Social Distance Model Based Risk Assessment of Spatial Configuration on COVID-19 Transmission

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T-ARCH

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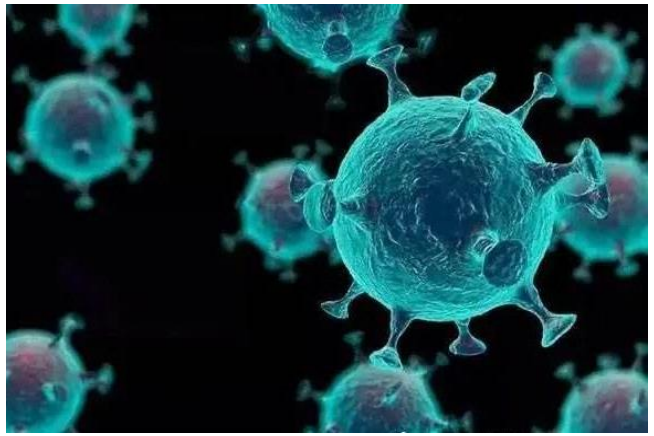
PART 1

Background

Background COVID-19

COVID-19 global prevailing



- As of June 2021, more than 230 countries and regions were recorded over 1.6 hundred million Coronavirus disease 19 (COVID-19) confirmed cases and almost 3.4 million deaths

Social distancing Effective measures

- Milne et al. found that when social contact decreased by 70%, the infection rate decreased from 66% to 1%;
- Based on SEIRS model, Huang et al. found that 50% isolation degree in long-term social distancing is the turning point to control the transmission of the epidemic.

epidemic prevention regularly

- **From top to down:** Many countries have implemented population-level physical distancing measures and movement restrictions such as business closure, community lockdown, and large-scale public gatherings cancellation
- **From down to top:** People stay at home, wear masks, change their travel mode. But lack efficient and accurate travel strategy.

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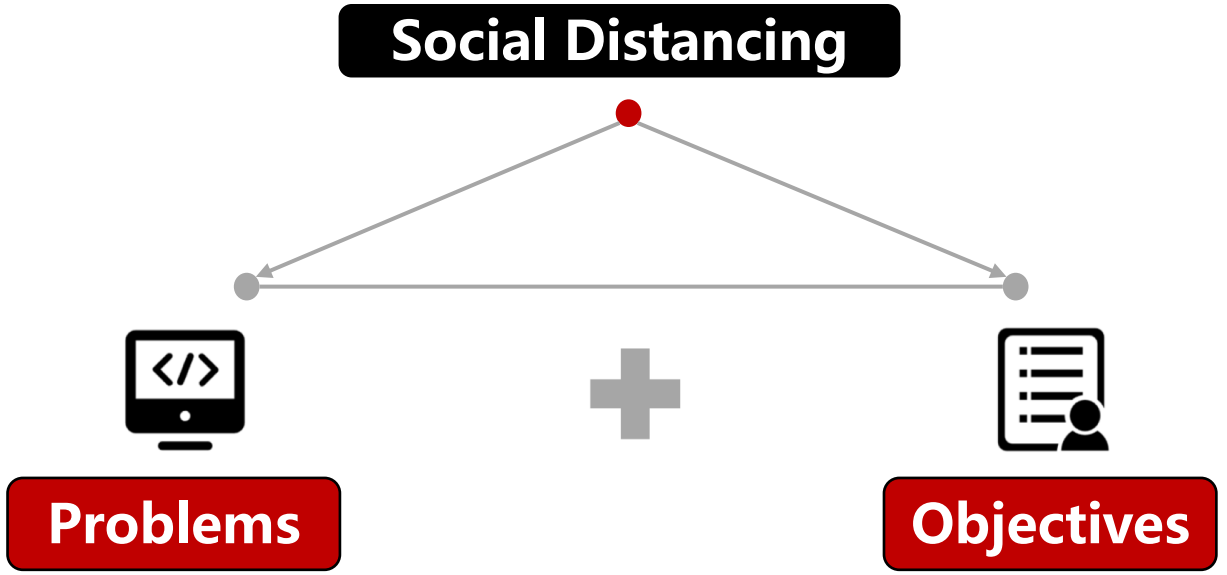
PART 2

Literature Review

Literature Review Problems and Objectives



- How to simulate social distancing motion?
- What spatial factors influence social distancing?

- Develop a systematic simulation-based approach through integrating pedestrian dynamics with a modified susceptible-exposed-infectious model.

Literature Review Related Works

- According to the multidisciplinary features, existing works can be categorized into two main aspects, epidemiology and pedestrian dynamics.

Epidemiology

SIR	• Carli R et al. combined nonlinear model predictive control and improved SIR Model to support the government to determine the most effective strategy in the multiregional mitigation.
SEIRS	• Based on SEIRS model, Huang et al simulated the epidemic situation of 4 countries and found that 50% isolation in long-term social distancing is the turning point to control the transmission of the epidemic.
CFRD	• Yu et al. Based on the computational fluid particle dynamics model simulation, confirmed the validity of wearing masks in public places;

Weakness

- Population remains constant, but the volume of pedestrians in real is variable
- Fails to observe actual infections because not considered human interactions in crowds

pedestrian dynamics

Agent Based	• Zhao et al. analyzed the agent simulation data through spatial clustering algorithm, which helps to reveal the spread of the epidemic situation and plays a positive role in the monitoring and prevention of epidemics.
AI	• Based on reinforcement learning, Fang et al. established the interaction model between individual and environment to simulate the development process of covid-19 epidemic without intervention and with intervention respectively
Force	• Namilae et al. have formulated a SFM based multiscale model to study the Ebola transmission within airplanes, the results of which guide boarding and deplaning policies on the geospatial spread of infectious diseases.

Weakness

- Few attentions have been paid to the social distancing dynamics.
- Self-organization phenomena were not mainly considered in pedestrian dynamics

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PART 3

Modeling Methodology

Modeling Methodology The Social Force Model

■ Advantages

Qualitative +

Collective effects

qualitatively describe the phenomenon of crowd dynamics

Force model +

Continuous simulation

move continuously by defining some forces

Interaction +

psychology & social interaction

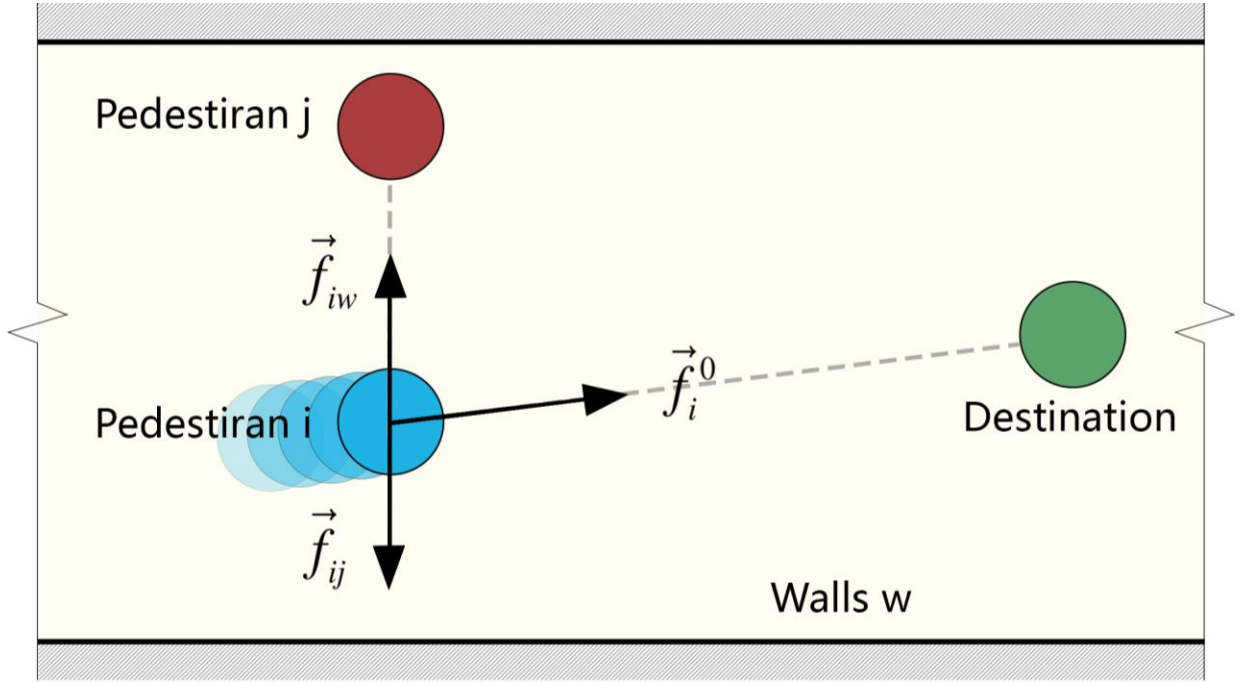
considering physical and motivational forces

this study chooses the social force model as the basic to study the social distancing dynamic.

Social Force Model Basic Concepts

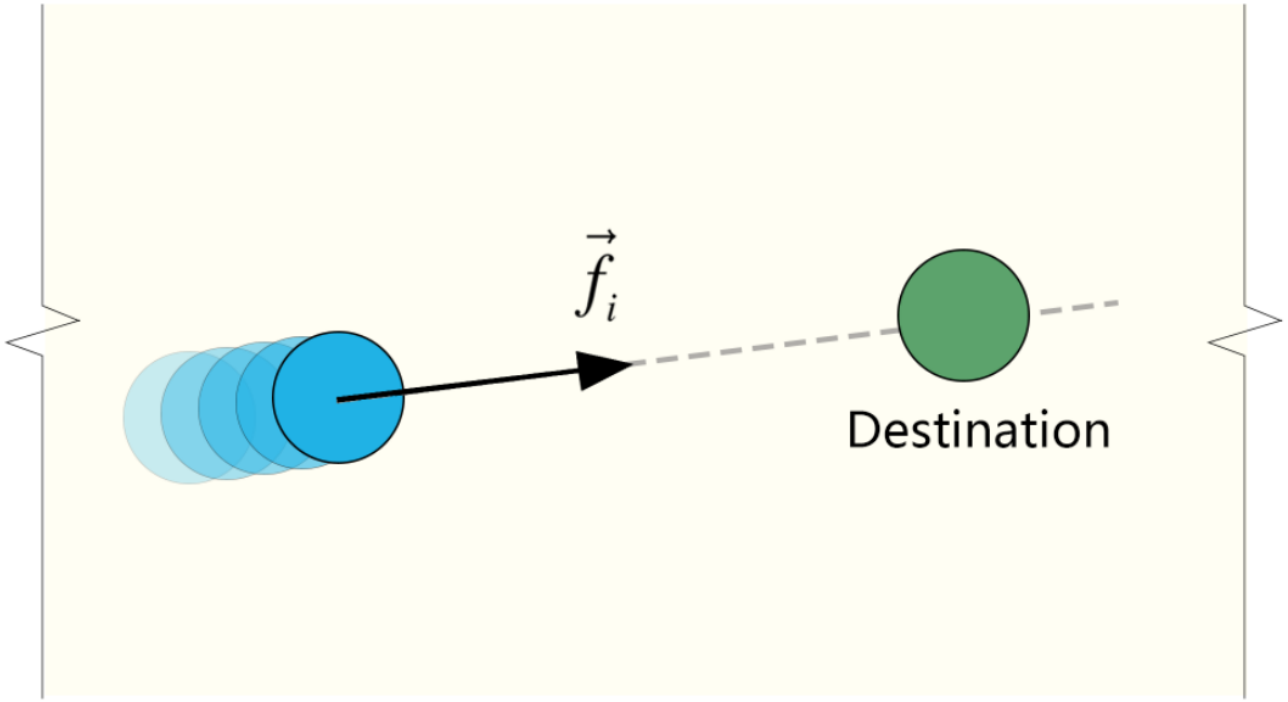
The conception of “social force” was introduced to keep reasonable distances among individuals. The social force model is proposed by Helbing and Molnár in 1995, where the pedestrians were driven by three forces:

desired force $\vec{f}_i$, interaction force between pedestrians $\vec{f}_{ij}$, interaction force between pedestrian and walls $\vec{f}_{iW}$



$$\vec{F}_i = \vec{f}_i + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_{W} \vec{f}_{iW}$$

