Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: D Wang *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 082017

CISBAT 2025 IOP Publishing
Journal of Physics: Conference Series **3140** (2025) 082017 doi:10.1088/1742-6596/3140/8/082017

Enhancing urban digital twin interfaces to support thermal comfort planning

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Abstract. Urban Digital Twins (UDTs) integrate multilayered spatial data to support urban planning and climate adaptation efforts. Although UDTs have advanced significantly in data integration and predictive modeling, their usability remains underexplored. This study evaluates the Baselining, Evaluating, Action, and Monitoring (BEAM) platform, a web-based UDT developed by the National University of Singapore (NUS) for thermal comfort analysis. Through usability testing with ten urban planners and researchers, five from Singapore and five from the United States, this research assesses navigation, data interpretation, and integration into real-world workflows. Participants completed guided tasks as well as usability surveys, revealing key challenges in data navigation, interface clarity, and analytical flexibility. User Experience Questionnaire (UEQ) results showed high scores for attractiveness (1.67) and stimulation (1.70), but lower ratings for perspicuity (0.75). The findings highlight the need to improve affordances, contextual information, and the ability to interpret complex data sets. Minor regional differences in usability preferences also emerged, particularly in seasonal analysis and measurement units. By bridging technical advances with practical usability insights, this study contributes to the development of more accessible and effective UDT platforms. The findings inform future design improvements to enhance the adoption of UDTs, ensuring that these tools better support urban planners, policy makers, and researchers in climate adaptation and decision-making processes.

1. Introduction

Urban Digital Twins (UDTs) are increasingly vital tools for managing resource allocation, mobility, and climate adaptation [1, 2]. In thermal comfort planning, UDTs help analyze urban heat dynamics, considering factors such as vegetation, surface materials, and street geometry [3]. While research has emphasized data integration and modeling, few studies explore how urban planners, policy makers, and researchers interact with UDTs in practice [4, 5]. This study evaluates the usability of the Baselining, Evaluating, Action, and Monitoring (BEAM) platform, a web-based UDT developed at the National University of Singapore (NUS) [6, 7]. It aims to assess user interaction with BEAM, identify interface improvements, and compare usability differences between Singapore and the United States. By bridging technical advances and real-world use, this research supports the development of more accessible and effective digital twin platforms for heat-related climate adaptation.

1.1. Recent UDT developments and usability challenges

UDTs are digital city models that can integrate real-time data from IoT sensors and satellite imagery. In urban heat mitigation, they enable analysis of heat stress and modeling of interventions [8]. Recent advances have expanded data integration capabilities of UDTs, for example, incorporating satellite-derived indices to assess vegetation density and surface moisture [9], and improving spatial resolution through wearable sensor data [10]. Artificial intelligence has further enhanced the predictive capabilities of UDTs, with notable examples including Afzalinezhad et al.'s Digital Twin-Based Planning Support System using Random Forest regression [9] and Lam et al.'s integration of Mixture-of-Expert models to forecast thermal comfort across demographic variations [11]. Despite these technical innovations, usability remains a major challenge. Ferré-Bigorra et al. found that only 18% of studies on UDTs address real-world applications, highlighting a gap between development and adoption [1]. Although user-centered approaches have emerged, such as Maiullari et al.'s interactive stakeholder feedback process for Gothenburg's City Digital Twin [4], broader adoption issues persist. Chan et al.'s evaluation of the Cooling Singapore Decision Support System highlighted diverse user needs and requirements for more flexible interactions and analysis methods [12]. These findings underscore the importance of refining UDT interfaces for practical use.

2. Methodology

This study evaluates BEAM, a NUS-developed UDT that integrates diverse environmental datasets including weather stations, thermal images, 360° street views, tree census data, and smartwatch-based surveys into a single platform. BEAM aims to make thermal comfort insights more intuitive for planners, researchers, and policy makers. Interviews were conducted with professionals experienced in urban design and heat mitigation to assess BEAM's usability and suggest improvements.

