HUMAN SPATIAL BEHAVIOR AND MICROCLIMATES IN URBAN PUBLIC SPACES USING AGENT–BASED SIMULATION MODELING

Abstract

Microclimates play a crucial role in peoples' participation in public urban spaces. It highlights an environmental impact on human spatial behavior in cities. Studies integrating microclimates and pedestrian behavior simulations are getting popular to help architects and planners toward an informed design process. This paper presents a case for Agent Based Model (ABM) as a microclimate integrated human spatial behavior simulation technique to develop socio-environmental focused, outdoor space design assessment tools. This study uses Federal Plaza in Chicago as a pilot study representing urban plazas with hot summer humid continental climate. The key findings of the study are: (1) current state-of-the-art modeling techniques to simulate human behavior and microclimates; and (2) to propose a public space design assessment framework using human spatial behavior and microclimates in ABM. This study contributes to research-informed outdoor public space designs for environmental, social, and economic upliftment of a city.

Author

Zahida Khan
Illinois Institute of Technology

Keywords

Human behavior, outdoor public space, microclimates, simulation modeling

Introduction

Outdoor urban spaces are focal points of public life in cities. A global shift in urban morphologies is recently witnessed by tall building development as the world population is expected to soar to 9.7 billion by 2050 (United Nations, 2019). This continuous rise has turned many cities into tall urban centers altering the microclimates of outdoor public spaces. Heat stress as a result of temperature rise is likely to affect peoples' thermal perceptions and their movement in urban public spaces. Studies have shown that low thermal comfort levels result in reduced human attendance and increased indoor energy consumption (Shooshtarian et al., 2018). Additionally, they hinder physical activity and contribute to sedentary lifestyle, which in turn cause increased morbidity and mortality rates especially in developed countries like the U.S. (WHO, 2010, 2018). However, well-designed outdoor public spaces can mitigate the problem and enhance public health (U.S. Department of Agriculture, 2018). This has triggered a recent research in developing public space design performance tools delivering informed designs for sustainable cities.

MODELING MICROCLIMATES AND OUTDOOR THERMAL COMFORT

Urban built forms create unique microclimates in outdoor public spaces affecting the Outdoor Thermal Comfort (OTC) levels and hence the user attendance (Sharmin et al., 2015). ASHRAE 55 defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE, 2013). Thermal factors affecting OTC levels are temperature (T), wind (W), relative humidity (RH), and mean radiant temperatures (Mrt), while non-thermal factors are metabolic rate (Met) and clothing insulation (clo). OTC assessment requires a comprehensive framework of climatic and physiological factors included in 'objective models,' while psychological and behavioral factors in 'subjective models' (Chen & Ng, 2012; Golasi et al., 2018). This research uses 'objective models' that are based on heat balance equations and are widely popular in computational modeling. There exist many OTC indices but the most frequently used ones are Predicted Mean Vote/Predicted Percentage Dissatisfied (PMV/PPD), Klima Michel model (KMM), SET*/OUT-SET*, Physical Equivalent Temperature (PET), and Universal Temperature Climate Index (UTCI) (Coccolo et al., 2016). Amongst these, UTCI is the most sophisticated and accurate thermal comfort model to date, developed since 1999 by a multidisciplinary group of experts (Bröde et al., 2012; Fiala et al., 2012). There are about 10 categories of thermal stresses expressed in UTCI equivalent temperature (Figure 7) with +46°C as extreme heat stress and -46°C as extreme cold stress; neutral sensation lies between 9°C-26°C (Bröde et al., 2012). Amongst various urban microclimate modeling tools to derive UTCI values, Ladybug/Honeybee is very popular due to the parametric modeling offered by the Rhino® platform.

