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Daamen, Winnie; Duives, Dorine

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CHAPTER THIRTEEN

Synthesis and the future of pedestrian space design and management

Winnie Daamen* **and Dorine C. Duives**
Department of Transport & Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
*Corresponding author. e-mail address: W.Daamen@tudelft.nl

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Abstract

More and more people will be living in urban areas. This requires responsive and inclusive urban planning, to keep the urban areas resilient, inclusive and sustainable. This also affects mobility in cities. Governments promote walking as a healthy and sustainable mode of transportation. However, the pressure on pedestrian infrastructure is rapidly increasing, while large crowds gather more and more frequently. We therefore need to get more insights in what pedestrian planning entails. This chapter covers the conclusions of all contributions to this book, ranging from insights into pedestrian traffic flow through data and insights in behavior to different types of models and crowd management. The chapter ends with an overview of innovations in pedestrian planning and management, and what is needed to keep urban regions sustainable and attractive for pedestrians and crowds.

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1. Why did we write this book?

UN Habitat predicts that by 2050, 68 % of the people will be living in urban areas (United Nations Human Settlements Program UN-Habitat, 2022). According to UN Habitat "the success of cities, towns, and urban areas will largely depend on policies that protect and sustain all, leaving no one behind." Responsive and inclusive urban planning is essential to develop resilient, inclusive and sustainable urban regions. Pedestrian infrastructure forms the backbone of any mobility system and should therefore be a key part of the resilient urban mobility systems of the future.

At the same time, the call for sustainable mobility systems is getting louder and louder every day. Also in this respect, walking has a vital role to play. A pedestrian emits very low amounts of carbon dioxide and no fine dust. Also, the noise pollution of a pedestrian pales into insignificance compared to the noise pollution of vehicular traffic. Thus, increasing the walking mode split in favor of vehicular mode split can support the more sustainable mobility systems of the future.

More recently, governments around the world have started to focus on "broad prosperity". This concept describes everything that influences the prosperity of people. This does not only include material prosperity, but also health, safety, accessibility, education, social connections, care, personal development, and the quality of the living environment (Snellen et al., 2021). Within this frame, walking as a mode of transport has two essential contributions. Firstly, the health benefits of walking have been frequently recorded (Kelly et al., 2017; Lee and Buchner, 2008). Secondly, good walking infrastructure is a great equalizer with respect to accessibility as no other means (e.g., money, vehicles) than one's legs and time are required to move from A to B.

Not surprisingly, governments worldwide are actively promoting walking (and cycling) as healthy, sustainable alternatives to vehicular modes of transportation. With success, we must conclude. Whether you are young, adult, or elderly, most of us walk on a daily basis. We walk for a myriad of reasons, amongst other things, to take children to their primary school, getting groceries, going to play sports, or just walking for leisure. In the Netherlands, citizens walked 1.1 km per person per day on average in 2023 (De Haas and Kolkowski, 2024). Roughly 23.2 % of the total number of trips in the Netherlands is made on foot. Within Europe, 15 % of citizens walk and cycle at least 30 min per day (Eurostat, 2025). These statistics do not yet account for all the public transport trips during which people walk on the first- and/or last mile of their trips.

However, with the pressure on urban regions growing, also the pressure on pedestrian spaces is rapidly increasing. Large crowds gather more and more frequently. We have all encountered them, for instance, as a commuter in a train station, as a soccer fan on your way to watch your favorite team, as a visitor of a music festival, or as a member of a political demonstration. As a crowd manager stated: "Large crowds occur more often, the crowds we need to manage are bigger, and the public spaces in which they gather are more complex."

With the rise of pressure on pedestrian spaces, also questions regarding the design and management of pedestrian spaces are surfacing more frequently. What do we know about the choice behavior and movement dynamics of pedestrians? What factors influence their behavior? Which (simulation) tools can aid the design and operational management of pedestrian spaces? Which technologies can we use to study their behavior, as well as monitor their movements? Up to this point in time, the knowledge on the planning, design and management of pedestrian infrastructures in urban areas was scattered.

