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MEASURING RESILIENCE, ECONOMY, SUSTAINABILITY, AND HUMAN WELL-BEING IN MULTIPLE SCALES FOR URBAN DIAGNOSTICS

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ABSTRACT

Climate change, energy security, and individual communities increasingly necessitate using urban modeling and management systems in handling complex challenges of emergent and connected systems. Urban Systems Design attempts to address these issues as a comprehensive framework which can simultaneously evaluate the important metrics of resilience, economy, sustainability, and human well-being. Building upon the Urban Systems Design framework, our study explores different ways of studying scaled problems, evaluation, energy supply and demand, and how best to employ these methods, using the Sumida Ward of Tokyo, Japan as a test case. The proposed evaluation methods can be utilized by city planners and citizens to diagnose existing characteristics of an urban area and to better decide between options for transforming it.

Keywords: urban systems design, evaluation criteria, energy and urban metric optimization, urban diagnostics, smart city, urban planning

NONMENCLATURE

Abbreviations	
USD	Urban Systems Design
RESH	Resilience, Economy, Sustainability, and Human Well-Being
FoCUS	Form, Context, Use, and Structure
CCM	*cho-cho-moku* (町丁目)
GIA	Gross Interior Area
Std.	Standard deviation
PV	Photovoltaic
EV	Electric vehicle
Symbols	
N	Total Amount
H	Height
A	Total Area
b	Building
S	Study Area
bl	Block
i	Intersection
o	Specific Study Area
Gr	Granularity

1. INTRODUCTION

Smart cities, urban management, urban systems, and urban diagnostic tools are increasingly taking larger roles in city planning and governance [1,2]. Though the growth in the method's use is not without skepticism nor completely new to the fields studying urban environments, recently more focus has been directed towards investigating these endeavors and how best to implement them [3,4]. Despite the criticism of these emergent approaches – information security, personal anonymity, how data is collected, and the role these smart systems can have in dehumanization urban spaces – smart cities and their management suites (software, hardware, etc.) are viewed with promise at being able to address the extensive challenges modern cities face.

Employing the latest advances of modeling and data collection offer the ability of studying the compounding effects of complex and emergent systems that exist in urban environments. Cities, and citizens, are faced with difficult mutually-exclusive options in contending with decarbonization, disaster resiliency, humanistic designs, and energy sustainability. Urban systems design aims at addressing urban challenges by developing smart communities through the unification of modeling and metric-based approaches and the personal and humanistic elements of conventional community planning methods. Four pillars (Fig 1) form the basis of this unified approach combining analytics with design principles in balancing urban requirements with those of humans and nature. The four pillars of RESH are

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Resilience, Economy, Sustainability, and Human Well-Being [5]. While each of these individual elements are broad topics more specific metrics are utilized: fire safety, resilience; transportation, economy (including EVs for sustainability); and energy supply and demand, sustainability (focusing on PVs for renewable energy).

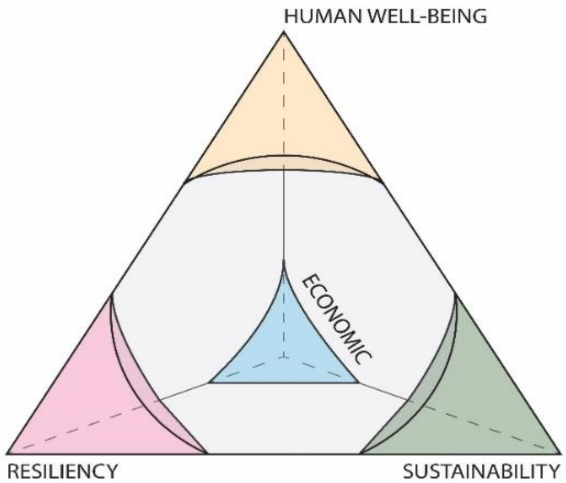

Fig 1 RESH Evaluation [5]

Urban systems contain complex systems in multiple scales – scaling up is not equal to the aggregation of performance in systems with complex interactions [6]. Assessing current and future conditions using RESH metrics requires a system boundary determined by the scope of the project in conjunction with the system scale. System scales, in the USD framework, are predicated on the holarchical nature of cities in which urban systems are studied as distinct discrete objects, but are connected as aggregated parts of larger systems; individual agents form the core, aggregated to households, placed in buildings, located in blocks, collected in neighborhoods, creating communities, and administered by wards and cities (Fig 2) [5]. The systems at each scale are simultaneously influenced and influencing those at higher and lower orders, while still being a complex distinct object in isolation – a holon [7].

