Leveraging a Digital Twin Interface for Multimodal Transportation Resilience, Connectivity, and Equity – A Case Study of Toyosu, Tokyo#

Adair Garrett[1], Katherine Ginensky[2], Xi Wang[3], Hina Ahmed[2], Jingyuan Shen[4], Takahiro Yoshida[5], Akito Murayama[6], Perry Pei-Ju Yang[2*]

1 School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, USA

2 School of City and Regional Planning, Georgia Institute of Technology, Atlanta, USA

3 Aerospace Systems Design Laboratory, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, USA

4 School of Building Construction, Georgia Institute of Technology, Atlanta, USA

5 Center for Spatial Information Science, the University of Tokyo, Tokyo, Japan

6 Department of Urban Engineering, the University of Tokyo, Tokyo, Japan
(Corresponding Author: perry.yang@design.gatech.edu)

ABSTRACT

Toyosu, a waterfront urban development on the reclaimed land of Tokyo Bay, faces issues such as a lack of walkability and high heat vulnerability. The main objective of this research is to leverage Digital Twins technology to enhance multimodal transportation system resilience, equity, and connectivity, utilizing the problem of heat on Toyosu of Tokyo as a case study. The research questions include: 1) What are the key variables (e.g., urban design, infrastructure, human) for designing a resilience hub? 2) Considering these key variables, how do we leverage emerging tools (e.g., Digital Twins systems) to inform planning and decision-making to reduce pedestrian vulnerability to heat? This study proposes a proof-of-concept Digital Twin Interface (DTI) utilizing geographic information system (GIS), agent-based modeling (ABM), and digital urban design modeling tools (Rhino/Grasshopper). Two scenarios were constructed to simulate the thermal comfort of Toyosu in 2023 and in 2030, demonstrating the potential for urban form to impact pedestrian comfort. The output of these simulations is integrated within the DTI to inform pedestrian decision making during high heat events. This study informs the design of resilience hubs broadly and is applied to the case of heat stress in Toyosu as a proof-of-concept. The variables impacting walkability, multimodal connectivity, and transportation resilience are further examined. This research extends and applies previous research efforts leveraging Digital Twin technology in transportation planning and decision making. This can aid transportation planners, engineers, and researchers who desire to enhance multimodal transportation system resilience with a focus on pedestrian comfort and safety.

Keywords: multimodal transportation, resilience, digital twin, urban heat, walkability, Tokyo

1. BACKGROUND & MOTIVATION

Japan has always faced a diverse array of climate hazards, but the frequency and intensity of these events has increased in recent decades (1). During the last 100 years, global temperatures have been breaking records – acting as a chronic stressor on populations and infrastructure internationally (2). Warmer air temperatures are exacerbated by the urban heat island effect, a phenomenon that occurs in part because of the design of urban spaces (3). For active transportation modes and users of public transportation, hot temperatures may reduce the distance users are able to travel, increase the stress experienced by the transportation users, and potentially cause heat-related illnesses, such as heatstroke (4). In the first week of July 2024, over 9,000 people were transported to hospitals in Japan due to heatstroke (5). Additionally, the population

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of Japan is aging, indicating a need for infrastructure design changes considering the needs of elderly and potentially less mobile transportation users.

Heat vulnerability has also been identified as an issue for Toyosu. The northeastern part of Toyosu experiences slightly higher temperatures than the southern part (6). The northern part of Toyosu connects to nearby neighborhoods, meaning that pedestrians and public transportation users will likely pass through this area to reach other destinations on the island. During the hottest portion of the day, visitors and employees of Toyosu could be vulnerable to extreme heat. A higher density of buildings, concrete, and impervious surfaces leads to heat absorption during high sunlight hours, which contributes to higher temperatures throughout the day and night (7).

In response to these challenges, the case study for this research examines how digital twin technology can address heat impacts on pedestrian mobility on Toyosu. This research specifically creates an interactive dashboard – a Digital Twin Interface (DTI) - to enable stakeholders and visitors to examine conditions on Toyosu and make data-informed decisions.