Social Force Model desired force



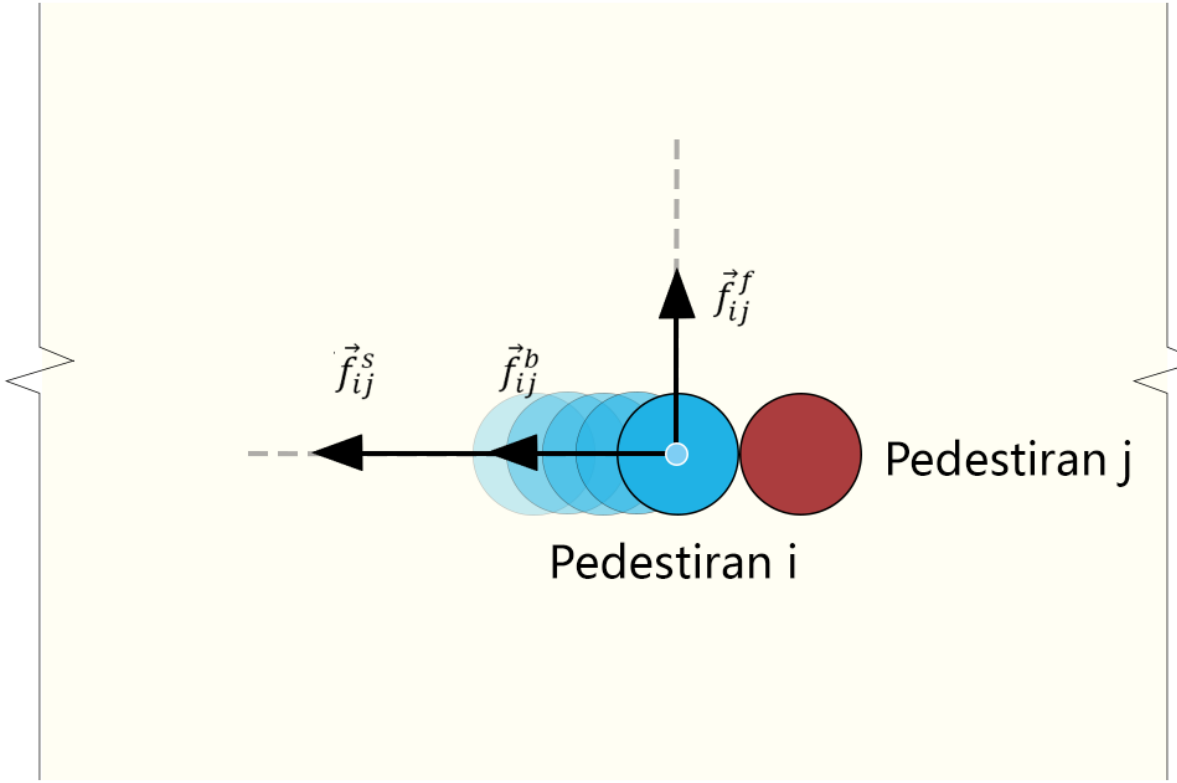
Newton's second law: $\vec{F} = m\vec{a}$

Acceleration Formula: $\vec{a} = \frac{\Delta v}{\Delta t}$

$$\vec{f}_i = m_i \frac{\left(v_i^0(t)\vec{e}_i^0(t) - \vec{v}_i(t)\right)}{\tau}$$

pedestrians i of mass m_i likes to move with a certain desired speed v_i^0 in a certain direction e_i^0 , and therefore tends to correspondingly adapt the actual velocity v_i with a relax time τ_i

Social Force Model interaction between pedestrians

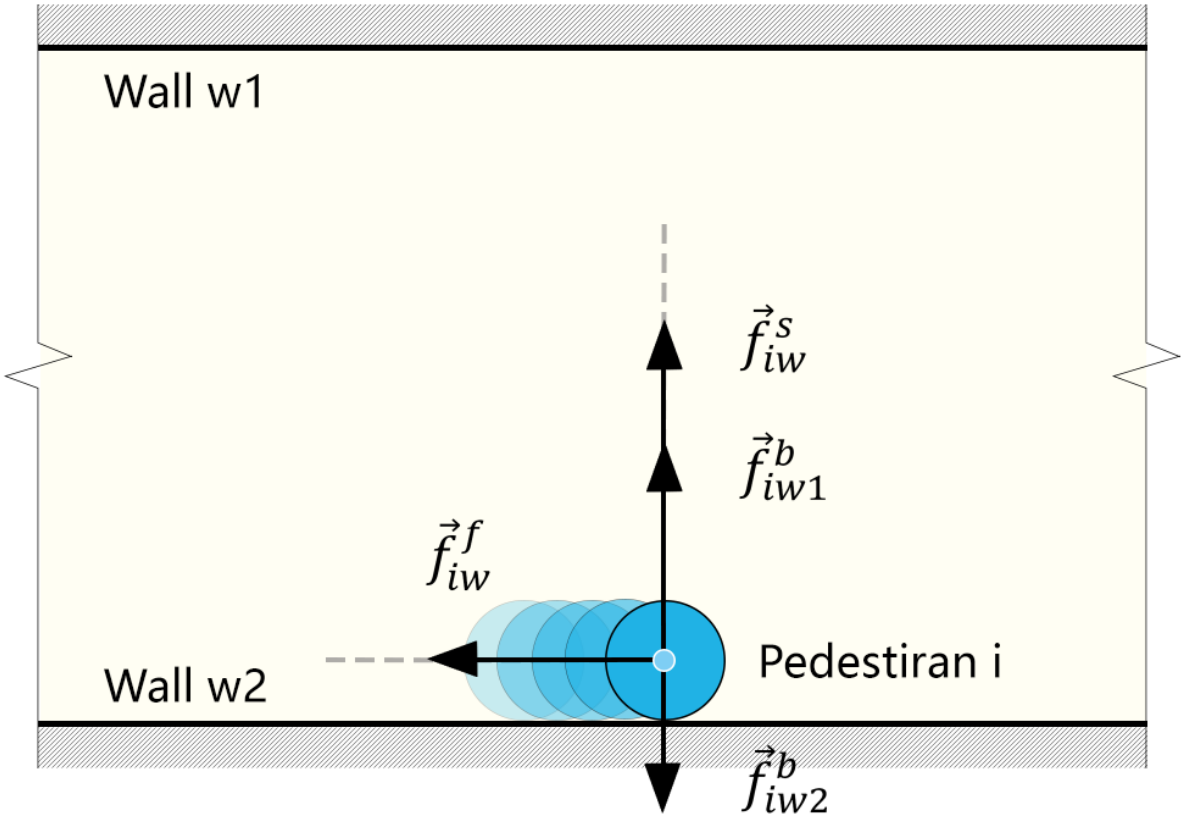


$$\vec{f}_{ij} = \vec{f}_{ij}^{\,s} + \vec{f}_{ij}^{\,b} + \vec{f}_{ij}^{\,f}$$

$$\begin{cases} \vec{f}_{ij}^{\,s} = A_i \exp\left[\left(r_{ij} - d_{ij}\right)/B_i\right]\vec{n}_{ij} \\ \vec{f}_{ij}^{\,b} = kg(r_{ij} - d_{ij})\vec{n}_{ij} \\ \vec{f}_{ij}^{\,f} = \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^{t}\,\vec{t}_{ij} \end{cases}$$

Including repulsive interaction force ($\vec{f}_{ij}^{\,s}$), body force ($\vec{f}_{ij}^{\,b}$), sliding friction force ($\vec{f}_{ij}^{\,f}$). A_i interaction strength, B_i interaction range. $d_{ij} = \|\vec{r}_i - \vec{r}_j\|$ is the normalized vector pointing from pedestrian j to i. $r_{ij} = (r_i + r_j)$ the sum pedestrian radii.

Social Force Model interaction between pedestrian and walls



$$\vec{f}_{iW} = \vec{f}_{iw}^{s} + \vec{f}_{iw}^{b} - \vec{f}_{iw}^{f}$$

$$\begin{cases} \vec{f}_{iw}^{s} = A_i \, exp\left[\left(r_{ij} - d_{iW}\right)/B_i\right]\vec{n}_{iW} \\ \vec{f}_{iw}^{b} = kg(r_i - d_{iW})\vec{n}_{iW} \\ \vec{f}_{iw}^{f} = \kappa g(r_i - d_{iW})(\vec{v}_i \cdot \vec{t}_{iW})\vec{t}_{iW} \end{cases}$$

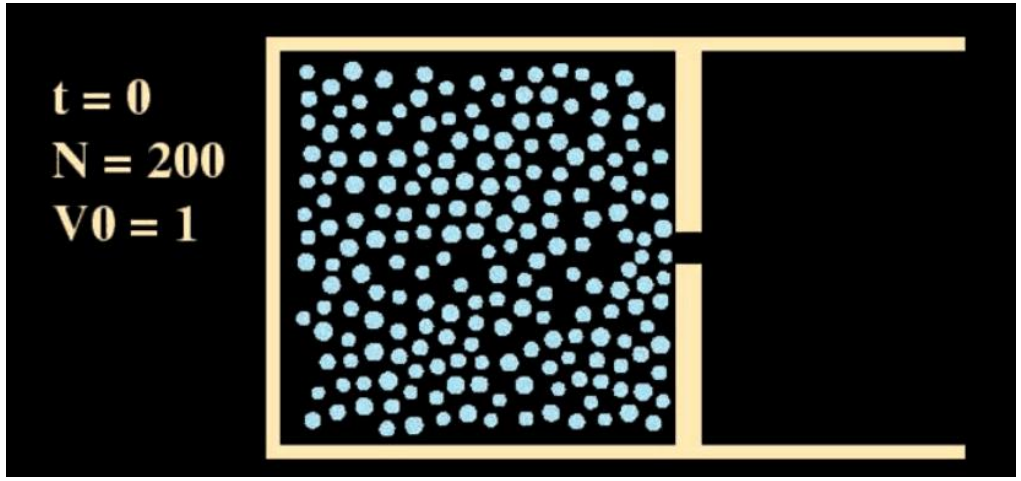
$$g(x) = \begin{cases} 0, & x < 0 \\ x, & \mathrm{x} \geq 0 \end{cases}$$

Similar to the interaction between pedestrians

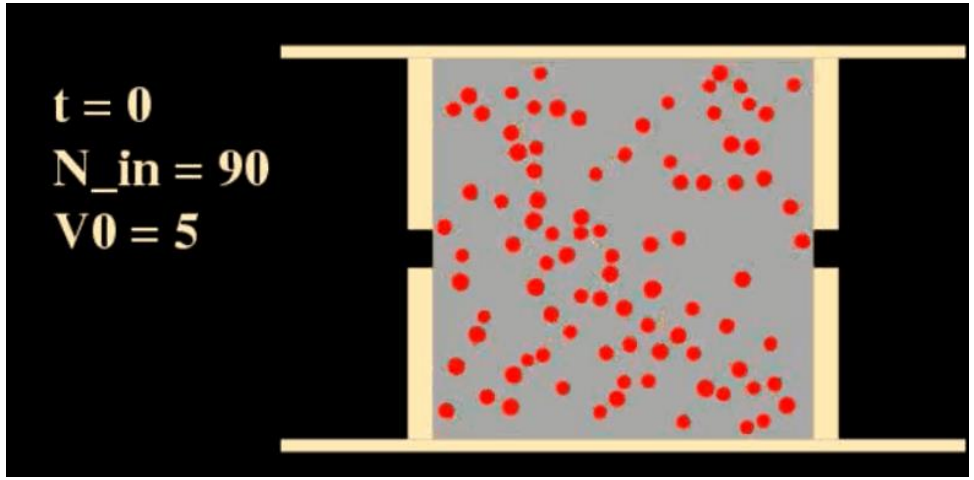
Social Force Model The Simulation Outcome

picture source:

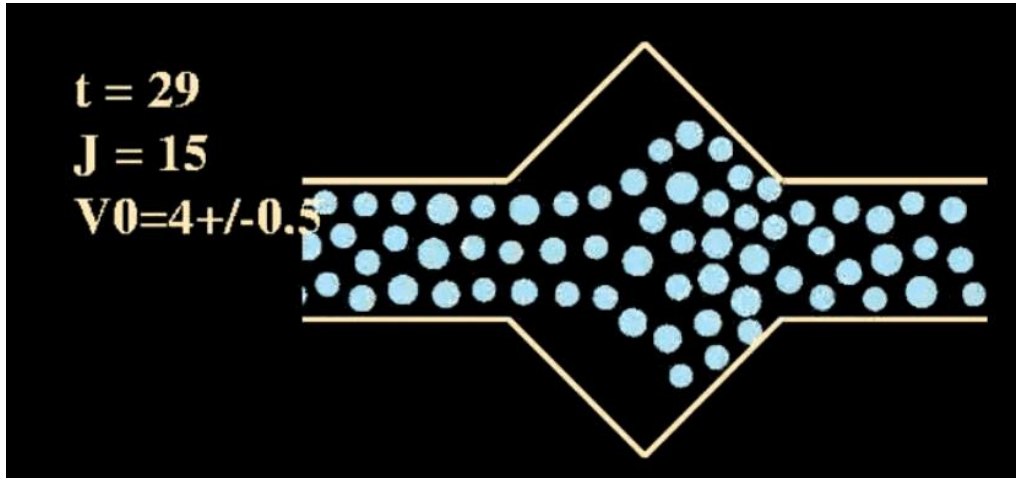
Helbing, D., I. Farkas, T. Vicsek. Simulation Dynamical Features of Escape Panic[J]. Nature, 2000(407): 487-490.