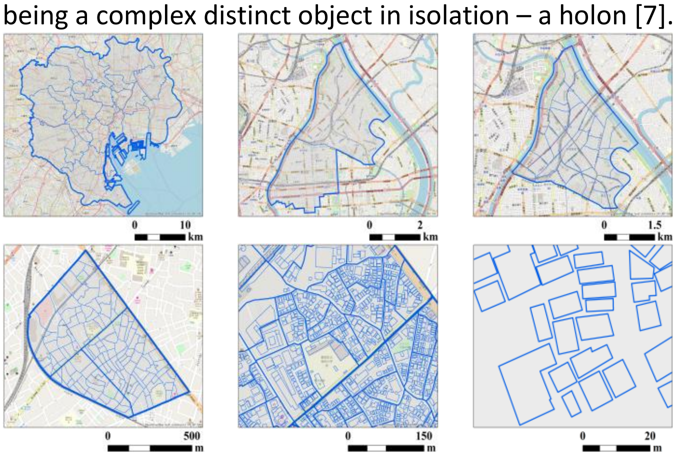
Fig 2 Urban Scale [5]

Our study explores the different methods of scenario analysis using the USD framework, which metrics are important for evaluation, development of urban typologies, and which system scales they are best applied to. The analysis results will diagnose existing urban status and establish customized strategies for transforming urban areas, which will help develop and support a further understanding, and bridge the gaps, of differential spatial scales in a city.

2. DATA AND METHODS

Multiple large datasets, public (Tokyo municipal government, etc.) and private (Zenrin, NTT Data/RESTEC, etc.), were employed for this study. The focus was on applying the USD framework to the northern section of the Sumida ward in Tokyo and expanding on previous studies [8].

2.1 North Sumida

Sumida ward, one of 23 wards that comprises the city of Tokyo in Japan, is composed of 104 administrative neighborhoods (census tracks) called cho-cho-moku (町丁目 or CCM) which are the scale of study. Although the entire ward is 13.74 km^2, only the northern 8.40 km^2 was examined for our purposes. The mean size of the CCM in the northern half area is 0.20 km^2, and Std. is 0.09 km^2. The southern portion of the ward has already undergone extensive redevelopment mirroring the international, or cosmopolitan, style of most modern cities. Whereas, the northern section maintains the smaller, organic, and more intimate streets of traditional Japanese urban form owing to the area's agricultural roots. While these forms aid in the promotion of social networks and interactions, they present clear challenges to energy consumption; flooding, as Northern Sumida is located at or below sea level; and general disaster relief and mitigation. In response, the ward government has begun several initiatives to work with its citizenry to identify what changes are necessary without losing the key localized and contextual elements.

2.2 Classification and evaluation

The methodology of our study is divided between two simultaneous processes, classification and evaluation, which converge to create the final analysis. Classification (urban typologies) rely on intrinsic attributes of urban morphology (FoCUS) to create classes of like elements. These classes are utilized in the creation of building- and block-level typologies to better represent the stochastic nature of cities [5]. Evaluation (RESH metrics) is the modeling, or surveying, conducted to evaluate current and future conditions and applied to individual entities or typologies.

