Enhancing Urban Heat Risk Resilience in Tokyo's Nihonbashi through Urban Digital Twins of 4-Step Scenario Planning

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Abstract

Nihonbashi in Tokyo is a high-density urban environment that faces increasing risks of disaster such as heatwaves, yet current disaster management plans lack dynamic, real-time response mechanisms to address uneven vulnerability across neighborhoods. This study enhances Nihonbashi's urban heat resilience using urban digital twins, a dynamic virtual replica integrating real-time data to simulate and optimize urban systems. Employing a 4-step scenario planning model (descriptive, evaluative, predictive, prescriptive), it integrates real-time heat risk, resilience hub occupancy, and social demographic data to optimize access to cool spaces and transportation routes. Leveraging open-sources tools like Network X, OSMnx, and Getis-Ord Gi*, the framework identifies high-risk zones such as office headquarters and subway stations to identify vulnerability hotspots and simulates urban network performance during heatwaves. A heat scenario classifier achieves 96.7% accuracy in predicting heat risk levels. Built on ArcGIS Experience Builder, the platform enables dynamic rerouting to less occupied shelters and shaded pedestrian pathways, prioritizing vulnerable populations, particularly the elderly. Unique contributions include real-time data integration, high-accuracy heat prediction, and an equity-focused approach, distinguishing it from static GIS-based simulations. Data from OpenStreetMap, PLATEAU, and e-Stat ensure reliability, although real-time data access poses challenges. Stakeholders, including planners, emergency responders, and residents, can engage via the interactive platform to simulate scenarios and enhance resilience. This scalable, open-source framework offers a transformative model for urban heat management adaptable to other cities.

1. Introduction

1.1 Urban Heat Risk in Tokyo

Urban areas worldwide face escalating risks from extreme heat, driven by climate change and urbanization. In Japan, temperatures that exceed 35°C are classified as extremely hot days. In 2024, more than 10 cities had over 50 days of this extreme weather. The elderly are particularly vulnerable, with over half of Tokyo's heatstroke cases occurring among those aged 65 and older, within indoor spaces (Tochibayashi & Ota, 2025). Temperature rise within Tokyo has been attributed to urbanization and anthropogenic heat in central parts of the city sometimes exceeds 400 W/m², posing an "extreme danger" (Harlan et al. (2006).

To address these challenges, the Japanese government has implemented several measures. These include subsidies for energy-efficient cooling devices, ensuring a stable electricity supply with reserve margins well above the 3% threshold during summer months. Other initiatives include the distribution of smart technology, such as heat stroke prevention watches and Internet of Things (IoT) services that monitor rising heat levels of people and adjust interior temperatures through remote digital devices (Tochibayashi & Ota, 2025). Tokyo's Climate Adaptation Plan proposes heat countermeasures, with urban enhancements such as cool pavements, urban greening, and the establishment of cool spots. However, these measures lack immediate response mechanisms for heatwave events. Official government guidance remains limited to recommendations like staying hydrated and sheltering in place. In contrast, a technical report by the WHO Kobe Centre in 2013 (WHO, 2013) advocates for proactive measures, such as relocating vulnerable individuals to air-conditioned environments during heatwaves.

1.2 Objectives of the Study

Given these gaps in current heatwave response strategies, this study aims to enhance urban heat resilience in Nihonbashi area of Tokyo through the development of urban digital twins and a 4-Step Scenario Planning. The objectives are (1) to improve urban heat mapping of the Nihonbashi area using interactive visual tools to identify areas of heat accumulation, (2) to optimize access to cooling centres by integrating real-time heat risk and occupancy data, and (3) to create a scalable framework of digital twins system design that is adaptable to other urban areas. This will be achieved through the development of a digital twin platform on ArcGIS Experience Builder, utilizing a 4-step model that leverages real-time heat risk data and resilience hub occupancy information. This platform is designed to keep inhabitants informed about the nearest cool areas and the most optimal routes to get there. This approach not only enhances Tokyo's existing climate adaptation plan by focusing on a specific neighbourhood but also builds upon government initiatives that employ smart technologies to safeguard vulnerable populations.

2. Literature Review

2.1 Heat-health action in Japan

The maintenance of blue-green networks, such as parks and water bodies within Tokyo is pivotal to urban heat reduction. However, current policies often rely on the Wet Bulb Globe Temperature (WBGT) metric to assess heat exposure, which has notable limitations. According to Tochibayashi & Ota (2025), WBGT does not account for factors such as human metabolic rate, leading to an underestimation of the impacts of extreme heat in vulnerable areas. As a result, over 96% of Tokyo's wards seem to have similar heat-illness risks during summer, except for a few days in July, suggesting a need for more nuanced, neighborhood-level heat mapping (Tochibayashi & Ota, 2025).

