Crowd Movement - DTCC Milestone Project

Research Report

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The importance of pedestrian movement for urban design and planning

Pedestrian movement has always been a main concern for urban design and planning but has become more important in the light of the Sustainable Development research agenda (UN Agenda 2030), especially related to Goal 11. 'Sustainable cities and communities'. The agenda clearly calls for promotion of sustainable mobility and transport (i.e., public transport, walking, cycling, micro-mobility) that targets especially climate and health. The decrease of private car usage and increase of public ridership reduces greenhouse gas emissions (e.g., Litman 2020), and the increase of active modes of transport promotes public health and well-being (e.g., Roe et al. 2020, Bird et al. 2018). Furthermore, sustainable mobility and active travel support social inclusion and cohesion because while walking, we are co-present in public space (e.g., Legeby et al. 2015, Legeby 2013). Also, pedestrian flows are recognized as an important driver of local economies (e.g., Hillier et al. 1993, Hillier 1996a, Litman 2020). Pedestrian movement is thus brought to the front of sustainable urban development (Stavroulaki, keynote SS13, 2022).

To explain, assess and predict pedestrian movement in the built environments, we need appropriate methods to model pedestrian flows. Such methods are currently lacking in transport and traffic modelling that are still highly car-oriented. Pedestrians are sometimes included in traffic modelling, but mainly as 'vulnerable users' in simulations of vehicle-pedestrian interactions aiming to improve safety (e.g. Rinke et al. 2016, Pascucci et al. 2015, Obeid et al. 2017).

Pedestrian movement has been studied with different approaches and on different scales for many decades. Within the field of Space Syntax, models have been developed that are primarily pedestrian-oriented and in accordance with the informal, unregulated, and free-flow nature of pedestrian movement (Stavroulaki, keynote SS13, 2022). They explain pedestrian flows based on characteristics of the built environment, primarily the spatial configuration of the street network and built density.

The prediction of pedestrian flows can be based on statistical models where characteristics of the built environment (e.g., street centrality, activities along these streets and built density) are calibrated against hourly observed pedestrian counts collected via any kind of pedestrian-sensing technology (for a review of such technologies, see Dong et al. 2020). Different types of models are used, where a rough distinction can be made between macroscopic and microscopic models. Macro- and microscopic refers in this case to the size of the area studied that in the first case typically is a city district or complete city and in the latter case a public square, street crossing or small neighbourhood. In both situations, the pedestrian flows are predicted in the level of the individual street.

From a macroscopic perspective, different modelling methods have been developed to simulate pedestrian flows on the street network. Route-choice models are adapting traffic-modelling methodologies to simulate pedestrian trajectories from origins to destinations on a street network, e.g. Basu and Sevtsuk (2022); Sevtsuk et al. (2021). Network models are predicting aggregated pedestrian flows on the street level based on the characteristics of the network itself using for instance measures of centrality, e.g. Stavroulaki et al. (2020); Berghauser Pont et al. (2019a); Bolin et al. (2021); Ozbil et al. (2011, 2015). While route-choice models have a high accuracy, they are highly data demanding and rely on many predictors that are too detailed to specify in the early design and planning stages (e.g., specific attractions, sidewalk width, street lighting, exact land-use mix) or include socioeconomic predictors that are not predefined in development plans (e.g., income, age). Network models have moderate accuracy but can be more directly applied in scenario analysis and assessment to guide the early design and planning stages, since they only rely on spatial predictors that can be affected by design, as street centrality and urban density.

A typical example of microscopic models are cellular automata models. They divide the walking space for pedestrians into a discrete grid, through which pedestrians move based on constraints defined in the model (Blue et al. 1997). In contrast, the social force model represents pedestrians in a continuous space with force-based interactions and movements (Chen et al. 2017, Helbing 2000). Other examples are activity-choice-models and velocity-based models of pedestrians (see Blue et al. 1997, Helbing et al. 2000, Hoogendoorn and Bovy 2004 and Paris et al. 2007). The activity-choice-model is a continuation of the social force model adding an active route choice for pedestrians, whereas in the velocity-based model pedestrians choose their path based on knowledge of surrounding obstacles to get to their destination as directly as possible. In most examples, agents move on OD (origin destination) paths. Other approaches assume a random walk, where pedestrians do not aim to reach a predefined destination (Hanna 2021, Turner and Penn 2002).