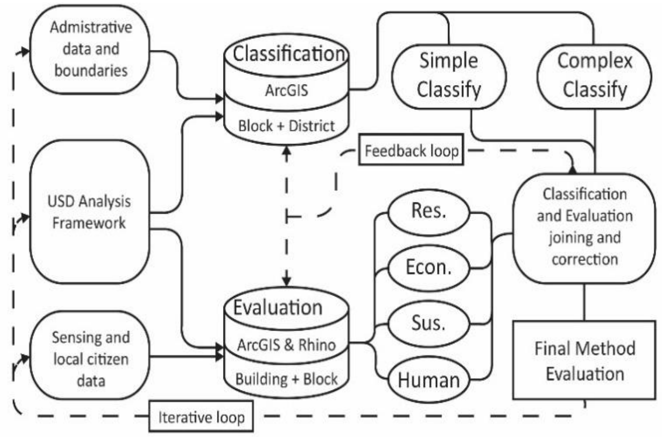

Fig 3 Research Methodology

2.2.1 Urban typologies

Five types of classification were employed for this study: gross interior area, granularity, road type, building typology, and urban morphology. Gross interior area refers to the total built area located inside the area of study and calculated using the following equation:

$$GIA = \frac{\Sigma_b(A_b * H_b)}{A_s} \text{ [8]}$$

GIA ranges from -2 std. very low density (0.00 – 0.50) to +2 std. very high density (6.00+). Granularity works in conjunction with GIA to show how the built area is distributed and how fine grain or coarse the area is:

$$Gr = \frac{\Sigma_o(N_b+N_i+N_{bl})}{A_s} \text{ [8]}$$

granularity ranges from -2 std. monolithic (0.00 – 0.35) to +2 std. very fine grain (1.00+). Roads were classified on the presence of one, or all, six road types: highway, arterial roads, collectors, boundary, small gridded streets or small organic street (mutually exclusive options), and shopping streets. Building typologies were created from a mixture of land use (single family, apartment, commercial, etc.), structure (wood, concrete, steel), mixed use, size (0-50m^2, 50-100m^2, 100-250m^2, etc.), and height (single story, low rise, midrise, etc.). Urban morphology combined road type and building typology to create block-level classifications.

Table 1 Classification Metrics

METRIC	PURPOSE
GIA	Measuring the amount of floor area
Granularity	Number of objects in an area
Road Type	Connecting building and infrastructure
Building Typologies	Grouping minorly different buildings together, making simulation easier
Urban Morphology	Grouping minorly different entities together, making simulation easier

2.2.2 Metrics of evaluation

Seven metrics of evaluation, based on local concerns of the residents and their intersection with RESH, were used: fire risk, earthquake vulnerability, flooding risk, transit connections, economic strength, vacancies, and energy supply and demand. Fire risk was determined by the nearness of one building to another based on 30%, 60%, and 100% protection distance intervals from how far a fire can jump, a buildings construction, and the proximity to a wooden structure with values ranging from 1 (no risk) to 6 (high risk) [9,10]. Earthquake vulnerability was a function of building to building distance plus building height, with taller buildings posing greater risks. Flooding risk was simulated and provided by Ministry of Land, Infrastructure, Transport and Tourism, Japan [11]. Transit connection shows the absolute distance one has to travel from a building to reach a bus stop (200m threshold) and/or a train station (400m threshold). A smaller threshold was used, less than 804m (1/2 mile), due to the demographics of the area being older and more dependent on public transportation [12]. Economic strength was a function the worker population, in a block, divided by the total population weighted by its transportation connection value, where areas with higher worker populations and better access transit scored higher. Energy demand was simulated using the EnergyPlus engine by parameterizing individual buildings as thermal zones and their surroundings as shading objects [13,14]. The Rhinoceros 3D Grasshopper plugin was used for the parametric modeling, and the Honeybee plugin was used to model a script running EnergyPlus [15]. Supply was estimated using the solar radiation tool in ArcGIS to measure the expected amount of potential solar energy hitting each building's roof. Supply was divided by demand to estimate the percentage the building could utilize, at 100% efficiency, and the final metric being -3 (less than 15% covered at 40% PV efficiency) to +3 (greater than 75% covered at 20% PV efficiency).