Figure 1 shows the BEAM interface, which consists of three main components: main viewer, top navigation bar, and left navigation bar. The main viewer displays terrain, 3D building models, and selected datasets. Users can zoom, pan, and rotate the camera. The top navigation bar controls display settings (e.g., toggling buildings, greenery, and context layers; switching between 2D & 3D views). The left navigation bar shows options for data displays and updates the main viewer upon user selection. The platform supports two primary data visualization modes: point-based data and area-based data. For point-based data, such as weather stations, users access each data point through interactive markers. The markers open modals with details, with multiple modals viewable simultaneously. Area-based data (e.g., microclimate map) appears as overlays with toggleable sub-datasets and time-series exploration. The legend options include dynamic and static, which allow for temporal or fixed-scale comparisons. BEAM also features an integrated thermal walk view that overlays route-based maps with point-specific data, allowing users to analyze paths while accessing geolocated environmental measurements and survey responses (marked by watch icons) at specific locations.

2.1. User Study Design

Ten participants, five from Singapore and five from the United States, were recruited through personal referrals and LinkedIn outreach. They worked in government, academia, or private practice, with expertise in planning, data analytics, or climate resilience. Each participant completed a 60-minute interview with one researcher, which consisted of five components: background questions, exploration phase, guided tasks, survey, and open-ended discussion. All participant responses and additional visualizations are accessible in a public GitHub repository[13].

Participants began by describing their familiarity with Urban Digital Twins and data analysis tools. This was followed by a five-minute exploratory period, allowing participants