Besides having a macro- or microscopic perspective, the model described above varies in what is modelled. The macro-simulations described above model the built environment to explain, simulate or predict the pedestrian flows (the phenomenon), while the micro-simulations model the flows of agents with certain rules that include the agents' behaviour. Rarely, approaches for hybrid models that combine macro- and macro- simulations and models of structure (built environment) and flows (agents/pedestrians) have been developed, e.g. Xiong et al. (2009), who created a multi-resolution model by coupling an agent-based and a flow-based model. Another example is agent-based models developed within the field of Space Syntax where agents' random walks depend both on visual parameters (i.e., angle and field of view) and the configurational properties of the spatial layout (urban or building layout) (Turner and Penn 2002).

The Crowd Movement Milestone Project, initiated by the Digital Twin City Centre, aims to develop such a hybrid model, coupling a macroscopic network model of the built environment and a microscopic agent-based model of pedestrians.

The technological deliverables of the project are stand-alone solvers for macroscopic and microscopic simulations and the coupling of the macroscopic network model and a microscopic agent-based model. Requirements for a user-friendly decision support tool as web app in the DTC platform has not been developed but is an obvious next step. This requires close collaboration with the developers of this milestone project and the developers of the DTC platform.

In this report, we summarize the findings of the project by first, highlighting some principal differences in modelling pedestrian movement. The next two sections summarize the work done in relation to the macroscopic network and microscopic agent-based model respectively, as well as their coupling. The following section presents use cases where such models can be valuable in urban planning and design practice based on a workshop with urban stakeholders. The report ends with a summary of the results and next steps to be taken in the understanding of pedestrian movement and its use in urban planning and design practice.

Aligning ontologies in modelling pedestrian movement

Based on unpublished chapter of a book due 2024 (MIT press) by Lars Marcus[1]

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The shared conceptual understanding of cities, albeit interpreted with different emphases in different disciplines, can be summarized either as in traffic planning as a land use – transport problem (Lowry 1964), or as in urban modelling as a location – flows problem (Batty 2013), or as in architecture and urban design (Hillier 1996) as a morphology – movement problem. The common ground here is arguably, that cities are constituted by a series of locations characterized by some kind of attraction or activity that will generate interaction and flows between these locations, which in turn may influence the attractions and activities at each location. This serves for a neat division of labor between urban design, dealing with the stationary dimension of cities, such as buildings and public places, and transport planning, taking care of its mobile dimension, such as car traffic and public transport. Importantly, this also creates distinct foci on cities as structure-process entities, where urban design addresses its physical structure and only implies processes of mobility, while traffic planners do the opposite. While being a simplification, it is clear how this division increasingly is becoming an obstacle for contemporary urban development to reach its aims.

Importantly, in recent decades there has been a shift in emphasis that in principle at least, has opened for a closer exchange between these disciplines. Where urban models, such as traffic models, traditionally were built on the assumption that locations generate flows, the modelling of which could support the planning of new infrastructure, the more recent understanding is that flows define location, that is, that the patterns of infrastructures such as rail and roads create a landscape of locations with highly varying accessibility that to a high degree defines potential activity at the locations (Batty 2013). This means that traffic does not only serve place but to some degree generate and define place, which challenges the old division of labor.

Similar ideas have in more recent research in architecture and urban design put an emphasis on the configuration of urban space as defined by built form, giving rise to a system of streets and open spaces, and its influence on pedestrian movement patterns (Hillier 1996). The street system often constitutes the primary infrastructure in cities, used by various transport modes over time, including rail based (such as trams), why it also comes to structure these. In parts of architecture and urban design this has meant an important shift from a focus on the built form of cities in itself, to the spatial system it defines and in turn the flows that it structures.

Hence, we can see recent developments that on the one hand, has made transport planning more concerned with the active role of patterns of built form, such as street networks, in distributing flows and in turn defining land use at different locations, and on the other hand, has made urban design more attentive to patterns of space and how they influence flows and how that in turn allocates land use. That is, we see a convergence between disciplines that for a long time have developed knowledge and trained practices isolated from each other.

The disciplinary development as described above, has affected the modelling of cities in more particular the modelling of flows, including pedestrian flows.