Table 2 Elvauation Metrics

METRIC	PURPOSE
Fire Risk	Fire risk to buildings and blocks
Earthquake Vulnerability	Risk of damage or damage to other buildings by an earthquake
Flooding Risk	Risk of inundation resulting from a flood
Transit Connections	Ease and accessibility to nearby transportation hubs
Economic Strength	Measuring the economic vitality of a specific area
Energy S&D	Comparing energy supply and demand

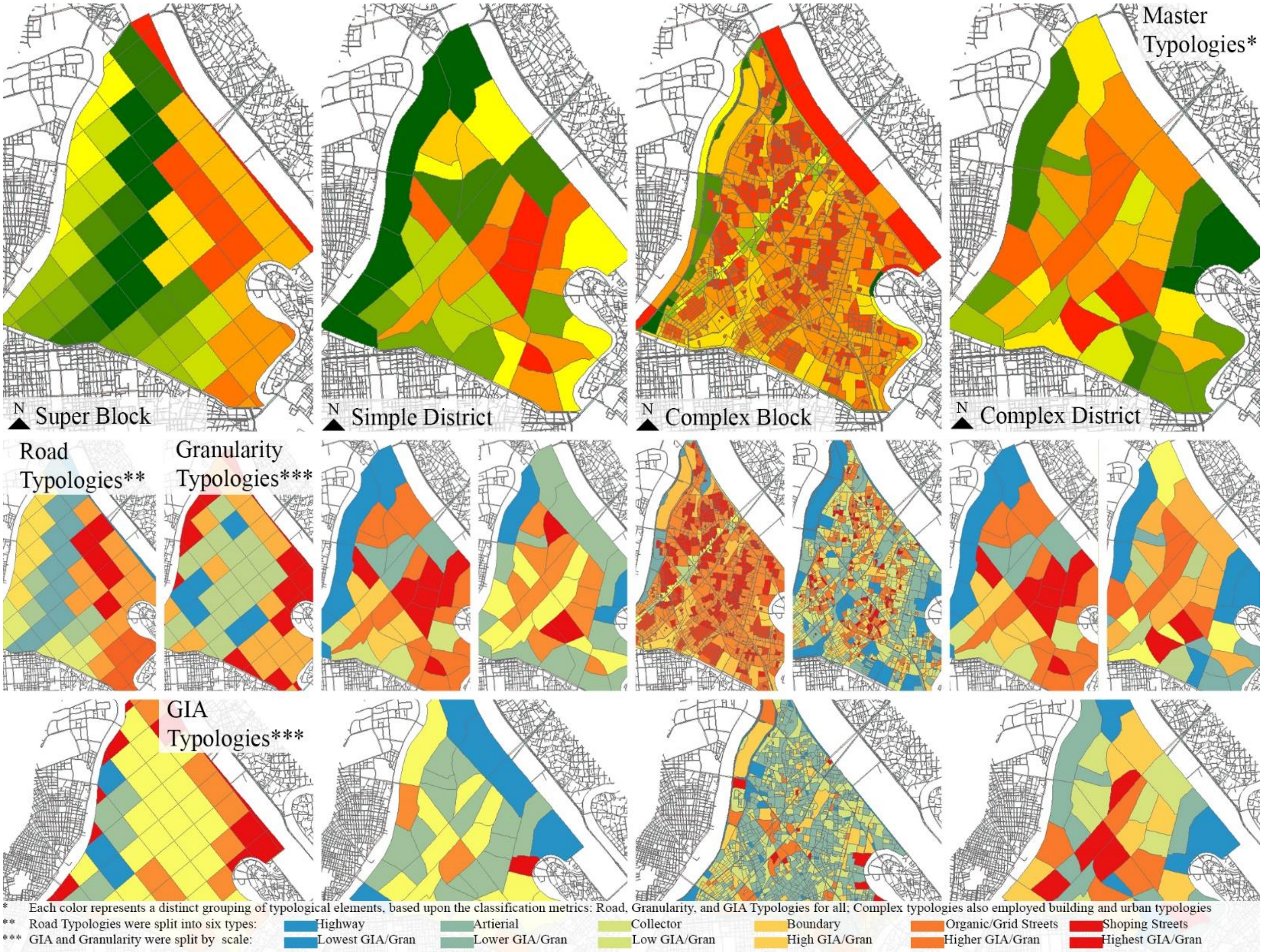

Fig 4 Four Methods of North Sumida Analysis and Classification

3. NORTH SUMIDA EVALUATION

The classification and evaluation methodology were run three separate times for a simple district level analysis, using road types, GIA, and granularity alone; complex block level, using all metrics; and complex district level, using all metrics. These results were also compared against the previous analysis, simplified super blocks, as investigated in *"Urban Systems Design Applicability Case Study"* [8].