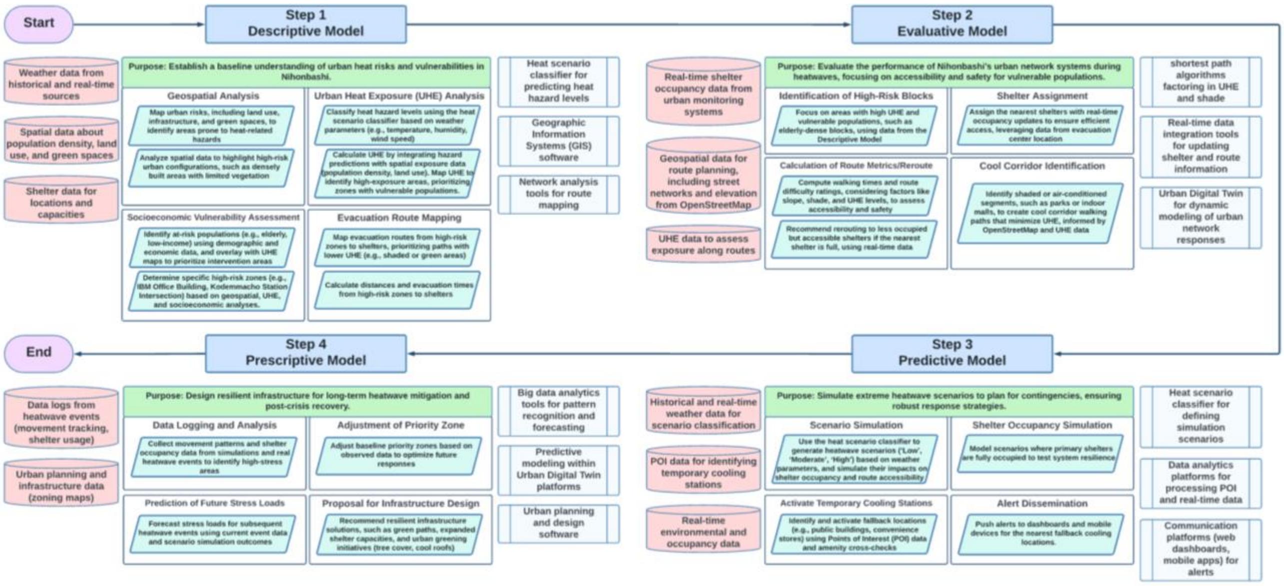

Figure 1 Process Flow Chart of Research Design and Methodology

Heatstroke trends in Japan further underscore the urgency of effective interventions. Studies indicate that heatstroke illness often begins indoors, with older adults being particularly susceptible (Kim et al., 2023; Tochibayashi & Ota, 2025). Most cases occur between July and August, while incidents have been reported in as early as May. Japan has reported an increased risk of mortality associated with heatwaves, where this effect is shown to be stronger in densely populated metropolitan areas. The 2018 Climate Change Adaptation Act has introduced both "soft" and "hard" measures to reduce urban temperatures and mitigate health impacts. "Soft" measures include public awareness campaigns, while hard measures involve infrastructure improvements like urban greening (Kim et al., 2023). Heat Wave Warning Systems (HWWS) play a key role, with the Japan Meteorological Agency (JMA) issuing "High-Temperature Warnings" since 2011 for daily maximum temperature of 35 °C or higher, and the "Heat Stroke Alert" launched in 2020 by JMA and Ministry of the Environment Japan (MOEJ) for WBGT levels of 33 °C or above (Oka et al., 2023). The Japanese government is considering an additional alert level to address the increasing severity of heatwaves due to climate change (Kim et al., 2023).

2.2 Digital Twins for Urban Risk Planning

The concept of Urban Digital Twins (UDT) has emerged as a powerful tool for urban risk management, enabling real-time, data-driven decision-making. Digital Twins is a digital replica of a physical system that maintains a continuous, bi-directional data exchange with its real-world counterpart, allowing for simulation, prediction, and optimization across an asset's lifecycle (Jones et al., 2020; Qi et al., 2021). Unlike static digital models or digital shadows, digital twins incorporates live data streams and feedback loops, offering an interactive and adaptive representation capable of scenario testing and responsive control (Boschert & Rosen, 2016).

Key characteristics of digital twins include real-time sensor integration, lifecycle management, predictive modeling, and a modular architecture that integrates heterogeneous data sources from Building Information Modeling (BIM), Geographic Information Systems (GIS), IoT feeds, and behavioral simulations (Barricelli et al., 2019; Kritzinger et al., 2018). These capabilities distinguish digital twins from traditional digital models by enabling simulation-informed interventions and dynamic system state tracking. For example, in urban heat management, UDT can simulate the impact of extreme heat on populations, accounting for factors like building materials, green spaces, and human behavior, to optimize cooling strategies and evacuation plans. This makes UDT particularly valuable for addressing complex urban challenges like heatwaves, where real-time data integration can enhance resilience and response strategies.

3. Research Design and Methodology

This study employs a comprehensive methodology to enhance urban heat resilience in Tokyo's Nihonbashi district through the development of urban digital twins and a four-step scenario planning framework. Three research questions are to be answered throughout the study, which are: (1) To what extent can a four-step scenario planning model optimize evacuation routes for vulnerable populations during heatwaves in Nihonbashi? (2) What are the key factors influencing the identification of high-risk zones and vulnerability hotspots in Nihonbashi, and how can they be addressed through geospatial analysis? (3) How effectively can real-time heat risk data and resilient hub occupancy information be integrated into urban digital twins to improve access to safe spaces?

By integrating diverse data sources and advanced analytical tools, the approach addresses the challenges posed by extreme heat events, prioritizing safety and accessibility for vulnerable populations, particularly the elderly. Here is a diagram demonstrating the entire process flow (Figure 1).

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3.1 Data Sources and Analytical Tools

The research draws on a robust set of data sources to support its analyses. Historical meteorological data, spanning 2015 to 2024, are sourced from the National Oceanic and Atmospheric Administration (NOAA) and Weather.gov to calculate heat indices and assess urban heat exposure during summer months (Figure 2). Socioeconomic data, including social demographic and economic indicators such as age and income distributions, are obtained from the Statistics Bureau of Japan and Tokyo Metropolitan Government Open Data to evaluate population vulnerability (Figure 3). Geospatial data, encompassing street networks, building footprints, points of interest (POIs), and shelter locations, are derived from OpenStreetMap (OpenStreetMap), Plateau CityGML, and the Geospatial Information Authority of Japan, formatted in CSV and GeoJSON (Figure 4). High-frequency GPS data capture pedestrian and vehicular movement patterns within Nihonbashi, providing insights into traffic flow and mobility dynamics (see Figure 5).