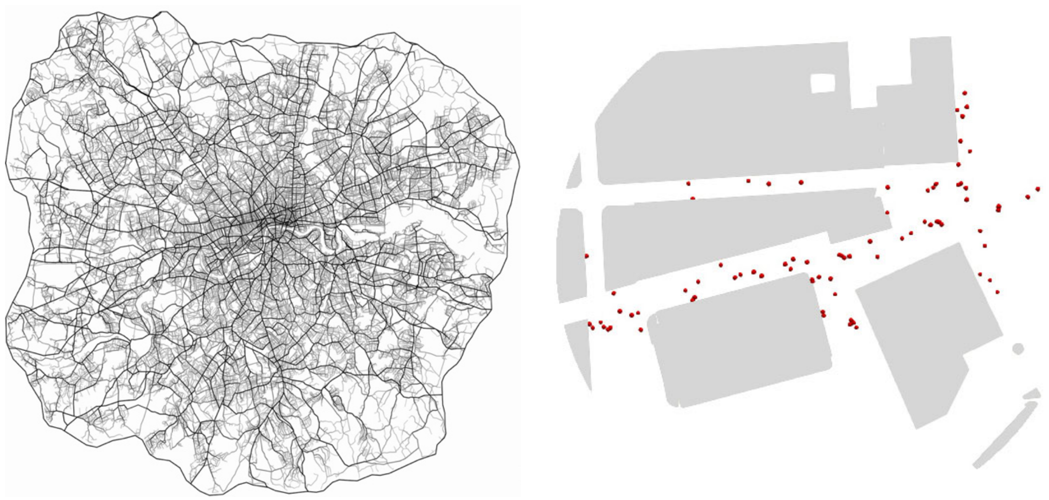

Figure 1. Varieties of spatial representation in urban modelling: Network representations of urban space as developed in the particular form of urban modelling called space syntax (left, source: UCL Bartlett) and agent-based models (right, source: FCC).

As we discussed in the introduction of this report, a distinction can be made between route-choice models that are adapting traffic-modelling methodologies to simulate pedestrian trajectories from origins to destinations and network models that base their prediction of aggregated pedestrian flows on qualities of the network itself.

Both models are simplified representations of an entity of interest, constructed in accordance with certain methodological needs and theoretical assumptions, directed by a particular line of enquiry concerning the entity at hand. We therefore need to pay attention to the theoretical assumptions when it comes to how they are interpreted. Of particular interest is what kind of representation is used for the spatial variable in these different models.

Besides these two different types of space-based models, agent-based models are relevant for simulating pedestrian movement and used in this project for the microscopic modelling of pedestrian behaviour. In essence, agents do not have fixed locations but act or interact with one another as well as the environment.

Despite differences, the models share the similar aim to capture how the urban environment affects pedestrian behaviour. The difference is that the network model emphasizes the physical environment to predict pedestrian flows, while the agent-based model emphasizes the agent's behaviour implied by the behavioral rules of the agent to predict pedestrian flows. Observed pedestrian count data is used in both cases to calibrate the models. And, as will be discussed later, the two models can be coupled to forecast the aggregated flow.

Modeling pedestrian movement on city scale

Based on abstract of unpublished paper 'Street network simulation for predicting pedestrian flows on the streets of existing and planned urban areas' by Ioanna Stavroulaki[1], Oscar Ivarsson[2], Meta Berghauser Pont[1], Vilhelm Verendel[2]

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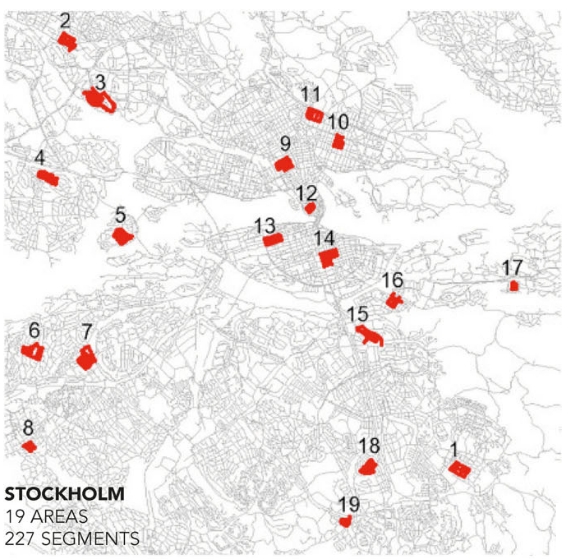
In this paper (in development, to be published 2023), a street network simulation is presented that can be used in urban design and planning from the early stages of an urban development plan. It is based on a machine learning model using LASSO regression (Least Absolute Shrinkage and Selection Operator), that predicts pedestrian flows (i.e., numbers of pedestrians) on the level of street segments and can be applied on neighbourhood scale or on entire cities.