MODELING HUMAN SPATIAL BEHAVIOR

Human spatial behavior models in the building industry are popular for traffic, evacuation, and route choice design studies (Bonabeau, 2002; Papadimitriou et al., 2009). Human spatial behavior simulation in outdoor public spaces belongs to route choice studies that mainly uses Agent-Based Models (ABM) involving microsimulation with bottom-up simulation strategy. ABMs are "a class of computational models for simulating the actions, behavior, and interactions of autonomous individual or collective entities, with the goal of exploring the impact of one agent or a behavior type on the system as a whole" (Clarke, 2014). The structure of ABM includes autonomous agents, a context in which the agent moves, and a set of rules that determines the agent's local behavior.

There exist numerous ABM platforms for pedestrian flow analysis, including, but not limited to, Brahms®, PDES-MAS®, PedSim®, Repast®, SeSAm®, Simio®, and many more (Abar et al., 2017). Although highly sophisticated, these tools are not very commonly used by architects because: (1) very few are open sourced, and (2) they require good programming skills to use it. However, a few recent platforms such as PedSim and Quelea® are developed as add-ons to Rhino, a popular parametric design tool used by architects and designers. Quelea is based on a 'Boids algorithm' by Craig Reynolds to understand the flocking behavior of birds (Reynolds, 1999). It has "a rule-based design library" and an intuitive interface for agent-based modeling (Fisher, 2015). Because of its flexibility, the tool has been used in various research topics (Rogers et al., 2018; Ghaffarian et al., 2018; Serdar & Kaya, 2019; Asriana & Indraprastha, 2016) but not in microclimate integrated human spatial behavior simulation studies.

INTEGRATING HUMAN SPATIAL BEHAVIOR AND MICROCLIMATES IN ABM

Human-built environment interaction in ABM has been studied from time to time in outdoor (Hollmann, 2015) as well as indoor (Langevin, 2014) contexts. Although most of them are focused on social factors (Therakomen, 2001), very few have explored environmental effects (Lam, 2011). The key challenge is not restricted to multidisciplinary engagement but also the complexities involved in microclimatic assessments for outdoor environments. This includes limitations in using steady-state models (Höppe, 2002) and limited research in transient-state models (Chen & Ng, 2012; Chokhachian et al., 2018). Despite these challenges, few studies have explored integrating OTC assessment in human behavior simulation (Bruse, 2002; Chen, 2011; Melnikov et al., 2017). A dissertation by Chen (2011) develops an integrated thermal comfort assessment system using ABM in Repast platform. Another work, a dissertation by Lam (2011), explores the microclimatic effects on human behavior simulation using ABM. Similar studies by Bruse (2002, 2007) explored human behavior and microclimate simulations. This study presents an ABM simulation methodology addressing this topic using Rhino-GH scripting and its plug-ins.

Methodology

This paper presents a method to address two research objectives:

- To understand the interrelations between microclimate, urban morphology, and human behavior
- To develop a human spatial behavior simulation framework using ABM, featuring parametric modeling of urban forms and urban microclimate modeling

The proposed research methodology involves computer simulation and on-site field measurements. The simulation model is developed in Rhino and Grasshopper® (GH) as a base platform allowing parametric modeling of urban forms; Quelea an ABM plug-in to simulate human spatial behavior; and Ladybug/ Honeybee for microclimatic simulation. Data on climatic variables, namely temperature, wind velocity, relative humidity, and mean radiant temperature, and UTCI will be correlated to human attendance. Federal Plaza in downtown Chicago is used as a pilot study to evaluate the research methodology. Additionally, a video survey of the plaza will be conducted to collect data on people flow. Figure 1 presents a workflow involving survey and computer simulation.

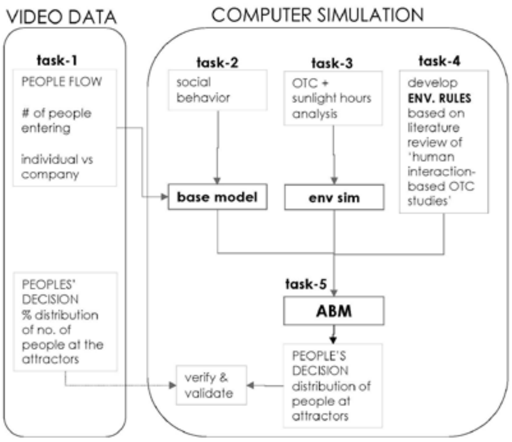

Figure 1: Workflow. (Source: Author.)

