Crowd control and social dynamics – which way out?

The picture shows the crowd an hour and a half before the crowd disaster occured at the Love Parade electronic music festival in Duisburg in 2010.

- Crowd management is key to evacuation safety. Evacuation simulation programmes often lack experimental verification due to the inadequacy of benchmarks with real-world experiments.
- Constructing a mathematical model can be difficult, or even impossible, so a modelling approach is often not feasible.
- Ilias Panagiotopoulus, Jens Starke, and Wolfram Just from the University of Rostock, Germany, have developed a model-free approach to analyse field experiments.
- This innovative method provides quantitative benchmarks and extends our understanding of crowd dynamics.

The dynamics of crowds is probably one of the most important issues which hugely impacts our quality of life. Terrible accidents and disasters, such as the King's Cross Station fire, the Duisburg Love Parade disaster, or the Hillsborough disaster, have demonstrated how our safety depends on managing pedestrian dynamics. While mathematical models derived from first principles are of huge help in understanding the dynamics in science and engineering, similar approaches for social systems are still at their infancy [1], as there is no scientific consensus about the principles governing the motion of individuals.

In an attempt to overcome such a challenge, Ilias Panagiotopoulus, Jens Starke, and Wolfram Just from the University of Rostock, Germany, have developed a model-free approach to analyse field experiments of human crowds. The concept is entirely data-driven and based on minimally invasive control methods, aiming to uncover the relevance of unstable, unobservable flow patterns for managing crowds successfully.

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The concept of a model-free approach has been successfully applied to both social dynamics [2,7], and to problems in science and engineering [3,4,5 & 6].

Pedestrian route choice

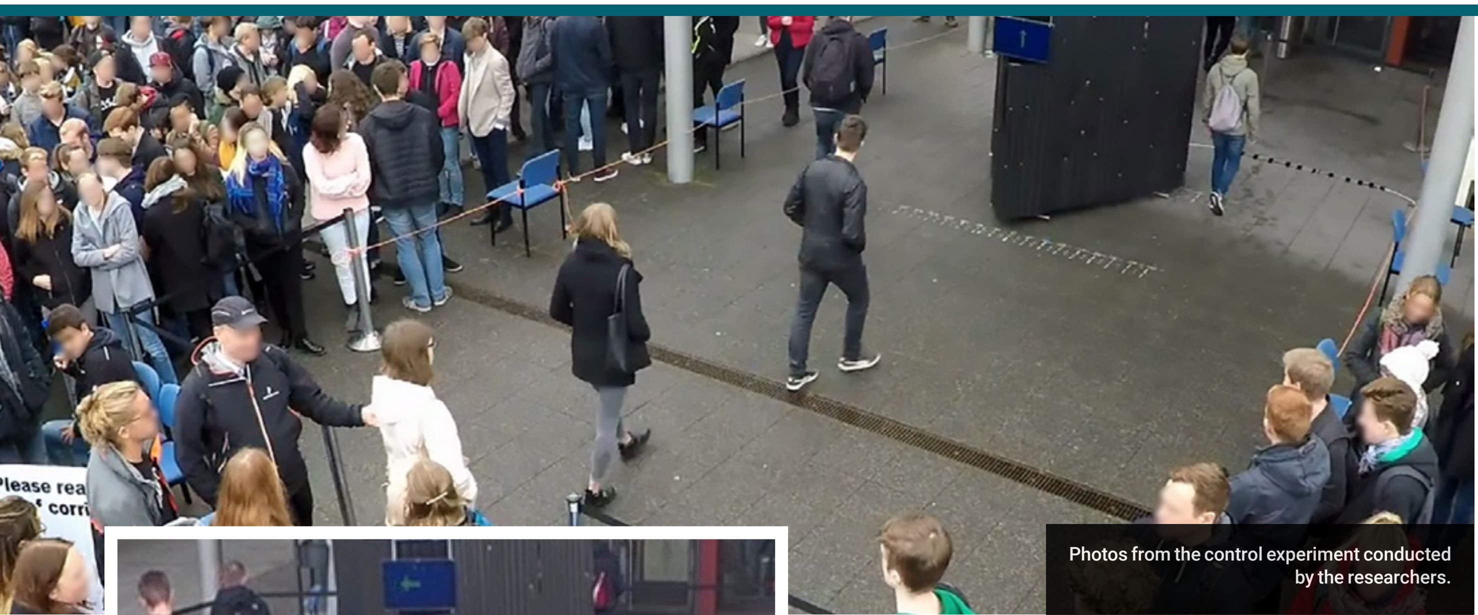
The researchers designed an experimental paradigm where key elements of pedestrian flows, such as crowding, decision-making, or congestion, could be investigated by quantitative means. An obstacle was placed in a corridor where pedestrians were moving towards an exit. Pedestrians had to choose whether to pass left or right of the obstacle (Figure 1). The tendency of humans to follow each other, the so-called 'Lemming effect' – a key psychological feature in humans – results in pedestrians passing predominantly on the same side, causing unnecessary congestion.