4. FOUR METHODS OF ANALYSIS

All four methods of analysis and evaluation followed the same process and means of classification to create typological groupings for each classifying metric and then in turn the master typologies for North Sumida (Fig 4). Super blocks' level of abstraction into 400m x 400m blocks enable a quick study of a large area, but loose local significances and fine resolution [8]. Simplified districts by contrast maintain the local attributes but are slightly less fine grain due to the scale of individual CCMs. Complex block analysis maintains both the localization of the data and the fine grain information (building-level) important in distinguishing objects and areas from each other. While Complex districts are based on the information of complex blocks, the aggregation of the data destroys the information and makes it more difficult to identify key areas. Comparing these four methods reveals that complex analysis, for assessment and change, is best done two level down from the point of study, i.e. blocks for communities (wards). Whereas, simplified analysis is most useful in low data environments and one step down from the point of study, i.e. neighborhoods (CCM) for communities (wards). The strength and weakness of these methods are displayed in Table 3.

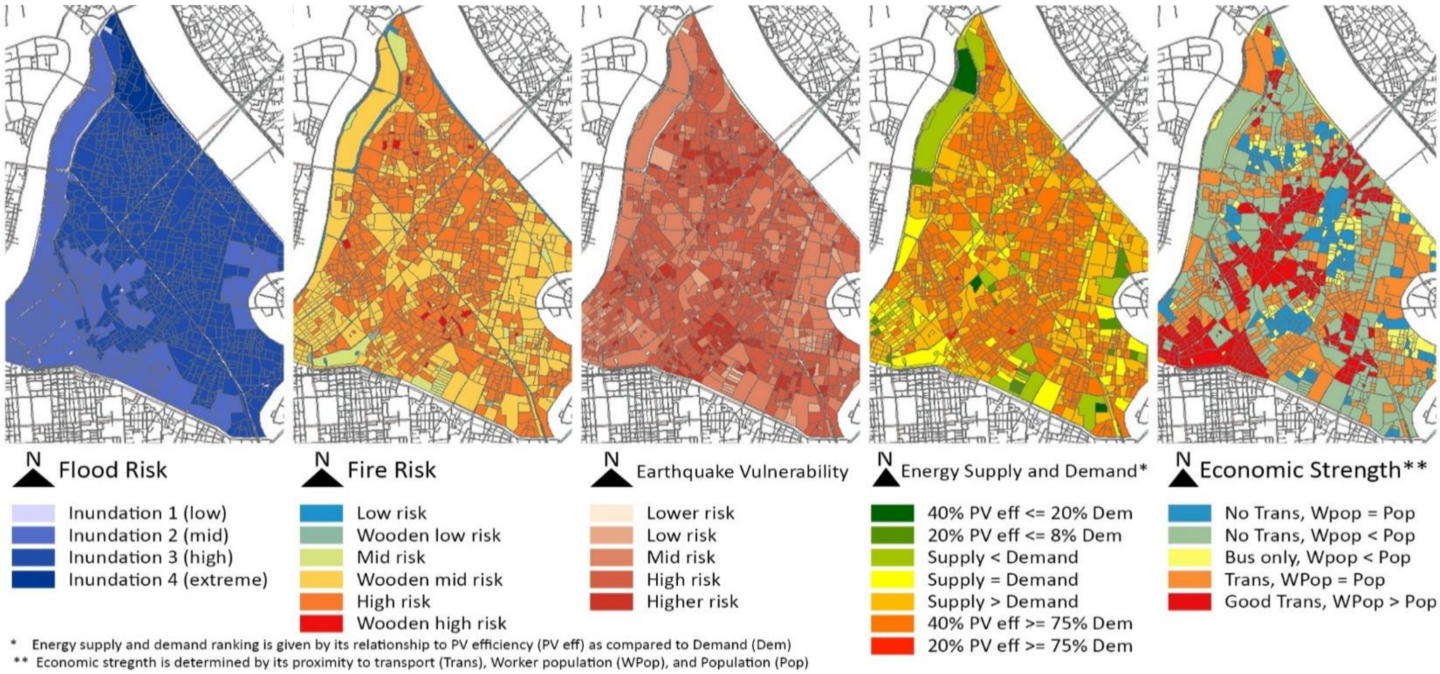

Fig 5 Complex Block Level Evaluation Metrics

Table 3 Strengths and Weaknesses of Analysis Methods

ANALYSIS	STRENGTHS	WEAKNESSES
SUPER BLOCK	- Low data requirement - Good level of abstraction - Useful at examine large areas, not district scale - Standardized block size: easy to compare	- Inaccurate and lowest resolution - Not tied to local parameters
SIMPLE DISTRICT	- Useful at examining district scale objects - Quickly denotes key areas	- Low resolution - Unable to capture fine grain changes
COMPLEX BLOCK	- Finest grain analysis - Identifies problem areas - Facilitates targeted plans	- Data heavy - Requires blocks - Time intensive
COMPLEX DISTRICT	- Fine grain analysis - Useful for analyzing evaluation metrics more than classification metrics	- Data heavy - Lowers resolution of fine grain data - Possibility of misleading information

5. CURRENT CONDITION ASSESSMENT

Assessment of the current conditions based upon the RESH metrics was performed at the complex block scale of classification (Fig 5). In addition to the RESH metrics discussed in section 2.2.2, vacancies were also included in current condition assessment. As Tokyo, and Japan in general, experiences negative birthrates and a declining population vacancy in homes and apartments become increasingly common, there are both challenges and opportunities for communities. Vacancies were determined using purchased private building data which contained the use, construction, and vacancies for all buildings in the North Sumida area.

