta \leq 1$$

is a weight concerning the relative importance that these angles assume in $i$'s cost function.

The presence of a non-zero value of $\eta$ introduces a non-Newtonian term (i.e., the cost function optimised by $i$ is different from the one optimised by $j$) and, once the model is explicitly implemented as a second order differential one in which the acceleration of $i$ due to the presence of $j$ is given by

$$\ddot{\mathbf{r}}_i = -\boldsymbol{\nabla} U(\mathbf{r}_{ji}), \tag{7}$$

and calibrated on an ecological data set of social group motion, allows it to explain not only the abreast formation of dyads, but also their difference in velocity with individuals. Furthermore, if the model is extended to triads through the first neighbour framework explained below in Section 3.2, it predicts also the spatial formation and velocity of three people groups.

Nevertheless, for most purposes, the model can also be simplified by using $\eta = 0$, i.e.

$$\Theta^0(\theta) = \left(\theta - \operatorname{sgn}(\theta)\frac{\pi}{2}\right)^2, \tag{8}$$

where we have ignored an additive constant which is irrelevant to group dynamics. This simplified model will be useful to direct some of our qualitative discussions below.

## 3. Extension to $n$ people

### 3.1. Pair-wise model

To understand how to extend the model to an $n > 2$ social group, we may take in consideration their spatial structure, and in particular the one of triads [5]. Groups of three pedestrians, when located in large, low density environments (i.e., when the non-group terms of their cost function may be ignored), tend to walk in almost abreast V formations, in which the pedestrians on the flanks are located at a distance roughly twice the distance assumed between pedestrians in a dyad, $\approx 2r_0$.

Furthermore, in those cases in which larger groups (i.e., groups of 4 or 5 people) keep an extended formation, they do it in almost abreast formations in which the distance between the farthest pedestrians is close to $\approx (n-1)r_0$.

It should be clear that in case of an $n$ people group, this result cannot be obtained just by extending the cost function to the $n$-body pair-wise cost function

$$\mathcal{G}_i = \sum_{j \neq i}^{n} U(\mathbf{r}_{ji}), \tag{9}$$

because pedestrians located at distances quite larger than $r_0$ are not in equilibrium positions. In other words, group behaviour does not satisfy a superposition principle.

### 3.2. First neighbour model

By noticing that, in low density settings, the distance between first neighbours inside a V or U formation is basically equivalent to the relative distance between the members of a dyad, [5] proposed to extend the dyad model to larger groups by assuming interaction only with first neighbours, namely

$$\begin{aligned} \mathcal{G}_1 &= U(\mathbf{r}_{2,1}), \\ \mathcal{G}_{1<i<n} &= U(\mathbf{r}_{i-1,i}) + U(\mathbf{r}_{i+1,i}), \\ \mathcal{G}_n &= U(\mathbf{r}_{n-1,n}). \end{aligned} \tag{10}$$

In this equation, the labelling of pedestrians may be (dynamically) taken by using a reference frame with the $y$ axis aligned to the goal direction $\mathbf{g}$, and requiring that the $x$ coordinates of pedestrians satisfy

$$x_i < x_j, \ \forall i < j,$$

i.e. labelling with growing indices from left to right.

In [5], using this approach and parameters calibrated using only the two people trajectories, allows for a reproduction of the spatial formation and velocity of triads. Furthermore, if the model is applied on 4 and 5 pedestrian groups, it leads to the emergence of the U formations shown in Figure 2 and observed in the ecological data of [4].

Nevertheless, as reported in [5, 19], such U formations are highly unstable, and tend to split into more stable 2 and 3 people sub-groups, which, by having a reduced width, are more efficient for motion in low and medium density crowds (at higher densities there is a tendency to walk on files, [21]).