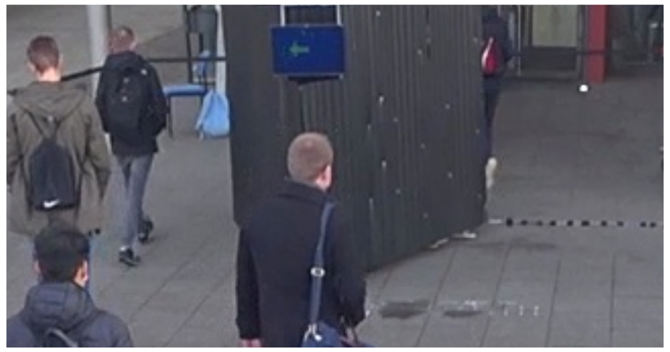
By implementing crowd management through dynamical signage, they aimed to split the flow pattern, so that pedestrians pass on both sides of the obstacle, to reduce crowding and increase social distancing. The researchers found that they could only achieve a particular split of the flow which corresponds to an unstable flow pattern, and which is prescribed by the geometry of the corridor and the position of the obstacle. Crowd management and implementing social distancing by signage or traffic lights are like balancing a stick. Thus, the state or position which can be achieved by minimally invasive control has to be an unstable position of the dynamical system under consideration.

A model-free approach for crowd dynamics

During the experiment, while people were walking along the corridor towards the exit, the obstacle was moved from one side to the other, slow enough for the participants to not notice the shift. Initially, all pedestrians were passing on the same side of the obstacle. At a critical position of the obstacle, the space on that side became too narrow and the route on that side became disadvantageous – this led to pedestrians choosing to pass on the opposite side of the obstacle.

Moving the obstacle back resulted in no change in the pedestrian flow even at the previous critical position. The researchers observed that they had to wait longer for the flow pattern to change at a second critical obstacle position. Once again this was due to the Lemming effect causing this 'hysteresis effect'.





Photos from the control experiment conducted by the researchers.

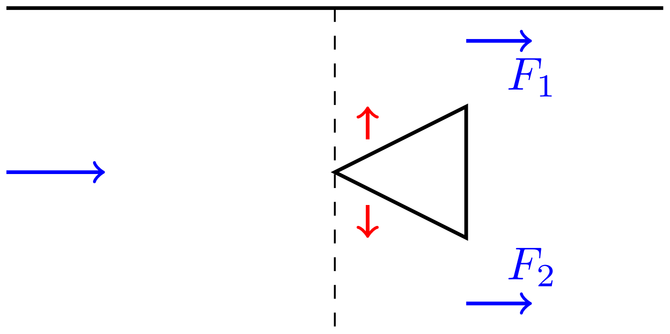


Figure 1. The researchers designed an experiment with an obstacle placed in a corridor where pedestrians were moving towards an exit.

At intermediate obstacle positions, two stable flow patterns exist, where almost all pedestrians pass on one of the two sides of the obstacle. Such a bistable situation is accompanied by an additional unstable flow pattern where pedestrians pass on both sides of the obstacle, but such an unstable state does not emerge per se without any further intervention.

The researchers developed an algorithm for stabilisation – to analyse even the unstable states of a social system during field experiments. They introduced minimally invasive control with dynamical signage. Depending on the particular pedestrian movements, (time-dependent) arrows were displayed on monitors, to provide data-based feedback to the pedestrians.

This research provides an opportunity to understand crowd dynamics when there are no first principles for modelling available.

Control and field experiments

Applying their model-free approach to the analysis of pedestrian movement, the researchers carried out field experiments to achieve a quantitative understanding of crowd dynamics. Around 600 first-year students at the University of Rostock took part in the control experiment whereas the field experiments involved over 1,000 participants comprising passengers disembarking cruise ships at Warnemünde port.

In the university experiment, the obstacle was placed in a corridor in front of an entrance to a lecture theatre. Students entering the corridor queued briefly to create a constant inflow rate of about 0.6 people per second. In the port experiment, the obstacle was placed 8m inside the entrance to the terminal building. It was observed that the passengers wanted to leave the pier quickly while remaining close to their families and friends as they entered the terminal. The average inflow rate was about 1.5 people per second.

A complete bifurcation diagram, summarising the parameter-dependent, qualitative dynamic behaviour, also including unstable flow patterns was obtained by implementing a model-free approach in terms of suitable non-invasive control schemes. The methodology of a model-free approach is not limited to a socio-dynamical setting. In preliminary studies with mechanical engineers, minimally invasive control was applied to trace solutions for a periodically driven impact oscillator, a simple mechanical toy system that displays strong nonlinearity caused by colliding bodies [2,4,5], and another mechanical system with interesting properties, Zeeman's catastrophe machine [3].

Non-invasive crowd management strategies

Crowd control and crowd management still rely strongly on mathematical modelling, and the research team draw attention to the lack of benchmarks with real-world experiments. The team's research provides an opportunity to understand crowd dynamics when there are no first principles for modelling available. The innovative approach can inform crowd management and the implementation of soft, non-invasive management strategies, such as signage and traffic lights. Moreover, it offers quantitative benchmarks to judge the quality of mathematical models for pedestrian motion and social systems.

