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Misanthrope process for large-scale simulation of pedestrian dynamics

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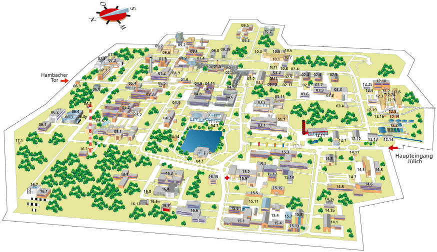
Forschungszentrum Jülich

- **Multidisciplinary research center**
  - Health
  - Energy
  - Environment
  - Information technology



- Approx. 5000 employees

- **Jülich Supercomputing Centre – Division Civil Safety and Traffic**
  - Experimentation and modelling of pedestrian dynamics
  - Fire and evacuation simulation
  - Safety of large-scale events
  - Collaboration with Wuppertal and Cologne Universities

Motivations

- Nowadays more than **half of mankind lives in cities**
- **Dense crowds** are frequent in train stations, fairs, city centers or during large-scale events (sport, spectacle, concert, demonstration. . .)
- Knowledge of pedestrian dynamics is important for the design and optimization of facilities with respect to **safety or level of service**
- **Complex system**: experimentation, data collection, modelling and simulation of pedestrian dynamics are necessary

Misanthrope process

- Borrowed from **Interacting Particle Systems** widely studied in theoretical physic[3] (see also zero-range, exclusion, or mean average processes)

- **Continuous time Markovian jump process** describing evolution of particles in a lattice

- **Unique stationary distribution** (finite set) that can easily be calculated by simulation (Monte Carlo experiments)

- **Misanthrope process :** Each site can contain several particles and the jump rate depends on particle numbers in departure and arrival sites[4]

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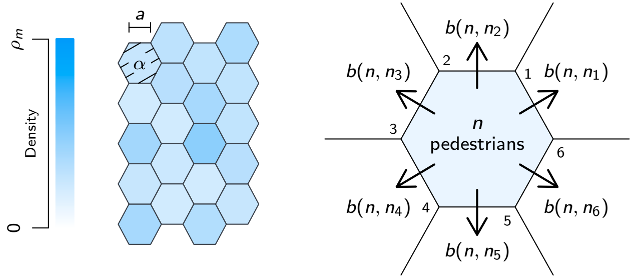
[3] T Liggett (1985) *Interacting particle systems* Springer

[4] C Cocozza-Thivent (1985) Z Wahr Verw Gebiete 70:509-523

Pedestrian model

- Hexagonal lattice with $a > 0$ the face length (area $\alpha = 1.5\sqrt{3}a^2$)
- Each hexagon can contain $n \in [0, N]$ pedestrians, $N \geq 1$
- Jump rate b to define



Model characteristics

Discrete space / **Continuous time** (also for the simulation)

Intrinsically stochastic (jump times exponentially distributed)

Several pedestrians by cell (size cell sufficiently big)

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$\rightarrow$ **Mesoscopic approach :** Pedestrians are individually considered but their dynamics are aggregated by cell

$\rightarrow$ **Exclusion model for** $N = 1$ (size of the cell = size of a pedestrian)

Jump rate function

- **The jump rate** of a pedestrian from a cell with $n \geq 1$ pedestrian to cell i with $n_i \geq 0$ pedestrians is

$$b_i(n, n_i) = \kappa \times J(n, n_i) \times D_i(J(n, n_i)) \quad (1)$$

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- The flow $J(n, n_i)$ is the **minimum between the demand** of the considered cell and **the supply** of the destination cell i :

$$J(n, n_i) = \min\{\Delta(n/\alpha), \Sigma(n_i/\alpha)\} \qquad (2)$$

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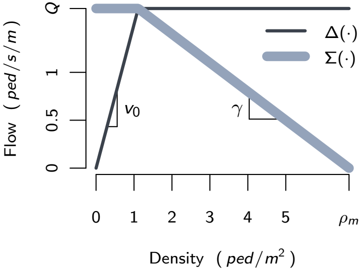
- The selected direction $D_i(J(n, n_i))$ **maximizes the weighted flow to the desired direction** h :

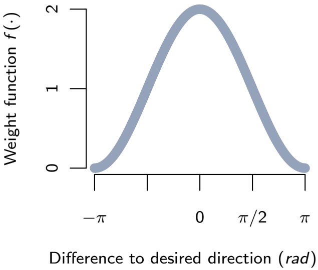
$$D_i(J(n, n_i)) = \begin{cases} 1 & \text{if } f(h - h_i)J(n, n_i) = \max_i f(h - h_i)J(n, n_i) \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

Model parameters

Supply $\Sigma(\cdot)$ **and demand** $\Delta(\cdot)$ **functions** (fundamental diagram)

Weight $f(\cdot)$ for the **desired direction** (here $x \mapsto 1 + \cos(x)$)





