Converging Smartwatch and Urban Datasets for Sustainable City Planning
A Case Study in Seoul, South Korea

Mosteiro-Romero, Martín; Park, Yujin; Miller, Clayton

DOI
10.1051/e3sconf/202456203004

Publication date
2024

Document Version
Final published version

Published in
E3S Web of Conferences

E3S Web of Conferences **562**, 03004 (2024) https://doi.org/10.1051/e3sconf/202456203004
BuildSim Nordic 2024

Converging Smartwatch and Urban Datasets for Sustainable City Planning: A Case Study in Seoul, South Korea

Martín Mosteiro-Romero[1,*], *Yujin* Park[2,], and *Clayton* Miller[3]

[1]Department of Architectural Engineering and Technology, TU Delft, Delft, Netherlands
[2]Department of Urban Planning and Real Estate, Chung-Ang University, Seoul, South Korea
[3]Department of the Built Environment, National University of Singapore, Singapore

Abstract. The widespread availability of open datasets in cities is transforming the way urban energy systems are planned, simulated, and visualized. In this paper, a cross-scale approach is pursued to better understand the reciprocal effects between building energy performance, the urban climate, and urban dwellers' indoor and outdoor thermal comfort. On the one hand, monthly building electricity and gas demand data at the parcel level was collected, along with hourly weather station data at the urban scale. On the other hand, a longitudinal experiment was carried out in which 22 participants wore smartwatches for 4–6 weeks and filled out hourly micro surveys on their activities, location, and thermal comfort. In addition to survey responses, the smartwatches collected participants' physiological data and location throughout the period of the study. The project was conducted in Seoul, South Korea, the highest-ranked Asian country in open data readiness, implementation, and impact. This paper reports on the data collection effort and provides some preliminary analysis of the results. The work carried out is expected to help develop methodologies for the convergence of district-scale and occupant-scale data in urban areas. A number of expected applications are proposed, including urban-scale studies on the impact of urban form on the local climate and building energy performance, district-to-building-scale building energy simulations accounting for occupant thermal comfort-related behaviors, and district-scale analyses of occupants' outdoor thermal comfort and its relationship with location and wayfinding in urban areas.

1 Introduction

The widespread availability of open datasets in cities is transforming the way urban energy systems are planned, simulated, and visualized. Urban-scale datasets, including geographic information systems (GIS), smart energy meters, and telecommunications information, are facilitating the development of urban information models that can provide reliable estimates of energy demands for planning applications. In particular, urban digital twin platforms enable informed decisions and avoid costly ad-hoc problem-solving by facilitating the inclusion of stakeholders and have been used for various applications, including energy forecasting, operational optimization, participatory planning, policy development, and scenario modeling

*e-mail: m.a.mosteiroromero@tudelft.nl

[1]. There is also an emerging focus on the health, safety, fitness, and overall well-being of people in indoor and outdoor environments [2].

Smart city initiatives aim to integrate data collection in urban areas to optimize the performance of infrastructures such as transportation and energy. Such data-driven initiatives, however, often neglect the central role of urban dwellers, whose activities create the demand for energy and mobility in urban areas [3]. Urban digital twins should address social functions in the built environment, enabling participatory process and involving humans as sensors to learn about the local context [4]. However, building occupant data is typically not openly available for many reasons, including the difficulty of tracking individuals at the urban scale and privacy and safety concerns [5]. In addition, the interface between humans and the built environment surrounding them is important for this type of data collection in the first place, and it is also challenging in many respects [6, 7].

In this paper, a cross-scale approach is pursued to assess the reciprocal effects of building energy performance, the urban climate, and indoor/outdoor thermal comfort. On the one hand, urban datasets such as satellite imagery, remote sensing, and building geometries are collected to study the effects of urban form on a district's energy and climate performance. On the other hand, subjective thermal comfort data from urban dwellers is collected to analyze how the urban environment affects their choices and behaviors and how these might, in turn, affect energy performance. The project was conducted in a case study area in Seoul, South Korea, the highest-ranked Asian country on open data readiness, implementation, and impact [8] and home to one of the most digitally skilled populations in the world [9].