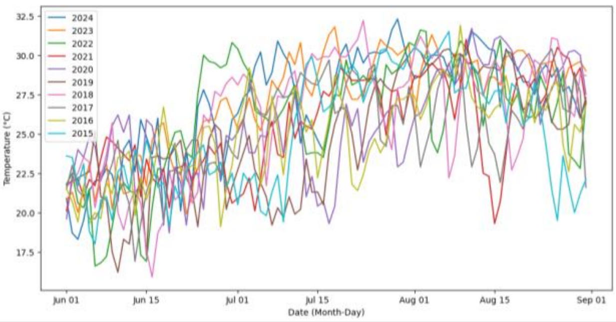

Figure 2 Average Temperature during Summer Months in Tokyo

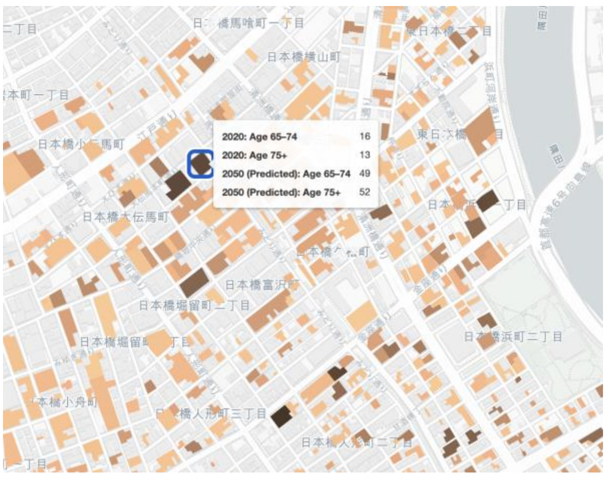

Figure 3 Actual Vulnerable Population Distribution in Tokyo

A suite of analytical tools processes and visualizes these data to enable precise and actionable outcomes. NetworkX, a Python package, facilitates the creation and analysis of complex network structures, including pedestrian, vehicle, and public transit networks, supporting route mapping and network optimization (Figure 6). OSMnx, another Python library is a Python package for high-powered analysis of geospatial features sourced from Geoff Boeing (Boeing, 2025). This library utilizes OpenStreetMap's libraries and data to visualize the physical infrastructure and movement within a geographical area. It retrieves and models street networks from OpenStreetMap, enabling detailed analysis of urban infrastructure and movement patterns (Figure 7 and Figure 8). The Getis-Ord Gi* statistic, a spatial autocorrelation tool, calculates Z-scores and P-values to identify statistically significant clusters of vulnerable populations, generating hotspot maps for targeted interventions (Figure 9). Kepler.gl, an open-source platform, creates interactive maps to visualize high-frequency GPS data, enhancing accessibility for researchers and planners (Figure 14). Additionally, a Random Forest Classifier categorizes heat risk levels based on meteorological data. This classifier, referred to as the heat scenario classifier, supports both historical analysis and real-time predictions (Figure 10), forming a critical component of the methodology.

Figure 4 Visualization of Geospatial Data for Nihonbashi Area

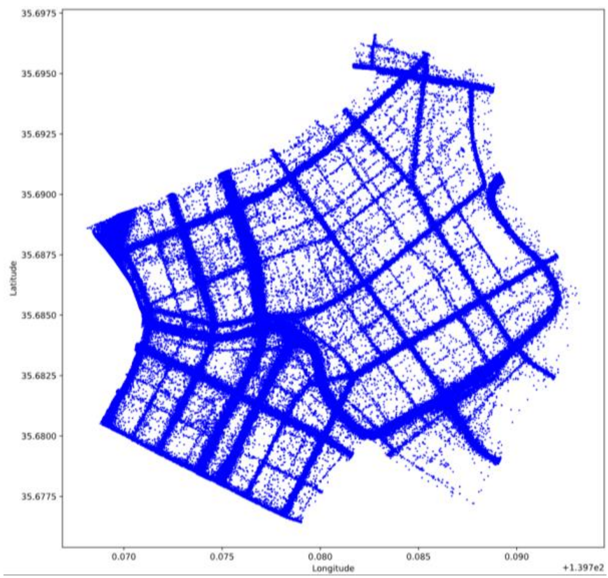

Figure 5 GPS Points Capturing Pedestrian Patterns within Nihonbashi Area

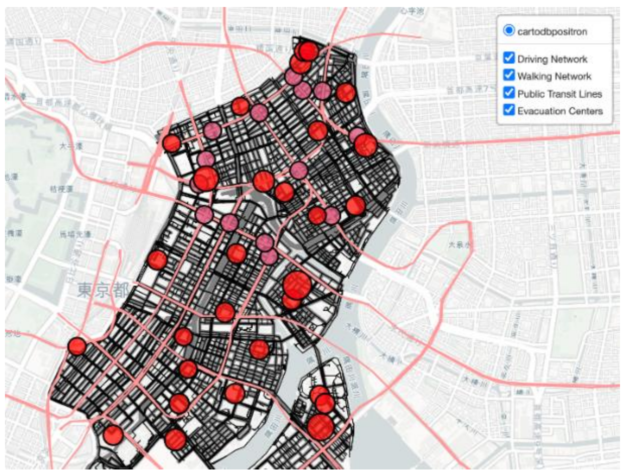

Figure 6 Walking, Driving, Biking, and Public Transit paths of the Chūō Ward of Tokyo from Network

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Figure 7 Evacuation paths to closest shelters in Nihonbashi, Tokyo