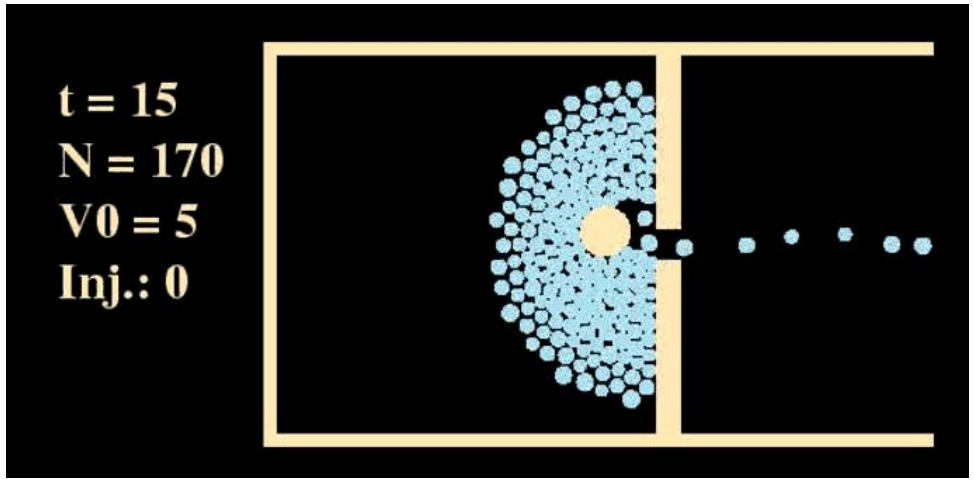
- Closed room



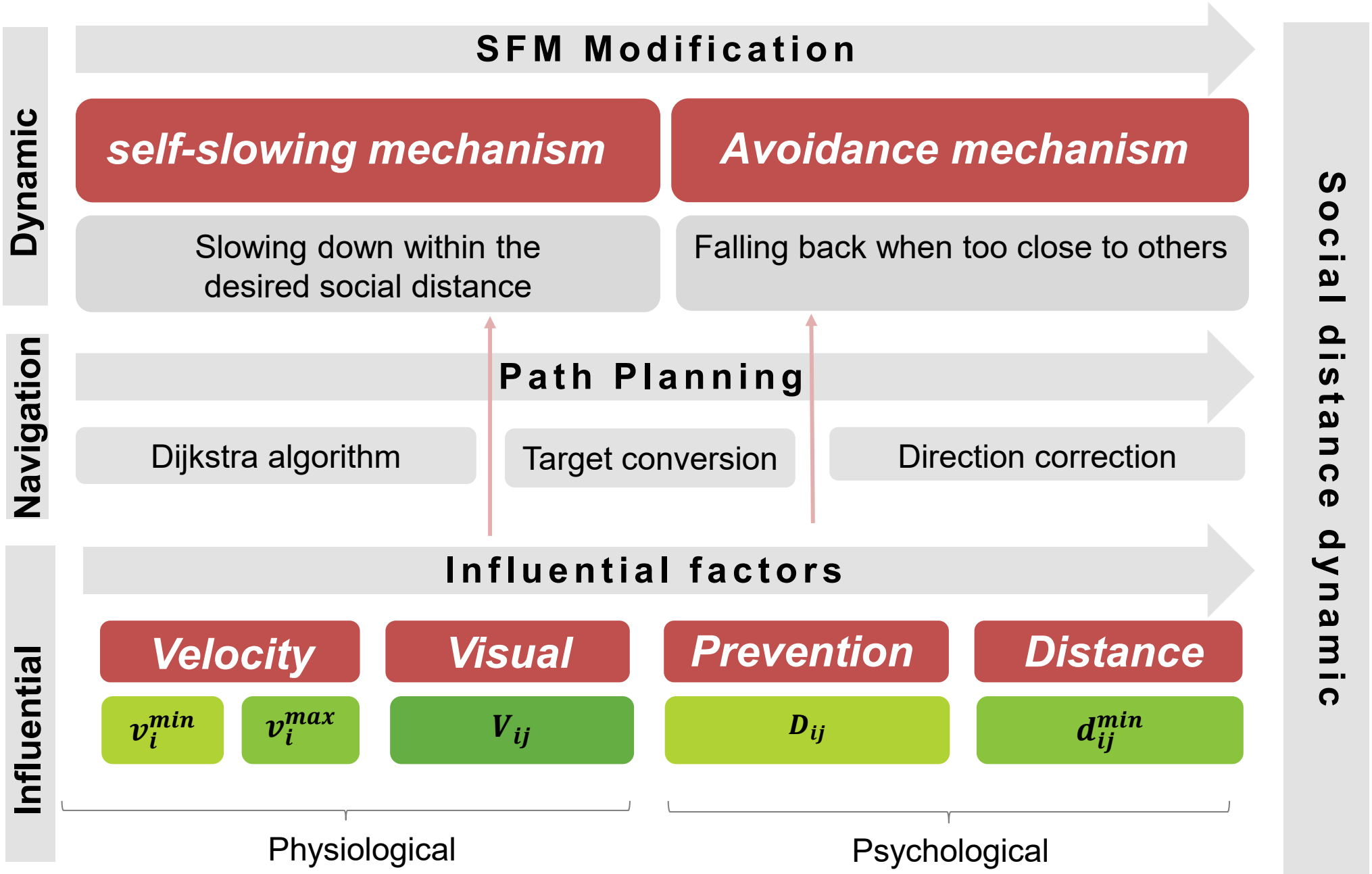
- smoke



- passageway



- obstacle



Velocity

v_i^{min} v_i^{max}

$$\vec{v}_i(t) = \vec{e}_i^{\,0} \begin{cases} v_i^{min}, & v_i \quad (t) < v_i^{min} \\ v_i(t), & v_i^{min} \le v_i \quad (t) \le v_i^{max} \\ v_i^{max}, & v_i \quad (t) > v_i^{max} \end{cases}$$

Visual

V_{ij}

$$V_{\alpha\beta} = arccos\left(\frac{\vec{v}_\alpha \cdot (x_\beta - x_\alpha, y_\beta - y_\alpha)}{\|\vec{v}_\alpha\| \sqrt{(x_\beta - x_\alpha)^2 + (y_\beta - y_\alpha)^2}}\right)$$

Prevention

D_{ij}

$$D_{\alpha\beta} = (D_\alpha + D_\beta)/2$$

Distance

d_{ij}^{min}

$$d_{\alpha\beta}^{min} = min\{d_{\alpha\beta} - r_{\alpha\beta}; \beta \neq \alpha\}$$

$$d_{\alpha\beta} = \sqrt{(x_\beta - x_\alpha)^2 + (y_\beta - y_\alpha)^2}$$

$$r_{\alpha\beta} = r_\alpha + r_\beta$$

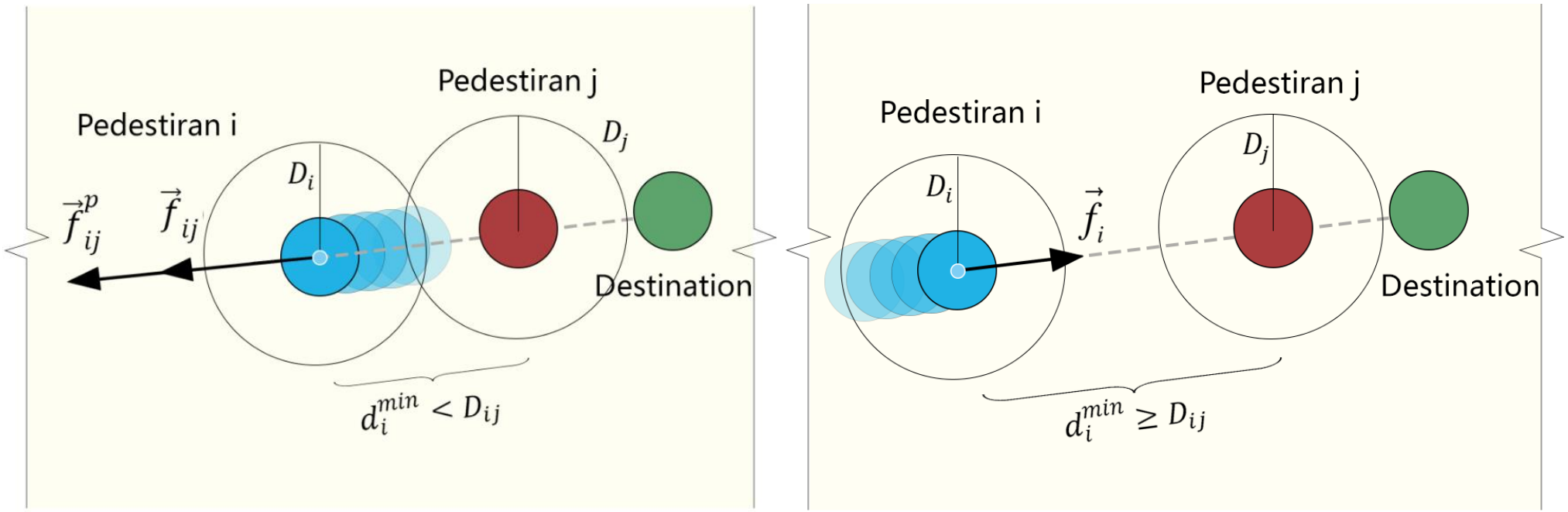
Social Distance Model desired force

■ Increasing distance dependence:

$$\vec{f}_i(\vec{v}_i) \qquad \vec{f}_i(\vec{v}_i, \vec{r}_i, \vec{r}_j^{\,i}) = \nabla_{\vec{r}_i} V_j(\|\vec{r}_i - \vec{r}_j^{\,i}\|)$$

Deceleration movement with the desired speed of 0

expressed as a potential V_j monotonically increasing with distance



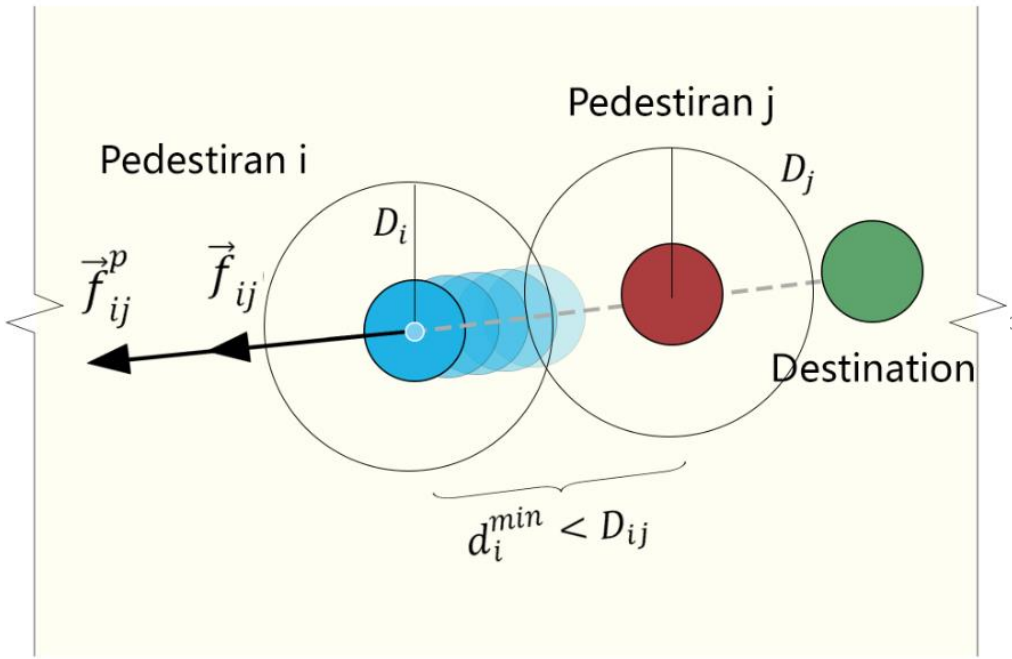
Social Force Model interaction between pedestrians

■ Increase social distance repulsion:

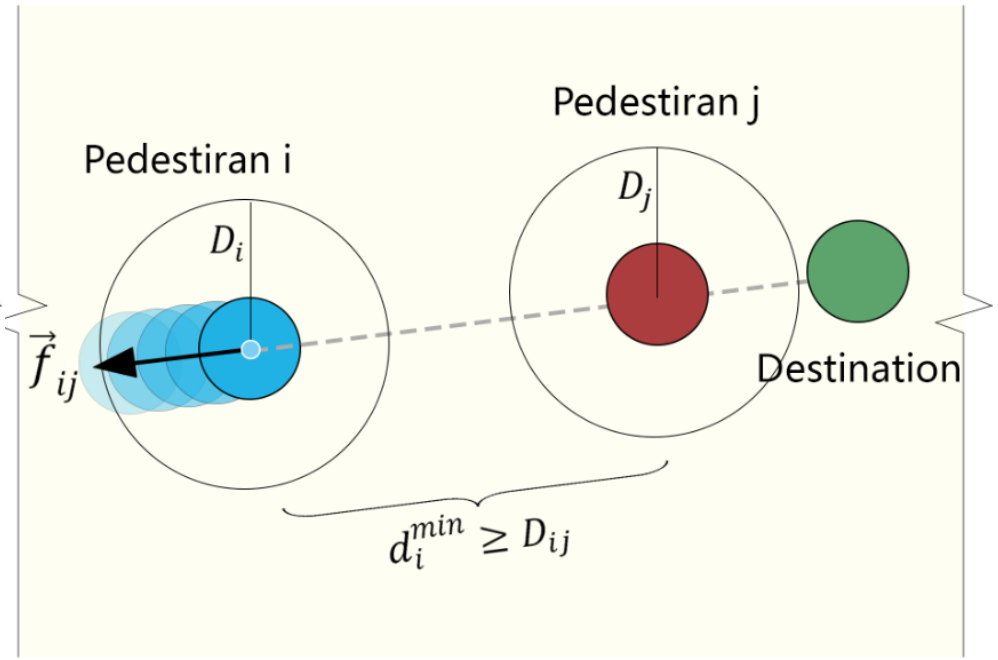
$$\vec{f}_{ij}(t)' = \sum_{j(\neq i)} \vec{f}_{ij}(t) + \vec{f}^{p}_{ij}(t)$$