In individual metrics, the area scores highly (good to neutral) in most areas (Table 4); however, this hides the extreme outliers in each category. Although most areas in energy supply and demand score within the 40% to 20% PV efficiency range, the total simulated energy consumption of the area is 1,239 million kWh a year with a total supply of 873 million kWh from solar radiation. When accounting for vacancies, total energy drops to 721 million kWh a year of demand, but this notes a secondary issue as the area experiences a high rate of vacancies that is not concentrated. Further, buildings and blocks performing well for energy balance often were associated with lower resilience metrics, suggesting more holistic system measures are needed in considering decisions. However, when these analyses are combined with the high-resolution building data, they provide planners, government officials, and citizens an active role in identifying and creating alternatives.

Table 4 North Sumida RESH Evaluation

METRIC	GOOD (NO – LOW)	NEUTRAL (LOW -MID)	BAD (MID – HIGH)
FLOODING RISK	569	390	949
FIRE RISK	575	540	793
EARTHQUAKE VULNERABILITY	578	400	930
ENERGY SUPPLY AND DEAMND	1,158	680	70
ECONOMIC STRENGTH	864	722	322
TRANSPORATION CONNECTIONS	698	393	817
VACANCIES	1,521	340	47
TOTAL RISK	8	1,424	476

Several metrics key to better understanding the human well-being and resilience were not included in this study, or on Table 4. These include the amount of greenery present in each block or proximity to buildings; the streetscape and how pleasant each road is to utilize compared to its actual utilization; heat island; local climate zones, to better understand external comfort; and sensory gathered local data (heartrate, thermal sensors, etc.). These are potentially useful metrics to be included in future iterations, along with the inclusion of other RESH metrics, to aid in current and future condition benchmarking, testing, and opportunity identification.

6. CONCLUSION

Cities are constructed from a complex series of holarchical scaled systems that are complete entities in themselves as well as being intertwined with those located above and below them. Urban systems design functions as an integrated urban management methodology and framework which account for this inherent nature. This research explored urban systems design by integrating urban diagnostic tools and their analysis results in a designated urban context. Analysis in multiple scales and different granularities informed performance gaps across scales and the different potentials of transforming an urban area. According to the discussion section (refer to Table 4), about 41.6% and 48.7% of blocks in North Sumida are encompassing the high-risk of fire and earthquake, respectively. On the other hands, about 60.7% of blocks have potentials to increase solar power generations and about 54.72% of blocks have potentials to be strengthened in economic viability. By providing comprehensive metrics related to RESH for current and future conditions at different scales, these results can be disseminated for city planners to establish transformation strategies customized by a community's vision.

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