The street network simulation can be used for estimating both the volume and the distribution of pedestrians on future streets with the aim to support scenario analysis, assessment and decision making in urban design and planning. It can also be used to simulate pedestrian flows in existing streets, where this information cannot be collected through real-world observations with manual counts or with the use of sensors or cameras because of time, budget or GDPR constraints.

The simulation is built on street network modelling and relies on a handful of predictors, namely local street network centrality, density, number of lanes and speed limit, walking accessibility to local markets and street segment length, all of which can be calculated or easily estimated for a planned urban area or an infrastructural change, already from the early stages of design and decision making.



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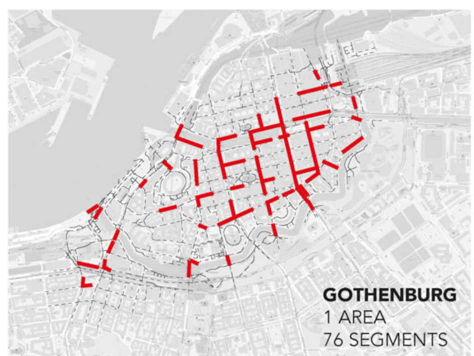

b

Figure 2. Neighborhoods included in the training data from Stockholm (a), Street segments included in the model validation in Gothenburg (b).

The paper describes the methodology of developing the machine learning model and its results. The model is written in Python and is published in Github (https://github.com/SMoG-Chalmers/crowd-movement). It is trained using data gathered in Stockholm, Sweden and tested by predicting full-day pedestrian counts in a different city, specifically on 75 street segments in central Gothenburg (Fig1). The model was tested against real-world observations collected in Gothenburg by capturing anonymised wi-fi signals from mobile phones in October 2018 (Traffikontoret 2019). Two variations of the model are presented; one is trained in 224 street segments distributed in different areas in Stockholm and one is trained in 121 street segments of central Stockholm.

The models have a regression coefficient (R^2) of 0,50-0,52, which can set a good stage for scenario analysis and early assessment of urban development plans and infrastructural changes in relation to estimated pedestrian flows. Apart from predicting the volume and distribution of full-day pedestrian counts, the model is also tested for predicting hourly counts, simulating fluctuations during the day.

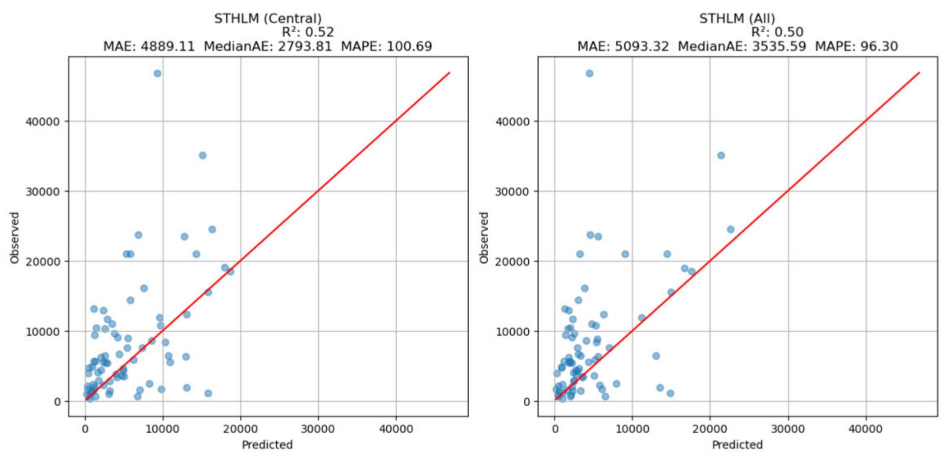

Figure 3. Plots of Observed (y axis) vs Predicted values (x axis) for the two models a. trained in 6 central areas of Stockholm, b. trained in all 19 areas in Stockholm. The values represent daily number of pedestrians and the dots represent each of the 75 street segments tested. The results show R^2, Mean Absolute Errors (MAE), Median Absolute Error (Median AE)