$$\vec{f}_{ij}(t)' = \sum_{j(\neq i)} \vec{f}_{ij}(t)$$

Repulsive force from pedestrian j to i



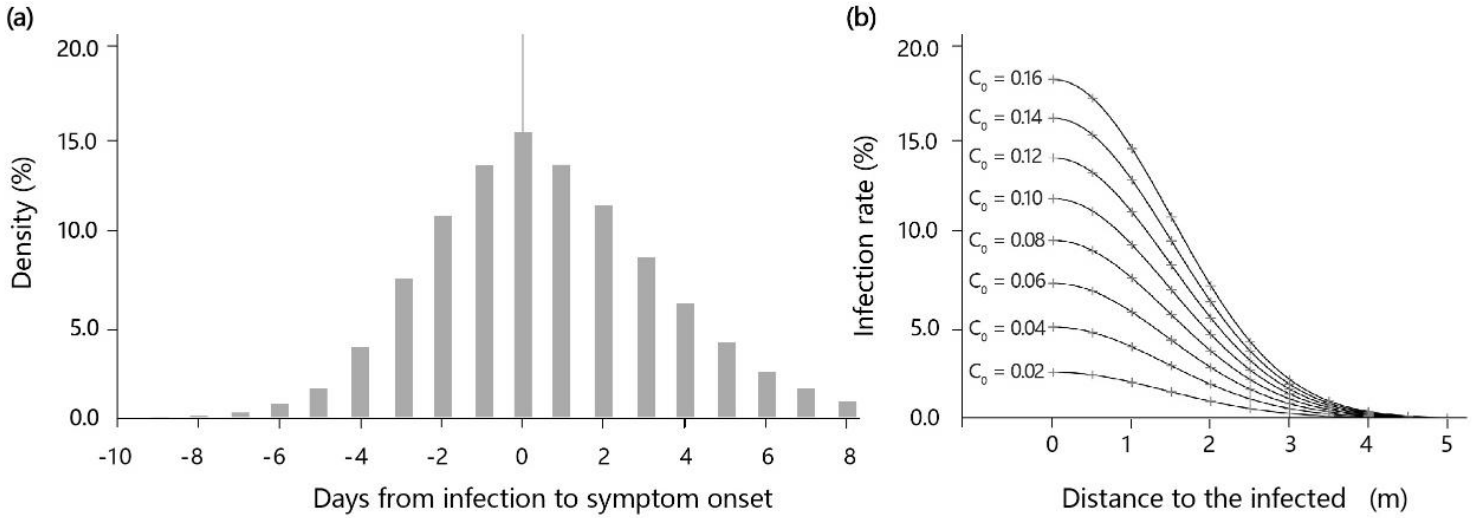
No repulsive force



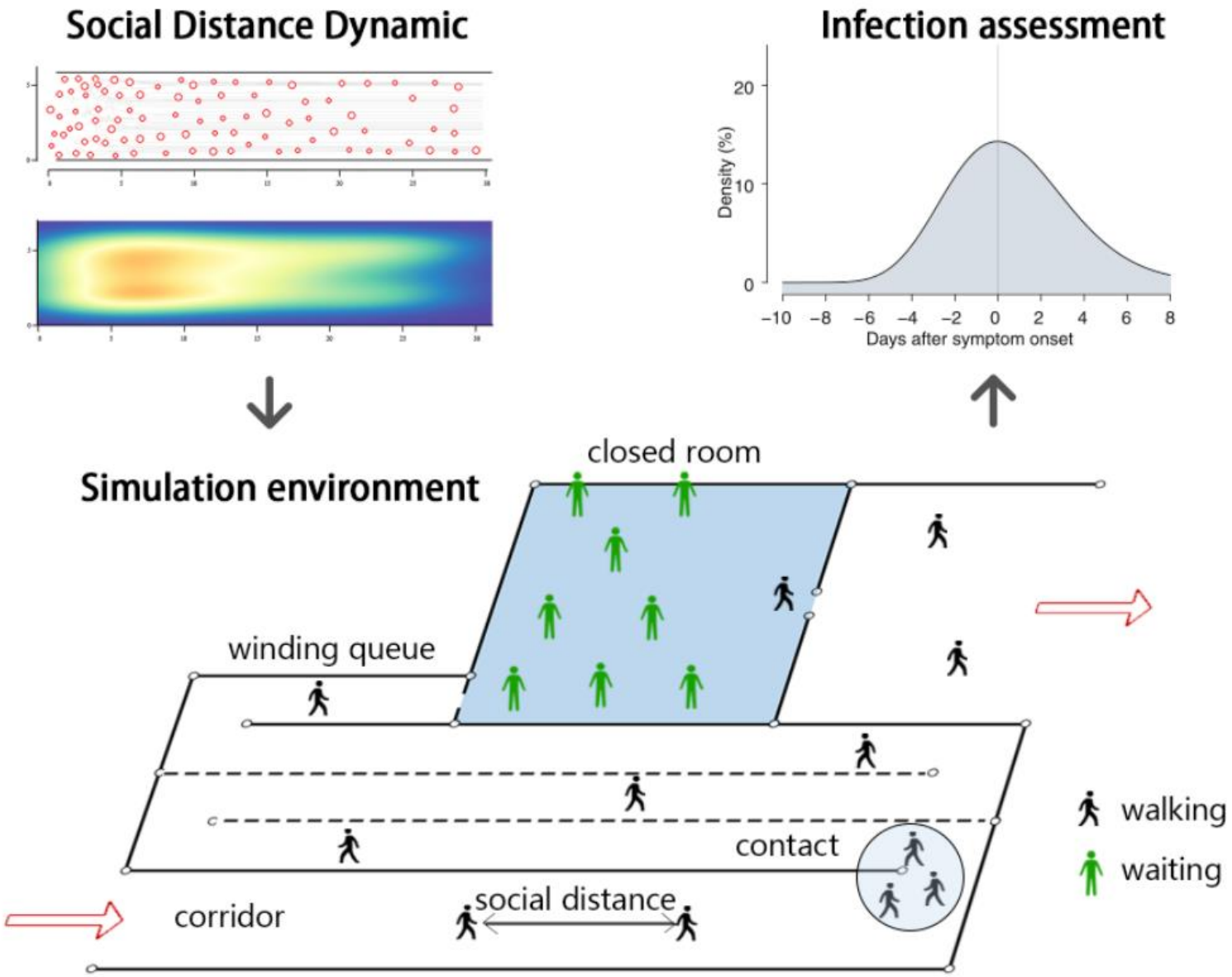
Social Force Model Infection Assessment

- denote by C_n the quanta of contaminants of aerosols that a pedestrian contact in a breathing cycle with adjustment coefficient γ. Then the probability for infection p is given by a Poisson distribution：

$$p = 1 - e^{-\gamma C_n}$$



Social Force Model Pattern diagram



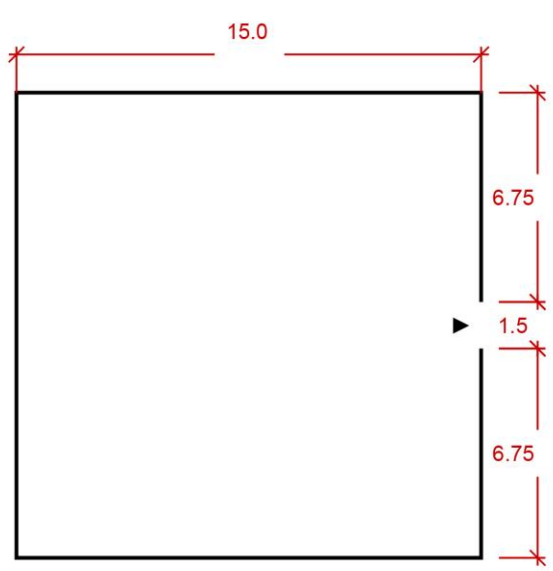
PART 4

Computer Simulation and Observations

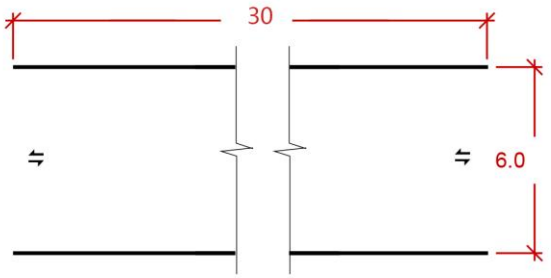
Computer Simulation environment

■ Simulation environment

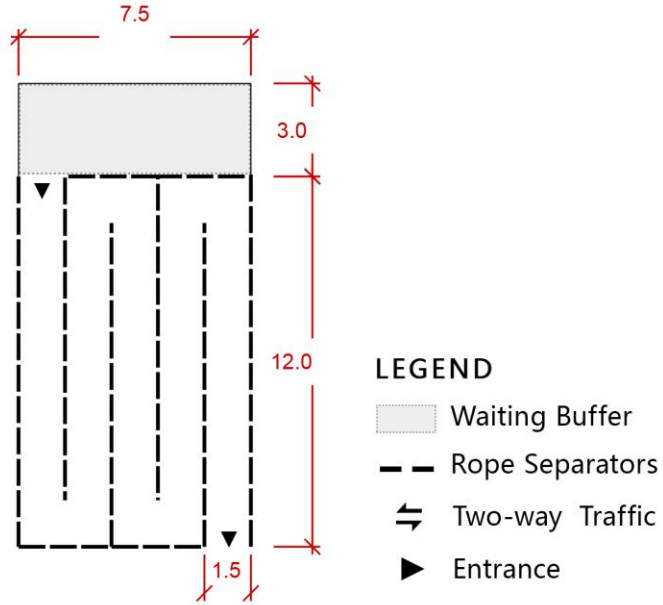
To verify the utility of the social distance model under the epidemic situation, we designed three pedestrian activity scenarios as follows



Closed Room



Corridor



Winding Queue

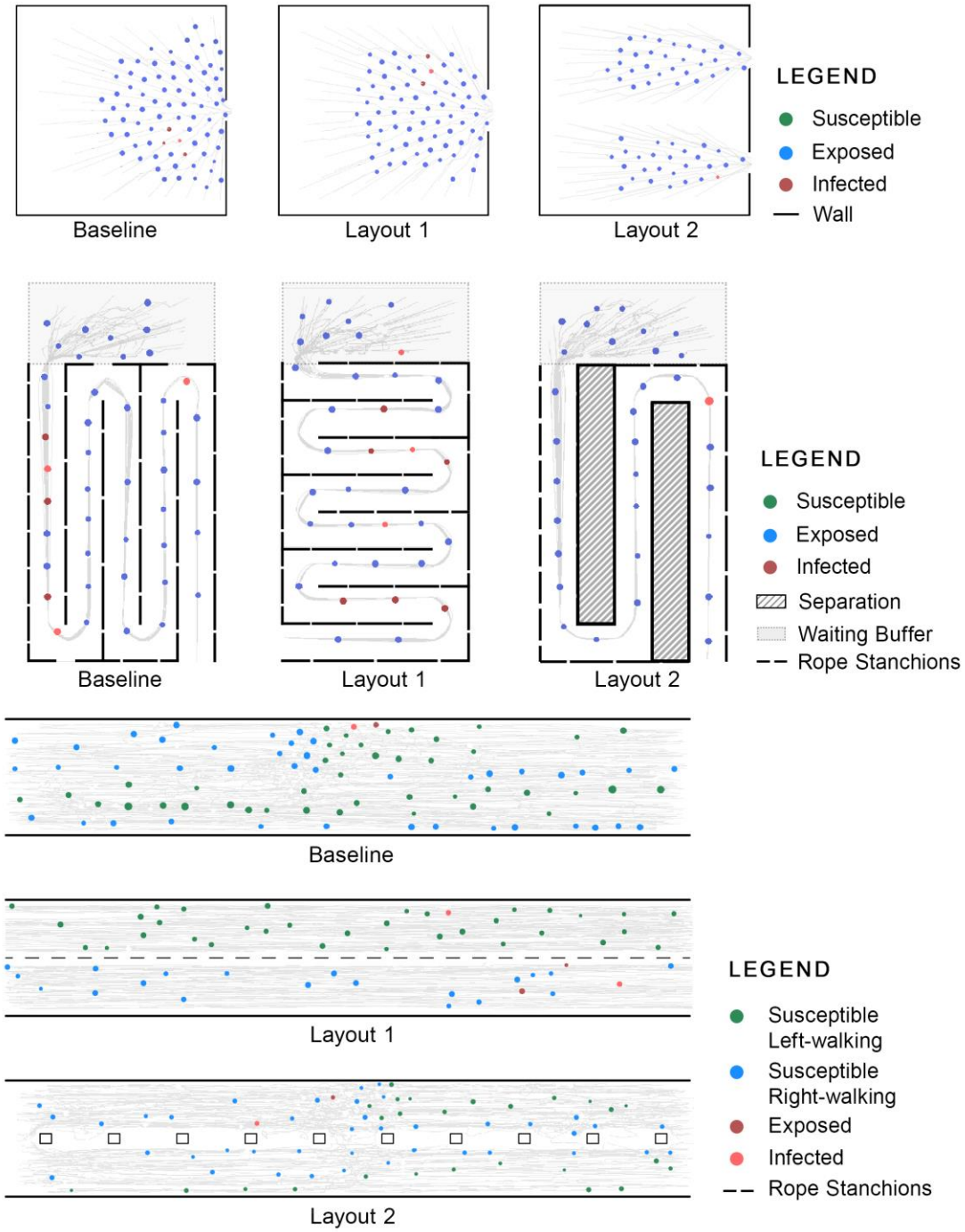
The mean number of new infections and average contact number are two essential measures to assess performance of different space management.