CASE STUDY

Federal Plaza in Chicago, located at the intersection of S. Dearborn and W. Adams Streets, is selected for the pilot study. A recent study by the author (Khan & Du, 2020) on urban plaza typologies in Chicago highlights Federal Plaza as the popular typology. It is an urban square enclosed by three buildings designed by Mies Van der Rohe: the high-rise John C. Kluczynski building (1974), the mid-rise Everett McKinley Dirksen building (1964), and the single-story U.S. Post Office building (1974). The iconic 'International Style' of glass and steel architecture attracts many visitors and tourists. The plaza also includes a red-colored, 53-feet tall steel sculpture "Flamingo" by Alexander Calder, and low rectangular granite benches placed in the northern and southern ends of the plaza. North bench is shaded with four deciduous trees (TCLF, n.d.).

Figure 2: Federal Plaza – location plan and Google map. (Source: Author.)

HUMAN SPATIAL BEHAVIOR SIMULATION

Urban block with Federal Plaza is parametrically modeled in Rhino V6 using GH scripting. Attractors, namely the "Flamingo" sculpture by Alexander Calder, north bench and south bench, are represented as points with color, yellow, blue, and pink, respectively (Figure 2). Human spatial behavior is simulated using the plug-in Quelea. Agents — representing pedestrians — are modeled as particles with individual attributes. The number of agents entering the space is modeled at two corners of the test surface. The table in Figure 3 shows a list of rules/forces applied in this model.

The output provides the location (i.e., 'x' and 'y' coordinates) of each agent tracked along their movement at every 20 m. Using the "data recorder" component in FIREFLY, the position can be recorded for each Quelea in CSV format. The simulation was conducted using five, one and 15 agents. The findings of this task outline a method to simulate agents' spatial behavior based on social forces. As an extension to this study, the model will be developed further to add complexity. Additional work on this simulation will include the following, but will not be limited to:

— Increase the number of people to see the agent-agent interaction
— Apply the environmental rules on outdoor thermal comfort and sunlight hour simulation and couple the two simulation models.
— Add people at the four entry points for the plaza to represent the actual scenario

Agent Life	
Continuous Flow	Boolean, repeated at the R^th^ rate if true otherwise only once if false
Creation Rate	R^th^ step; Default = 1
Number of Quelea	# of quelea to be alive in system; set to 1
Steering Forces	
Flocking Behavior: Mimics group of people / companionship	
	Separate force; W = 0.5
	Cohese force; W = 0.25
	Align force; W = 0.25
Individual Behavior: Mimics one person	
	Wander force; W = 0.25
Avoiding obstacle such as buildings, objects, etc.	
	Avoid Obstacle force; W = 0.25
Seek Behavior: Determines the agent's attraction to the targets	
	Seek force; W = 0.70 (flamingo sculpture)
	Seek force; W = 0.21 (shaded north bench)
	Seek force; W = 0.09 (unshaded south bench)

Figure 3: Quelea (ABM) Settings for human spatial behavior simulation. (Source: Author.)