Coupling macroscopic and microscopic simulations to model pedestrian flows

Based on abstract of paper (in review) 'Improving agent-based pedestrian movement simulations using network models in outdoor urban environments' by Anita Ullrich[1], Franziska Hunger[1], Klas Jareteg[2], Adam Bilock[2], Yuri Tarakanov[3] , Gianna Stavroulaki[4], Alexander Gosta[5], Johannes Quist[1], Meta Berghauser Pont[4], Fredrik Edelvik[1]

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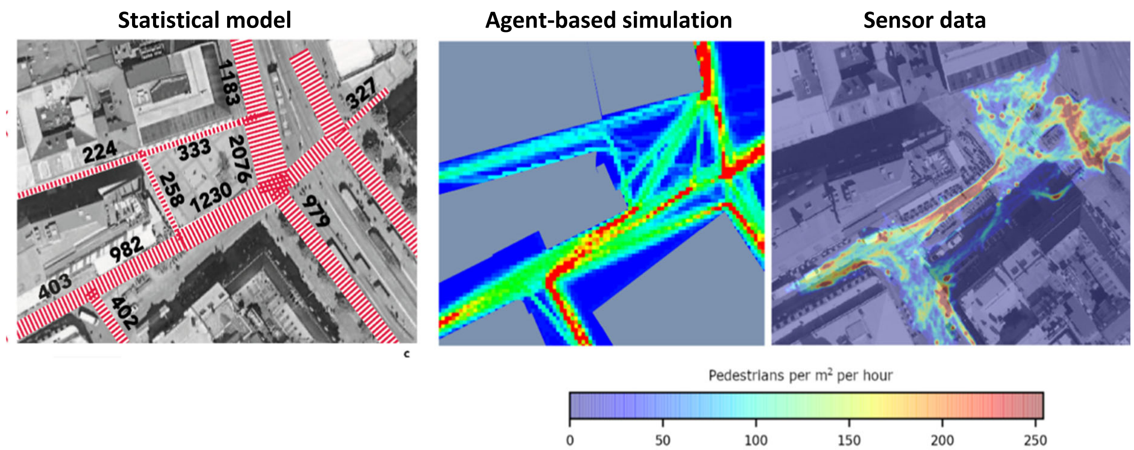

Figure 3. Comparison of the data from the statistical model (left) used to calculate the pedestrian occupancy on the local scale (middle) with the pedestrian occupancy recorded using sensor data (right) for a pedestrian precinct in the city centre of Gothenburg, Sweden.

This paper (in review) describes how an agent-based modeling approach targeting the resolved movement of pedestrians in outdoor urban environments is combined with the macroscopic network model predicting aggregated pedestrian flows to develop a methodology assisting (quantitative) scenario testing in various phases of urban planning. The model framework is applied to two cases in the city centre of Gothenburg, Sweden. For both cases, sensor data is available. The first case has been used to calibrate and validate the agent-based model, while the second is more complex and justifies the applicability of the combined workflow using the agent-based and network model. The comparison with the sensor data shows a very reasonable agreement depicting the model's capability to capture main structures of the pedestrian movement. Moreover, the model enables the analysis of pedestrian movement and conflicts being important quantities for planning and optimizing the pedestrian flow.

The use of pedestrian modelling in urban design and planning practice

Based on a workshop 22-10-28 led by Alexander Gösta, Liljewall arkitekter, Sweden. The workshop aimed at gaining insight in how modelling pedestrian movement is useful in urban planning and design practice (for whom and when in the design process). Besides possible use cases, risks and difficulties are highlighted.