### 3.3. Shielding model

It is thus necessary to introduce a model that, while able to reproduce large U formations as those shown in

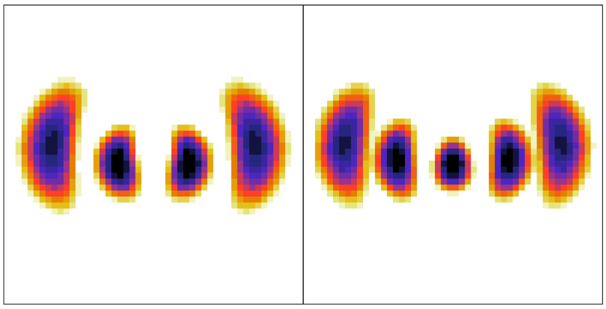

FIGURE 2. 4 (left) and 5 (right) people U formations as predicted by the first neighbour extension of the model introduced by [5].

Figure 2, will also predict that these formations split in smaller 2 and 3 people groups under external disturbances, such as collision avoidance or environmental constraints.

We name the proposed model a *shielding model*, since it is based on the assumption that the interaction with the group partner located at the minimum value of the cost function will effectively shield the interaction with the other partners.

According to the spirit of this contribution, this model is going to be a recipe to turn a dyad cost function $U(\mathbf{r})$ into an $n$ people cost fuction. We will assume that the cost function $U$ defines a single connected portion of the plane $\Omega$ on which we have "attractive interaction",

$$\boldsymbol{\nabla} U \cdot \mathbf{r} \geq 0,$$

but this technical requirement is needed just to simplify the mathematical expressions.

For each pedestrian $i$ we first define the minimum value of $U$ over all partners as

$$U^i_{min} = \min_j U(\mathbf{r}_{ji}). \tag{11}$$

We then define a reference point $\mathbf{r}_m$ as a point

$$\mathbf{r}_m \in \Omega, \ U(\mathbf{r}_m) = U^i_{min} \tag{12}$$

(as we will see below, if such a point does not exist, we simply have $U_{ji} = U$ for all pairs).

We may now define the cost function with respect to all partners as

$$U_{ji}(\mathbf{r}_{ji}) = \begin{cases} U(\mathbf{r}_{ji}), \\ \ \text{if } \mathbf{r}_{ji} \notin \Omega \text{ or } U(\mathbf{r}_{ji}) \leq U^i_{min}, \\ U^i_{min} + \int_{\mathbf{r}_m}^{\mathbf{r}_{ji}} e^{-\frac{\left(U(\mathbf{s}) - U^i_{min}\right)^2}{\Delta_U^2}} \boldsymbol{\nabla} U(\mathbf{s}) \cdot d\mathbf{s}, \\ \ \text{otherwise}, \end{cases} \tag{13}$$

where $\Delta_U$ is a new model parameter.

Before explaining the meaning of this definition, let us first show that this is a properly defined function, i.e. that the integral

$$\int_{\mathbf{r}_m}^{\mathbf{r}} e^{-\frac{\left(U(\mathbf{s}) - U^i_{min}\right)^2}{\Delta_U^2}} \boldsymbol{\nabla} U(\mathbf{s}) \cdot d\mathbf{s}$$

does not depend on the path.

This is true as long as the integrated vector field has zero curl, and this can be shown by using

$$\nabla \times (f(U)\nabla U) = \frac{\mathrm{d}f}{\mathrm{d}U}\nabla U \times \nabla U + f(U)\nabla \times \nabla U = \mathbf{0}, \quad (14)$$

from which follows

$$\nabla \times \left( e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}) \right) = \mathbf{0}. \quad (15)$$

Indeed, we can now see that the integral does not depend on the path by choosing two different (arbitrary) paths $c_1$ and $c_2$ between the reference point $\mathbf{r}_m$ and $\mathbf{r}$ and rewriting their difference as a circulation over a closed path $c$, and then use Stokes' theorem to rewrite the circulation as a flux through a surface $S$ enclosed by $c$ to obtain

$$\begin{aligned} &\int_{c_1} e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}) \cdot \mathrm{d}\mathbf{s} + \\ &-\int_{c_2} e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}) \cdot \mathrm{d}\mathbf{s} = \\ &= \oint_{c} e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}) \cdot \mathrm{d}\mathbf{s} = \\ &= \int_{S} \left[ \nabla \times e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}) \right] \cdot \mathbf{n} = 0, \end{aligned} \quad (16)$$

i.e. the result does not depend on the chosen path, as desired.