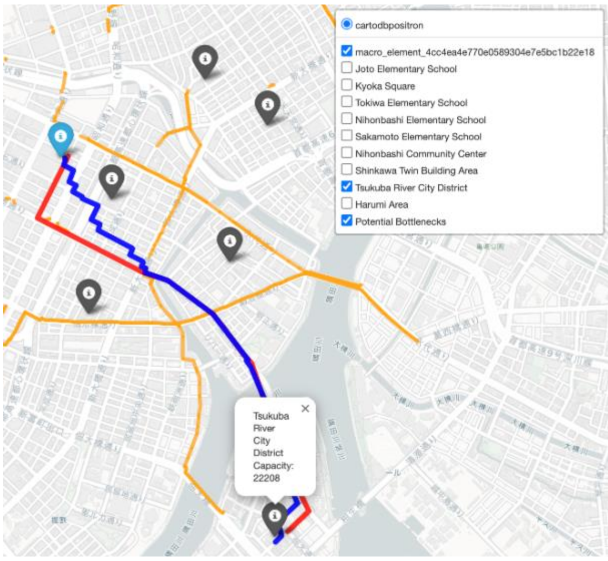


Figure 8 Example of evacuation path, distance, capacity, and travel time calculated using OSMnx.

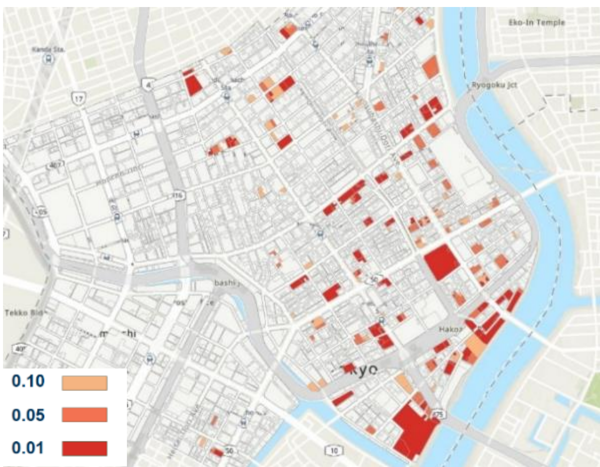


Figure 9 Map depicts significant levels of vulnerable populations by tract

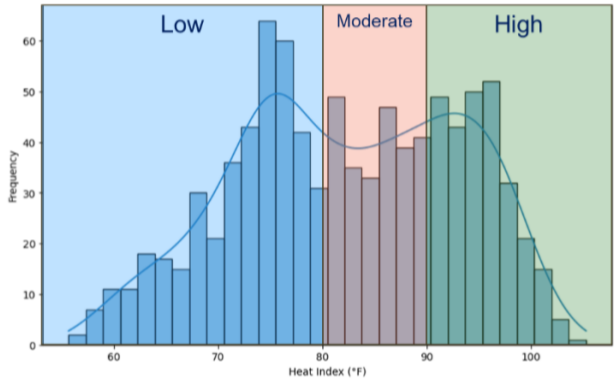


Figure 10 Heat Index Distribution for Historical Weather Data During Summer Months from 2015 to 2024 in Tokyo

4. Four-Step Scenario Planning Model

The core of the methodology is a four-step scenario planning model, which leverages the analytical capabilities of digital twins to enhance urban heat resilience. Each step integrates specific data and tools to address distinct aspects of heatwave response and planning.

4.1 Descriptive Model: Mapping and Modelling of Current Conditions for Preparedness of Heatwave

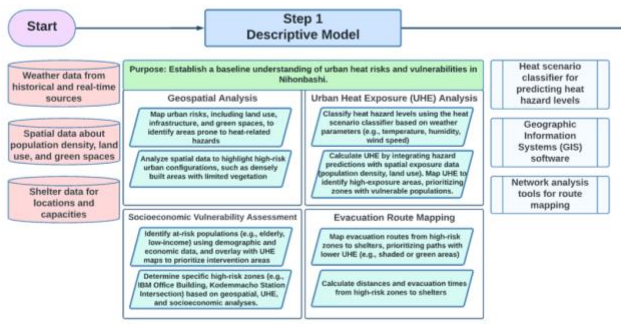


Figure 11 Step 1: Descriptive Model

The Descriptive Model establishes a foundational understanding of urban heat risks and vulnerabilities in Nihonbashi. Geospatial analysis maps pathway networks, including pedestrian, vehicle, and public transit lines, using NetworkX and OSMnx to model movement patterns across transportation modes. Urban heat exposure is assessed by classifying historical meteorological data from 2015 to 2024 into heat risk levels ("High," "Low," "Moderate") using the Random Forest Classifier, which employs the NOAA Rothfusz regression formula to calculate heat indices based on temperature and humidity (Figure 12). The classifier's high accuracy ensures reliable identification of high-risk zones, which are visualized to guide subsequent analyses. Socioeconomic vulnerability is evaluated by analyzing the distribution of vulnerable populations, particularly those aged 65–74 and 75+ in 2020, with projections for 2050, using the Getis-Ord Gi* statistic to identify hotspots of vulnerability, such as areas with high concentrations of elderly or low-income residents. Evacuation routes from these high-risk zones to the nearest cooling shelters are mapped using NetworkX and OSMnx, incorporating factors such as shortest distance, street density, and traffic levels to ensure efficient and safe access.

$$
\begin{aligned}
T_{hi} = &-42.379 + (2.04901523 \times T) \\
&+ (10.1433127 \times RH) - (0.22475541 \times T \times RH) \\
&- (6.83783 \times 10^{-3} \times T^2) - (5.481717 \times 10^{-2} \times RH^2) \\
&+ (1.22874 \times 10^{-3} \times T^2 \times RH) + (8.5282 \times 10^{-4} \times T \times RH^2) \\
&- (1.99 \times 10^{-6} \times T^2 \times RH^2)
\end{aligned}
$$

T = temperature in degrees Fahrenheit (°F)

RH = relative humidity (%)