Integrating urban-scale datasets with subjective occupant feedback could allow planners to better understand the effects of planning decisions on urban energy performance and occupant well-being. The developed dataset is expected to be used in various applications, from urban building energy modeling to analyzing the effects of urban form on outdoor thermal comfort and wayfinding.

2 Methodology

The first phase of this project entails collecting datasets at urban and building occupant scales. These datasets will then be used to explore various questions at the interface between urban planning, building energy performance, and occupant comfort and well-being.

2.1 Urban dataset

The goal of the collection effort at the urban scale is to develop a 3D city model for a case study district, including building typologies, energy performance, and outdoor comfort-related infrastructure such as shading and green measures. The data collected prioritized the use of open-access databases for geospatial modeling.

The urban scale dataset comprises building geometries, building energy demand, weather station measurements, and satellite imagery. The monthly electricity and natural gas demand over a 10-year period for every building parcel in Seoul and hourly measurements from 54 automatic weather stations throughout the city are collected [10]. Building footprints and heights are similar to those available on the open data platform of the government of South Korea. Satellite imagery, including Landsat and ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) images, is also collected in order to account for land surface temperatures (LST) at the urban scale. Based on this remote sensing imagery, the effect of LST on outdoor thermal comfort can be explored [11].

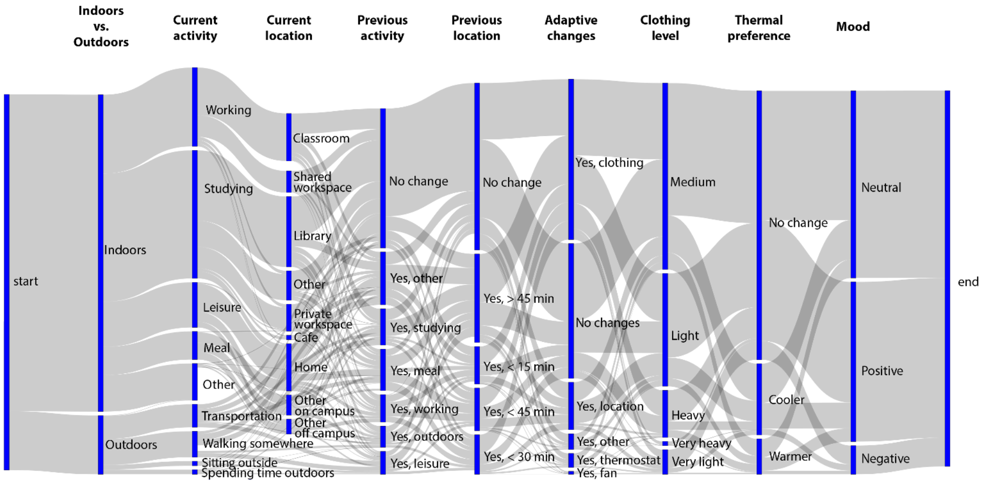

Figure 1. Distribution of survey responses for all participants at the end of the study. Participants were asked for their location (indoors vs. outdoors), current activity, current location, changes in activity and location, adaptive comfort interventions taken in the past hour, clothing level, thermal preference, and mood.

2.2 Occupant dataset

In parallel with the urban data collection effort, a longitudinal study was carried out to collect subjective thermal comfort feedback data from dwellers of that same urban area. This was done using Cozie Apple, an open-source smartwatch application to collect feedback from building occupants in real-time [12]. The measurement campaign aimed to obtain real-time data about building occupants' outdoor and indoor thermal comfort, location, and activities in a case study district.

The study was conducted at Chung Ang University (CAU) between 4 October and 17 November 2023. 22 participants were recruited through advertising in university courses, online social media, and word of mouth. The participants were undergraduate and master's students between 20 and 31 years old. The majority of participants identified as female (16 participants, 73%), and most owned their own Apple Watches (14, 64%). Participants who did not own Apple Watches were loaned one for the duration of the study.

The participants were asked to wear a smartwatch for 4 to 6 weeks, and during this time, their physiological and location data was recorded. The collected physiological information comprised the resting heart rate, heart rate variability, blood oxygen saturation, and wrist temperature. Noise levels, stand times, step counts, and walking distances were also recorded. In addition to this data, participants were requested to respond to hourly micro surveys on their location, current and past activities, clothing level, adaptive interventions, thermal preference, and mood. Occupants were required to complete a minimum of 100 microsurveys in order to complete the study.