2. Synthesis of the book

This book on pedestrian planning and management aimed to provide an overview of the current state-of-the-art with respect to pedestrian planning, design and management. To structure the content of the book, we use Figs. 1 and 2.

Pedestrian choice behavior plays a crucial role in designing, managing, and optimizing urban spaces to support walkability and active mobility. Understanding how individuals make walking-related decisions allows planners to create environments that align with pedestrian needs and preferences. Fig. 1 shows the pedestrian choice behaviors, based on the four-step model, which is a traditional framework used in transportation planning to predict travel demand and assess the impact of infrastructure projects, policies, and land-use changes (McNally, 2007). The choice behaviors are split into the strategic level, the tactical level, and the operational level (Hoogendoorn and Bovy, 2004). In this hierarchical structure, the expected utilities of lower-level options impact decision-making at higher levels, while higher-level choices shape the available options at lower levels. Each level corresponds to a distinct time scale. Strategic choices have the most significant long-term impact, tactical choices influence behavior within the current trip or tour, and operational choices govern actions during parts of a trip.

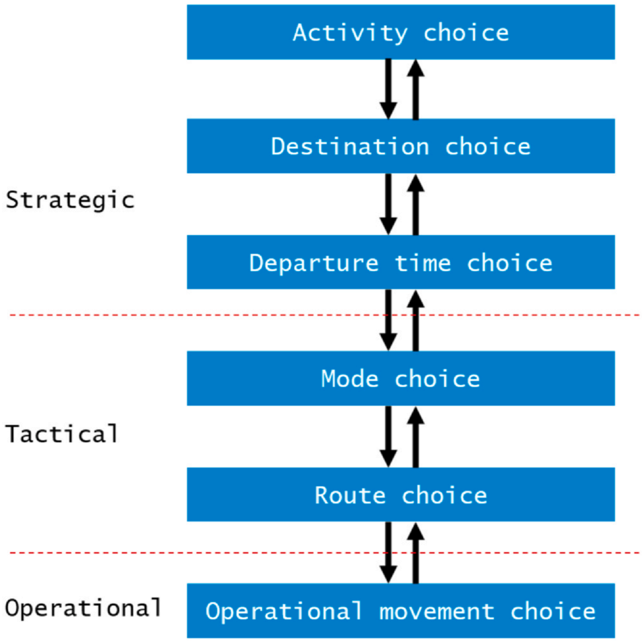

Fig. 1 Visualization of the framework featuring choice levels.

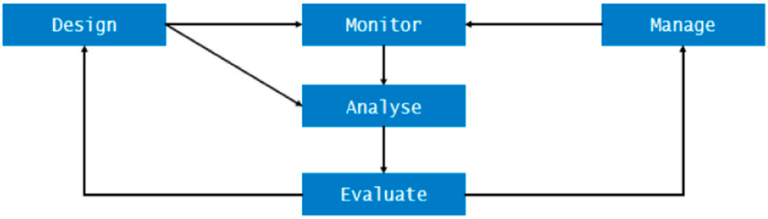

Fig. 2 Visualization of the relationships between the various actions a planner of pedestrian infrastructures can undertake.

Using our insights into pedestrians' choice behaviour, infrastructure can be designed to better accommodate their needs. The framework presented in Fig. 2 conceptualizes the key actions and interdependencies a planner of pedestrian infrastructure may take within the design and management process.

Initially, infrastructure is developed at a conceptual stage, where design principles are followed. Prior to implementation of the design, a systematic analysis and evaluation process is conducted to identify and mitigate potential shortcomings. After construction of the infrastructure, continuous monitoring provides empirical data for assessing real-world performance. If the evaluation indicates that the infrastructure functions as intended, no further intervention is required. However, if deficiencies are identified, corrective measures must be taken to optimize functionality and user experience. This can be done either through short-term management interventions or long-term design modifications.