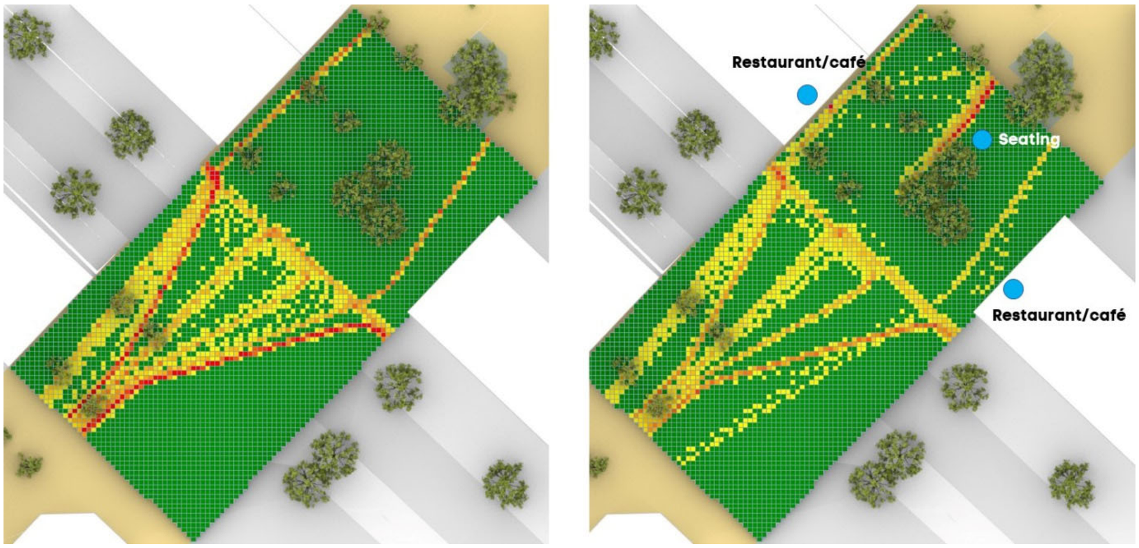

Figure 4. A comparison of pedestrian flow heatmaps with and without attraction points discussed during the workshop.

From the workshop, six categories of use cases of the models predicting pedestrian movement were identified:

- Understanding pedestrian behaviour (at various times and for separate groups)
- Directing people flows
- Evaluation of bottleneck situation
- Traffic safety
- Dimensioning of public space
- Evaluation of perception of a place

The use cases span from the detailed comprehensive planning to the building design phase with an emphasis on the detailed development planning. This means the tools and method can be of interest for municipalities but also for private developers, with different uses of varying interest.

More data in the early stages of design give more informed decisions for stakeholders. The ability to evaluate and compare different alternatives with data promotes a fairer, and maybe a more objective, decision-making process. Being able to visualize and communicate the effects on pedestrian movement in the early design and planning stages might lead to a more valued design solution. There is consensus among the workshop participants that other issues that are easier to simulate like motorized traffic, currently weigh more in the decision-making process. Another case in point raised during the workshop was cyclability, and how the movement of bicycles has been more in design focus, since simulations of cycling flows became available and used. There is an acknowledged need to simulate the pedestrian movement in a combined simulation with other traffic such as bicycles and cars.

Risks and difficulties that were highlighted include lack of data, lack of regulation and increasing planning costs. Further, there is a fear that lacking data and too many assumptions in the simulation will result in faulty and misleading prediction results. In areas where existing flows can be measured and included in the simulation model, more trust in the results might be achieved.

The workshop participants did not perceive that the Swedish Planning and Building Act (PBL, see https://lagen.nu/2010:900, https://www.boverket.se/sv/PBL-kunskapsbanken/) includes regulations to secure a functional pedestrian environment, while such regulations are given for motorized traffic. Historically, PBL 1 kap § 1 has indeed mostly resulted in the evaluation of motorized traffic in the planning process. However, it might be argued to also include pedestrians and 2 kap § 6 point 6 says that land must be planned in such a way that it is suitable with regards to "traffic supply and the need for a good traffic environment". In the light of the Convention on the Rights of the Child which was signed by Sweden in 1990, a good traffic environment must include the child perspective as they do not drive cars and are highly dependent on functional pedestrian public space. We could thus argue that there are also juridical reasons to evaluate the impact of planning on pedestrian movement flows.

An obstacle to including the simulations in the design process might be added costs. There is no desire to pay for simulations with unclear benefits, given that there is no regulation that needs to be met by the design, which would require assessments and simulations. Either being able to show that simulations, good predictions, and assessments decrease costs long term or that they add monetary value to the design in the end (such as successful commercial spaces and added rent) might be needed to promote their use, depending on who the client is (municipality, private).