This implies that the gradient of $U_{ij}$, which is the relevant quantity in an optimisation problem, is

$$\nabla U_{ji}(\mathbf{r}_{ji}) = \begin{cases} \nabla U(\mathbf{r}_{ji}), \text{ if } \mathbf{r}_{ji} \notin \Omega \text{ or } U(\mathbf{r}_{ji}) \leq U^i_{min}, \\ e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}} \nabla U(\mathbf{s}), \text{ otherwise.} \end{cases} \quad (17)$$

As a result, the interaction with the group partners that are located inside $\Omega$, i.e. those to which $i$ would be attracted, excluding the one located at $U^i_{min}$, is scaled by the factor

$$e^{-\frac{\left(U(\mathbf{s})-U^i_{min}\right)^2}{\Delta_U^2}},$$

while the interaction with the partner at $U^i_{min}$ and with those that are too close is left unchanged.

Let us understand the meaning of this formulation by considering the simple potential of Eq. 8 in which pedestrians tend to keep an abreast position with $\theta = \pm\frac{\pi}{2}$ and $r = r_0$. A member of the group will always seek to have a partner located at such a position, but after this is attained, they will interact only with other members located very close to the other available minimum (the definition of "very close" depending obviously on the value of $\Delta_U$).

This allows for the creation of large abreast formations (or U formation if the model allows for it, e.g. for $\eta \neq 0$ in the model of Eq. 6), as isolated pedestrians will try to join such formations. Nevertheless, formations can be easily broken in two or three people ones, since the interaction between people in different chains will be negligible[1]. On the other hand, dyads and triads cannot be broken, since their breaking would cause at least an individual to be isolated. For example, in the case of a triad, if an individual got isolated, it would be mostly ignored by the other two partners, but would strongly seek to join them (or another subgroup).

## 4. Simulations and results

Let us verify this qualitative considerations through explicit computations.

### 4.1. Simulation setting

All the simulations presented in this section are based on the same, simple setting. The crowd is composed of 20 individual pedestrians and four groups, respectively composed of 4, 5, 6, and 7 people. They move in a straight corridor of length 40 meters, with periodic boundary conditions, and a width of 4 meters. The preferred speed of all pedestrians is obtained from a normal distribution with average $1.3\,\mathrm{m\,s^{-1}}$ and standard deviation $0.1\,\mathrm{m\,s^{-1}}$, but to all members of a group the same preferred speed is assigned. The goal direction (direction of the vectorial preferred velocity) is always parallel to the corridor's axis, although to each pedestrian a right-to-left or left-to-right goal orientation is assigned with equal probability (again, the same orientation is assigned to all members of the same group).

Collision avoidance follows the "long range, circular specification" model proposed in [22], i.e. the simplest model analysed in that work, without implementation of body shape and body orientation features, and without explicit prediction of the point of collision between the pedestrians' bodies.

While [22] performed a genetic algorithm based optimisation of parameters based on actual human trajectories, for these simulations the parameters were fixed by hand to "reasonable values" (Table 1), i.e specified by assuming that pedestrians perform a collision avoidance when their motion, if linearly extrapolated, would lead to a future distance of less than 1 m.

No actual collision avoidance with walls was implemented, and pedestrians were simply kept inside the corridor using a linear recall "force"

$$\ddot{\mathbf{r}} = -Kd\mathbf{n} \quad (18)$$

when they passed the corridor limits, $K$ being a model parameter, $\mathbf{n}$ the normal to the wall, and $d$ the distance to the corridor limit (no force was applied if the pedestrains remained inside the limit).