This book starts with the formal definitions for the key flow variables characterising walking behaviour, and thus a pedestrian flow. These variables can be classified into three levels: microscopic (describing pedestrian flow at the individual level), macroscopic (capturing the flow using aggregate measures) and mesoscopic (representing flow through distributions of individual-level characteristics).

The fundamental variables speed, density and flow are related to each other via the so-called fundamental diagram describing pedestrian streams. Different representations of the fundamental diagram exist, such as speed-density, flow-density, flow-speed and speed-distance, which allow different conclusions to be drawn about the considered pedestrian stream. Fundamental diagrams from multiple empirical studies were analyzed. These studies utilize experimental datasets on pedestrian flow across various spatial configurations, encompassing different flow patterns such as unidirectional, bidirectional, and multi-directional movement. The fundamental diagrams exhibit similar overall trends, reflecting different flow states such as free flow, bounded flow, congested flow, and stop-and-go congestion. However, the specific shape of the fundamental diagram varies depending on the geometry of the traffic system and the characteristics of pedestrian flow. Even within the same flow type, there are variations in the course of the diagrams, often caused by using slightly different definitions of the fundamental variables.

Data are not only used to get insights into fundamental relations describing walking behavior but are also used to get insight into other types of pedestrian behavior, as well as for monitoring the current and historical situation on the urban infrastructure. To identify which data are needed, a conceptual model has been developed for pedestrian behavior in relation to pedestrian planning. From this conceptual model, four types of data can be derived:

- Environment and infrastructure data, containing details of land use, transport infrastructure, and their impact on pedestrian safety and attractiveness.
- Data on the use of Infrastructure, or traffic data. These data provide information on pedestrian, cyclist, and vehicle flow, public transport timetables, vehicle occupancy and routes.

- Data on pedestrian characteristics. Socio-demographic information, attitudes, habits influencing pedestrian behavior, collected through various studies and surveys.
- Physiological data. These data consist of biological measurements like heart rate, skin response, brain activity, and muscle engagement to assess pedestrian stress, cognitive load, and physical exertion.

These data can be collected through various data collection techniques, including sensors, surveys, social media and extended reality. While practitioners are typically interested in real-life data collection to monitor pedestrian flows in urban areas, a researcher can choose between real-life data collection and performing laboratory experiments. Either way, essential features for effective data collection and analysis include accuracy, validity, controllability, confidentiality, representativeness, bias, reproducibility, and cost. The different types of data that have been distinguished in chapter 4 have varying degrees of these features.

To understand pedestrian behavior, an interdisciplinary approach is necessary. By integrating insights from engineering, psychology, physiology, transport, architecture, and sociology, we can better analyze pedestrian actions in both routine and emergency contexts. Despite the shared focus on safety and efficiency, a gap remains in applying human factors knowledge to pedestrian planning, as engineers and designers often lack expertise in this area. Chapter 5 addresses these limitations, by presenting a framework categorizing human factors in pedestrian research across three dimensions: physical vs. psychological crowds, routine vs. emergency situations, and urban vs. rural settings. It examines crowd characteristics, including size, density, time, novelty, and collectivity, and explores perspectives from sociology, psychology, and biology. While early theories viewed crowds as irrational, more recent perspectives recognize collective behavior as rational and responsive. Biological and cognitive insights highlight the impact of stress, biomechanics, and decision-making on pedestrian behaviors. A multilevel approach, considering individual, group, and collective factors, is essential for a comprehensive understanding. Key individual-level factors include age, gender, personality, risk perception, attention, and sensory impairments. At the social level, group size and cultural differences influence walking speed, evacuation times, and interpretation of spatial cues. Contextual factors, such as carrying luggage or adverse weather conditions, affect pedestrian movement and safety. In Chapter 5, these factors have been further detailed.

