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Carbon-Neutrality Architecting and New-Age Visions for Urban Areas Using Systems Design (CANVAS) – A Case Study of Tokyo Nihonbashi

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ABSTRACT

This paper addresses the imperative goal of achieving carbon neutrality in Tokyo's historic Nihonbashi district by 2050. The proposal of a systems design model based on the reconstruction and renovation of the existing built environment through design changes enables meeting the goals of net-zero emissions targets. Our study proposes the integration of 3D modeling techniques and scenarios generation for complex urban neighborhood systems and explores design decisions aimed at further reducing carbon emissions. By leveraging advanced technologies, such as digital urban modeling tools (building energy modeling and design generation based on Rhino 3D, Grasshopper, Ladybug, Climate Studio, and ArcGIS) as well as systems architecting tools (including morphological matrix, alternative concepts analysis, and model-based systems engineering, MBSE), we seek to provide a comprehensive framework for decision-makers and urban planners to assess the environmental impact of design choices. Our approach involves developing a digital representation of the Nihonbashi district, incorporating various architectural and environmental parameters. Through simulation, we analyze the potential carbon reduction benefits of alternative design interventions, including the following variables: materiality (structure), building density, building type/use, façade, and renewable energy integration. The findings of our research highlight the potential for significant carbon emission reductions through innovative design decisions. By quantifying the environmental impact of various design scenarios, decision-makers can make informed choices that align with the district's carbon neutrality objectives. Additionally, our study investigates the economic viability and feasibility, as well as the equitable impacts of implementing these design changes, considering factors such as cost, construction logistics, and stakeholder involvement. This paper contributes to the existing body of knowledge related to planning decision support systems by exploring the role of digital modeling as a transformative tool of urban planning for carbon neutrality. By emphasizing the importance of incorporating design changes to address carbon emissions, we aim to provide actionable insights for urban development in Nihonbashi and inspire similar initiatives worldwide.

Keywords: carbon neutrality, urban carbon emissions, systems architecting, urban systems design, urban revitalization, Tokyo

1. BACKGROUND & MOTIVATION

High-density cities around the world both contribute to carbon emissions, as well as suffer from climate change. In October 2020, the government of Japan announced its goal to achieve carbon neutrality by 2050. Significant investments have been allocated towards this

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goal. The Ministry of Economy, Trade and Industry devised the “Green Growth Strategy through Achieving Carbon Neutrality in 2050”.

To meet the United Nations Sustainable Development Goals (SDG), it is necessary to make a fundamental shift in urban design and development methods that currently exist in these communities. This study aims to explore new methods for high-density cities—specifically Tokyo—to address the challenges they are facing, and ultimately meet carbon neutrality projections by 2050.

This study focuses on the Nihonbashi district in Tokyo, a bustling urban commercial and residential area. This district has the densest population in Tokyo and is geographically located at the center of Tokyo. Nihonbashi combines modern financial & commercial establishments with historical and cultural landmarks. For these reasons, Nihonbashi is a significant testbed to study and examine how such an area can be transformed to achieve 2050 carbon neutrality goals.

The typical process of urban carbon mapping and revitalization involves several key steps (Dixon and Eames. 2014) [1]. It begins with data collection, where relevant information on energy consumption, transportation patterns, waste generation, and other emission sources are gathered. This data serves as the foundation for creating a baseline assessment of the city's carbon footprint. Stakeholder engagement is crucial in setting ambitious carbon reduction goals and gaining support from government, communities, businesses, and NGOs. Carbon mapping utilizes Geographic Information Systems (GIS) and remote sensing technologies to spatially visualize emissions and identify hotspots. Building upon the carbon mapping results, low-carbon strategies are identified, encompassing renewable energy integration, energy-efficient infrastructure, sustainable transportation, waste reduction, and green building practices. An integrated urban revitalization plan is then developed, aligning low-carbon strategies with broader urban planning objectives. Policy and regulation development play a vital role in incentivizing sustainable practices and enforcing carbon reduction targets. Public awareness campaigns encourage behavioral changes and active participation in carbon reduction initiatives. Continuous monitoring ensures progress tracking and necessary adjustments to achieve desired outcomes, leading to the transformation of urban areas into sustainable, resilient, and low-carbon cities. Large-scale urban retrofitting requires systemic change in the organization of built environment and infrastructure, and this study will focus on the current 154 buildings in District 2 of Nihonbashi.