Simulation of the model

- Each cell with at least one pedestrian has an **exponential clock**

$$T_0 = t + \mathcal{E}(b) \tag{4}$$

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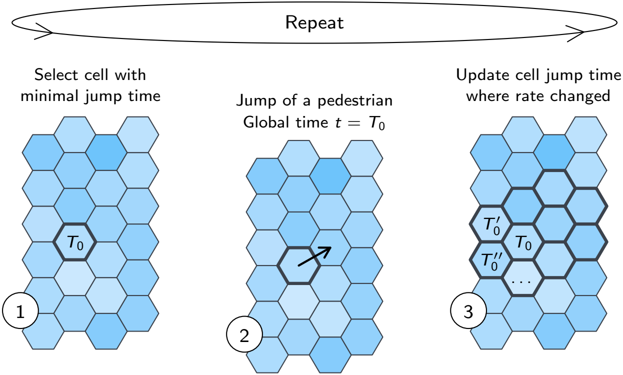
- **Event-based simulation in continuous time** by taking successive minimum jump times :

  Step 1. Select the cell with minimal jump time
  Step 2. Set time to selected cell jump time / Do the jump
  Step 3. Update jump times of the cells where jump rate b changed
  Step 4. Return to step 1

Simulation of the model



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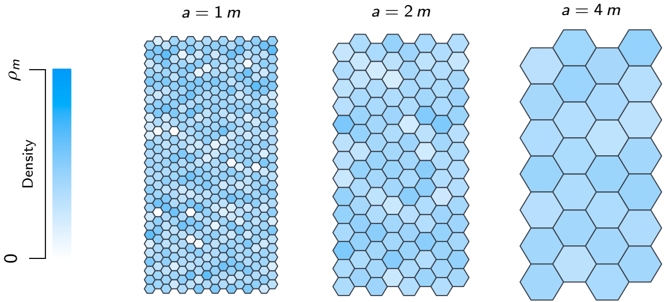
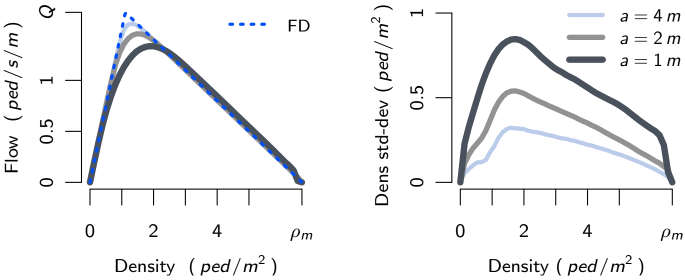
Simulation of uni-directional flows

Snapshots in stationary state according to a



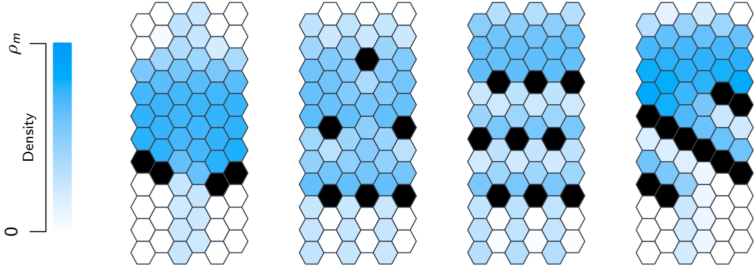
Simulation of uni-directional flows

Fundamental diagram in stationary state according to a



Presence of obstacles

Mean performances in stationary state



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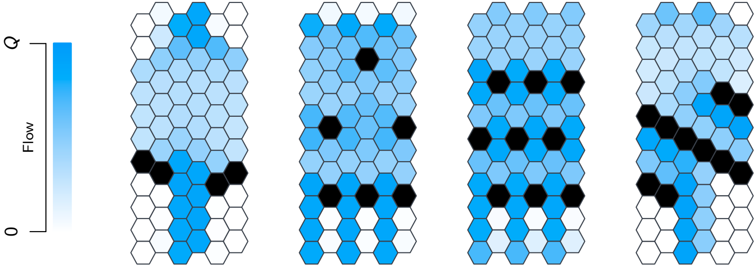

Multi-directional flow model

- $d \in \mathbb{N}^\star$ **possible desired directions** $(h_1, h_2, \dots h_d)$

→ System described by pedestrian numbers by direction $(n^{h_1}, \dots n^{h_d})$

Proportion of pedestrians by direction

$$p^h = \frac{n^h}{\sum_h n^h} \tag{5}$$

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- **Jump rate for the pedestrians with direction** h to cell i:

$$b_i^h(n, n_i) = p^h \times b_i(n, n_i) \tag{6}$$

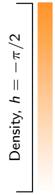
Proportion p^h of total flow affected to pedestrians with direction h

Uni-directional model if only one direction exists ($p^h = 1$)