[1] The interesting problem of maintaining some level of interaction between subgroups is not explored here also for the lack of relevant ecological data.

| Parameter | Definition | Value |
|---|---|---|
| $C$ | Eq. C.13 in [22] | 5 |
| $d_{int}$ | Eq. C.13 in [22] | 0 m |
| $d_{ext}$ | Eq. C.13 in [22] | 1 m |
| $\mu_v$ | Mean of vel. distr. | $1.3\,\mathrm{m\,s^{-1}}$ |
| $\sigma_v$ | St. dev. of vel. distr. | $0.1\,\mathrm{m\,s^{-1}}$ |
| $k_{v_p}$ | Eq. C.2 in [22] | $1.5\,\mathrm{s^{-1}}$ |
| $\Delta t$ | Time step (Sec. 4.3 of [22]) | 0.05 s |
| $C_r$ | Eq. 4 | $1.5\,\mathrm{m^2\,s^{-2}}$ |
| $C_\theta$ | Eq. 4 | $0.16\,\mathrm{m^2\,s^{-2}}$ |
| $r_0$ | Eq. 5 | 0.75 m |
| $\eta$ | Eq. 6 | -0.23 |
| $v_{max}$ | Maximum velocity, Sec C.4 in [22] | $3\,\mathrm{m\,s^{-1}}$ |
| $K$ | Eq. 18 | $5\,\mathrm{s^{-2}}$ |
| $\Delta_U$ | Eq. 19 | Computed from the eq. and parameters above |

TABLE 1. Model parameters. Parameters specified in [22] but not reported here refer to modules of the model that were not implemented.

No sort of actual physical dynamics was implemented, i.e. pedestrians are simulated as point particles whose dynamics is determined solely by their preferred velocity, collision avoidance and group behaviour (to be discussed below). No stochastic term was added to the equations of motion. Table 1 reports the used parameter value using the same notation of [22], to which readers are referred for further details.

The collision avoidance and navigation aspects of the simulation setting described above are kept simple by design, since we assume that in order to observe the group formation and splitting phenomena under investigation it is sufficient to introduce just the basic aspects of environmental constraints to group motion.

Group dynamics always uses, in all simulations, as a basic dyadic cost function the model proposed in [5], using the parameters obtained by calibration on ecological data in such work (see again Table 1). The parameter $\Delta_U$ in Eq. 13 was chosen as one tenth of the value assumed by the function $U$ in its theoretical minimum,

$$\Delta_U = \frac{U\left(r = r_0, \theta = \frac{(1-\eta)\pi}{2}\right)}{10}. \tag{19}$$

## 4.2. Results

The purpose of the simulations is obviously to compare the results obtained using the first-neighbour model of Eq. 10 with those obtained using the shielding model of Eq. 13.

Figure 3 shows the initial condition for a simulation using the first-neighbour model of Eq. 10 (a video is available at [23]). Pedestrians (circles) in black are moving independently, while pedestrians of the same colour belong to the same group. Initial velocities are zero, while initial positions are assigned randomly, allowing pedestrians from the same group to be distant.

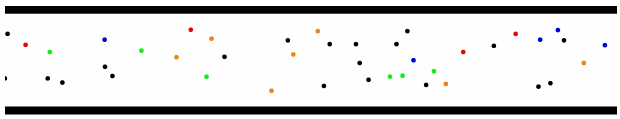

FIGURE 3. Initial condition for a simulation using the first-neighbour model of Eq. 10 (same initial conditions were used for the simulation using the shielding model of Eq. 13 in Figure 5). Pedestrians (circles) in black are moving independently, while pedestrians of the same colour belong to the same group. Initial velocities are zero, while initial positions are assigned randomly, allowing pedestrians from the same group to be distant. The orange group moves towards the right, the other groups towards the left.

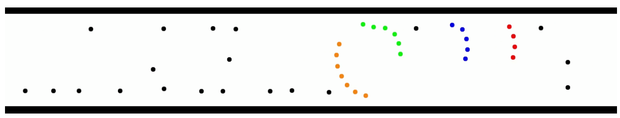

FIGURE 4. Snapshot of the simulation using the first-neighbour model of Eq. 10 and the initial conditions from Figure 3. The snapshot is taken after group formations were established. The orange group moves towards the right, the other groups towards the left. Video available at [23].