Previous work of urban carbon mapping of the Nihonbashi district has been developed by Mitsui Fudosan UTokyo Laboratory [2]. By focusing on buildings in the district, this carbon mapping studied the decarbonization of Nihonbashi and their trends. Current CO_2 emission estimations of every building were mapped for the entire district. Using the low carbon urban revitalization strategy, CO_2 emission estimations projected for 2050 were also mapped. The urban revitalization strategy focused on applying different “energy conservation and renewable energy initiatives” to buildings and public spaces, including [2]:

1) Reconstruction
2) Renovation
3) Operational improvements
4) Improvement of electricity emission factors
5) Increase in green energy technologies (i.e. electrification)

The subsequent impact on building energy consumption and decarbonization projections were observed. Our preliminary results from this carbon mapping study showed how challenging the decarbonization of a densely populated urban area is. Based on these results, the current urban redevelopment practices are not sufficient for Nihonbashi to achieve carbon neutrality by 2050. There is a need to bridge this existing gap.

2. PROBLEM FORMULATION

How do we achieve the goal of carbon neutrality by 2050 through urban revitalization processes for a high-density urban district such as Nihonbashi of Tokyo? This study integrates data-driven approaches and design modeling methods. To make the urban carbon mapping method useful in meeting zero-carbon, there is a need to define a new framework of research to examine existing building and environmental systems based on data inventory. There is also a necessity to incorporate design for systems changes, in which design is seen as a key variable in the modeling of complex urban systems of systems. There needs to be a catalyst agent—in the form of systems architecting— to create future smart cities that can meet the carbon neutrality projections for 2050. In order to bridge this gap, new methods, techniques, and processes need to be introduced. This challenge is best approached from a multi-disciplinary and multi-domain perspective.

Therefore, it is beneficial to approach this challenge from a system architecting context, bringing in best practices to address the shortcomings of the more traditional architecting perspective. Design considerations and questions that arise include:

1) How is the current system performing in the realms of energy and carbon based on empirical data?
2) How can the current system be enhanced to perform better in future scenarios through urban revitalization strategies, and how big is the gap between what the strategy would achieve and the goals moving toward carbon neutrality?
3) What design changes are needed to bridge the existing gap?
4) Building energy consumption is based on technologies that currently exist (i.e. the status quo). Are there new technologies that can be infused to achieve carbon neutral goals?

The question that remains however, is how can we project the changes of Nihonbashi's carbon neutrality goals by 2050? Therein exists the solution to discovering future scenarios and urban systems designs that may facilitate this transformation to occur. To do so, one such answer we are presenting incorporates "design" for

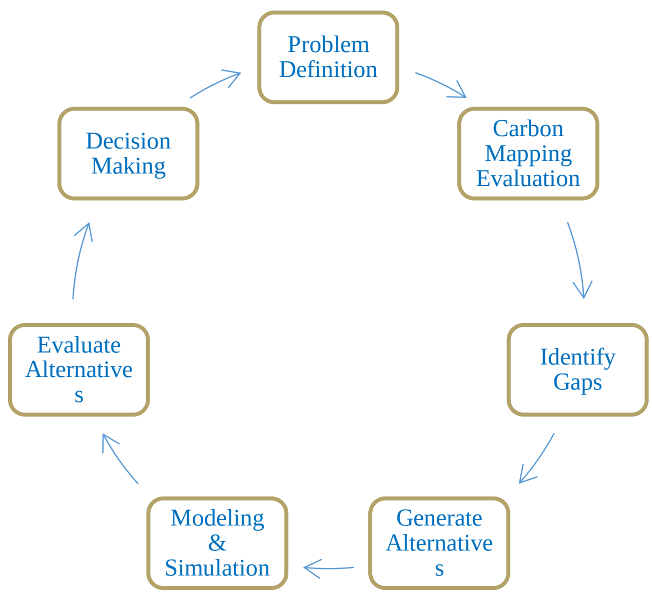

Fig. 1. Proposed CANVAS model framework

systems of systems in diverse ways, which focus on incorporating data-driven carbon accounting with simulation & modeling by design.