Closed room：Altering the exit width to 3-m-wide (layout 1) and the number of exits to two 1.5-m-wide (layout 2).

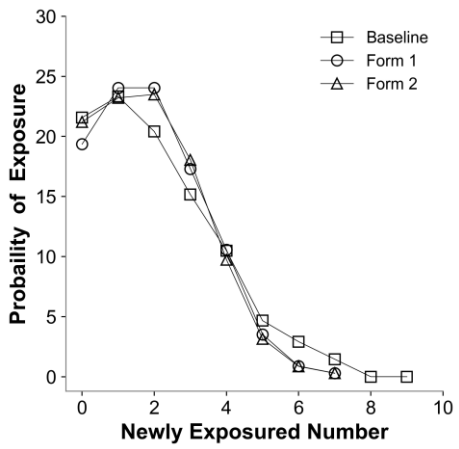
Winding queue：Horizontal queue (layout 1) and queue with sideward separations (layout 2).

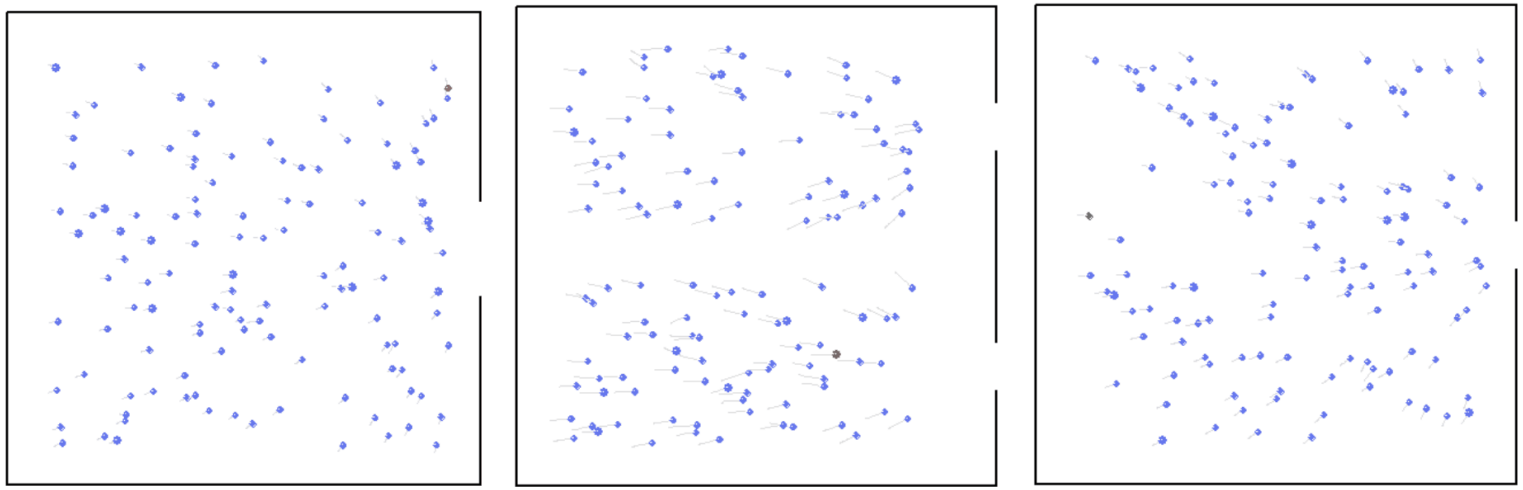
Corridor: A series of columns in the middle (layout 1) and unbridgeable railings in the middle (layout 2).