This part of the study aimed to create a representative sample of actual occupants of the case study campus to better understand the urban environment's impacts on their behaviors and their behaviors' effects on building energy demand.

https://doi.org/10.1051/e3sconf/202456203004

Figure 2. Recorded occupant locations throughout the study at the urban scale.

3 Preliminary results

The distribution of survey responses from all participants is shown in Figure 1. Unsurprisingly, most survey responses were conducted indoors, with only about 20% of survey responses indicating an outdoor location. Most responses indicated "Studying" as the current activity, which is also expected given that all participants were students. The participants tended to indicate no change in activity or location with respect to the previous survey. Participants indicated satisfaction with their indoor environment most of the time (73% of indoor survey responses), with a slight preference for cooler environments than warmer (17% vs. 9% of indoor responses). Still, they often indicated that they had changed their clothing level to improve their thermal comfort.

In addition to the participants' survey responses, their physiological information and location were recorded every time they changed their location by 50 meters or more. The distribution of all participants' location records throughout the entire study is shown in Figure 2. Most of the records are concentrated in Dongjak District, where the CAU campus is located, as well as on major roads and subway lines.

Figure 3 shows the thermal preference votes within Dongjak District during the entire study period. As discussed for the indoor environment, most of the responses (62%) indicate that participants preferred "no change" to their thermal environment outdoors as well. This could be explained by the relatively mild weather experienced during the study, and at the end of October in particular, as shown in Figure 4.

Numerous "prefer cooler" and "prefer warmer" responses are also observed. In particular, there was a large number of "prefer cooler" responses at the end of October, when temperatures were higher than average for that time of the year. After that, temperatures dropped sharply, and "prefer warmer" responses started increasing. Part of the goal of this study was to precisely study how participants' perceptions changed during this time of the year when temperatures in Seoul typically drop rapidly. The unusually mild and constant weather experienced during October ultimately strongly influenced the results. Therefore, future studies

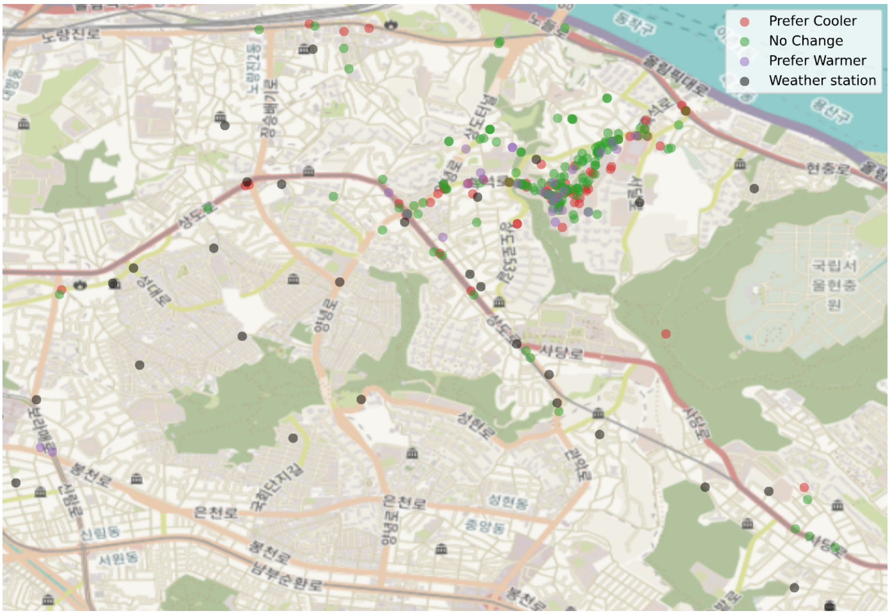

Figure 3. Thermal preference survey responses along with the location of weather stations within Dongjak District.