3. APPROACH & METHODOLOGY

A framework was developed, called CANVAS (carbon-neutrality architecting and new-age visions for urban areas using systems design) (Fig.1), to address this question. This integrates Georgia Institute of Technology's Aerospace Systems Design Laboratory (ASDL) proposed methods and techniques for such paradigms (Mavris, 2021) [3]. The framework developed for this effort applies these innovations and techniques, alongside systems design, architecting, and optimization. Using ASDL's processes, the carbon mapping method can experience accelerated growth, and provide a means to develop some digital representation of the Nihonbashi district to quantify the district's carbon emissions and performance. This in turn will aid in the decision-making process by predicting outcomes and impacts of alternative scenarios. This method addresses our research question: how do we design an urban digital twin or digital platform, in our case CANVAS, for making complex decisions in order to promote zero carbon urban systems? Our novel method, CANVAS, goes beyond strictly using urban design strategies, strictly using digital technologies (Fig. 2), or strictly using aerospace/digital twin systems design. It ventures to integrate various systems into a multi-disciplinary, multi domain approach, incorporating aspects from diverse design theories within one cohesive framework.

3.1 CANVAS Framework: Concept

The CANVAS framework will culminate in an interactive, visual dashboard which takes the carbon mapping as an input, identifies gaps within the method, generates alternatives, dynamically models & simulates the Nihonbashi urban area, performs carbon analysis, and finally outputs the feasible design space environment. This dashboard would ultimately be used by stakeholders as a decision-making tool.

Key enablers to applying the CANVAS framework include a carbon map of Nihonbashi, climate and building analyses, digital modeling tools (i.e. Rhino 3D, Grasshopper, Ladybug, Climate Studio, and ArcGIS), and systems architecting tools (including morphological matrix, alternative concepts analysis, and model-based systems engineering, MBSE).

3.2 CANVAS Framework: Carbon Mapping Evaluation

The next step is to study and analyze the results from the carbon mapping method. In this portion of the framework, the urban district's carbon map (ideally already existing) is brought in as an input. Other inputs include the 3D-model and data of the district's buildings and infrastructure. These inputs are used as the starting point for the carbon mapping evaluation assessment.

To reduce carbon dioxide emissions from buildings, the following aforementioned measures were used as a roadmap for the mapping assessment: reconstruction, renovation, operational improvements, improvement of electricity emission factors, and increases in green energy technologies.

3.3 *CANVAS Framework: Identifying Gaps*

After the evaluation simulation and assessment of the results outputted from the carbon-map have been completed, the next step is to identify the gaps existing between the stakeholders' goals and the current progress in CO_2 reduction. The following steps illustrate how each measure was examined and shows how it falls short of the 2050 goals, with the ideal solution having the margins reduced down to zero.

3.3.1 Identifying Gaps in Measure 1 (Reconstruction)

The first carbon reduction measure detailed by the previous urban revitalization strategy is building reconstruction. The building(s) that are chosen for reconstruction each year are determined by the residual building ratio function [2].

$$R = e^{-\left(\frac{t}{\beta}\right)^{\alpha}}$$

where R = residual ratio
α = building structure
β = building use
t = building age

The residual ratio number is represented by the value of R, predicated on the values of the building structure, use, and age. Buildings chosen for reconstruction have a 0.6x improvement in energy consumption. To enhance the urban revitalization strategy, the following needs are to be considered, including changing building materials, changing building use, increasing or decreasing total floor area (TFA), and implementation strategies of these changes. It is important to note that building window-to-wall ratios and material details are needed, however this data is currently uncatalogued.

3.3.2 Identifying Gaps in Measure 2 (Renovation)

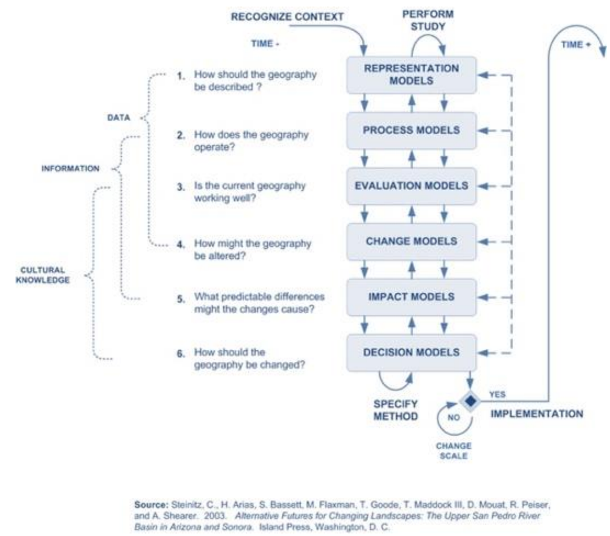

Fig. 2. Geodesign model (Steinitz, 2012) [4]