The paper begins with a literature review, followed by the Methodology section on the steps taken to perform geographic, thermal comfort, and agent-based modeling. The proof-of-concept Digital Twin interface is presented in the Results section. The paper concludes with a discussion of recommendations to mitigate the impact of the urban heat in Tokyo.

2. LITERATURE REVIEW

2.1 Digital Twins for Disaster Preparedness

Digital Twins (DTs) are defined as a representation of a physical system with automatic data flow between the digital and physical systems (8). Orgunsakin et al. (9) state that DTs require systems to adapt and adjust strategies to ensure desired outcomes are achieved; thus, DTs should be able to autonomously recognize perturbations, re-allocate variables to enact changes, and optimize control parameters considering internal and external conditions. This approach requires sensors and data collection technologies to be synchronized with the DT platform to achieve optimized performance. Fan et al. (10) claim that “typical data sensing techniques (such as remote sensing and satellite images) are not sufficient to gain reliable situational awareness about disruptions that affect communities at a local scale.” Fan et al. (10) promote social sensing to better reflect the experience of local communities.

Previous research has identified DTs as a potentially promising platform for disaster prevention in Japan (11). Additionally, DTs have been identified as having great value for planning, disaster preparedness, and improving accessibility (12). Macatulad and Biljecki (12) also state that digital twins can inform urban disaster risk management and sustainable, resilient cities by providing a platform for collaboration and policy as well as a model for simulating city processes. Vivita et al. (13) highlight the importance of “place attachment” to disaster preparedness, where familiar social and cultural places are ideal evacuation sites and can contribute to the sustainable development of cities.

2.2 Resilience Hubs

Considering transportation resilience, a type of mobility hub may be developed. Based on a study from Ciriaco and Wong (14), resilience hubs need to determine 1) how people and relief supplies will travel to and from hubs and 2) what potential transportation services could be offered by these hubs. Resilience hubs operate in three modes, which are: normal mode (no disruption), response or disruption mode (both short- and long-term disruption), and recovery mode (post-disruption). These modes of operation are useful in determining the key variables necessary to leverage digital twin technology.

2.3 Mitigating Urban Heat in Tokyo

The annual average temperature, annual average daily maximum temperature, and number of sweltering days (a day on which the temperature rises above 30ºC) have been increasing in the 23 wards, Tama area, and islands of Tokyo (15). To address issues related to urban heat, the following steps are proposed as an approach to mitigate urban heat in Japan (adapted from 16): 1) Agreement on a leading institution (to coordinate a multipurpose collaborative mechanism between bodies and institutions and to direct the response if an emergency occurs), 2) Accurate and timely alert and communication systems (heat-health warning systems trigger warnings, determine the threshold for action and communicate the risks), 3) A heat-related health information plan (about what is communicated, to whom and when), 4) Particular care for vulnerable population groups, 5) Long-term urban planning (to address building and urban design as well as infrastructure-focused policies to ultimately reduce heat exposure), and 6) Real-time data collection and evaluation.

3. METHODOLOGY

The first step of this study involved formulating the problem; here, the problem is defined as: "**The aging population, lack of walkability, and intensifying heat conditions in Toyosu put the area's vulnerable transportation users – namely, pedestrians – at risk for heat-related illnesses.**" To begin to address this problem using Toyosu as a case study, data was gathered on climate conditions (e.g., temperature, humidity, solar radiation), origin-destination movements from travel surveys, the transportation network (shapefiles for road locations, sidewalk locations, and rail line and station locations), three-dimensional (3D) building elements (from Tokyo's Plateau model, a 3D model for the city), and urban form (including tree canopy, proximity to the water front, etc.).

Once the preliminary data collection effort was complete, the geographic analysis and modeling phase began. ESRI ArcGIS Pro and ESRI Experience Builder were utilized to build the preliminary versions of the DTI using the 3D model of Tokyo Plateau layers combined with the Strava foot sport heatmap (for pedestrian behavior in Tokyo). The combination of these two data sources provided insight on where the most popular pedestrian paths fall in comparison to the urban form factors on Toyosu.