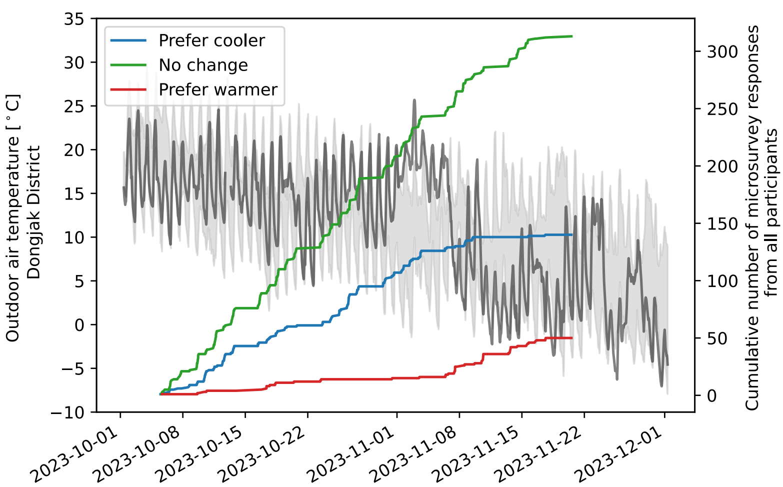

Figure 4. Cumulative number of microsurvey responses by thermal comfort preference from all participants compared to the outdoor temperature in Dongjak District during the study (in black) along with the range of temperatures observed on the same date and time over the previous ten years (in gray).

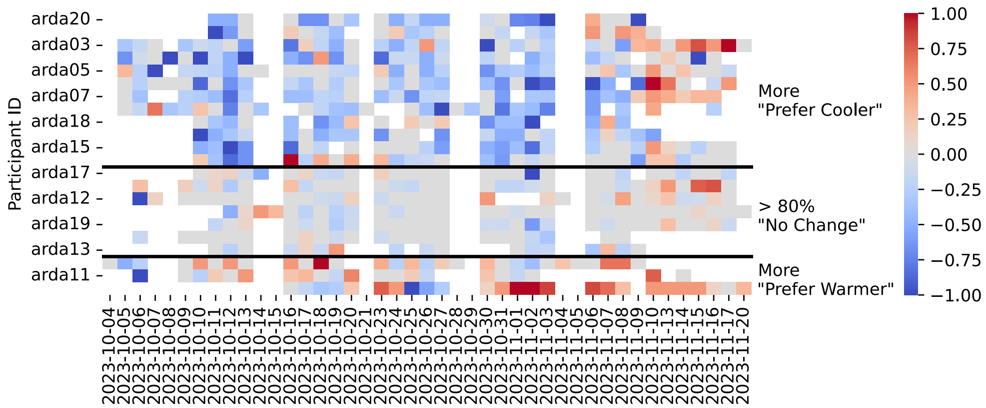

Figure 5. Mean daily thermal preference reported by each participant by date (-1: "Prefer Cooler", 0: "No Change", 1: "Prefer Warmer"), clustered by the share of their survey responses: ≥ 80% "No Change", more "Prefer Cooler" than "Prefer Warmer", and more "Prefer Warmer" than "Prefer Cooler". The most common response for all participants was "No Change".

could benefit from extending the period of study to capture a greater diversity of weather conditions. Given the number of weather stations located within the area (Figure 3), the outdoor conditions leading to occupants' subjective assessments can be further explored.

Participants' responses are shown in a calendar view in Figure 5. Since the number of responses by date by participant varies, the results are shown as daily means by coding the values reported by participants ("Prefer Cooler": -1, "Prefer No Change": 0, "Prefer Warmer": 1). For all participants, the most common response was "No Change". Therefore, the participants are clustered into three groups: participants with 80% or more of "No Change" responses, participants with less than 80% "No Change" and more "Prefer Cooler" responses, and participants with less than 80% "No Change" and more "Prefer Warmer" responses. The results again show that the majority of "Prefer Cooler" responses occur during the mild month of October, with the number of "Prefer Warmer" responses increasing towards the end of the study. A relatively large share of participants (7) consistently reported "No Change" as their response. Among the remaining participants, "Prefer Cooler" was more common than "Prefer Warmer".