Nevertheless, regardless of initial conditions, the crowd converges in short time to a condition similar to the one of Figure 4, with large formations including all the pedestrians in the group. Although, in particular for the largest groups with 7 members, the environmental constraints modify the U formation that would be attained at a very low density in a large enough environment, all pedestrians in a group move together.

When the same initial conditions of Figure 3 are used for a simulation using the shielding model of

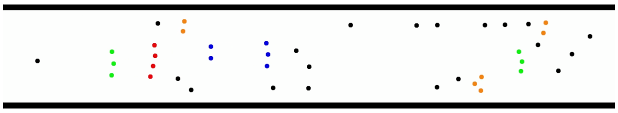

Figure 5. Snapshot of the simulation using the shielding model of Eq. 13 and the initial conditions from Figure 3. The snapshot is taken after group formations were established. The orange group moves towards the right, the other groups towards the left. Video available at [24].

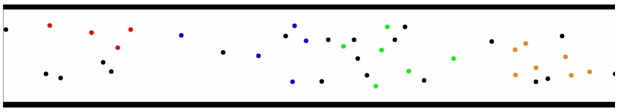

Figure 6. A different initial condition for a simulation using the shielding model of Eq. 13. Pedestrians in black are moving independently, while pedestrians of the same colour belong to the same group. Initial velocities are zero, while initial positions are still assigned randomly, but imposing a maximum allowed distance between pedestrians in the same group, to facilitate the emergence of large formations. The orange group moves towards the right, the other groups towards the left.

Eq. 13, the results are quite different, as it is shown in Figure 5 (a video is available at [24]). We can see that in this case pedestrians are able to move in smaller sub-groups composed mostly of two and three pedestrians, as theoretically predicted.

Another major difference between the simulations shown in Figures 4 and 5 is that while the pedestrians using the first-neighbour model have to wait for all the members of their group to join the formation before starting to move towards the goal, when pedestrians use the shielding model they start moving towards the goal as soon as they have a single partner (more partners can obviously join at a following time).

As a result, the simulation in Figure 5 does not show any group formation with more than four members, due to the choice of the initial conditions. To facilitate the emergence of such large formations, we performed also a simulation in which pedestrians in the same group started close in space (Figure 6). As a result, large formations emerged (Figure 7), although, as expected, they were short-living (Figure 8). A video is available at [25].

We can thus state that the simulations agree with the theoretical predictions, and satisfy the purpose the shielding model was built for.

## 5. Conclusions

In this work we discussed the problem of extending a cost function that describes the dynamics of a dyad of pedestrians (a social group formed by two walking pedestrians) to a larger group composed of $n > 2$ ones.

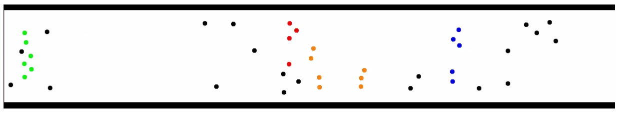

Figure 7. Snapshot of the simulation using the shielding model of Eq. 13 and the initial conditions from Figure 6. The orange group moves towards the right, the other groups towards the left. We can notice the presence of a large formation including all the 6 members of the group in green. Video available at [25].

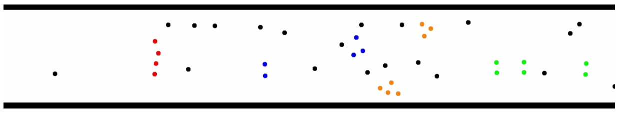

Figure 8. Snapshot of the simulation using the shielding model of Eq. 13 and the initial conditions from Figure 6, taken at a later time with respect to the one shown in Figure 7. The 6 people group in green has now split in 3 dyads. The orange group moves towards the right, the other groups towards the left. Video available at [25].