To understand the pattern of potential movement of pedestrian traffic to and within Toyosu, an agent-based model (ABM) was conducted using randomized points. This method allowed the visualization of movement within the multi-modal transportation networks including sidewalks, roads, and train lines. To improve this process, GPS data collected was filtered by any one Trip ID (an identifying number to represent a singular person's movements through Tokyo) that intersected at least once with the Toyosu boundary. The ABM was re-run considering the filtered GPS data to improve accuracy. The ABM showed the general movement of people over time within Toyosu.

Any mode of transport into Toyosu, in normal conditions and in the event of a major disruption, will require at least some walking to complete the trip. To ensure the safety and comfort of pedestrians, the model of thermal comfort, normally modelled within buildings, was used to analyze the outdoor thermal comfort between buildings. Thermal comfort here is based on the simulated 'perceived temperature' output from Ladybug plug-in tools in Rhino. 'Perceived temperature' is the Universal Thermal Climate Index (UTCI). Using two scenarios – a set of climate conditions from May 2023 and a set of predicted climate conditions for an unusually hot day in 2030, a model was constructed to understand how the three-dimensional urban form would impact the thermal comfort of pedestrians on Toyosu. The outputs of this simulation were integrated into the DTI so that this information can be easily communicated with pedestrians planning their routes and stakeholders that may wish to include thermal comfort as a variable in future urban planning efforts. Recommendations for urban design interventions that may mitigate some of the consequences of high urban heat are presented in the discussion. The methodology for this research is summarized in Figure 1.

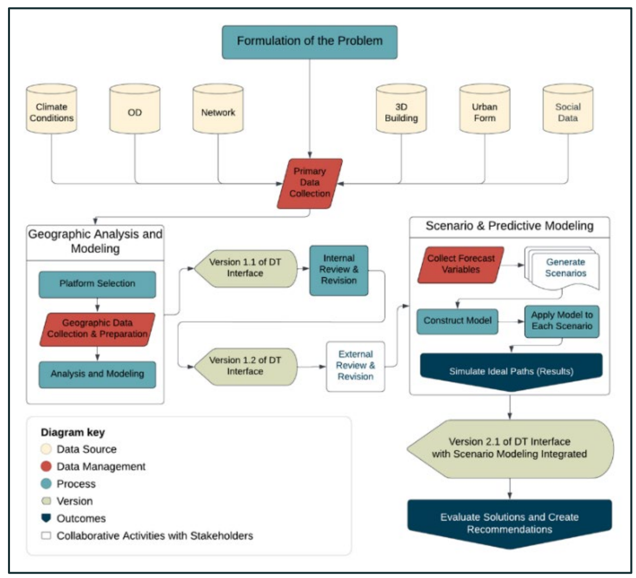

Fig 1. Methodology for DTI Development and Analysis

4. RESULTS: PROOF-OF-CONCEPT DTI

4.1 Overview

The results from the thermal comfort simulations are demonstrated in Figures 2 (2023) and 3 (2030). It should be noted that UTCI > 26 °C indicates a hot condition and heat stress. As shown in both figures, the simulated UTCI in the demonstrated area is under hot conditions. People walking within an area with a UTCI larger than 26°C are considered to be experiencing heat stress. Increasing shadows and wind flow are two potential strategies for mitigating heat stress. A limitation of this approach is that the modeled buildings are not spaced exactly as they are on the island of Toyosu. Not all urban design factors that may influence thermal comfort are considered in the model.