To develop effective policies and design efficient and comfortable urban areas, understanding the effect of the previously mentioned influencing factors on pedestrian travel choices, both positively and negatively, is crucial. Chapter 6 shows that, in addition to choices for their operational walking behaviour, pedestrians make six types of choices during the day: activity choices, destination choices, departure time choices, mode choices, strategic route choices, and operational route choices (see also Fig. 1). There are various discrete choice models available for studying pedestrian travel behaviour, each making its specific assumptions and best suited to particular travel choice scenarios. Chapter 6 demonstrates how these models help unravel pedestrian travel decisions, highlighting the many factors that influence their choices. Moreover, these factors are very diverse. Some are spatially very detailed, while others describe aggregate spatial features of neighborhoods. A similar distinction can be made for the time scale, where some factors influence the travel behavior in the next few seconds, while others remain stable for relatively long periods. Four pivotal determinants of pedestrian travel have been deduced from literature, namely enforcement of physical and social safety while walking, the time needed to walk, the effort and discomfort involved when walking and the rewards the individual receives for walking.

Pedestrian crowd movements in urban environments are complex due to interactions between individuals, their environment, and context. Predicting these movements is challenging, but microscopic pedestrian simulation models help identify patterns and potential issues. Over the past 50 years, various models have been developed to simulate pedestrian dynamics. Chapter 7 introduces key pedestrian simulation models, including Cellular Automata (CA), Social Force (SF), Predictive Collision Avoidance (PCA), Optimal Step Model (OSM), Discrete Choice (DC), and Artificial Neural Network (ANN) models. Each model represents pedestrian movement differently, influencing operational and global movement dynamics. Each fundamental version of each model is shortly introduced to illustrate general pedestrian behavior, along with notable extensions, advantages, and challenges of each approach.

While microscopic models are suited to predicting the behaviour of individuals or small groups, large crowds exhibit collective behaviour that can be captured using macroscopic models. These models treat crowds as a fluid, where individual pedestrians are indistinguishable, and movement is characterized by local averages of density and velocity.

Unlike classical fluid equations, pedestrian density and velocity evolve based on target or preferred speeds, which may differ among groups.

Chapter 8 examines the benefits and limitations of conservation laws adapted for pedestrian movement and explores related numerical methods. Special focus is given to the connections between microscopic, mesoscopic, and macroscopic models. Additionally, macroscopic approaches provide access to established mathematical techniques, such as phase transition analysis and traveling wave studies.

To ensure accurate simulation of pedestrian behaviour, key processes of verification, calibration and validation need to be performed, which are further detailed in Chapter 9. Verification tests whether the implemented model correctly reflects its conceptual design. Calibration fine-tunes model parameters to minimize errors, while validation evaluates how well the model represents real-world pedestrian movement. A multi-objective approach, considering various scenarios and metrics, is commonly used. The choice of objectives is crucial, as it must capture relevant behaviours based on the model's intended use. Given the stochastic nature of most pedestrian models, multiple replications are necessary during calibration and validation. Additionally, sensitivity analysis helps identify the most influential parameters, improving the efficiency of the calibration process.

Once pedestrian models have been calibrated and validated, they can be applied by practitioners. Over the past 25 years, several documents have been developed to guide the use of pedestrian dynamics models, providing valuable support for young practitioners and occasional users. However, applying pedestrian models remains complex despite these guidelines. The diversity of pedestrian behaviours leads to wide variations in empirical data, making it difficult to define absolute rules or optimal parameter settings. Guidelines help navigate these uncertainties, but final decisions rest with project managers. Additionally, modelling projects have unique objectives, requiring tailored approaches rather than a one-size-fits-all guideline. Selecting the right framework remains an expert task. Still, as organizations refine and cross-reference these documents, the quality and consistency of pedestrian modelling guidelines are expected to further improve over time.