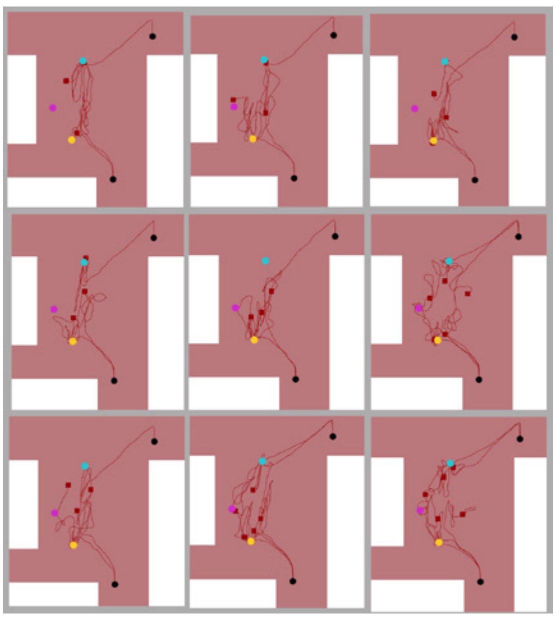

Figure 4: Simulations showing movement track of agents in Federal Plaza. (Source: Author.)

MICROCLIMATE SIMULATION

The Ladybug/Honeybee plug-in in Rhino GH is used for microclimate analysis involving sunlight hours and outdoor thermal comfort simulations using the algorithm sourced from the link by Chris Mackay. The geometry of Federal Plaza developed in Rhino is used as the context geometry while EPW and STAT files for Chicago, IL, are imported for weather data. The input and output parameters are listed in the table for each simulation. The output is also presented as a heat map as shown in Figures 5 and 6.

Results

The outputs for sunlight hours and outdoor thermal comfort (UTCI) simulations are heat maps with values ranging from 0 to 9 hours and 17°C to 19°C, respectively, spread over 438 test points in and around the plaza. The time period of the simulations is between 11 am and 1 pm for June 13. It is found that the sunlight hours for the “Flamingo” sculpture are least with 3.5 hours, as against the other two namely north shaded bench with 5.3 hours and south shaded bench showing a value of 4.5 hours. This shows that the north bench is exposed to sun as opposed to the “Flamingo” and south bench, which are shaded by the tall buildings. On the other hand, UTCI values for the three selected attractors (Figure 8) are similar and within the no stress zone of UTCI scale (Figure 7). This shows that all three points have good thermal comfort levels for people’s attendance. Furthermore, the simulated microclimatic variables, namely wind speed (W), relative humidity (RH), and dry bulb temperature (T), affecting the UTCI differ from the synoptic climate readings (Figure 8). Additionally, studies have shown that various wind speeds affect pedestrian comfort levels (Arens & Bosselmann, 1989) especially in tall urban conditions (Stathopoulos, 2009). The findings of this simulation show the wind speed value to be 6.2 m/s creating a slight discomfort (Stathopoulos, 2009).

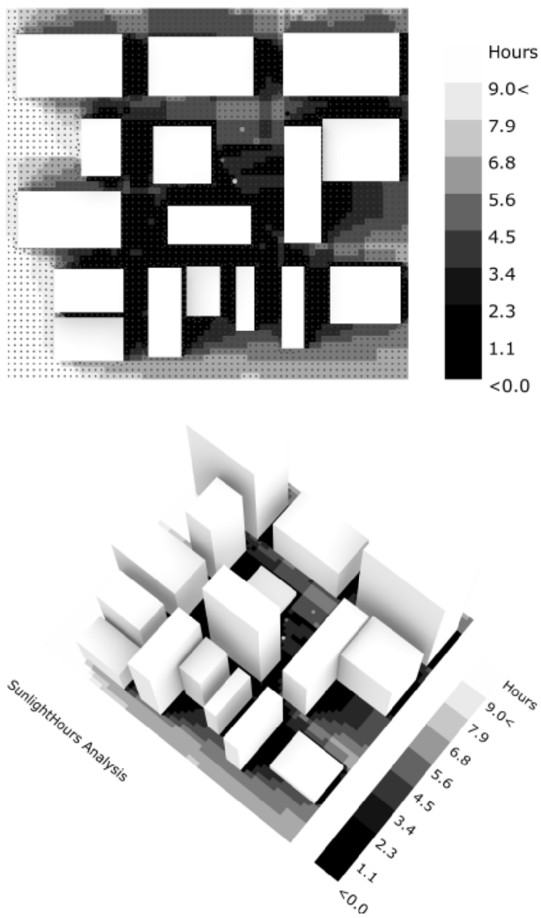

Figure 5: Sunlight hour analysis: plan and iso view. (Source: Author.)