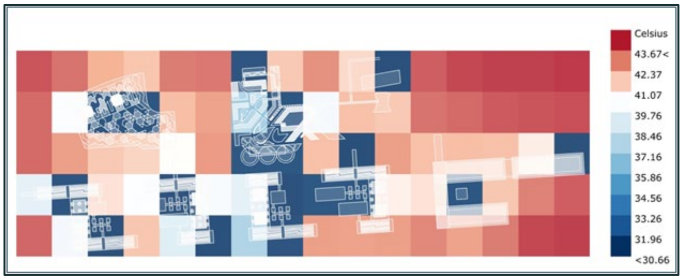

Fig 2. Perceived temperature around proposed resilience hubs in 2023

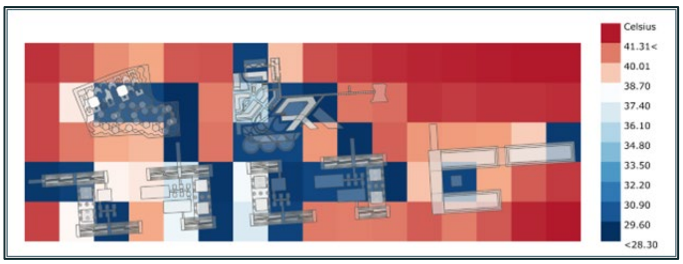

Fig 3. Perceived temperature around proposed resilience hubs in 2030

These results inform the specific interventions that may reduce pedestrian discomfort on various sides of the modeled buildings. The results from the ABM and geospatial modeling efforts were integrated into the proof-of-concept DTI. The proof-of-concept DTI was developed using the multi-page capability of ESRI Experience Builder. This allowed the interface to include three modes – aligned with the three modes of resilience hub operations. In "normal mode", the information presented on the DTI promotes tourism, presents the most common walking paths, and provides an opportunity for general feedback for the pedestrian experience on the island. The "disruption mode" provides information for pedestrians in Toyosu that may need to prioritize paths considering factors impacting walkability and thermal comfort and allows pedestrians or users of the resilience hub to share their experience. In "recovery resources and insights" mode, summary statistics are presented on the experiences that pedestrians had during the normal and disruption modes. To facilitate the use of the DTI, an ArcGIS StoryMaps was created to provide train scheduling details for getting to Toyosu, additional tourism opportunities, and information on live weather conditions.

4.2 Proof-of-Concept DT Interface

4.2.1 *Normal Mode*

Normal mode includes an overview of the three modes and is intended to be used during day-to-day, nonextreme conditions. Additionally, the map shows buildings on Toyosu (which may be clicked for additional information) and popular paths (indicated by the white color in the map; darker colors indicate less popular paths). Along the right panel, there are a series of questions for Toyosu visitors to fill out. These questions are: 1) Why are you visiting Toyosu? 2) What transportation mode(s) did you use within Toyosu? 3) While you were walking, how was the path on a scale of 1 (poor) to 5 (excellent) in terms of accessibility, comfort, beauty, shade, safety, and locations/sites?

These questions facilitate the flow of live information between users of Toyosu's transportation system and decision makers. The insights from these questions are provided on the "recovery resources and insights" page. Figure 4 shows a snapshot of the Normal Mode on the DTI.

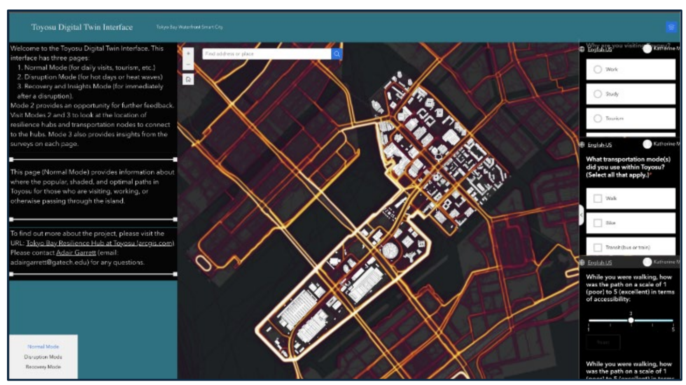

Fig 4. Normal Mode on DTI

4.2.2 Disruption Mode

The disruption mode is intended to provide users with the locations of safe destinations during a heat wave (resilience hubs). These locations should provide shade, cooling, and other services or supplies to ensure pedestrian safety. The page also allows Toyosu visitors to provide feedback on their experience. The questions on this page are: 1) What services are you using at the resilience hub? 2) What transportation mode(s) did you use to reach the resilience hub? 3) How was the path to the resilience hub on a scale from 1 (poor) to 5 (excellent) in terms of comfort, accessibility, and safety?