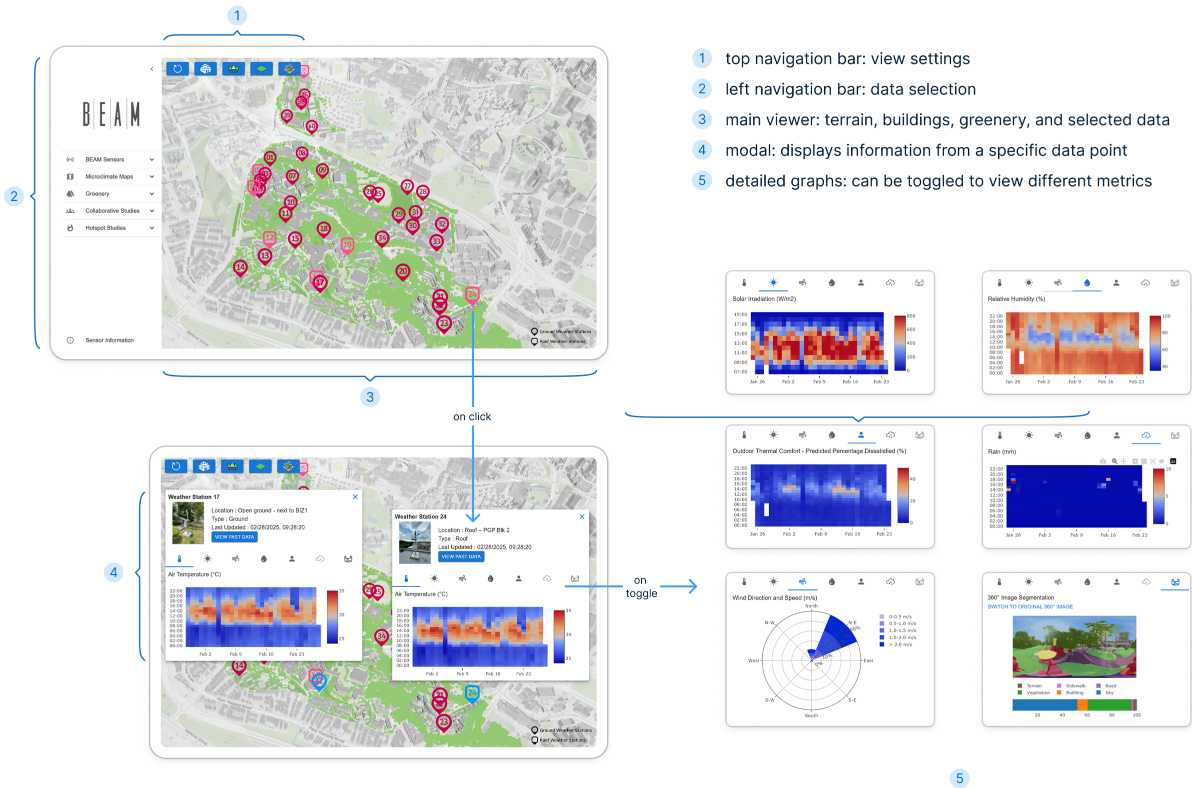

Figure 1: Organization and user flow of BEAM.

to develop an initial understanding of BEAM's features and ask the researcher questions. The participants then completed three tasks of increasing complexity using BEAM: retrieving thermal comfort data from a specific weather station, identifying hot spots using microclimate maps, and synthesizing the results of the perception survey with objective climate measurements on thermal walks. Throughout, participants used the think-aloud method to share their reasoning and provide live feedback. Immediately after the tasks, the participants completed an online survey consisting of the User Experience Questionnaire (UEQ) [14], which evaluates usability in six dimensions, and questions based on Gemini Principles [15], a framework that evaluates digital twins in terms of purpose, trust, and function. The session concluded with a discussion that gathered qualitative feedback on interface design, data visualization, analytical features, accessibility, and community engagement. This combination of structured and open-ended input provided a comprehensive assessment of BEAM's usability and areas for improvement.

3. Results and discussion

Of the ten participants, half were unfamiliar with UDTs, one recognized the term but had never used it, and four had limited prior exposure. All participants had experience with data-driven tools, primarily GIS or climate simulation software. Most expressed interest in using quantitative analysis to compare the impacts of different decisions, but acknowledged challenges in data collection and interpretation.

3.1. Open Navigation and Guided Tasks

During open exploration, participants actively interacted with the features of BEAM, but often requested more contextual information. 3D view manipulation and left navigation bar often posed usability challenges, prompting suggestions for clearer data categorization and the addition of explanation panels.

In the first task, participants were instructed to open a weather station modal and locate the thermal comfort data. Participants encountered issues with icon clarity, several suggesting the addition of text labels or hover descriptions. While all users identified correlations between climate variables such as air temperature and thermal comfort, only 40% discovered advanced chart features such as zooming, time-period adjustments, and image download without guidance. Users requested clearer metric explanations, particularly for calculated indices like "Predicted Percentage Dissatisfied (%)," and raw data export options. The second task required users to identify urban hot spots over time and infer causal relationships with surrounding elements. All participants successfully activated the time-lapse simulation and identified persistent hot spots, but many struggled with scale settings. Users were divided between fixed scales (better for cross-temporal comparisons) and dynamic scales (enhanced within-period contrast), although most preferred fixed scales as the default. When analyzing heat causes, most participants correctly associated thermal comfort patterns with vegetation and morphology. Key suggestions included integrating detailed base maps to clarify land use and displaying rooftop temperatures for more comprehensive heat analysis. For the final task, users were asked to analyze data from a thermal walk and connect subjective survey responses with objective climate measurements. While all participants successfully initiated the thermal walk playback, they struggled with inconsistent interface conventions (for example, microclimate maps timelapses use "start/stop" buttons while thermal walks use play icons) and had difficulty locating thermal walk surveys via watch icons. Only 20% successfully synthesized survey responses with objective environmental data (e.g., recognizing the influence of solar radiation and cloud cover on thermal perception), highlighting a critical analytical gap. To facilitate better synthesis, the participants suggested linking survey responses to the corresponding time-stamped objective data, so that selecting a survey response would automatically adjust the timeline on the objective data panel. Users also expressed interest in additional contextual information, including demographic insights, terrain data, and definitions of perceived thermal comfort. Further enhancements were proposed, such as layering microclimate data, enabling comparisons across multiple thermal walks, and leveraging generative AI to summarize key insights.