Urban infrastructure is constrained in size, and with the continuous increase in traffic flows, congestion occurs, and concerns are raised regarding pedestrian safety. To tackle these challenges, crowd management strategies are implemented, ranging from short-term measures like adding signage to long-term solutions such as redesigning entire neighbourhoods. Crowd management entails the systematic process of planning, organizing, and monitoring large gatherings of people to establish and maintain a safe and secure environment. Chapter 11 suggests that IT-based steering mechanisms, such as aural stimuli and lighting, can influence pedestrian flow and route choice. However, gaps remain in understanding their full impact, highlighting the need for further validation. Other crowd management strategies, like signage, have a proven positive effect on route choice and wayfinding during evacuations, though their influence on flow rate and walking speed is unclear. Additionally, personal traits and architectural features shape pedestrian behaviour, but certain factors, such as educational background, remain underexplored. The review in Chapter 11 emphasizes the need for further research to refine crowd management strategies and enhance pedestrian modelling accuracy. Chapter 12 offers a toolbox for identifying crowd incident risks, developing dynamic crowd management systems, and designing effective crowd management interventions. It also provides practical guidance on implementing these strategies and highlights key challenges for the future.

3. The future of pedestrian planning and management

This book has provided a thorough overview of all the knowledge pertaining to urban pedestrian infrastructure planning and management. We have attempted to provide a comprehensive overview of the essential knowledge a planner and/or engineer requires when (re)designing or managing overcrowded pedestrian spaces. Here, we have focused on established (empirical) facts as much as possible. Consequently, it provides a nice overview of what is currently the state-of-the-art.

Yet, we have the feeling that there is more to come. Exciting things are happening as we are writing this book. Underneath, we have attempted to highlight the most important developments for the years to come.

3.1 Walking to enhance inclusivity, equity and broad prosperity

Even though researchers have been studying pedestrian movement dynamics and choice behavior for decades, little is known about the relationship between walking infrastructure and broad prosperity. If we look at the individual parts of the definition, one could assume that safe, reliable, and efficient walking infrastructure is a key element to achieving a prosperous inclusive society. Yet, it is essential to further substantiate these preliminary claims with facts and figures. How many deaths can be saved directly (i.e., via traffic deaths) and indirectly (i.e., via a healthier population) by safe and connected pedestrian street networks? How much more accessible are jobs in a region when we invest in pedestrian infrastructure for complete walking trips? How is the pedestrian infrastructure on the first- and last-mile legs of public transit trips supporting public transit ridership? To what extent can walking infrastructure serve as the great equalizer?

3.2 Exploding computational power provides new opportunities

At this moment, the use of simulation models is still limited by their computational burden. To run a city-scale simulation, one is lucky if the simulation provides results after a few hours. Consequently, simulation models are now primarily used in the preliminary stages of pedestrian infrastructure designs and urban planning where there are already worries with respect to pedestrian safety (e.g., shopping mall, soccer stadium, and event venue design).

Yet, with the rise of Artificial Intelligence (AI), also computers' computational power has quickly exploded. This opens up new opportunities in the field of pedestrian space design. Instead of only checking the final design, interactive design tools could be developed that quickly check the safety ramifications of design alternatives. Instead of simulating one deterministic scenario to check the safety of a large infrastructure design, a full-scale sensitivity study can be performed to better understand the right-hand tail of the density and flow rate distributions (high densities and flows). What is the probability that things may go wrong in a given pedestrian infrastructure design? Instead of using the simulation model in the design phase, one could use the model in real-time to monitor potential safety risks in the near future. Moreover, accurate demand predictions will become feasible, making it possible to anticipate crowdedness and supporting real-time crowd management. All in all, it is going to be interesting to see how the increase of computational power can support pedestrian infrastructure designers and crowd managers in the years to come.

3.3 Big data brings insights and big responsibilities

During the last decade, many new technologies have been introduced to sense pedestrians and crowds. By now, crowd sensors are relatively cheap, more accurate and standardized enough that municipalities can easily implement them in their cities and public space managers adopt them to improve the efficiency of their crowd management operations. The first steps with respect to the adoption of crowd management systems to monitor risks and dynamically manage crowded spaces are currently being taken by various parties.