4 Discussion and Outlook

The collected dataset can be used to facilitate a variety of possible research directions across spatial scales in cities. This section outlines the potential impacts of the application of this method on the urban, district, building, and human dimensions of the built environment in addition to machine learning models.

4.1 Urban scale: Digital Twin

The urban dataset can be used to develop an urban digital twin using a bottom-up approach similar to Alva et al. [13]. A 3D geometry base is created from the building footprint and height data and categorized by building typology. This geometry base can be combined with building energy demand and urban weather station data to create an integrated 3D city dataset. Such a dataset could then be visualized in a dashboard to allow users to access the urban data

 https://doi.org/10.1051/e3sconf/202456203004

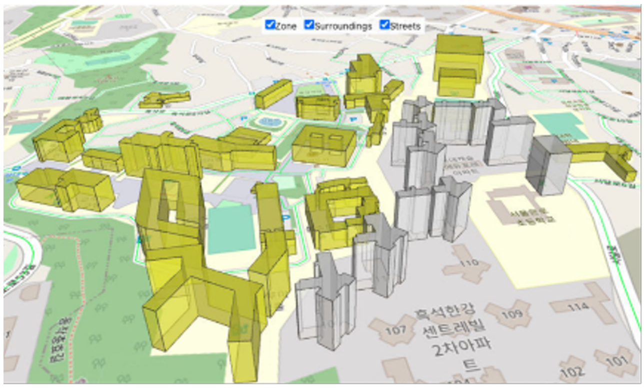

Figure 6. Screenshot of the City Energy Analyst model of the Chung Ang University campus.

and analyze energy and climate patterns at the urban scale. By combining it with urban energy simulations, users could also view the effects of different future scenarios on urban energy performance and climate resilience. Digital twin analysis is conducted with different levels of detail and specificity that can impact the usability of performance calculation based on those models [14].

4.2 District to Urban scale: Building energy modeling

A district-scale energy model of the CAU campus was developed using the City Energy Analyst (CEA), an open-source platform for district energy optimization (see Figure 6). Building use types were assigned according to the university's campus map. In the absence of construction material properties and building management systems (BMS) data, the model could be calibrated using the collected meter data as done by Mosteiro-Romero et al. [15]. A simplified method could be used to expand to the urban scale, as described in Alva et al. [13]. This type of analysis would form the foundation for scalable strategies for improving the building stock across districts or portfolios of buildings for maximum impact [16]. Furthermore, the building energy demand model could incorporate occupants' activities and thermal preferences, as discussed in the building scale section below.

4.3 District to Urban scale: Outdoor thermal comfort

The collected dataset includes occupants' physiological response and movement at different locations at the urban scale, as well as their subjective perception of the outdoor environment. Coupled with the weather station dataset, we can explore the effects of the urban microclimate on occupants' outdoor thermal comfort assessments within a highly dense urban environment. On a preliminary analysis of the smartwatch and weather station data, mean daily outdoor air temperature was found to correlate best with participants' daily step count and walking distance (Figure 7). The correlation is not strong, as the factors leading to a participant walking more or less throughout a day might be numerous. However, the fact that temperature appears to be the most relevant environmental factor indicates a potential for further analysis of specific microclimatic and urban form features that lead to occupants' thermal comfort satisfaction ratings.

A further application of interest is assessing how urban dwellers' wayfinding and location choices relate to the land surface temperatures (LST) obtained from the satellite data.

 https://doi.org/10.1051/e3sconf/202456203004

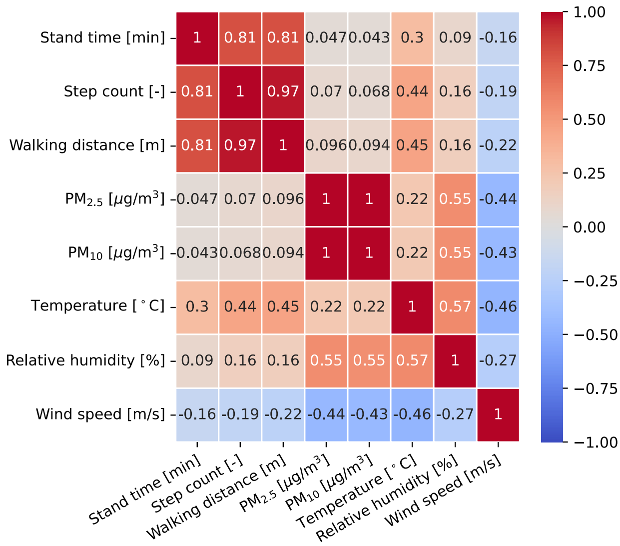

Figure 7. Pearson correlation matrix between daily stand time, step count, and distance walked for all participants in the study and the daily mean value of different parameters measured by the urban weather stations.