The second carbon reduction measure is building renovation. Non-reconstructed buildings that are 25 years old (or more) are considered for renovation [2]. Energy intensity is improved by 0.9x every 25 years [2]. To improve the strategy, further considerations need to be made, such as possible energy savings from utilizing new technologies, installing PV panels on rooftops, and/or introducing on-site water recycling, as well as expanding the scale of Machizukuri, which is Japanese for incremental community-based improvement of urban areas.

3.3.3 Identifying Gaps in Measure 3 (Operational Improvements)

The third carbon reduction measure is operational improvements in buildings. Electrical energy demand is calculated as being a 0.5% emission factor improvement up until 2030, and as a 0.3% emission factor improvement after 2030. This measure may be further improved in the future by infusing new-age technologies and concepts that may heighten the emission factor improvement even further. Hence contributing to closing the existing "gap" of reaching zero-carbon goals. The model may benefit from identifying further operational improvements and incorporating it into the alternative generation aspect of the CANVAS framework, such as energy efficient appliances, and/or smart building automation.

3.3.4 Identifying Gaps in Measures 4 & 5

The first three measures mentioned (reconstruction, renovation, and operational improvement) are classified as "active" strategies and are therefore prioritized over the more "passive" measures, including improvement of electricity emissions factor (measure 4) and an increase in electrification (measure 5). The improvement in electricity emissions factor is 0.452 kg- CO_2/kWh as of year 2022, and 0.200 kg- CO_2/kWh by year 2050. As for measure 5, the electrification rate improvement is 63% in year 2022 and 100% by year 2050. This measure, however, does not consider other "green technologies" that may be infused and incorporated into the carbon map of Nihonbashi. It also fails to consider different techniques and methods of improving the electrical emissions factor.

3.4 *CANVAS Framework: Generating Alternatives*

Once all the gaps have been identified in the last step, these gaps are then to be used as the starting point to generate alternative concepts and technologies. In this step, key variable parameters are identified, and a morphological matrix is then developed based on the different options. Thereafter, the design space that can meet stakeholder requirements is established, and its feasibility is inspected.

A morphological matrix is utilized to decompose the current model into individualized characteristics. This matrix is also used to analyze potentially new and unexplored permutations of different options and generate alternative concepts and technologies. One such morphological matrix is shown below in Table 1.

Table 1: Alternative Concepts for reducing carbon emissions.

	Alternative Concepts			
Evaluation Characteristics	1	2	3	4
Structure Materiality	Steel	Timber	Reinforced Concrete	
Building Density	Current FAR*	Increased FAR by 1.2x	Increased FAR by 1.4x	
Building Typology/Use	Commercial	Residential	Office	Mixed-Use

* FAR = Floor Area Ratio

3.5 *CANVAS Framework: Modeling & Simulation*

After the alternatives have been generated, model-based simulation tools are then used in the next steps of the CANVAS framework. Certain tools are identified for use in modeling and simulating to build the Modeling & Simulation (M&S) environment. This project utilized Climate Studio for climate simulations of the existing built environment. This allowed for a better understanding of the climactic impacts on the current building stock which would inform future design decisions, such as determining the availability of solar energy for the sizing of photovoltaic panels. Rhino 3D, Grasshopper, and Ladybug were used to model the building energy demand, carbon savings, and M&S efforts discussed in section 4.

3.6 *CANVAS Framework: Evaluating Alternatives*

The results extracted from Rhino 3D, Grasshopper, and Ladybug are evaluated using dynamic, interactive environments. For example, JMP evaluations of the data results can be performed to assess the design-space and run trade-offs. Other tools, such as a pareto analysis can further help the study with multi-objective optimization [5].

3.7 *CANVAS Framework: Decision Making*

Finally, the culmination of the CANVAS framework tool ends with a decision-making capability or tool that would be beneficial to the stakeholders. Ideally, stakeholders will use a dashboard to interactively test different scenarios and options. This tool is powerful in its ability to visualize the results and guide in the decision-making process.