3.2. Survey Results

The User Experience Questionnaire (UEQ) indicated a generally positive evaluation of BEAM. The UEQ scales range from -3 (strongly negative) to 3 (strongly positive), with values below -2 and above 2 being rare in practical applications. Scores between -0.8 and 0.8 are considered neutral, while values below -0.8 are deemed negative and those exceeding 0.8 positive [14]. In this study, the BEAM platform received the following scores: attractiveness (1.67), perspicuity (0.75), efficiency (1.25), dependability (1.33), stimulation (1.70), and novelty (1.25). These dimensions correspond to key aspects of usability: attractiveness reflects the overall user impression; perspicuity measures learnability; efficiency assesses task completion effort; dependability evaluates user confidence in system reliability; stimulation considers engagement and excitement; and novelty indicates the innovation of the system. To contextualize these results, scores were compared with the UEQ benchmark dataset, which comprises responses from 21,175 users across 468 products [16]. As shown in Fig. 2, attractiveness, stimulation, and novelty were classified as good (75th to 90th percentile), efficiency and dependability were above average (50th to 75th percentile), and perspicuity was below average (25th to 50th percentile). These results suggest that while BEAM offers a novel and exciting interface, its complexity can hinder usability, with room to improve efficiency and reliability.

Users also evaluated the platform based on eight key questions adapted from the Gemini Principles, which assesses trust, purpose, and function in digital twins. These questions covered

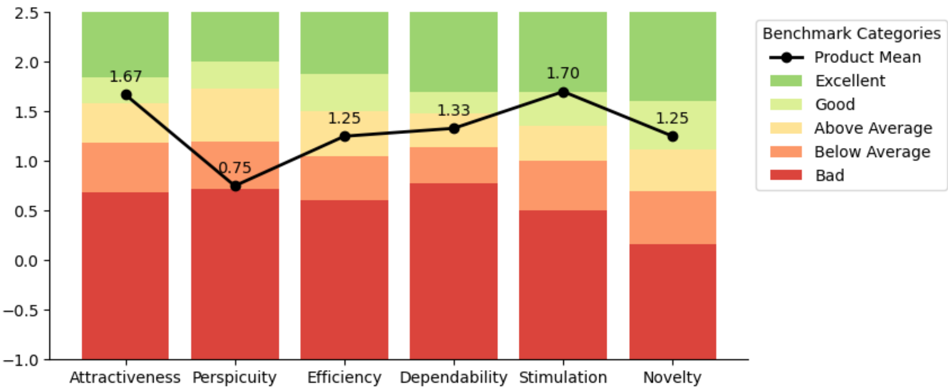

Figure 2: Mean ratings from UEQ by category, plotted against benchmark results.

aspects such as public benefit, value, security, openness of data, adaptability to workflows, ownership transparency, and the platform's ability to evolve. Users rated each aspect on a scale from -3 (strongly negative) to 3 (strongly positive), with higher scores indicating a greater perceived value or benefit of the platform. The results (Fig. 3) reflect that users largely recognized the potential of the BEAM platform, particularly in providing insight into the built environment as it received the highest mean rating (2.4). Participants also acknowledged BEAM's public benefit (1.8), general value (1.6), and potential to adapt with future technological advancements (1.8), though some questioned its relevance to their daily workflows (1.5). Security perceptions were moderate (0.9), indicating no major concerns but revealing the need for clearer communication about data protection and privacy. The relatively low rating for data openness (0.4) reflected frustration with the inability to upload or download datasets, which may limit broader adoption and integration. Notably, the lowest-rated aspect was ownership transparency (-0.9), signaling a critical gap in understanding who manages and maintains the platform's data ecosystem. This ambiguity could affect trust and long-term engagement. These findings highlight the need to improve governance transparency, enhance data accessibility, and better address security communication to support long-term user trust and adoption.