This information could help understand how urban planning decisions might affect outdoor thermal comfort and well-being in an urban district. This type of innovation would rely on the development of prediction models that leverage the combination of spatial, temporal, and subjective preference data with the objective of interfacing with an urban dweller in real time. These types of machine learning models are emerging as methods to create such data sets [17]. The development of these models could also help to personalize system responses in the built environment [18] as well as just-in-time information to assist a person in making the right decisions to impact their immediate comfort [19].

4.4 Building scale: Occupant behavior and thermal comfort

Personal comfort data could be used to develop a building occupancy model as an input to the district energy simulation in order to assess how urban dwellers' activities and choices affect district energy performance. Using Cozie data to develop an agent-based model of building occupants was presented by Mosteiro-Romero et al. [20]. Activity and location profiles can be estimated based on the corresponding questions in the smartwatch dataset (Figure 8) and used as inputs into an agent-based activity and location choice model.

Personal comfort profiles can also be developed based on the dataset, and based on the self-reported comfort adaptation options available to each participant, occupant adaptive behaviors in a case study building can also be modeled. However, without BMS data, the relationship between occupants' behaviors and thermal responses to the indoor environment cannot be studied, so the scope of the application will need to be defined clearly. One possibility would be to estimate occupants' thermal preference responses based on outdoor air temperature. As expected, the distribution of "Prefer Cooler" and "Prefer Warmer" responses to micro surveys carried out outdoors strongly relates to the outdoor air temperature (Figure 9). While the relationship is less straightforward for indoor responses, especially for

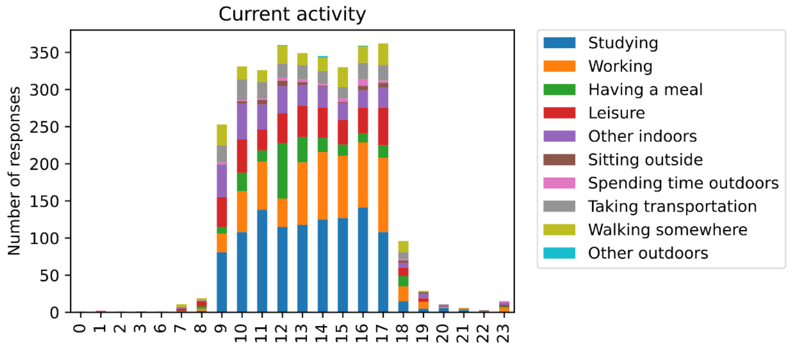

Figure 8. Distribution of the reported current activity at each hour of the day for all participants.

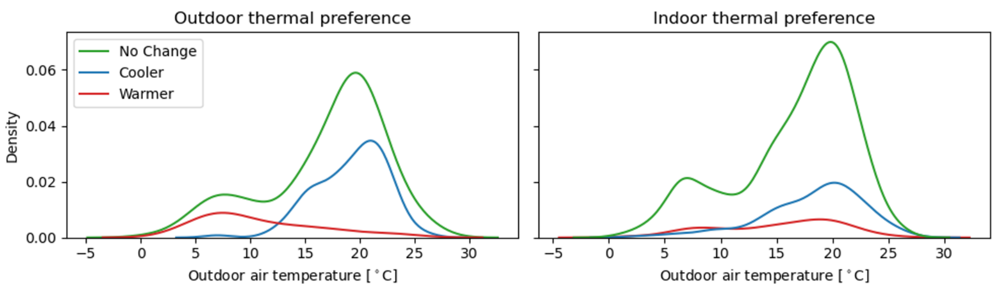

Figure 9. Empirical density distribution of the current thermal preference reported by all participants in outdoor locations (top) and indoor locations (bottom) as a function of temperature (taken from the closest weather station at the time of the microsurvey).