Figure 12 Heat Index Calculation using NOAA Rothfusz Regression Formula (Tempest, 2018)

4.2 Evaluative Model: Identifying Problems of Urban Network System During Heatwave

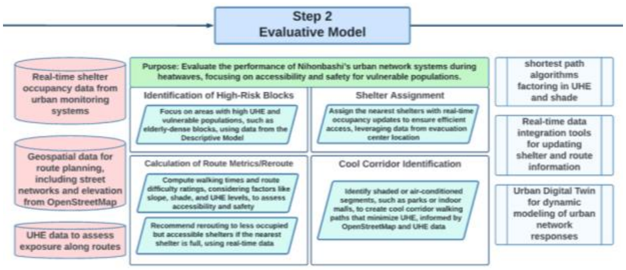


Figure 13 Step 2: Evaluative Model

The Evaluative Model assesses the performance of Nihonbashi's urban network systems during heatwaves, with a focus on accessibility and safety for vulnerable populations.

High-risk areas are identified by overlaying urban heat exposure and socioeconomic vulnerability data, prioritizing zones with elevated heat indices and vulnerable demographics. Optimal routes to assigned shelters are calculated using OSMnx, considering metrics such as distance, travel time, elevation, and safety factors like shade availability. Rerouting strategies are developed to address potential obstacles, ensuring efficient access to cooling centers. Real-time shelter occupancy data are integrated to monitor usage during heatwaves, providing insights into capacity constraints and informing dynamic response strategies. Paths intersecting shaded or air-conditioned segments, such as parks or indoor malls, are identified as cool corridors using OpenStreetMap data, reducing heat exposure during evacuation. High-frequency GPS data are visualized using Kepler.gl to analyze movement patterns, including a 24-hour human flow cycle in Nihonbashi, with edge betweenness centrality calculated to identify network bottlenecks and enhance efficiency and accessibility (Figure 14).

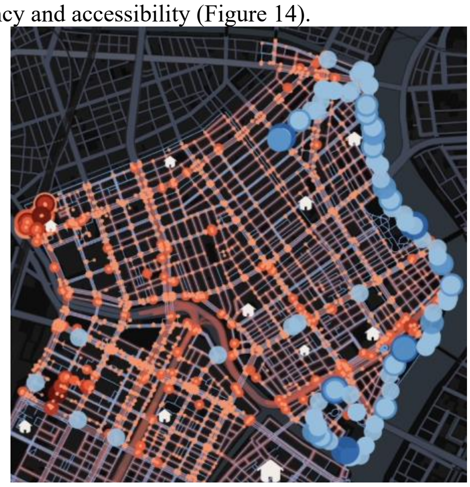


Figure 14 Visualization of 24-hour cycle of human flow within Nihonbashi Area using Kepler.gl

4.3 Predictive Model: High Frequency Planning of Human Responses to Heatwave

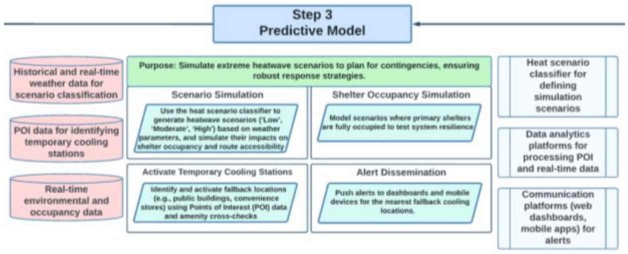
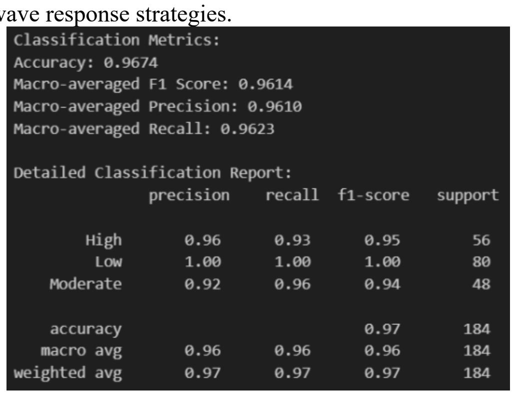


Figure 15 Step 3: Predictive Model

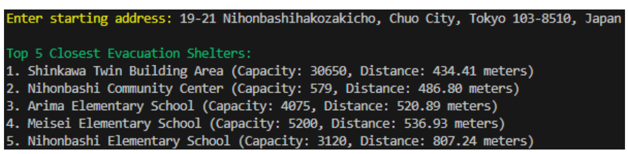
How human responses to heatwave was simulated through a route planning system, implemented through a Python script, leverages real-time weather data and advanced analytics to optimize evacuation routes to resilient hubs. The system employs a Random Forest Classifier, trained on historical weather data from 2015 to 2024 sourced from the National Oceanic and Atmospheric Administration and Weather.gov, to predict heat scenarios (Low, Moderate, High) with an accuracy of 96.74%, a macro-averaged F1 score of 96.14%, precision of 96.10%, and recall of 96.23% (Figure 20). Real-time weather data from OpenWeatherMap are used to categorize current conditions, enabling dynamic route adjustments based on heat risk. The system constructs routable street-level graphs using OSMnx and NetworkX, incorporating heat hazard levels, elevation data, and building access constraints. By applying shortest path and Ant Colony Optimization algorithms, it supports adaptive rerouting in response to blocked routes or congestion, ensuring efficient and safe access to cooling facilities. The system's high accuracy and adaptability highlight its effectiveness in enhancing heatwave response strategies.



```
Classification Metrics:
Accuracy: 0.9674
Macro-averaged F1 Score: 0.9614
Macro-averaged Precision: 0.9610
Macro-averaged Recall: 0.9623

Detailed Classification Report:
              precision    recall  f1-score   support

        High       0.96      0.93      0.95        56
         Low       1.00      1.00      1.00        80
    Moderate       0.92      0.96      0.94        48

    accuracy                           0.97       184
   macro avg       0.96      0.96      0.96       184
weighted avg       0.97      0.97      0.97       184
```