Even though data-driven pedestrian infrastructure management is still at its infancy, we expect disruptive changes in crowd management within the years to come. We are at the brink of moving from an age where crowd incidents happened because "we could not have seen it coming" to a new age where we could have known that crowd incidents were about to happen if we had installed and adopted crowd monitoring systems. We expect that the availability of crowd sensing equipment is going to 'force' managers of crowded pedestrian spaces to use them to limit their liability in case of crowd incidents. To facilitate this change, we need to better understand when, where and how crowd monitoring systems can best support crowd management operations.

The mainstream use of crowd monitoring systems will have a second side effect. Pedestrians will be watched wherever they go. Consequently, the words "big brother is watching you" are going to get a completely new meaning if we are not consciously designing crowd monitoring systems that preserve the privacy of the individuals that make up the crowd. In some parts of the world, regulations are in place to protect the privacy of their citizens, for instance, the General Data Protection Regulation (GDPR) of the EU. Yet, these regulations do not relieve us of the obligation to discuss the do's and don'ts of large-scale crowd monitoring systems more carefully. What is the balance between safety and privacy? Which infringements on the right to privacy do we allow to ensure the social and physical safety of individuals in (public) pedestrian spaces? Can we design systems that by default protect citizens' right to privacy (so-called privacy-by-design)? And how do we ensure that these rights are still protected when we use sophisticated data fusion algorithms featuring multiple types of data sources?

3.4 Responsible AI and machine learning

In addition to big datasets featuring crowd choice behavior and movement dynamics, also the algorithms that we are using to analyze these big datasets are rapidly evolving. Machine learning algorithms are transforming how we work at an incredible pace. Within the field of pedestrian infrastructure management, machine learning is also slowly introduced. Smart computer vision algorithms currently support the analysis of crowd movement dynamics and deep learning approaches are developed to predict crowd dynamics at train stations. Yet, we expect that way more advanced algorithms will be introduced in the coming years. This will give rise to two types of questions: (A) how can advanced machine learning algorithms best support pedestrian infrastructure designers and crowd managers in their work, and (B) how do we ensure that these new tools function in an ethically responsible manner? Next to developing the best machine learning algorithms, our focus should also be on developing responsible AI. In particular, can we develop AI algorithms whose code is transparent, their training sets unbiased and open-access, and their responses explainable and reliable?

3.5 International design guidelines for the design and simulation pedestrian spaces

As cities grow and mobility needs evolve, well-designed pedestrian spaces are essential. However, current pedestrian infrastructure design standards vary widely across countries, leading to inconsistent pedestrian infrastructure (networks) that are unsafe and/or inaccessible for many citizens. Within this book, we have gathered the state-of-the-art on pedestrian knowledge, but what is missing is a comprehensive set of design guidelines that could support planners and engineers when (re)designing pedestrian spaces. Harmonized guidelines would benefit urban planners, policymakers, and designers by promoting best practices and fostering walkable, people-friendly cities worldwide.

To develop a comprehensive set of guidelines, more insights into the current preferences of pedestrians are required. We need to better understand what elements of pedestrian spaces support the perception of safety and the objective safety of pedestrians. In addition, we need to understand better why pedestrians prefer specific pedestrian spaces over others and the interactions between network-level connectivity and local street design.

Next to developing a comprehensive set of design guidelines, we also see that there are several sets of partial guidelines featuring the setup, verification, calibration, validation, and usage of pedestrian simulation models. They all have their particular focus and cover specific simulation scenarios. For example, IMO focusses on ship evacuations, and MNIST focusses more on the verification of simulation software. We currently need a comprehensive set of simulation guidelines that aligns the different standards in practice and regulations. Over time, the development of international simulation guidelines allows researchers and engineers to develop trustworthy pedestrian simulation software and to create a seal of excellence for pedestrian simulation software usage.

4. Final words of the authors

Given all of these innovations on the horizon, we see a bright future for the design and management of pedestrian spaces ahead of us. After reading this book, we hope that we have inspired you to be part of this exciting future!.

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