Personal response

Why did you choose to develop a model-free approach for analysing pedestrian movement?

For pedestrian flows, there are no first principles available, thus alternative scientific approaches are needed. For traditional subjects in science and engineering, such as physics, chemistry, and (to a certain extent) biology, suitable models derived from well-established theories exist; however, virtually no consensus has been established about the mathematical principles of social behaviour. Thus, to uncover the building blocks of a mathematical description of social dynamics, a model-free approach for analysing motion in social systems is essential.

What were the most challenging aspects for you as researchers conducting these experiments?

Unlike statistical surveys where one observes and records the behaviour of people, proper dynamical experiments with crowds require large groups of individuals moving in a daily-life environment under the influence of external inputs, such as traffic lights or signs. As the behaviour of individuals changes when exposed to the same setup repeatedly, each pedestrian can only participate once in an experiment. Further, the experiment relies on an unbiased group of individuals who are not recruited for a particular purpose. Obtaining permission from authorities to run such experiments and to ensure the safety of participants all the time is certainly one of the major challenges of the current research.

What were the most surprising findings?

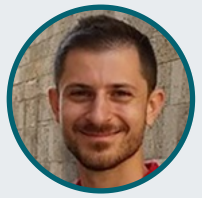
The biomechanics of humans, the perception of signals, and the data processing in our brain are hugely complex processes which all contribute to the movement of individuals. Nevertheless, the behaviour of crowds seems to rely only on a few guiding principles, and through our experimental studies, we were able to uncover some of them.

The Lemming effect, the tendency of humans to follow each other, is a crucial feature of crowds. Signage and traffic lights act as a non-invasive input on the movement of individuals, and such small stimuli may have a huge impact on the dynamics of groups, such as reducing congestion or increasing social distancing. However, such a kind of crowd management can only succeed if we aim at target patterns which are unstable motions of the underlying systems. In this regard, crowd management has much in common with the problem of balancing.

What has been the most satisfying aspect of this research?

Unlike science and engineering where findings and studies are cast in a quantitative way, an analogous approach in social sciences is still in its infancy if one discounts statistical surveys. Some experts in the area of pedestrian research questioned whether it is possible to set up successful experiments in crowd dynamics which have the same power as experiments in physics or engineering. With our approach, we have shown that a quantitative data-based analysis of crowd dynamics is feasible, opening up the new field of quantitative social sciences.

Details



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Collaborators

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Bio

Ilias Panagiotopoulus studied mathematics at the University of Patras, at Queen Mary University of London, and at the University of Rostock. He was recently appointed as design engineer at ASML, Eindhoven. His research interests include dynamical systems and chaos theory.

Jens Starke studied mathematics and physics at the University of Stuttgart. He held positions at the University of Heidelberg, at the Technical University of Denmark in Copenhagen, and at Queen Mary University of London, before joining as professor in mathematics at the University of Rostock. His research interests cover a broad range of subjects in applied mathematics and scientific computing, with a particular focus on applications of bifurcation theory and model-free analysis.

Wolfram Just studied theoretical physics at the Technical University of Darmstadt. He held positions at Kyushu University, the Max Planck Institutes in Dresden and Göttingen, at Queen Mary University of London, and at the University of Chemnitz. He recently joined the Department of Mathematics of the University of Rostock. His research interests cover areas in theoretical physics and applied mathematics, with a focus on statistical mechanics, dynamical systems theory, and applications of control.

Further reading

[1] Helbing, D, Johansson, A, (2009) Pedestrian, Crowd and Evacuation Dynamics. In: Meyers, R, (eds) *Encyclopedia of Complexity and Systems Science*. New York: Springer, 6476–6495.

[2] Panagiotopoulos, I, Starke, J, Just, W, (2022) Control of collective human behavior: Social dynamics beyond modelling. *Physical Review Research*, 4(4), 043190.

[3] Bureau, E, Schilder, F, Santos, IF, Thomsen, JJ, Starke, J, (2013) Experimental bifurcation analysis of an impact oscillator—Tuning a non-invasive control scheme. *Journal of Sound and Vibration*, 332(22), 5883–5897.

[4] Dittus, A, Kruse, N, Barke, I, Speller, S, Starke, J, (2023) Detecting stability and bifurcation points in control-based continuation for a physical experiment of the Zeeman catastrophe machine. *SIAM Journal on Applied Dynamical Systems*, 22(2), 1275–1299.

[5] Bureau, E, Schilder, F, Elmegård, M, Santos, IF, Thomsen, JJ, Starke, J, (2014) Experimental bifurcation analysis of an impact oscillator—Determining stability. *Journal of Sound and Vibration*, 333(21), 5464–5474.

[6] Schilder, F, Bureau, E, Santos, I, Thomsen, JJ, Starke, J, (2015) Experimental bifurcation analysis – continuation for noise-contaminated zero problems. *Journal of Sound and Vibration*, 358, 251–266.

[7] Panagiotopoulos, I, Starke, J, Sieber, J, Just, W, (2023) Continuation with noninvasive control schemes: Revealing unstable states in a pedestrian evacuation scenario. *SIAM Journal of Applied Dynamical Systems*, 22(1), 1–36.

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