3.3. Open-ended Discussion

Overall, participants expressed a strong need for clearer interface elements, better navigation, and greater contextualization of the data. Key usability challenges included the organization of the data layers in the left navigation bar, the discoverability of interactive features, and the interpretability of thermal comfort metrics. Many users, particularly those less experienced with climate data, requested more explanations on measurement methodologies and data sources. Navigation patterns were largely consistent between participants in the United States and Singapore, with U.S.-based users placing greater emphasis on seasonal variability. Two U.S.-based participants also suggested incorporating imperial units, as the current platform displays only metric measurements. In terms of envisioned use, practitioners saw BEAM as valuable for site analysis to inform early design decisions, evidence-based storytelling to communicate insights to stakeholders, and scenario testing to evaluate the thermal effects of proposed developments. These findings underscore the importance of balancing analytical depth with accessibility, ensuring that both expert and novice users can derive meaningful insights from BEAM.

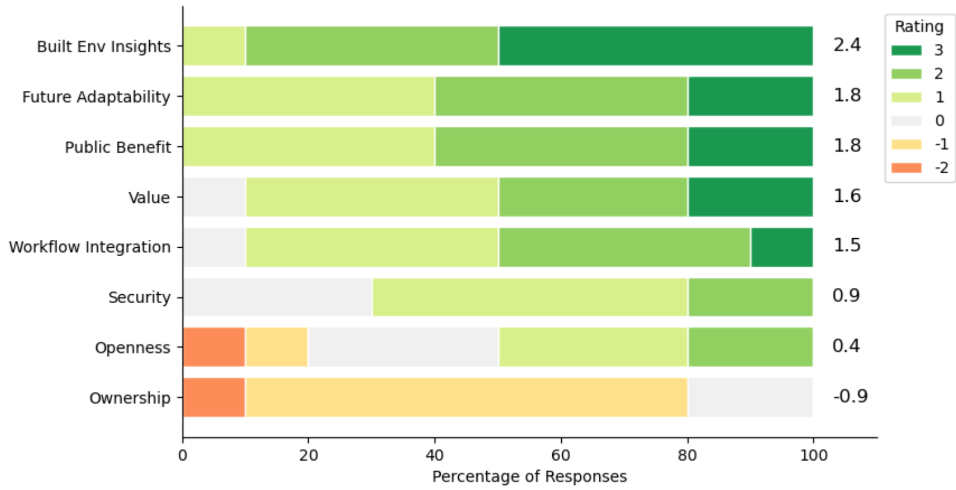

Figure 3: Distribution of ratings for questions related to Gemini Principles.

3.4. Limitation and Future Work

This study presents several limitations. First, the small sample size of ten participants, while diverse in geography and professional background, limits the generalizability of findings and the statistical strength of derived metrics such as the UEQ scores. Second, each participant underwent an individual 60-minute session, which likely introduced variability in explanation, engagement, and prior knowledge despite the use of a consistent task structure. These factors may have influenced how users interpreted the platform and completed the usability tasks.

Future work could address these limitations by conducting larger-scale studies with more standardized onboarding and training procedures. Additionally, future usability research could employ iterative testing cycles, where interface changes are implemented based on user feedback and evaluated for effectiveness. This would allow a deeper understanding of how specific design adjustments affect usability, and support the broader goal of making UDT platforms more intuitive, accessible, and impactful in real-world planning contexts.

4. Conclusions

This study evaluates the BEAM platform, a web-based UDT developed at the National University of Singapore, through usability testing with ten urban planners and researchers in Singapore and the United States. Findings reveal issues with data navigation, interface clarity, and analytical flexibility, limiting UDT adoption in real-world workflows. These insights highlight the key challenges that hinder the development of more effective urban digital twin platforms, such as the need for better support for users with limited technical expertise and improved capabilities for synthesizing diverse data sources. Addressing these challenges will help Urban Digital Twins reach their full potential as tools for data-driven decision-making and urban planning.

Acknowledgements

Desai Wang gratefully acknowledges financial support for this research by the Fulbright U.S. Student Program. The BEAM platform was developed by the CoolNUS-BEAM team, which is funded by the National University of Singapore and is supported by the University Campus Infrastructure (UCI) and Office of the Deputy President - Research & Technology.

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