Figure 16 Classification Results of Random Forest Classifier

A case study was simulated to evaluate the route planning system's performance using a sample starting address (IBM Japan) in Nihonbashi. The system identified the five closest evacuation shelters, such as Arima Elementary School (see Figure 17), based on distance and capacity, allowing user selection. For the chosen shelter, both walking and driving routes were calculated, with the walking route optimized to minimize heat risk (see Figure 18).



```
Enter starting address: 19-21 Nihonbashihakozakicho, Chuo City, Tokyo 103-8510, Japan

Top 5 Closest Evacuation Shelters:
1. Shinkawa Twin Building Area (Capacity: 30650, Distance: 434.41 meters)
2. Nihonbashi Community Center (Capacity: 579, Distance: 486.80 meters)
3. Arima Elementary School (Capacity: 4075, Distance: 520.89 meters)
4. Meisei Elementary School (Capacity: 5200, Distance: 536.93 meters)
5. Nihonbashi Elementary School (Capacity: 3120, Distance: 807.24 meters)
```

Figure 17 Top 5 Closest Evacuation Shelters from the Starting Address

In a simulated "Moderate" heat risk scenario, the heat-optimized walking path reduced total heat risk by approximately 18.25% compared to the shortest path. This trade-off demonstrates the system's ability to prioritize safety without significantly compromising efficiency. The system also provided practical outputs, including estimated travel time (adjusted for heat-affected walking speeds of 3.0 – 5.0 km/h), water needs (0.2 – 0.6 liters per km based on the heat scenario), and a vulnerability summary for the path. These results illustrate the system's capacity to deliver actionable guidance for residents, particularly vulnerable groups, during heatwaves.

Figure 18 Calculated Walking and Driving Routes of the Simulated Case Study

```
=== Walking Route to Arima Elementary School ===
🔥 Heat Scenario: Moderate
🔥 Heat Hazard: 50.00
🔥 Heat Exposure: 1.00 (simplified)
🔥 Heat Vulnerability: 1.00 (simplified)
🔥 Total Distance: 944.39 meters
🔥 Estimated Time: 14.17 minutes
🔥 Total Heat Risk: 33843.11
🔥 Heat Risk Reference: This path reduces heat risk by 18.25%
compared to the shortest path (41400.31).
🔥 Water Needed: 0.38 liters
🔥 Maximum Vulnerability Level: High
Route considers traffic density for vulnerability.

Vulnerability Summary along the Path:
Level      Total Length (m)      Number of Edges
Low        568.70                13
Medium     72.03                 5
High       303.67                8

=== Driving Route to Arima Elementary School ===
🚗 Total Distance: 907.78 meters
🚗 Estimated Time: 1.82 minutes
```

Figure 19 Route Summary for the Simulated Case Study

The route planning system also provides the assessment of vulnerability along evacuation routes. Traffic density data were categorized into low, medium, and high vulnerability levels based on quantiles, reflecting potential congestion or exposure to risks. In the case study, the heat-optimized walking path traversed segments with varying vulnerability levels are summarized as: 500 meters of low vulnerability, 300 meters of medium, and 200 meters of high vulnerability. This granular analysis, visualized with segments colored by vulnerability level (green for low, yellow for medium, red for high) as shown in Figure 18, enables planners to identify critical segments requiring interventions, such as shaded rest areas or water stations. Edge betweenness centrality was calculated to identify network bottlenecks, further informing infrastructure improvements. The integration of traffic density as a vulnerability proxy, while effective, highlights the need for more direct socioeconomic data to enhance precision in vulnerability assessments.

If in an extreme situation (due to a prolonged heatwave) that shelters were all occupied, then temporary "cooling stations" would be activated using Point of Interest (POI) tags. These cooling stations include air-conditioned convenient stores, supermarkets and other (semi) public spaces with a water supply, also considered as "Valid" POIs. The model will identify whether the shortest paths generated intersect with any "cool" POI buffer zones, and tags those paths as cool corridors when the shelter is occupied (Figure 20). Thermal risk is evaluated using Heat Index. Pedestrian mobility traces (Strava, GPS) are overlaid to identify high-exposure corridors and inform the siting of shaded routes and resilience hubs. Predictive model should be conducted based on heatwave scenarios to generate evacuation routing and re-routing options for decisions.

Figure 20 Area Map with Shelters and Point of Interests

4.4 Prescriptive Model: Post-crisis Recovery Through Resilient Infrastructure Design

The Prescriptive Model focuses on long-term heatwave mitigation and post-crisis recovery through resilient infrastructure design. Data analytics based on heatwave scenarios, including shelter occupancy logs, and evacuation route planning have produced results to inform future planning of resource allocation for shelters and cool corridor design. High-risk areas are revised based on observed data, ensuring interventions target the most vulnerable zones. Predictive analytics forecast future heatwave impacts, enabling proactive adjustments to resource allocation and infrastructure planning. Recommendations for resilient infrastructure, such as green roofs, increased tree cover, cooler path design and enhanced shelter capacities, are proposed to mitigate long-term heat risks and strengthen urban resilience.