Figure 5 provides a snapshot of the "Disruption Mode" page on the Digital Twin Interface.

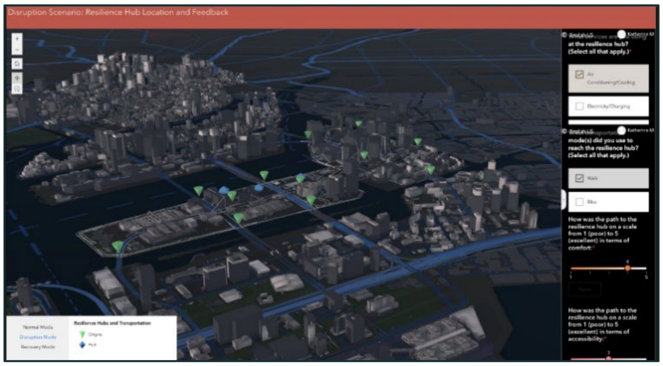

Fig 5. Disruption Mode on DTI

4.2.3 Recovery Resources and Insights

The final page provides insights from the surveys on the first two pages. This page is also intended to be used by Toyosu visitors that are looking to leave the resilience hubs following a disruption. Figure 6 provides a snapshot of the "recovery resources and insights" page from the DTI.

Fig 6. Recovery Resources and Insights Mode on the DTI

5. DISCUSSION

This research presented an approach leveraging DTs to address a chronic stressor for pedestrians: urban heat. This tool may be used for pedestrians trying to decide which path to take while visiting the island; it may also be used by planners looking to figure out where to implement urban design changes to provide areas with shade or cooling facilities. Considering the most likely paths that pedestrians may choose to travel through Toyosu, a few interventions may reduce the impact of the urban heat island effect, including (extended from 7; 15; 17):

- Installation of heat countermeasure equipment, including fine misting devices, in cooperation with municipalities
- Construction of heat blocking pavement
- Expansion of urban green and park space
- Changes to building codes, including requirements for awnings and other public shading elements
- Use of high-albedo (light-colored) coatings
- Promotion of UV-protecting umbrellas at cross-walks and other areas where pedestrians linger

6. CONCLUDING REMARKS & FUTURE WORK

This study examines how to leverage digital twin technology to address challenges associated with urban heat and walkability. Considering the case study of Toyosu, this study provides a proof-of-concept DTI that combines the outputs of geographic and agent-based modeling to communicate best paths with pedestrians. Future research directions include studies on how the buildings on the island can safely accommodate evacuees through the flexible design and re-allocation of space and resources for all three modes: normal, disaster, and recovery.

This research focuses on transportation systems, but transportation is just one system in the complex, multi-scale systems that facilitate a functioning society. Future studies examining how digital twins can be used to address challenges associated with infrastructure interdependence (e.g., the relationship between energy and transportation systems) will be beneficial to more accurately represent evolving conditions. This study began to examine the relationship between building design factors and the pedestrian experience by incorporating the thermal comfort output from Rhino. The increased energy demand that may be induced at resilience hub locations during heat wave events, unfortunately, may lead to increased demand on nonrenewable energy sources if the energy grid is not prepared for such events. Future DTIs should consider the energy impact of increased occupation of resilience hubs and installed cooling facilities that will provide planners and utilities with the information needed to proactively address these challenges.

This study leveraged digital twin technology for enhanced communication with pedestrians in the context of extreme heat. Previous studies discussed the potential of utilizing digital twins in the disaster context; this study defined an approach to apply these concepts in practice. The approach developed in this study can be advanced by agencies that collect sensor data to build real-time digital twin systems into interfaces for enhancing communication with stakeholders, including populations vulnerable to extreme heat.

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