■ Comparative experiments

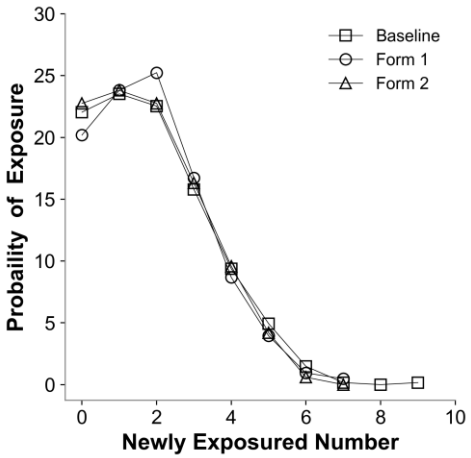


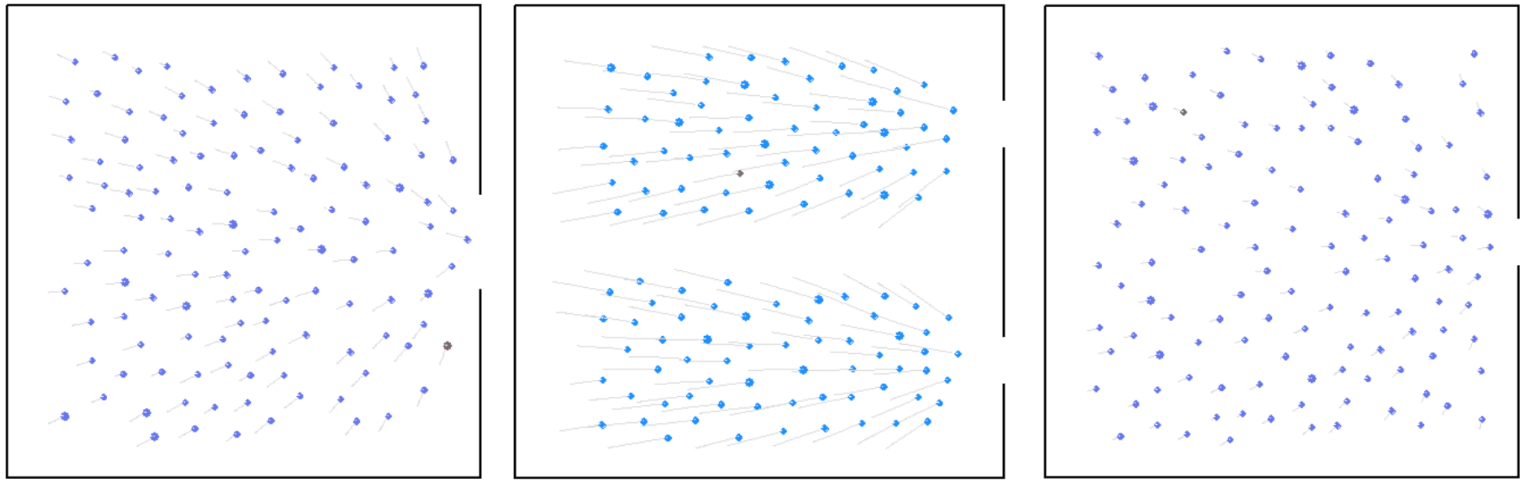
■ Closed room





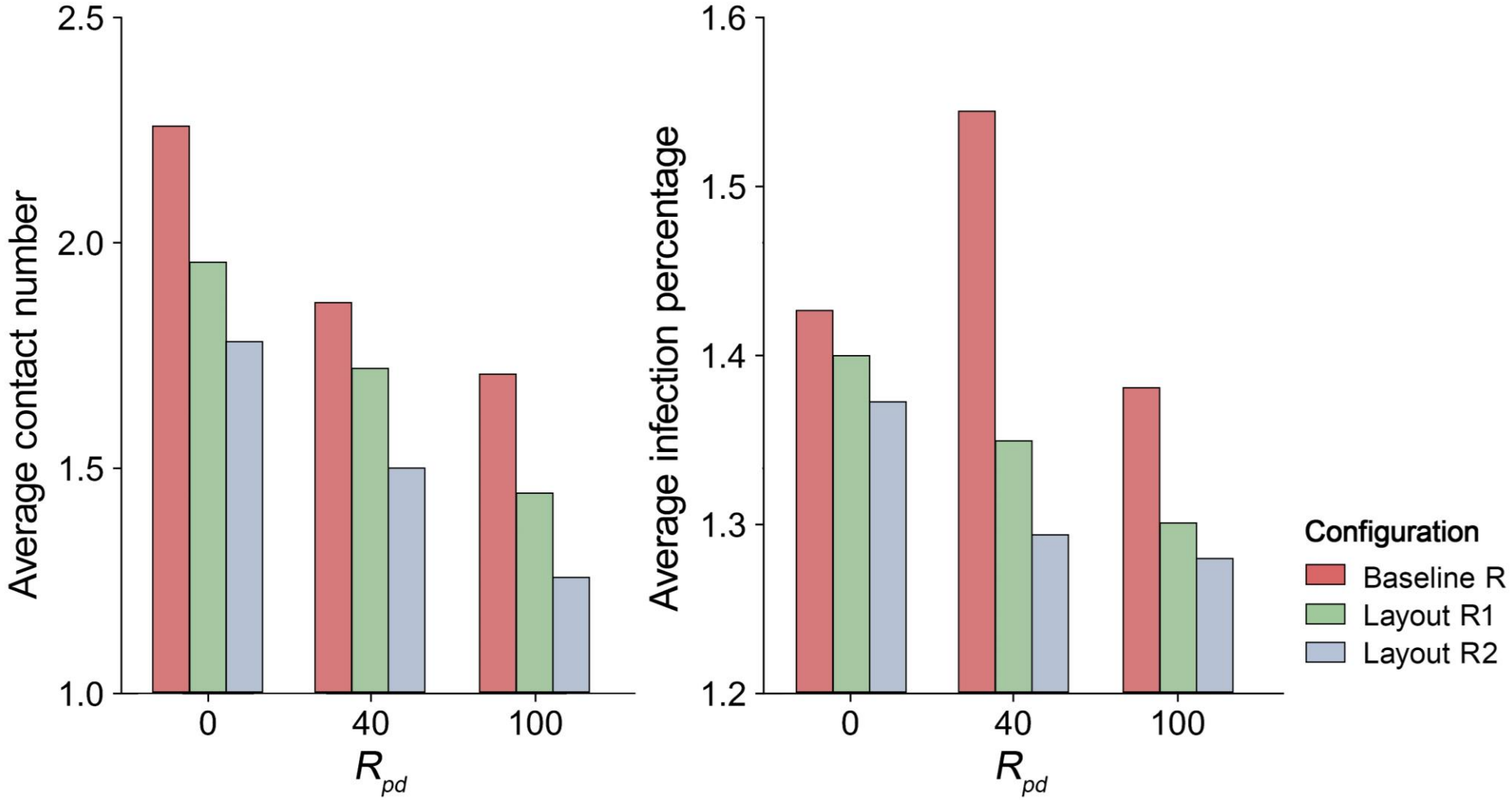
Social distance rate = 0%



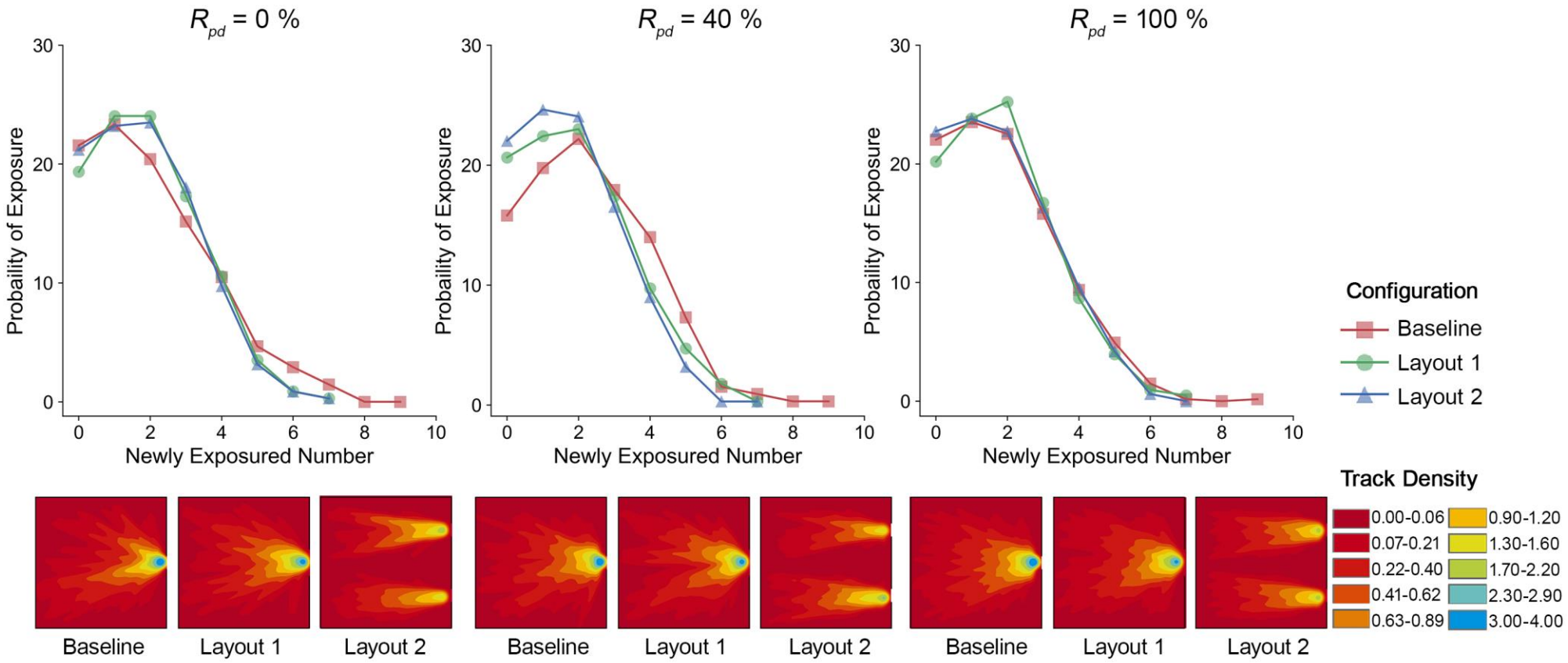


Social distance rate = 100%

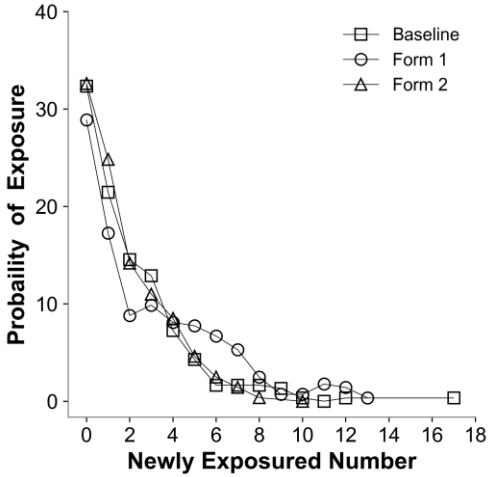
■ Closed room



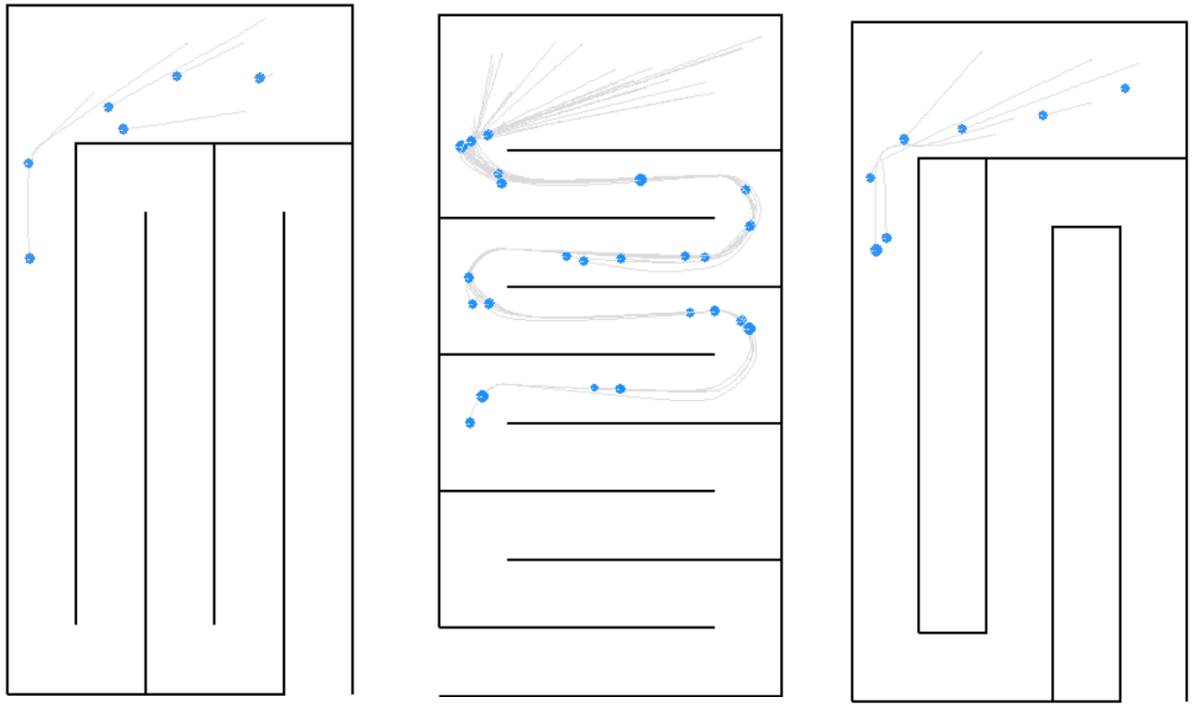
■ Closed room

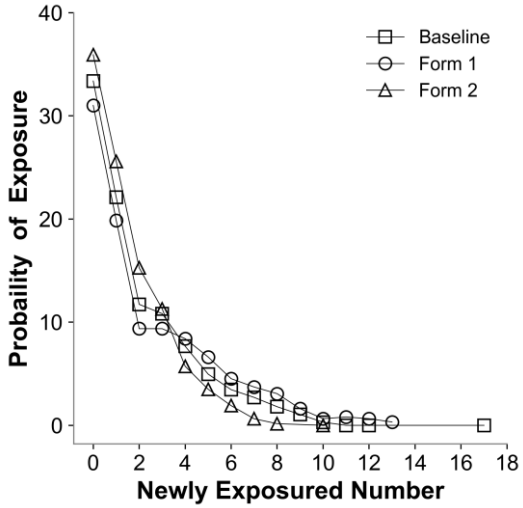


■ Winding queue

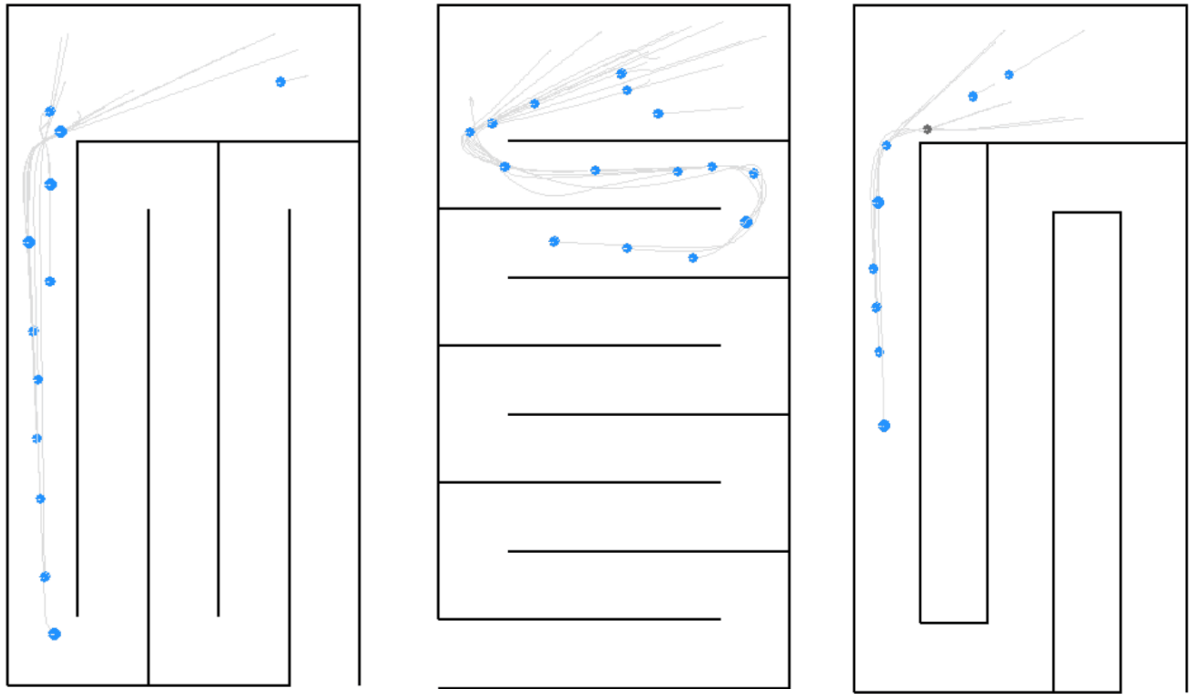


Social distance rate = 0%

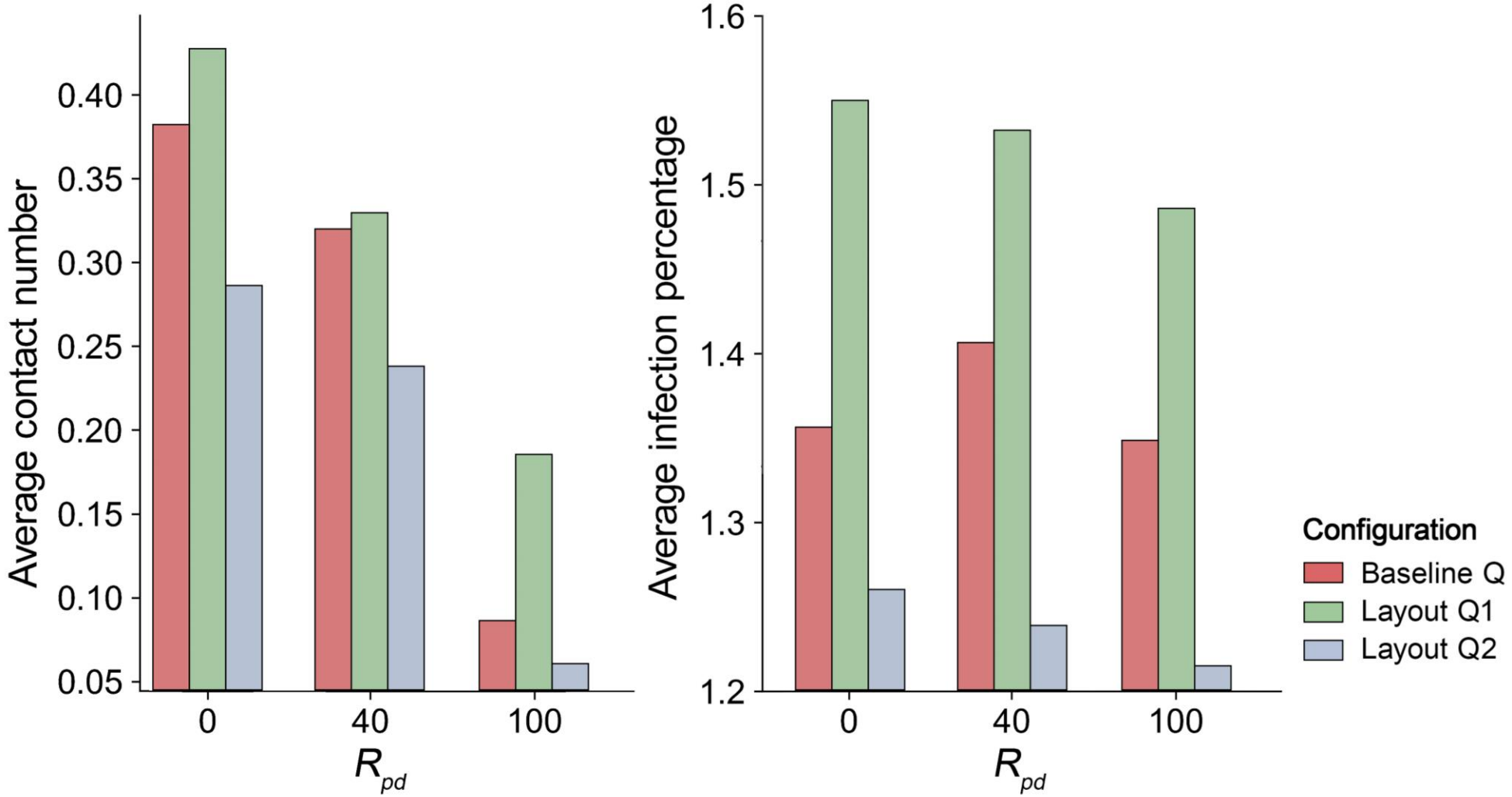




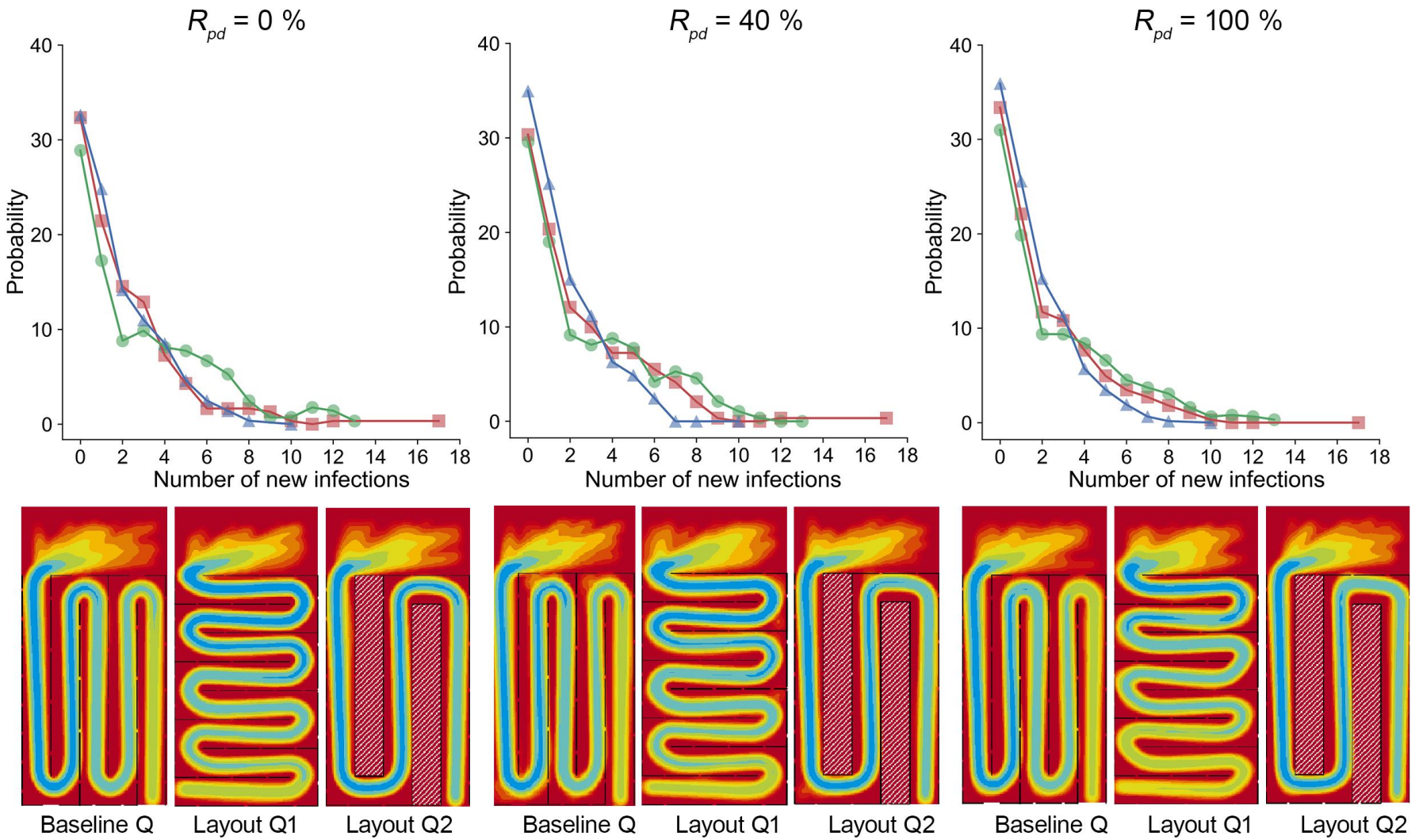
Social distance rate = 100%



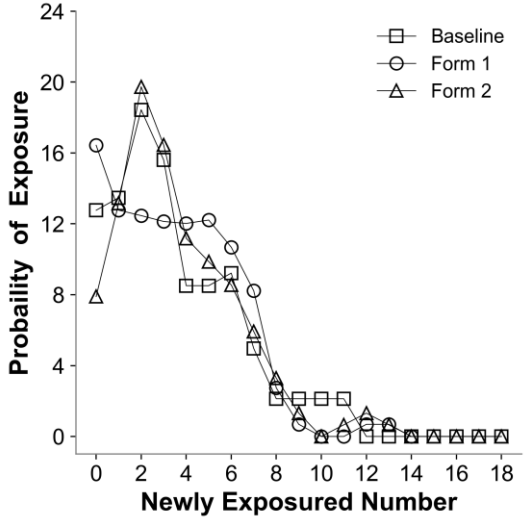
■ Winding queue



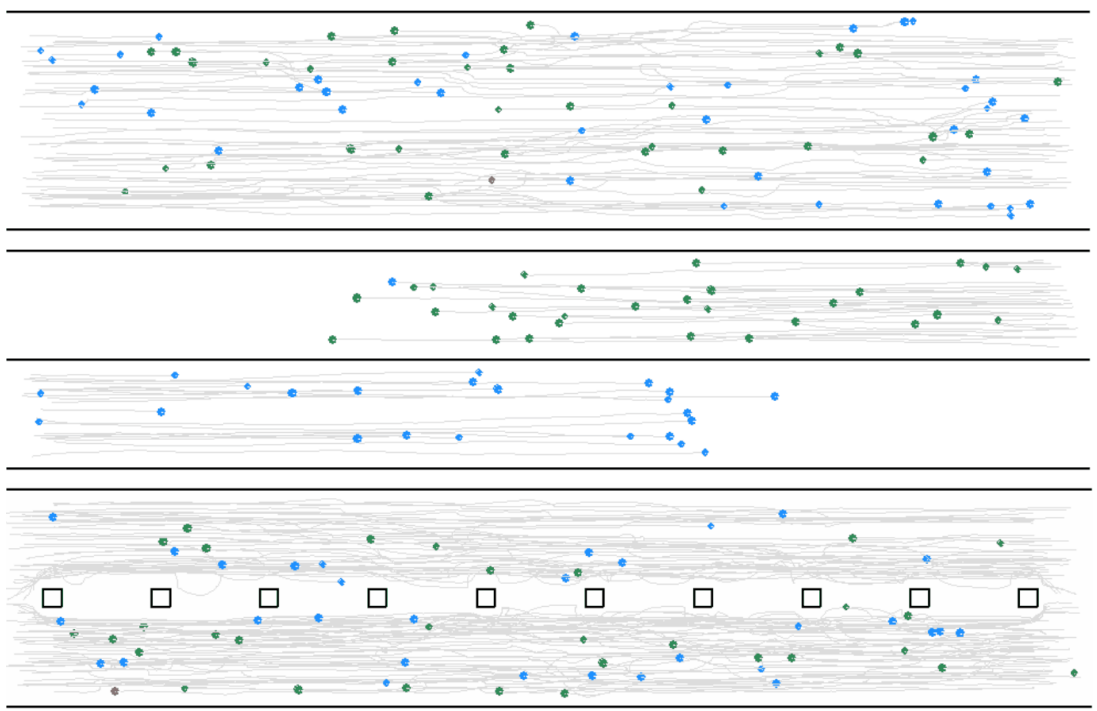
Winding queue

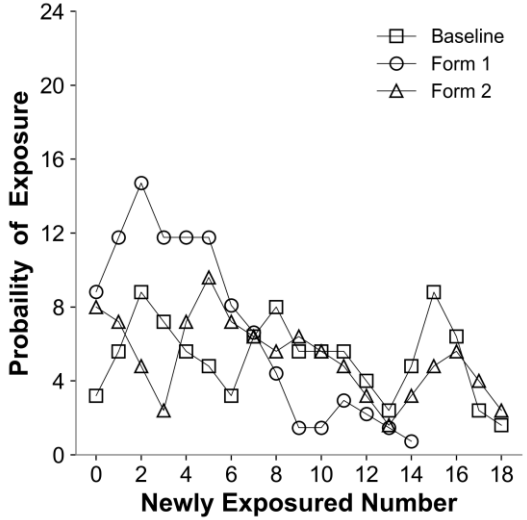


■ Corridor

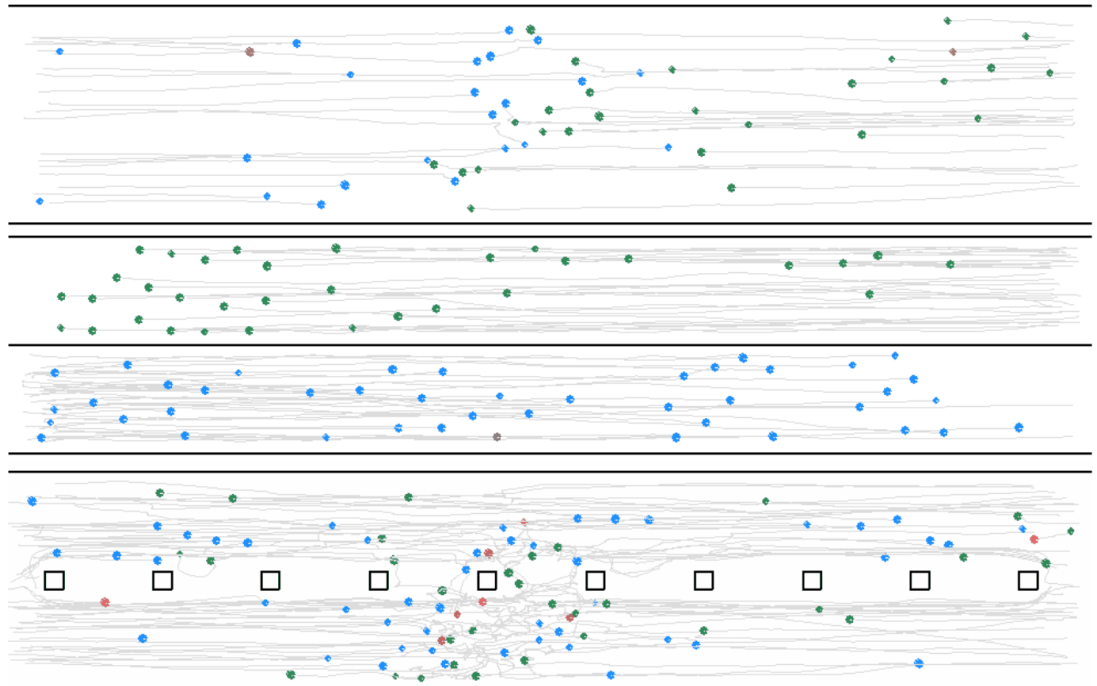


Social distance rate = 0%

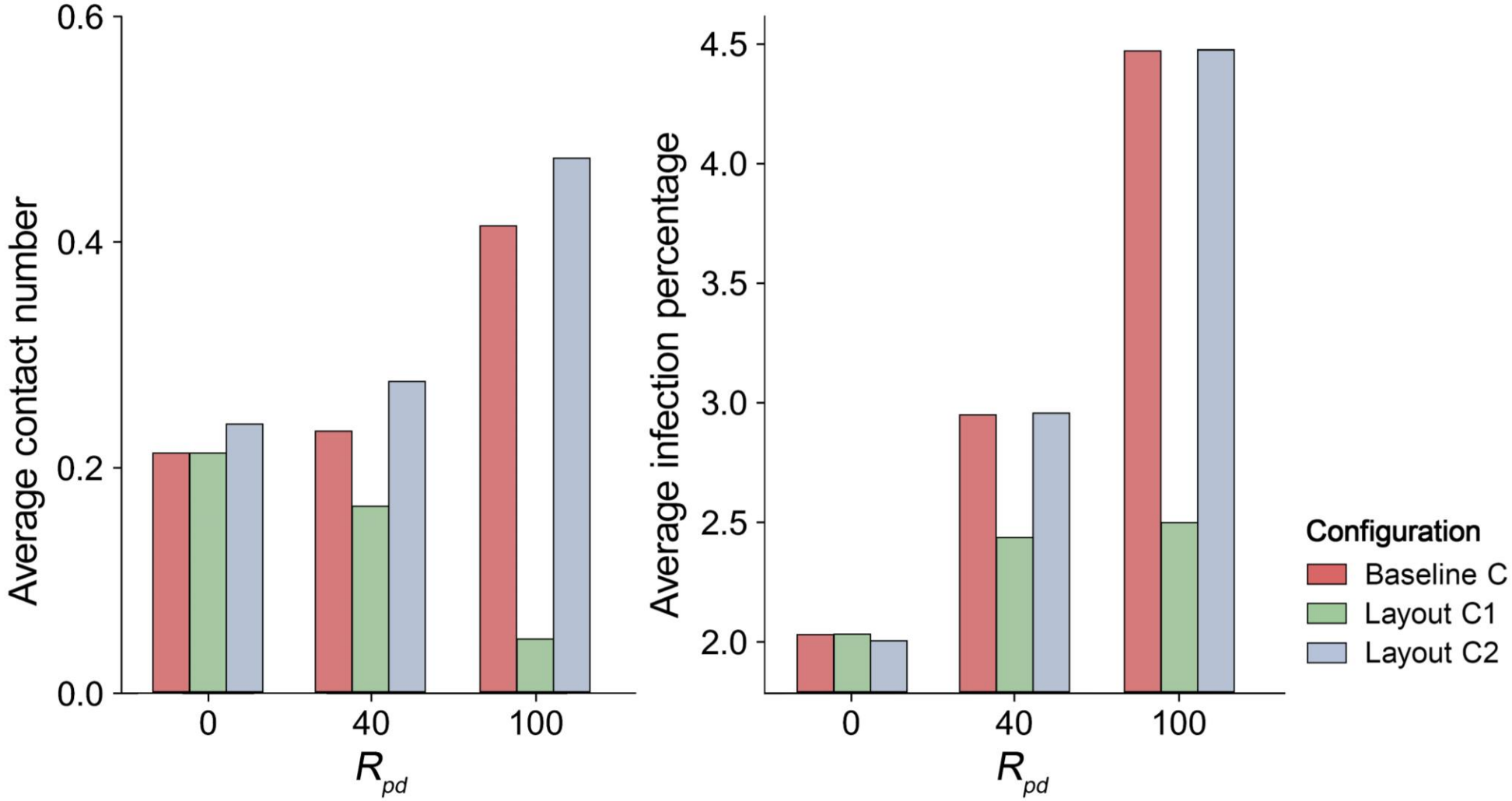




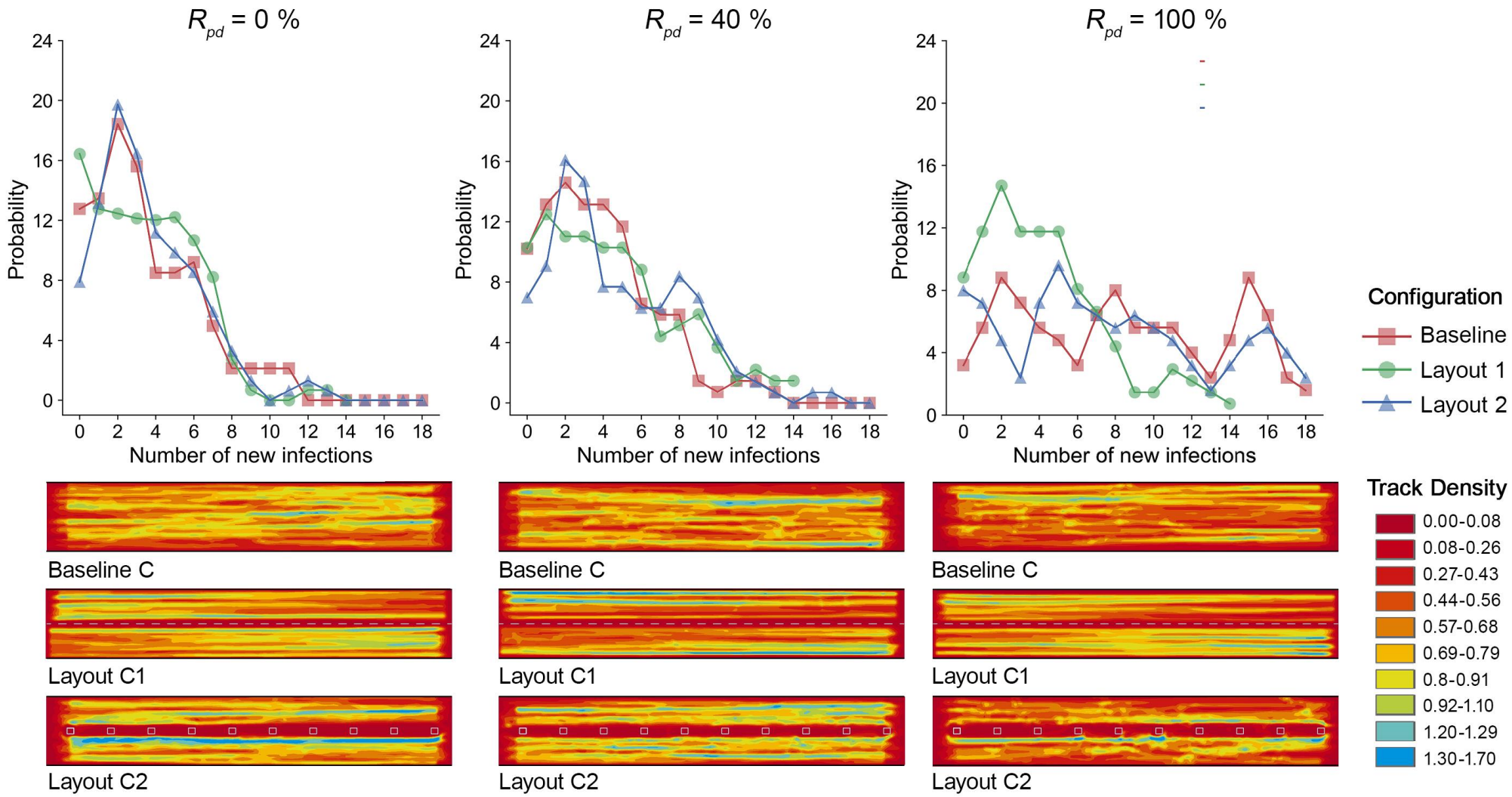
Social distance rate = 100%



■ Corridor



■ Corridor



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PART 5

Conclusions

Conclusions

Hypothetical scenario analyses indicated that proper plan layout plays a vital role in the spread of COVID-19 during social distancing.

Closed Room: Both strategies of increasing the numbers and width of the entries are effective in infection propagation in a crowd and closed room.

Corridor: the study found that social distancing in a linear corridor used by oppositely moving pedestrians may cause deadlocks and block the area, leading to large-scale infection transmission. Arranging railings in the middle of the corridor can avoid potential irregular motion, which effectively reduces contact number and suppressing the disease spread.

Winding queue: the simulation shows that a winding queue with fewer corners reduces the contact frequency of pedestrians and thus lowers the infection spread. Setting sideward separations between adjacent aisles is another effective configuration, leading to lower infective exposure.

Reference

[2] Chang, M., Kahn, R., Li, Y., Lee, C., Buckee, C., & Chang, H. (2021). Variation in human mobility and its impact on the risk of future COVID-19 outbreaks in Taiwan. BMC Public Health, 21.

[3] World Health Organization. COVID-19 STRATEGY UPDATE. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public

[4] Chinazzi, M., Davis, J., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Piontti, A.P., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M., Longini, I., & Vespignani, A. (2020). The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. Science (New York, N.y.), 368, 395 - 400.

[5] D. Helbing, P. Molnar, Social force model for pedestrian dynamics, Phys. Rev. E 51(1995) 4282–4286.

[6] W.O. Kermack, A.G. McKendrick, Contribution to the mathematical theory of epidemics, Proc. Roy. Soc. A115 (1927) 700–721.

[7] Andersson, H., & Britton, T. (2000). Stochastic Epidemic Models and Their Statistical Analysis.

[8] Chinazzi, M., Davis, J., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Piontti, A.P., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M., Longini, I., & Vespignani, A. (2020). The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. Science (New York, N.y.), 368, 395 - 400.