"Prefer Warmer" votes, the outdoor temperature could nevertheless be used as an indicator for the probability of occupants expressing a given thermal preference at different outdoor temperatures.

In addition to energy and thermal comfort, there are occupant behavioral aspects that are often neglected but warrant attention, such as noise, privacy, health, fitness, and interaction between people. A recent study used wearable data collection and sensors to understand the interactions between occupants regarding the quantity, quality, and impact on focus and productivity [21]. Additional data sets, such as smartphone data collected from Wifi networks, would also provide another layer of insights on occupant movement and interactions [22].

5 Conclusions

The collected dataset aims to help develop methodologies for integrating urban-scale and occupant-scale data in urban planning decisions. In this project, we developed an urban dataset comprising urban-scale building geometry, energy demand, urban microclimate data, and subjective thermal comfort feedback data from urban dwellers.

This project is intended to provide a framework for this integration. While the number of participants in the occupant data collection was reasonably limited at 22, the study is intended to show the potential for integrating subjective feedback data into larger-scale decision-making. Future applications could include feedback from anyone wearing a smartwatch on campus, similar to how online ratings allow users to provide subjective feedback on commercial establishments. Likewise, the integration with urban data should include a broader time span to observe occupant responses during hot and cold seasons.

Integrating urban-scale datasets with subjective occupant feedback can allow planners to better understand the effects of planning decisions on urban energy performance and occupant well-being. Future applications for this dataset were presented, ranging from building-scale occupant behavior modeling and district- to urban-scale building energy simulations and data analysis studies relating to outdoor thermal comfort and wayfinding and data visualization in urban digital twins.

Acknowledgments

The authors would like to thank Yun Xuan Chua for her support in getting the project's ethical review board approval, setting up the onboarding and offboarding questionnaires, and preparing advertising materials. We would also like to thank Mario Frei for his technical support in setting up the questionnaires on the Cozie application and his assistance in collecting the data through an API. We are also thankful to Deokyeon Geum for his assistance in translating the questionnaires and documentation for the project. This project was supported by a Gen A Alumni Travel Grant from Asia Society Switzerland.

References

[1] P. Alva, F. Biljecki, R. Stouffs, Use cases for district-scale urban digital twins, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. **XLVIII-4/W4-2022**, 5 (2022). 10.5194/isprs-archives-XLVIII-4-W4-2022-5-2022

[2] S. Altomonte, J. Allen, P.M. Bluyssen, G. Brager, L. Heschong, A. Loder, S. Schiavon, J.A. Veitch, L. Wang, P. Wargocki, Ten questions concerning well-being in the built environment, Build. Environ. **180**, 106949 (2020). 10.1016/j.buildenv.2020.106949

[3] A. Heydarian, C. McIlvennie, L. Arpan, S. Yousefi, M. Syndicus, M. Schweiker, F. Jazizadeh, R. Rissetto, A.L. Pisello, C. Piselli et al., What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories, Build. Environ. **179**, 106928 (2020). 10.1016/j.buildenv.2020.106928

[4] B. Lei, P. Janssen, J. Stoter, F. Biljecki, Challenges of urban digital twins: A systematic review and a Delphi expert survey, Autom. Constr. **147**, 104716 (2023). 10.1016/j.autcon.2022.104716

[5] G. Happle, J. Fonseca, A. Schlueter, A review on occupant behavior in urban building energy models, Energy Build. **174**, 276 (2018). 10.1016/j.enbuild.2018.06.030

[6] J.K. Day, C. McIlvennie, C. Brackley, M. Tarantini, C. Piselli, J. Hahn, W. O'Brien, V.S. Rajus, M.D. Simone, M.B. Kjærgaard et al., A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Build. Environ. **178**, 106920 (2020). 10.1016/j.buildenv.2020.106920

[7] B. Becerik-Gerber, G. Lucas, A. Aryal, M. Awada, M. Bergés, S. Billington, O. Boric-Lubecke, A. Ghahramani, A. Heydarian, C. Hölscher et al., The field of human building interaction for convergent research and innovation for intelligent built environments, Sci. Rep. **12**, 22092 (2022). 10.1038/s41598-022-25047-y