Next steps in modelling pedestrian flows

An obvious next step of the project is to develop a user-friendly decision support tool as web app in the DTC platform. This would also ease the use of the results of the project in decision making in urban development projects.

However, before doing so, we see a need to further develop the network model to improve the prediction of the aggregated number of pedestrians. The gathering of more real-world data on pedestrian movement is important to be able to do so and could be something DTCC takes the lead on. For the agent-based model, more studies in setups with different complexity and characteristics would be required to be able to include more real-world pedestrian behavior.

If this is in place, another development is to study the flow of pedestrians in combination with other modes (e.g. bicycles, e-bikes, cars, etc) and especially possible conflicts between these different modes.

Lastly, we see opportunities to combine the simulation of pedestrian flows with the analysis of other data. For example, the combination of pedestrian movement and the distribution of noise and air pollution could give insight in where to reduce car speed or plant trees to have a greater impact on the most vulnerable users of the streets, pedestrians. And where more people walk, the health impact will be higher.

The latter has been tested in a pilot project financed by the National Research Infrastructure for Data Visualization, Infravis (https://infravis.se/), where the hourly simulation of pedestrian flows was used in combination with hourly fluctuations in noise levels to visualise noise exposure during the day for a small area in Gothenburg. The simulations were developed both for the existing situation and for different design scenarios for the area. Although the pedestrian simulations were still in working progress, the small Infravis project tested their usefulness and applicability in combination with other types of simulations. This has also resulted in a joined EU application that is currently being prepared with the aim to develop methods for the assessment of the impact of future vehicles and equipment on the health and wellbeing of the urban population.

References

Basu R and Sevtsuk A (2022) How do street attributes affect willingness-to-walk? city-wide pedestrian route choice analysis using big data from boston and san francisco. Transportation research part A: policy and practice 163: 1–19. DOI:10.1016/j.tra.2022.06.007.

Batty. M. (2013) *The new Science of Cities*, MIT Press.

Berghauser Pont M, Stavroulaki G and Marcus L (2019) Development of urban types based on network centrality, built density and their impact on pedestrian movement. Environment and Planning B: Urban analytics and city science 46(8): 1549–1564.

Bird E.L., Ige J.O., Pilkington P., Pinto A., Petrokofsky C. and Burgess-Allen J., (2018), 'Built and natural environment planning principles for promoting health: an umbrella review', *BMC Public Health*, 18:930, https://doi.org/10.1186/s12889-018-5870-2

Blue V, Embrechts M and Adler J (1997) Cellular automata modeling of pedestrian movements. In: 1997 IEEE international conference on systems, man, and cybernetics. computational cybernetics and simulation, volume 3. Ieee, pp. 2320–2323.

Bolin D, Verendel V, Berghauser Pont M, Stavroulaki I, Ivarsson O and H˚akansson E (2021) Functional anova modelling of pedestrian counts on streets in three european cities. Journal of the Royal Statistical Society: Series A (Statistics in Society): 1–23DOI:10.1111/rssa.12646.

Xu Chen, Martin Treiber, Venkatesan Kanagaraj & Haiying Li (2017): Social force models for pedestrian traffic – state of the art, Transport Reviews, DOI: 10.1080/01441647.2017.1396265

Dong H, Zhou M, Wang Q, Yang X and Wang FY (2020) State-of-the-art pedestrian and evacuation dynamics. IEEE Transactions on Intelligent Transportation Systems 21(5): 1849–1866. DOI:10.1109/TITS.2019.2915014.

Hanna S (2021) Random walks in urban graphs: a minimal model of movement. Environment and Planning B: Urban Analytics and City Science 48(6): 1697–1711. DOI:10.1177/2399808320946766.

Hillier, B., Penn, A., Hanson, J., Grajewski, T., Xu, J. (1993) 'Natural movement: or, configuration and attraction in urban pedestrian movement.', *Environment and Planning B: Planning and Design,* vol.20, pp. 29-66.

Hillier, B. (1996) *Space is the Machine: A Configurational Theory of Architecture*. Cambridge University Press.

Helbing D, Farkas I and Vicsek T (2000) Simulating dynamical features of escape panic. Nature 407(6803): 487–490.

Hoogendoorn SP and Bovy PH (2004) Pedestrian route-choice and activity scheduling theory and models. Transportation Research Part B: Methodological 38(2): 169–190.