4. MODELING & SIMULATION

CANVAS aims to incorporate innovative approaches and generate alternatives to address carbon emissions while achieving global sustainability goals. Digital modeling tools offer significant potential in generating alternative design scenarios and providing performance-based modeling tools for assessing and optimizing designs with the objective of reducing carbon footprints. Rhino 3D, Climate Studio, Grasshopper, and Ladybug can be utilized to measure climactic averages and carbon emissions, as well as to facilitate informed design decisions.

The methodology employed in CANVAS involves a step-by-step process utilizing digital analysis and digital modeling instruments. First, a digital model of the buildings or urban area under consideration is created using Rhino 3D. This entails accurate modeling of the geometry including building footprint, heights, and shapes, beginning with different levels of details for modeling purposes. To enable environmental analysis, plugins such as Climate Studio, Ladybug, and Honeybee provide the necessary tools for evaluating environmental factors such as radiation, energy consumption, daylighting, and carbon emissions. Material properties are assigned to the digital model to capture accurate representations of the building components. This includes specifying building materials, insulation values, and glazing systems. These properties play a crucial role in assessing the energy efficiency and carbon impact of buildings in urban areas. Grasshopper, a visual programming plugin for Rhino 3D, is employed to develop parametric energy models. This involves setting up energy simulation workflows and defining inputs such as occupancy schedules, internal loads, and HVAC systems. The energy models are then simulated to calculate energy consumption and associated carbon emissions.

Through the use of Climate Studio, a plug-in for Rhino 3D, the climate analysis involves utilizing climactic data from the nearest weather station, in this case we used the Tokyo-Chiyoda Station, which is then be mapped to the created building/study area model. Once the data is mapped to the surfaces of the buildings, based on the analysis type selected, the simulation generates the impact that the climate data will have on the geometry, materiality, and orientation of the buildings. Once this data is collected, it informs future design decisions.

The initial data generated from Climate Studio includes the area's sun path, wind rose, diurnal average, and heat map. The sun path diagram provides an understanding of how building shadows will impact the solar exposure to its neighbors based on its geometry. Knowing this will allow for a more informed decision on building geometry for the proposed model scheme. The wind rose also provided valuable data for geometry to ensure that the impacts of heavy winds are mitigated and prevent the creation of any possible wind tunnels, as well as inform about orientation for wind turbines if applicable. The diurnal averages provide information related to which months may be the most energy-intensive for the study area, knowing this allows for insulation strategies, and energy distribution strategies to reduce the carbon impact of the buildings. The heat map is significant in that it establishes the coldest and warmest months, allowing for a determination of what strategy will be used in what month, and close to which day that shift in strategy will occur. In addition to this data, a psychrometric chart is generated to aid in determining humidity-mitigating factors, as well as other sustainable approaches to energy conservation.

After understanding the general climate of the area, simulations based on the climate data are mapped to the buildings. The radiation simulation utilizes a fluid number of sensors on a set number of surfaces to determine how radiation impacts the buildings based on their geometry, orientation, and materiality. Based on the study area examined in this paper, 908 surfaces were considered from District 2 of Nihonbashi, Tokyo. Upon these surfaces, an average array of sensors were placed, for a total of 499173 sensors. Once these parameters were set, a 4-pass granularity simulation was allowed to run. The data collected from this simulation suggested that the roofs and southern façade received the most radiation, as well as May having the highest radiation average of over 125 kWh/m^2 and December having the least radiation with under 75 kWh/m^2 (Fig. 3). This is extremely valuable in understanding energy absorption for the implementation of photovoltaics, and which months to expect high or low demand for energy.