The Resilient Hub Selection Dashboard serves as a pivotal tool for long-range planning of heatwave mitigation and resilient infrastructure design. It provides detailed insights into urban buildings and infrastructure, such as building types, structures, floors for shelter occupant capacity, and also stress load forecast for subsequent heatwave attack based on scenario simulation outcomes, The dashboard enables planners to identify high-

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density zones and specific building configurations that exacerbate urban heat island effects (Figure 21). The accompanying 3D visualization of the Nihonbashi area, with color-coded building types, further enhances the ability to pinpoint locations where interventions like green roofs, increased tree cover, or enhanced shelter capacities could have the greatest impact (Figure 22). This data-driven approach not only facilitates the revision of high-risk areas based on observed patterns but also ensures that resources are strategically allocated to the most vulnerable zones. Additionally, the dashboard's insights can be seamlessly integrated into predictive analytics models to forecast future heatwave impacts, allowing for proactive adjustments to infrastructure planning and strengthening urban resilience against extreme heat events.

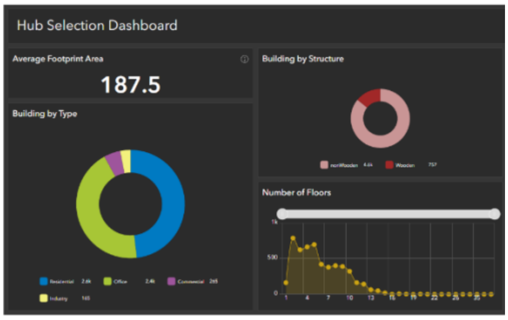

Figure 21 Resilient Hub Selection Dashboard

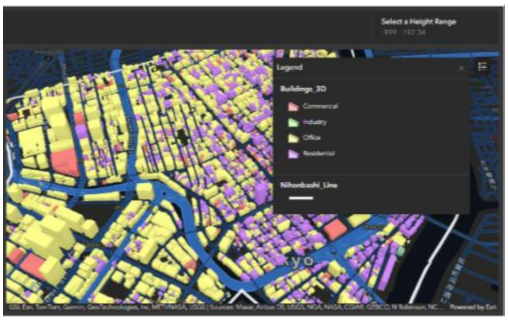

Figure 22 3D visualization of the Nihonbashi Area in the Dashboard

5. Discussions

This study developed urban digital twins (UDT) framework to enhance urban heat resilience in Tokyo's Nihonbashi district, integrating real-time data and advanced analytical tools to support heatwave response and planning. The framework, coupled with a route planning system implemented through a Python script, addresses the critical need for dynamic, data-driven strategies to protect vulnerable populations, particularly the elderly, during extreme heat events. The results demonstrate the framework's ability to map heat risks, optimize evacuation routes, and provide actionable insights for stakeholders, while also highlighting areas for further refinement.

5.1 Urban Digital Twins Implementation

The DT framework was implemented by integrating diverse data sources, including 3D city models from PLATEAU's CityGML, road networks from OpenStreetMap (OpenStreetMap), and heat hazard layers from Tokyo Government heat maps. These were processed using ArcGIS Pro and Python-based geospatial libraries, such as OSMnx and NetworkX, to create a comprehensive digital representation of Nihonbashi. Socioeconomic data from e-Stat, including age, income, and mobility limitations, were spatially joined to neighborhood and building-level units to identify social vulnerability hotspots. These hotspots, characterized by high concentrations of elderly or low-income residents, informed agent-based model attributes, such as response delay, evacuation speed, and destination preferences, enabling targeted interventions during heatwaves.

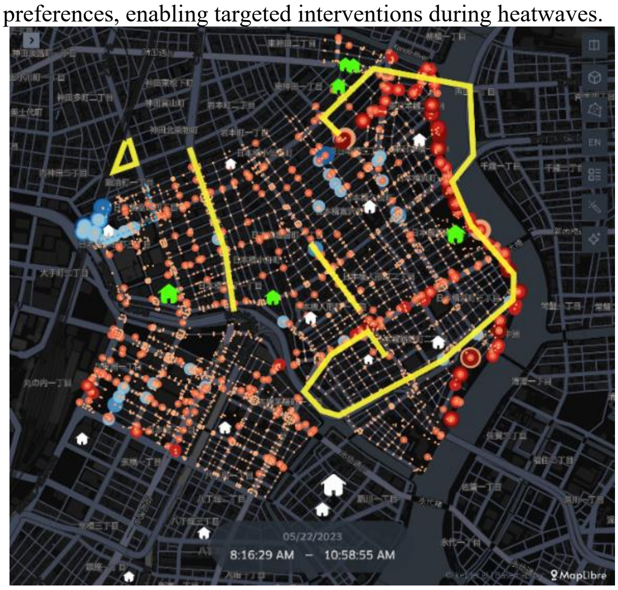

Figure 23 Traffic Analysis & Evacuation Recommendations

The UDT framework envisions a stakeholder-facing Digital Twin Interface (DTI) deployed through ArcGIS Experience Builder, although the current implementation outputs result via terminal and matplotlib plots. The DTI would enable planners, emergency responders, and the public to interact with the digital twins, simulating scenarios such as shelter overcrowding or route blockages. For instance, planners could assess how elderly or low-income populations might face longer routes due to occupied shelters, while urban design and transportation departments of the local government could prioritize investments in shaded corridors or backup routes to minimize heat exposure. This interface enhances the framework's applicability by providing actionable insights tailored to diverse stakeholders.

5.2 Limitations and Future Directions

Despite the promising results, several limitations must be addressed to enhance the framework's effectiveness. The route planning system's use of traffic density as a proxy for vulnerability may not fully capture socioeconomic factors like age or income, which are critical for identifying at-risk populations. Integrating e-Stat census data directly into the route planning algorithm could improve the accuracy of vulnerability assessments. The reliance on static data for road networks and shelter locations limits the system's responsiveness to real-time conditions, such as traffic congestion or shelter occupancy. Incorporating real-time data streams, as envisioned in the stakeholder-facing Digital Twin Interface (DTI) through ArcGIS Experience Builder, would address this gap (see Figure 24).