[8] World Wide Web Foundation, Open Data Barometer: Leaders Edition (World Wide Web Foundation, Washington DC, USA, 2018)

[9] Wiley, Digital Skills Gap Index 2021 (John Wiley & Sons, New York, USA, 2021)

[10] M.A. Su, J. Ngarambe, M. Santamouris, G.Y. Yun, Empirical evidence on the impact of urban overheating on building cooling and heating energy consumption, iScience **24**, 102495 (2021). 10.1016/j.isci.2021.102495

[11] Y. Park, J.M. Guldmann, D. Liu, Impacts of tree and building shades on the urban heat island: Combining remote sensing, 3D digital city and spatial regression approaches, Comput. Environ. Urban Syst. **88**, 101655 (2021). 10.1016/j.compenvurbsys.2021.101655

[12] F. Tartarini, M. Frei, S. Schiavon, Y.X. Chua, C. Miller, Cozie Apple: An iOS mobile and smartwatch application for environmental quality satisfaction and physiological data collection, J. Phys. Conf. Ser. **2600**, 142003 (2023). 10.1088/1742-6596/2600/14/142003

[13] P. Alva, M. Mosteiro-Romero, W. Pei, A. Bartolini, C. Yuan, R. Stouffs, Bottom-Up Approach For Creating An Urban Digital Twin Platform And Use Cases: A City Energy System Dataset Visualisation And Query, in *Proceedings of the 28th International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA) 2023* (Ahmedabad, India, 2023), pp. 605–614

[14] S. Cheng, Z.D. Tekler, H. Jia, W. Li, A. Chong, Evaluating different levels of information on the calibration of building energy simulation models, Build. Simul. **17**, 657 (2024). 10.1007/s12273-024-1115-8

[15] M. Mosteiro-Romero, C. Miller, A. Chong, R. Stouffs, Elastic buildings: Calibrated district-scale simulation of occupant-flexible campus operation for hybrid work optimization, Build. Environ. **237**, 110318 (2023). 10.1016/j.buildenv.2023.110318

[16] W. Li, G. Gong, H. Jia, Z. Ren, A. Chong, A real options-based decision-making model analysis for climate change mitigation strategies on buildings, J. Clean. Prod. **429**, 139524 (2023). 10.1016/j.jclepro.2023.139524

[17] C. Miller, M. Quintana, M. Frei, Y.X. Chua, C. Fu, B. Picchetti, W. Yap, A. Chong, F. Biljecki, Introducing the Cool, Quiet City Competition: Predicting Smartwatch-Reported Heat and Noise with Digital Twin Metrics, in *BuildSys '23: Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation* (Istanbul, Turkey, 2023), pp. 298–299

[18] L. Arakawa Martins, V. Soebarto, T. Williamson, A systematic review of personal thermal comfort models, Build. Environ. **207**, 108502 (2022). 10.1016/j.buildenv.2021.108502

[19] C. Miller, Y.X. Chua, M. Frei, M. Quintana, Towards smartwatch-driven just-in-time adaptive interventions (JITAI) for building occupants, in *BuildSys '22: Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation* (Boston, USA, 2022), pp. 336–339

[20] M. Mosteiro-Romero, M. Quintana, C. Miller, R. Stouffs, From Personal Comfort to District Performance: Using Smartwatch and WiFi Data for Occupant-Driven Operation, in *BuildSys '23: Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation* (Istanbul, Turkey, 2023), pp. 278–279

[21] K. Maisha, M. Frei, M. Quintana, Y.X. Chua, R. Jain, C. Miller, Utilizing wearable technology to characterize and facilitate occupant collaborations in flexible workspaces, J. Phys. Conf. Ser. **2600**, 142009 (2023). 10.1088/1742-6596/2600/14/142009

[22] M. Mosteiro-Romero, C. Miller, M. Quintana, A. Chong, R. Stouffs, Leveraging campus-scale Wi-Fi data for activity-based occupant modeling in urban energy applications, J. Phys. Conf. Ser. **2600**, 132008 (2023). 10.1088/1742-6596/2600/13/132008