[9] Balcan, D., Colizza, V., Gonçalves, B., Hu, H., Ramasco, J., & Vespignani, A. (2009). Multiscale mobility networks and the spatial spreading of infectious diseases. Proceedings of the National Academy of Sciences, 106, 21484 - 21489.

[10] Rvachev, L.A., & Longini, I. (1985). A mathematical model for the global spread of influenza. Bellman Prize in Mathematical Biosciences, 75, 3-22.

[11] Britton, T. (2010). Stochastic epidemic models: a survey. Mathematical biosciences, 225 1, 24-35 .

[12] Okazaki S. A Study of Pedestrian Movement in Architectural Space, Part 1: Pedestrian Movement by the Application on of Magnetic Models[J]. Transactions of the Architectural Institute of Japan, 1979, 283:111-119.

[13] Fukui M, Ishibashi Y. Jamming Transition in Cellular Automaton Models for Pedestrians on Passageway[J]. Journal of the Physical Society of Japan, 1999, 68(11):3738-3739.

[14] Helbing D (1992) A fluid-dynamic model for the movement of pedestrians. Complex Syst 6:391–415v

[15] Han, Y., & Liu, H. (2017). Modified social force model based on information transmission toward crowd evacuation simulation. Physica A-statistical Mechanics and Its Applications, 469, 499-509.

[16] Helbing, D., & Johansson, A. (2009). Pedestrian, Crowd and Evacuation Dynamics. Encyclopedia of Complexity and Systems Science.

[17] Ningbo, C., Zhaowei, Q., Yongheng, C., Li-ying, Z., Xian-min, S., & Qiaowen, B. (2017). Destination and route choice models for bidirectional pedestrian flow based on the social force model. Iet Intelligent Transport Systems, 11, 537-545.

[18] Steffen, B. (2010). A Modification of the Social Force Model by Foresight. arXiv: Physics and Society, 677-682.

[19] Farina, F., Fontanelli, D., Garulli, A., Giannitrapani, A., & Prattichizzo, D. (2016). When Helbing meets Laumond: The Headed Social Force Model. 2016 IEEE 55th Conference on Decision and Control (CDC), 3548-3553.

[20] Parisi, D., Gilman, M., & Moldovan, H. (2009). A modification of the Social Force Model can reproduce experimental data of pedestrian flows in normal conditions. Physica A-statistical Mechanics and Its Applications, 388, 3600-3608.

[21] Helbing, D., Buzna, L., Johansson, A., & Werner, T. (2005). Self-Organized Pedestrian Crowd Dynamics: Experiments, Simulations, and Design Solutions. Transp. Sci., 39, 1-24.

[22] Gao, Y., Luh, P., Zhang, H.B., & Chen, T. (2013). A modified social force model considering relative velocity of pedestrians. 2013 IEEE International Conference on Automation Science and Engineering (CASE), 747-751.

[23] Helbing D, Buzna L, Johansson A. Self-Organized Pedestrian Crowd Dynamics: Experiments, Simulations, and Design Solutions[J]. Transportation Science, 2005, 39(1): 1–24.

[24] Namilae S, Derjany P, Mubayi A, Scotch M, Srinivasan A. Multiscale model for pedestrian and infection dynamics during air travel. Physical review E. 2017 May 31; 95(5):052320

[25] Derjany P , Namilae S, Liu D, et al. Multiscale model for the optimal design of pedestri an queues to mitigate infectious disease spread[J]. PLoS ONE, 2020, 15(7):e0235891.

[26] Sun, H.C., Liu, X.F., Xu, X.K., & Wu, Y. (2020). Analysis of COVID-19 spreading and prevention strategy in schools based on continuous infection model. Acta Physica Sinica, 69, 240201-240201.

[49] Nasir, N., Hassan, A.S., Khozaei, F., & Nasir, M. (2020). Investigation of spatial configuration management on social distancing of recreational clubhouse for COVID-19 in Penang, Malaysia. International Journal of Building Pathology and Adaptation.