Legeby, A., (2013), *Patterns of co-presence: Spatial configuration and social segregation*, PhD thesis, Royal Institute of Technology, ISBN: 978-91-7501-920-8

Legeby, A., Berghauser Pont, M., Marcus, L., (2015), ‘Street interaction and Social inclusion’, In: Vaughan L. (ed.), *Suburban Urbanities. Suburbs and the Life of the High Street*, UCL Press, London, Ch.9, pp.239-263

Litman, T., (2020) *Evaluating Active Transport Benefits and Costs. Guide to Valuing Walking and Cycling Improvements and Encouragement Programs*, Victoria Transport Policy Institute

Lowry, I. S. (1964). *A Model of Metropolis*. Rand Corp Santa Monica CA. https://www.rand.org/pubs/research_memoranda/RM4035.html

Obeid, H.; Abkarian, H.; Abou-Zeid, M.; Kaysi, I. (2017) ‘Analyzing driver-pedestrian interaction in a mixed-street environment using a driving simulator’, *Accident Analysis and Prevention*

Ozbil A, Peponis J, Stone B (2011). ‘Understanding the link between street connectivity, land use and pedestrian flows’, *Urban Design International*. 6, pp.125-141.

Ozbil A, Yesiltepe D, Argin G (2015) ‘Modeling Walkability: the effects of street design, street-network configuration and land-use on pedestrian movement’, *A|Z ITU Journal of Faculty of Architecture*, 12, pp.189-207.

Paris S, Pettr´e J and Donikian S (2007) Pedestrian reactive navigation for crowd simulation: a predictive approach. In: *Computer Graphics Forum*, volume 26. Wiley Online Library, pp. 665–674.

Pascucci, F.; Rinke, N.; Schiermeyer, C.; Friedrich, B.; Berkhahn, V. (2015) ‘Modeling of shared space with multi-modal traffic using a multi-layer social force approach’, 18th Euro Working Group on Transportation

Rinke, N.; Schiermeyer, C.; Pascucci, F.; Berkhahn, V.; Friedrich, B, (2017) ‘A multi-layer social force approach to model interactions in shared spaces using collision prediction’, *Transportation Research Procedia* 25

Roe, J., Mondschein, A., Neale, C., Barnes, L., Boukhechba, M., & Lopez, S. (2020). ‘The Urban Built Environment, Walking and Mental Health Outcomes Among Older Adults: A Pilot Study’, *Frontiers in public health*, 8, 575946. https://doi.org/10.3389/fpubh.2020.575946

Saelens, B., Sallis, J., Lawrence F., (2003) ‘Environmental Correlates of Walking and Cycling: Findings From the Transportation, Urban Design, and Planning Literatures’, *Environment and Physical Activity,* 25:2

Sevtsuk, A., Basu, R., Li, X., Kalvo, R. (2021). ’A big data approach to understanding pedestrian route choice preferences - Evidence from San Francisco.’ *Travel Behavior and Society*. https://doi.org/10.1016/j.tbs.2021.05.010

Stavroulaki I., Berghauser Pont M., Marcus L., Sun K., Legeby, A. (2020) Non-Motorised network of Stockholm. Swedish National Data Service. Version 1.0. https://doi.org/10.5878/hfww-5y22

Stavroulaki, G., Bolin, D., Berghauser Pont, M., Marcus, L. & Hakansson, E. (2019) 'Statistical modelling and analysis of big data on pedestrian movement.' In: *Proceedings of the 12th Space Syntax Symposium,* pp.79.1–79–24. Beijing Jiaotong University.

Stavroulaki, G. (2022) Directions in Space Syntax. Space Syntax modelling of pedestrian flows for sustainable urban development, keynote SS13.

Turner, A., & Penn, A. (2002). Encoding Natural Movement as an Agent-Based System: An Investigation into Human Pedestrian Behaviour in the Built Environment. Environment and Planning B: Planning and Design, 29(4), 473-490. https://doi.org/10.1068/b12850

Xiong M, Cai W, Zhou S, Low MYH, Tian F, Chen D, Ong DWS and Hamilton BD (2009) A case study of multi-resolution modeling for crowd simulation. In: Proceedings of the 2009 Spring Simulation Multiconference. pp. 1–8.