As for the route planning with the heat scenario classifier, the evacuation model minimizes heat hazard exposure but overlooks benefits from green spaces or shaded areas, which could enhance safety. Future work could optimize routes to maximize green exposure or time in shade, using data on tree canopies or parks, despite challenges in high-density urban settings. The model's static heat assumptions fail to capture time-varying conditions,

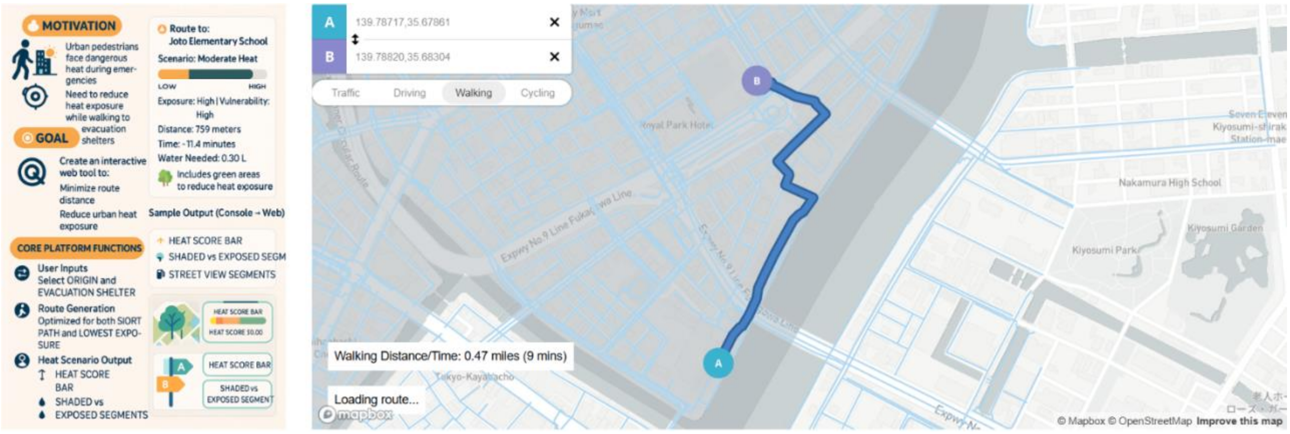

Figure 24 Proposed Route Planner using ArcGIS Experience Builder

such as diurnal fluctuations. Incorporating real-time weather data from OpenWeatherMap could improve accuracy, though it increases complexity. Static road and shelter data from OpenStreetMap limit real-time responsiveness, suggesting a need for live data streams. The heat scenario classifier, with 96.74% accuracy, may miss microclimatic variations, indicating a need for localized sensors. The digital twins' interface requires further development for stakeholder usability. Addressing these will enhance the framework's effectiveness and scalability.

6. Conclusion

This study presents a framework of urban digital twins to enhance urban heat resilience in Tokyo's Nihonbashi district, prioritizing vulnerable populations like the elderly. Integrating PLATEAU's CityGML, OpenStreetMap Tokyo Government heat maps, and e-Stat data, it maps high-risk zones and optimizes evacuation routes. The four-step scenario planning methodology, including Descriptive, Evaluative, Predictive, and Prescriptive models, uses tools like NetworkX, OSMnx, and a Random Forest Classifier (96.74% accuracy) to assess heat exposure, evaluate network performance, simulate scenarios, and green infrastructure like green roofs and cool paths. A case study showed heat-optimized paths reducing heat risk by 18.25%. The ArcGIS Experience Builder platform supports stakeholders' interaction. Future enhancements should include green exposure and time-varying heat conditions. This scalable framework offers a model for urban heat management, contributing to future resilient city systems design.

7. References

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access*, *7*, 167653–167671. https://doi.org/10.1109/ACCESS.2019.2953499

Boeing, G. (2025). Modeling and Analyzing Urban Networks and Amenities With OSMnx. *Geographical Analysis*, *n/a*(n/a). https://doi.org/10.1111/gean.70009

Boschert, S., & Rosen, R. (2016). Digital Twin—The Simulation Aspect. In P. Hehenberger & D. (Eds.), *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers* (pp. 59–74). Springer International Publishing. https://doi.org/10.1007/978-3-319-32156-1_5

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine*, *63*(11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, *29*, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Kim, Y., Oka, K., Kawazu, E. C., Ng, C. F. S., Seposo, X., Ueda, K., Hashizume, M., & Honda, Y. (2023). Enhancing health resilience in Japan in a changing climate. *The Lancet Regional Health: Western Pacific*, *40*, 100970. https://doi.org/10.1016/j.lanwpc.2023.100970

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Martinez, G. S., Imai, C., & Masumo, K. (2011). Local Heat Stroke Prevention Plans in Japan: Characteristics and Elements for Public Health Adaptation to Climate Change. *International Journal of Environmental Research and Public Health*, *8*(12), 4563–4581. https://doi.org/10.3390/ijerph8124563

Oka, K., Honda, Y., Hui Phung, V. L., & Hijioka, Y. (2023). Potential effect of heat adaptation on association between number of heatstroke patients transported by ambulance and wet bulb globe temperature in Japan. *Environmental Research*, *216*, 114666. https://doi.org/10.1016/j.envres.2022.114666

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., & Nee, A. Y. C. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, *58*, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001

Tochibayashi, N., & Ota, M. (2025, June 18). *Lessons from Japan for tackling extreme heat in the home*. World Economic Forum. https://www.weforum.org/stories/2025/06/japan-tackling-extreme-heat-living-spaces/

WHO, R. O. for the W. P. (2013). *Apia outcome: Tenth Pacific Health Ministers Meeting, 2-4 July 2013*. WHO Regional Office for the Western Pacific. https://iris.who.int/handle/10665/208167