[27] Helbing, D. (1991). A mathematical model for the behavior of pedestrians. Systems Research and Behavioral Science, 36, 298-310.
[28] Tilley, Alvin R., and Henry Dreyfuss Associates. 2002. The measure of man and woman: Human factors in design. Rev. ed. New York: Wiley.
[29] Knoblauch, R., Pietrucha, M., & Nitzburg, M. (1996). FIELD STUDIES OF PEDESTRIAN WALKING SPEED AND START-UP TIME. Transportation Research Record, 1538, 27-38.
[30] 国家技术监督局. 中华人民共和国国家标准GB10000-88中国成年人人体尺寸[S]. 1988.
[31] Helbing D, Farkas I, Vicsek T. Simulation Dynamical Features of Escape Panic[J]. Nature, 2000(407): 487-490.
[32] Centers for Disease Control and Prevention. Social Distancing: Keep a Safe Distance to Slow the Spread [EB/OL]. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/social-distancing.html.
[33] World Health Organization. How to protect yourself when travelling during the coronavirus (COVID-2019) outbreak [EB/OL]. https://www.youtube.com/watch?v=0KBvReECRrI&feature=youtu.be&t=1110.
[34] Queensland Government. How to protect yourself and others—coronavirus (COVID-19) [EB/OL]. https://www.qld.gov.au/health/conditions/health-alerts/coronavirus-covid-19/protect-yourself-others/coronavirus-prevention.
[35] Helbing D, Johansson A. Dynamics of crowd disasters: An empirical study[J]. Physical review. E, Statistical, nonlinear, and soft matter physics, 2007, 75: 046109
[36] Agrawal, A., & Prasad, A. (2003). Integral Solution for the Mean Flow Profiles of Turbulent Jets, Plumes, and Wakes. Journal of Fluids Engineering-transactions of The Asme, 125, 813-822.
[37] Agrawal, A., & Bhardwaj, R. (2021). Probability of COVID-19 infection by cough of a normal person and a super-spreader. Physics of Fluids, 33.
[38] Rudnick, S., & Milton, D. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor air, 13 3, 237-45 .
[39] Clark RP, de Calcina-Goff ML. Some aspects of the airborne transmission of infection. Journal of the Royal Society Interface. 2009 Oct 8; 6(suppl_6):S767–82
[40] Teunis PF, Moe CL, Liu P, E. Miller S, Lindesmith L, Baric RS, et al. Norwalk virus: how infectious is it?. Journal of medical virology. 2008 Aug; 80(8):1468–76. https://doi.org/10.1002/jmv.21237 PMID:18551613.
[41] Yinghui L, Ning Z, Chen Y, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals[J]. Nature, 2020, 582: 557-560.
[42] Lednicky JA, Lauzardo M, Fan ZH, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients[J]. International Journal of Infectious Diseases, 2020, 100: 476-482.
[43] Prather, K., Wang, C.C., & Schooley, R. (2020). Reducing transmission of SARS-CoV-2. Science, 368, 1422 - 1424.
[44] Moskal A, Grad L. Temporary and spatial deposition of aerosol particles in the upper human airways during breathing cycle[J]. Journal of Aerosol Science, 2002, 33: 1525-1539.
[45] He X, Lau EHY, Wu P, et al. Temporal dynamics in viral shedding and transmissibility of COVID-19[J]. Nature Medicine. 2020, 26: 672-675.
[46] Han, Y., & Liu, H. (2017). Modified social force model based on information transmission toward crowd evacuation simulation. Physica A-statistical Mechanics and Its Applications, 469, 499-509.
[47] Helbing, D., P . Molnár, I. Farkas, K. Bolay . 2001. Self-organizing pedestrian movement. Environ. Planning B 28 361–383.

Thank you for listening

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