Counter flows

Random initial condition

$\rho = 2.5\ ped/m^2 \qquad a = 2.5\ m$



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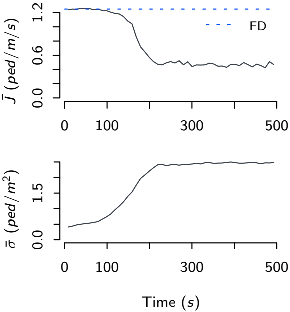

Multi-directional flow model (2)

♦ **Total flow bounded** by the proportion by direction to model **frictions for pedestrians with different directions**

$$J(n, n_i) \to J^h(n, n_i) = \min\{\, \tilde{p}_i^h Q,\ J(n, n_i)\,\} \tag{7}$$

with $\tilde{p}^h = p_0 + (1 - p_0)p^h$ and new parameter $p_0 \in [0, 1]$

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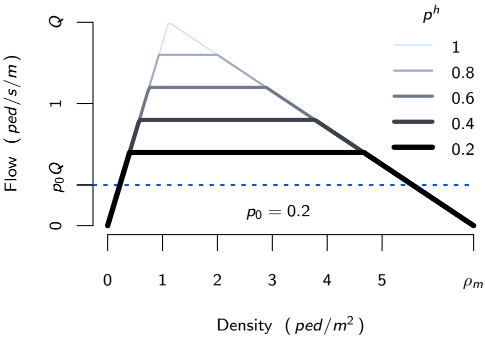
> Same model as previous one if $p_0 = 1$ ($J^h = J$ for all h)
> If $p_0 = 0$, then $\tilde{p}^h = p^h$: the jump rates to cells that do not contain any pedestrian with the same direction are nil

Bounded fundamental diagram



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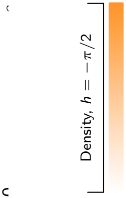

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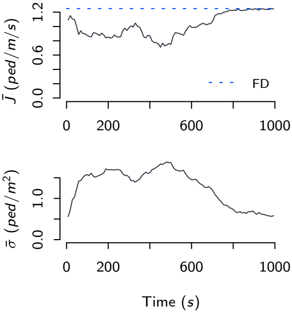

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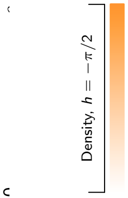

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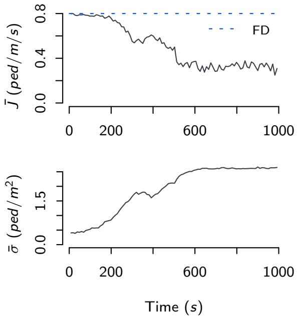

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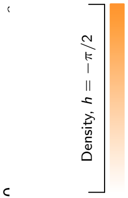

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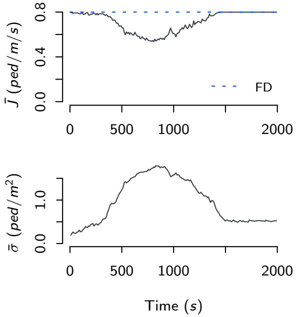

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Performances in stationary state[5]

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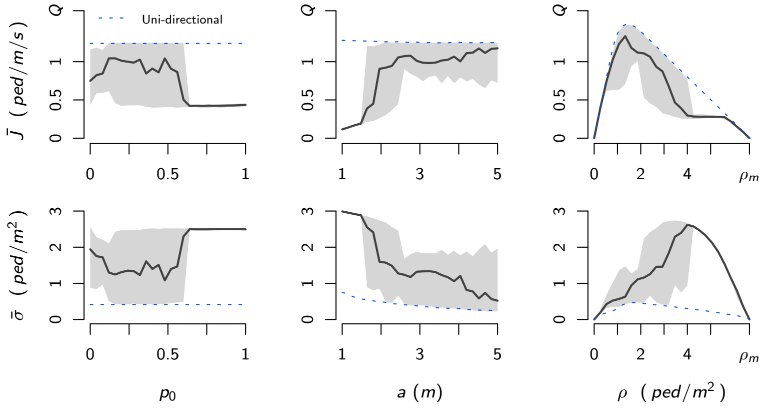

[5] 50 experiments per parameter value; Line: mean value; Grey area: Min-max interval

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Summary

- Stochastic pedestrian model in 2D with 5 parameters:

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Density (and flow) bounded between zero and given maximum value

Unique stationary distribution / Easy and fast to simulate

Description of **realistic fundamental diagrams, congestion/rarefaction** and **lane formation** for large cells (i.e. low variability – *Freezing by Heating effect*)

Working perspectives

♦ **Comparison to classical microscopic (force-based) and macroscopic (CTM or queuing models) approaches**

$\rightarrow$ Complexity, realism level, described phenomena

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→ Potential application scales and limits of the model

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- **Model to understand $\rightsquigarrow$ Model to predict**

$\rightarrow$ Technical and strategic planning motion modelling + other mechanisms

$\rightarrow$ Large-scale simulation of pedestrian dynamics