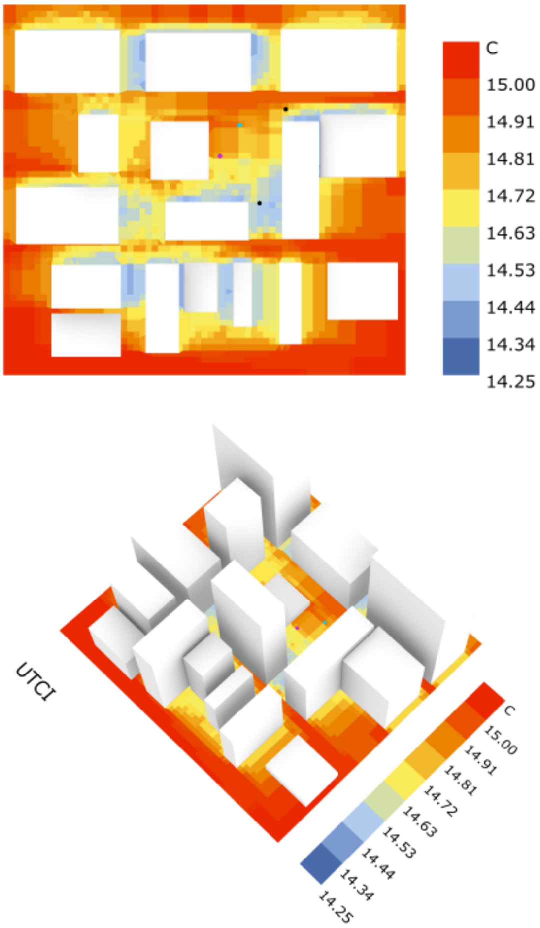

Figure 6: Outdoor thermal comfort analysis: plan and iso view. (Source: Author.)

Baseline for Outdoor Thermal Comfort	
UTCI - Strong Cold Stress	-13 to -27
UTCI - Moderate Cold Stress	0 to -13
UTCI - Slight Cool	0 to 9
UTCI - No Stress	9 to 26
UTCI - Slight Warm	26 to 28
UTCI - Moderate Heat Stress	28 to 32
UTCI - Strong Heat Stress	32 to 38
(UTCI = Universal Thermal Climate Index)	
Baseline for Wind Comfort	
W - Acceptable	< 5 m/s or 18 km/h
W - Onset of Discomfort	5 m/s or 18 km/h
W - Definitely Unpleasant	10 m/s or 36 km/h
W - Dangerous	20 m/s or 72 km/h
(W = Mean Wind Speed)	

Figure 7: UTCI values for OTC (Source: http://www.utci.org/); Wind comfort values (Source: Stathopoulos, 2009).

	Flamingo Sculpture	North Bench	South Bench
Survey (Env)			
T (°C)	17.2	17.2	17.2
RH (%)	50	50	50
W (m/s)	6.9	6.9	6.9
Simulation (Env)			
UTCI (°C)	14.58	14.78	14.63
Average Mrt (°C)	40.82	41.22	40.98
T (°C)	16.1	16.1	16.1
RH (%)	75	75	75
Average W (m/s)	6.2	6.2	6.2
SL-Hr	3.5	5.3	4.5
Simulation (HB)			
Position	(185, 245)	(191, 287)	(175, 262)
People Count Instances	26	9	0
Weight	0.5	0.5	0.1
Agents Simulated	1		

Figure 8: Survey and Simulation Results of people count and environmental variables. (Source: Environment variables in survey referred from https://www.wunderground.com/)

Discussion and Conclusion

This paper presents a framework for microclimate integrated human spatial behavior simulation to assess public space design. The study uses a pilot study to illustrate the initial results for simulations before coupling of plug-ins. The study helps in understanding the interrelationship between urban morphology, microclimates, and human behavior. Further work is proposed to develop a set of rules/algorithms using this interrelationship between microclimates and human behavior.