A previous work [5] had proposed to use a first-neighbour interaction system, which was able to properly describe the motion of triads (groups of three), and the emergence of large U formations for groups with 4 or more members. Nevertheless, such model was not able to describe the tendency of these large formations to split in smaller sub-groups with 2 or 3 members, and was based on a somewhat arbitrary definition of first neighbours determined by the position on an axis orthogonal to the goal direction.

In this work we proposed a "shielding model" in which the presence of a first neighbour, defined now as the partner found at the minimum value of the dyadic cost function, effectively shields the interaction with the other pedestrians. This model, while reproducing the formation obtained using the first-neighbour model, can correctly predict the tendency of large groups to split into smaller ones.

The current work has three main limitations. First of all, since as far as we know no quantitative ecological data concerning the mechanism of sub-group splitting and merging are available, it was not possible to calibrate the model's new parameter $\Delta_U$ on such data.

Furthermore, again for the lack of data and observations, no speculation has been proposed on the mechanism that may keep subgroups close between each other.

Finally, the shielding model has been proposed for cost functions using only relative position, and the proposed recipe is not applicable to cost functions depending also on velocity. Furthermore, while a theoretical formula for the cost function has been provided, its explicit calculation is cumbersome. On the other hand, the calculation of the gradient of the cost function is straightforward, and as a result the proposed method is particularly apt to second order differential implementations, such as the model of [5].

We nevertheless believe that, regardless of the explicit form of the equations, the shielding concept introduced in this work may be extended to more complex cost functions depending also on velocity, and adapted to different computational frameworks.

Possible future work may concern the implementation of a more realistic simulator, which may be used for a systematic study of the sub-group splitting and merging phenomenon, and of its dependence on crowd density and composition.

## References

[1] J. Adrian, N. Bode, M. Amos, et al. A glossary for research on human crowd dynamics. *Collective Dynamics* **4**:1–13, 2019. https://doi.org/10.17815/CD.2019.19

[2] M. Moussaïd, N. Perozo, S. Garnier, et al. The walking behaviour of pedestrian social groups and its impact on crowd dynamics. *PloS one* **5**(4):e10047, 2010. https://doi.org/10.1371/journal.pone.0010047

[3] M. Costa. Interpersonal distances in group walking. *Journal of Nonverbal Behavior* **34**(1):15–26, 2010. https://doi.org/10.1007/s10919-009-0077-y

[4] M. Schultz, L. Rößger, H. Fricke, B. Schlag. Group dynamic behavior and psychometric profiles as substantial driver for pedestrian dynamics. In *Pedestrian and Evacuation Dynamics 2012*, pp. 1097–1111. Springer, 2013. https://doi.org/10.1007/978-3-319-02447-9_90

[5] F. Zanlungo, T. Ikeda, T. Kanda. Potential for the dynamics of pedestrians in a socially interacting group. *Physical Review E* **89**(1):012811, 2014. https://doi.org/10.1103/PhysRevE.89.012811

[6] F. Zanlungo, T. Kanda. A mesoscopic model for the effect of density on pedestrian group dynamics. *Europhysics Letters* **111**(3):38007, 2015. https://doi.org/10.1209/0295-5075/111/38007

[7] F. Zanlungo, D. Brščić, T. Kanda. Spatial-size scaling of pedestrian groups under growing density conditions. *Physical Review E* **91**(6):062810, 2015. https://doi.org/10.1103/PhysRevE.91.062810

[8] F. Zanlungo, Z. Yücel, D. Brščić, et al. Intrinsic group behaviour: Dependence of pedestrian dyad dynamics on principal social and personal features. *PloS one* **12**(11):e0187253, 2017. https://doi.org/10.1371/journal.pone.0187253

[9] F. Zanlungo, Z. Yücel, T. Kanda. Intrinsic group behaviour II: On the dependence of triad spatial dynamics on social and personal features; and on the effect of social interaction on small group dynamics. *PloS one* **14**(12):e0225704, 2019. https://doi.org/10.1371/journal.pone.0225704