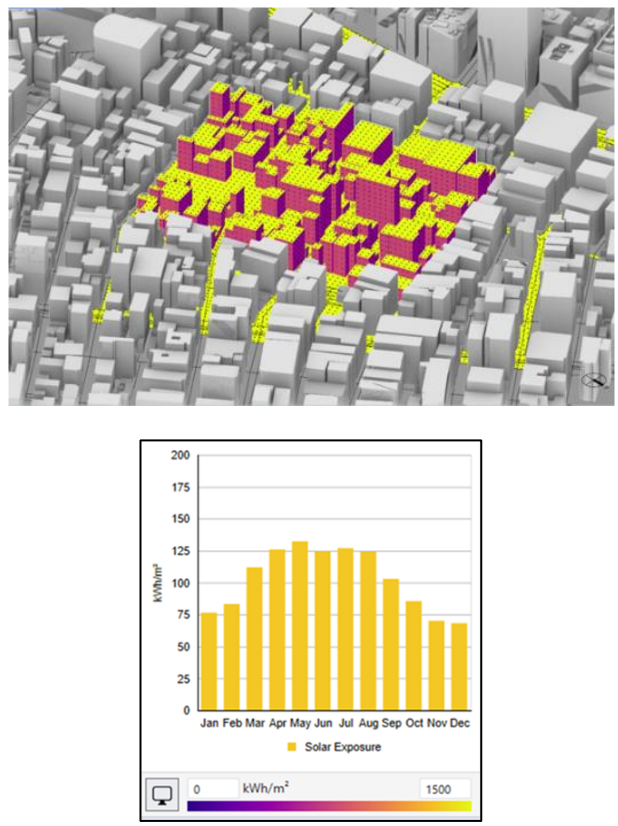

Fig. 3. The radiation simulation conducted on Nihonbashi East, Tokyo, Japan

5. CONCLUDING REMARKS & FUTURE WORK

Everything detailed hence far is for outlining the CANVAS method. In this early stage, a research design and a modeling test bed has been developed. Other elements of the framework including the morphological matrix, design generation, the pareto analysis, and the feasibility study analysis will be advanced in the next step to elaborate more details of the method, along with a more detailed modeling and simulation approach.

Financial consideration is one key factor that has not yet been fully incorporated in the current CANVAS model for urban revitalization, which normally plays a vital role in practices of urban development. An increase in FAR will allow for the owner or developer to gain greater returns on their initial investment in terms of their increased net operating income (NOI) and internal rate of return (IRR). FAR here is treated as a variable, in that it can be modified to better suit the stakeholders and owners involved in the process of redevelopment. The current CANVAS model suggests an average increase of FAR urban density to 1.2 and 1.4 as a projection of future growth scenarios based on current practices, which can be modified in actual project implementation based on the social and economic conditions. Policy also plays a significant role in this approach, in that it determines what the stakeholders can and can't do, but it also influences how much they are able to provide in the initial phases. The availability of governmental grants, tax-incentives, and other such monetary breaks allow for stakeholders to make more sustainable decisions. A green subsidy would also be a terrific way for the city of Tokyo to encourage stakeholders to make more climate conscious decisions. Finances and policy will also be examined in more detail while further developing the framework.

The CANVAS project outlines a potential path toward urban carbon neutrality. It provides urban planners with an interactive framework for revitalizing high-density urban communities. This framework serves as a tool to enable the community to reach the 2050 goals & projections for carbon neutrality. Modeling and simulation tools are embedded in the model with all the alternative options possible, hence expanding the available design space. CANVAS's interactive dashboard will allow the stakeholders and urban planners to easily visualize how different decisions impact their goals.

CANVAS also demonstrates the significance of an ongoing cross-disciplinary work culture between City Planning, Aerospace Engineering, Architecture, Public Policy, and Urban Analytics within Georgia Tech, in collaboration with the areas of Urban Engineering and Spatial Information Science within the University of Tokyo. Through this initiative, there is a strong potential to construct a shared framework between multiple disciplines across multiple countries, in which the idea of CANVAS promotes a new approach to the digital twin for urban systems in the design and development of the earth's future cities.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCES

[1] Dixon, Timothy & Eames, Malcolm, 2013, Scaling up: The challenges of urban retrofit. *Building Research and Information*, Vol. 41, Issue 5, 499-503.

[2] Yoshida, Takahiro & Murayama, Akito, 2023, *A Report of Urban Carbon Mapping for Nihonbashi*, the University of Tokyo [Unpublished manuscript]

[3] Mavris, Dimitri, 2021, *Advanced Design Methods*. Aerospace Systems & Design Laboratory. Georgia Institute of Technology.

[4] Steinitz, Carl, ed., 2012, *A Framework for Geodesign: Changing Geography by Design*. ESRI.

[5] Chang, Soowon, Saha, Nirvik, Castro- Lacouture, Daniel, Yang, Perry P. J., 2019, Multivariate relationships between campus design parameters and energy performance using reinforcement learning and parametric modeling, in *Applied Energy* 249, 253-264.