The primary application of this study is for architects and planners involved in the master plan design of outdoor public spaces and built forms. The study also benefits developers, policy makers, and other stakeholders responsible for determining design guidelines for a sustainable urban development. The overall contribution of this study will be toward sustainable growth of outdoor public spaces and urban neighborhoods to foster social, cultural, environmental, and economic upliftment in cities.

Acknowledgments

I acknowledge my dissertation committee members, Professor Brent Stephens, Professor Michelangelo Sabatino, Professor Mahjoub Elnimeiri, Professor Matthew Herman, and Professor Rahman Azari, for their invaluable guidance in this research.

References

Abar, S., Theodoropoulos, G. K., Lemarinier, P., & O'Hare, G. M. P. (2017). Agent Based Modelling and Simulation Tools: A review of the state-of-art software. *Computer Science Review*, *24*, 13–33. https://doi.org/10.1016/j.cosrev.2017.03.001

Arens, E., & Bosselmann, P. (1989). Wind Sun and Temperature-Predicting the thermal comfort of people in outdoor spaces. *Building and Environment*, *24*(4), 315–320.

ASHRAE. (2013). *Thermal Environment Conditions for Human Occupancy* (No. 55–2013). American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta.

Asriana, N., & Indraprastha, A. (2016). Making Sense of Agent-Based Simulation. *Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia*, 343–352. https://www.semanticscholar.org/paper/MAKING-SENSE-OF-AGENT-BASED-SIMULATION-Developing-Choo-Schnabel/fc710162e8f8507c282144223d5e031abc08fed6

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, *99*(suppl 3), 7280–7287. https://doi.org/10.1073/pnas.082080899

Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B., & Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, *56*(3), 481–494. https://doi.org/10.1007/s00484-011-0454-1

Bruse, M. (2002). Multi-Agent Simulations as a tool for the assessment of urban microclimate and its effect on pedestrian behaviour. *Proceedings of the 1st International Congress on Environmental Modelling and Software in June 2002, Lugano, Switzerland.*

Bruse, M. (2007). Simulating human thermal comfort and resulting usage patterns of urban open spaces with a Multi- Agent System. *Proceedings of the 24th International Conference on Passive and Low Energy Architecture PLEA, in November, 2007 in Singapore.* 69z–706.

Chen, L. (2011). *Towards an Integrated Pedestrian Thermal Comfort Assessment System: An Agent-Based Approach* [PhD thesis, The Chinese University of Hong Kong].

Chen, L., & Ng, E. (2012). Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities*, *29*(2), 118–125. https://doi.org/10.1016/j.cities.2011.08.006

Chokhachian, A., Ka-Lun Lau, K., Perini, K., & Auer, T. (2018). Sensing transient outdoor comfort: A georeferenced method to monitor and map microclimate. *Journal of Building Engineering*, *20*, 94–104. https://doi.org/10.1016/j.jobe.2018.07.003

Clarke, K. C. (2014). Cellular Automata and Agent-Based Models. In M. M. Fischer & P. Nijkamp (Eds.), *Handbook of Regional Science* (pp. 1217–1233). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-23430-9_63

Coccolo, S., Kämpf, J., Scartezzini, J.-L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban Climate*, *18*, 33–57. https://doi.org/10.1016/j.uclim.2016.08.004

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, *56*(3), 429–441. https://doi.org/10.1007/s00484-011-0424-7

Fisher, A. (2015). *Quelea: Agent-based design for Grasshopper*. http://quelea.alexjfischer.com/

Ghaffarian, M., Fallah, R., & Jacob, C. (2018). Organic architectural spatial design driven by agent-based crowd simulation. https://doi.org/10.22360/simaud.2018.simaud.017