[10] A. Gregorj, Z. Yücel, F. Zanlugo, T. Kanda. Ecological data reveal imbalances in collision avoidance due to groups' social interaction, 2024. ArXiv:2406.06084. https://doi.org/10.48550/arXiv.2406.06084

[11] A. Gregorj, Z. Yücel, F. Zanlungo, T. Kanda. Pedestrian motion along curves: A comparative study of dyads and individuals. *Acta Polytechnica CTU Proceedings* **57**:81–89, 2026. Pedestrian and Evacuation Dynamics 2025. https://doi.org/10.14311/APP.2026.57.0081

[12] A. Gregorj, Z. Yücel, F. Zanlungo, T. Kanda. Gait synchronisation in pedestrian dyads: The influence of social interaction. In *EPJ Web of Conferences*, vol. 334, p. 04007. EDP Sciences, 2025. https://doi.org/10.1051/epjconf/202533404007

[13] F. Zanlungo, L. Crociani, Z. Yücel, T. Kanda. The effect of social groups on the dynamics of bi-directional pedestrian flow: A numerical study. In *Traffic and Granular Flow 2019*, pp. 307–313. Springer, 2020. https://doi.org/10.1007/978-3-030-55973-1_38

[14] A. Corbetta, L. Bruno, A. Muntean, F. Toschi. High statistics measurements of pedestrian dynamics. *Transportation Research Procedia* **2**:96–104, 2014. https://doi.org/10.1016/j.trpro.2014.09.013

[15] C. Feliciani, K. Shimura, K. Nishinari. *Introduction to crowd management: Managing crowds in the digital era: Theory and Practice*. Springer Nature, 2022. https://doi.org/10.1007/978-3-030-90012-0

[16] D. Brščić, T. Kanda, T. Ikeda, T. Miyashita. Person tracking in large public spaces using 3-D range sensors. *IEEE Transactions on Human-Machine Systems* **43**(6):522–534, 2013. https://doi.org/10.1109/THMS.2013.2283945

[17] Z. Yücel, F. Zanlungo, C. Feliciani, et al. Identification of social relation within pedestrian dyads. *PloS one* **14**(10):e0223656, 2019. https://doi.org/10.1371/journal.pone.0223656

[18] Z. Yücel, F. Zanlungo, T. Ikeda, et al. Deciphering the crowd: Modeling and identification of pedestrian group motion. *Sensors* **13**(1):875–897, 2013. https://doi.org/10.3390/s130100875

[19] F. Zanlungo, T. Kanda. Do walking pedestrians stabily interact inside a large group? Analysis of group and sub-group spatial structure. In *Proceedings of the Annual Meeting of the Cognitive Science Society*, vol. 35, pp. 3847–3852. 2013.

[20] I. Echeverría-Huarte, A. Nicolas. Body and mind: Decoding the dynamics of pedestrians and the effect of smartphone distraction by coupling mechanical and decisional processes. *Transportation Research Part C: Emerging Technologies* **157**:104365, 2023. https://doi.org/10.1016/j.trc.2023.104365

[21] C. van der Laan, T. Harmsen, A. Corbetta. Modeling metastable dynamics of dyads from large-scale data. *Acta Polytechnica CTU proceedings* 2026. [In Print].

[22] F. Zanlungo, C. Feliciani, Z. Yücel, et al. Macroscopic and microscopic dynamics of a pedestrian cross-flow: Part II, modelling. *Safety science* **158**:105969, 2023. https://doi.org/10.1016/j.ssci.2022.105969

[23] F. Zanlungo, Z. Yücel. Simulation using the first neighbour model, 2026. [2025-02-25]. https://www.youtube.com/watch?v=jTRwNqpe3xo

[24] F. Zanlungo, Z. Yücel. Simulation using the shielding model and initial conditions that do not favour the formation of large groups, 2026. [2025-02-25]. https://www.youtube.com/watch?v=iP2Eq9VivaU

[25] F. Zanlungo, Z. Yücel. Simulation using the shielding model and initial conditions that favour the formation of large groups, 2026. [2025-02-25]. https://www.youtube.com/watch?v=CP2NMM2zojA