Golasi, I., Salata, F., de Lieto Vollaro, E., & Coppi, M. (2018). Complying with the demand of standardization in outdoor thermal comfort: A first approach to the Global Outdoor Comfort Index (GOCI). *Building and Environment*, *130*, 104–119. https://doi.org/10.1016/j.buildenv.2017.12.021

Hollmann, C. (2015). *A Cognitive Human Behaviour Model for Pedestrian Behaviour Simulation* [PhD thesis, University of Greenwich, London, England]. https://core.ac.uk/download/pdf/42391364.pdf

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings*, *34*(6), 661–665. https://doi.org/10.1016/S0378-7788(02)00017-8

Khan, Z., & Du, P. (2020). Typologies of Outdoor Public Spaces at Street Level of Tall Buildings in Chicago. *Prometheus, 4,* IIT Architecture Chicago, 90–97.

Lam, F. K. (2011). *Simulating the Effect of Microclimate on Human Behavior in Small Urban Spaces* [PhD thesis, UC Berkeley]. https://escholarship.org/uc/item/2pn2f0z7

Langevin, J. (2014). *Human Behavior & Low Energy Architecture: Linking Environmental Adaptation, Personal Comfort, & Energy Use in the Built Environment* [PhD thesis, Drexel University]. https://doi.org/10.13140/RG.2.1.4945.8728

Melnikov, V., Krzhizhanovskaya, V. V., & Sloot, P. M. A. (2017). Models of Pedestrian Adaptive Behaviour in Hot Outdoor Public Spaces. *Procedia Computer Science*, *108*, 185–194. https://doi.org/10.1016/j.procs.2017.05.006

Papadimitriou, E., Yannis, G., & Golias, J. (2009). A critical assessment of pedestrian behaviour models. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(3), 242–255. https://doi.org/10.1016/j.trf.2008.12.004

Reynolds, C. (1999). *Steering Behaviors For Autonomous Characters.*

Rogers, J., Schnabel, M. A., & Tiantian, L. (2018). DIGITAL CULTURE An Interconnective Design Methodology Ecosystem. *Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.*

Serdar, S. E., & Kaya, M. E. (2019). Generative Landscape Modeling in Urban Open Space Design: An Experimental Approach. *Journal of Digital Landscape Architecture*, *4*, 231–238. https://doi.org/doi:10.14627/537663025

Sharmin, T., Steemers, K., & Matzarakis, A. (2015). Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh. *Building and Environment*, *94*, 734–750. https://doi.org/10.1016/j.buildenv.2015.10.007

Shooshtarian, S., Rajagopalan, P., & Sagoo, A. (2018). A comprehensive review of thermal adaptive strategies in outdoor spaces. *Sustainable Cities and Society*, *41*, 647–665. https://doi.org/10.1016/j.scs.2018.06.005

Stathopoulos, T. (2009). *Wind and Comfort.* European & African Conferences on Wind Engineering. Fifth Conference on Wind Engineering, Florence, Italy.

TCLF. (n.d.). *Chicago Federal Center Plaza | The Cultural Landscape Foundation.* Retrieved April 8, 2020, from https://tclf.org/landscapes/federal-plaza

Therakomen, P. (2001). *Mouse.class The Experiments for Exploring Dynamic Behaviors in Urban Places* [PhD thesis, University of Washington].

United Nations. (June 2019). *World Population Prospects 2019: Highlights | Multimedia Library - United Nations Department of Economic and Social Affairs*. https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html

U.S. Department of Agriculture. (2018). *Urban Nature for Human Health and Well-Being: A research summary for communicating the health benefits of urban trees and green space* (p. 24). USDA, Forest Service.

WHO. (2010). *Global recommendations on physical activity for health.* World Health Organization.

WHO. (2018). *Physical Inactivity: A Global Public Health Problem*. World Health Organization. https://www.who.int/dietphysicalactivity/factsheet_inactivity/en/