Computational Model for Quantifying Usage, Social Capital, and Benefits Derived from Public Open Spaces

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First, let me provide a brief note on my vision of where civil engineering is heading, and how this relates to parks and public open spaces. Throughout history, the primary needs of humans—and therefore the focus of civil engineers—has changed, and has been reflected in the design and management of the built environment. In ancient civilizations, a central focus was placed on basic needs, or the foundational level of Maslow's hierarchy, such as shelter, aqueducts, and granaries. Moving into the Middle Ages and Renaissance, we witnessed the emergence of fortresses and walls, symbolizing the desire for security and a sense of belonging. Around 200 years ago, the Industrial Revolution brought about the need for mass housing, factories, and industrial workplaces. At that time, civil engineers primarily focused on economic efficiency and safety when designing infrastructure systems. Civil engineers played a key role during World War I and II in the rapid design and construction of vital military infrastructure to address the need for roads and defense systems. After World War II, civil engineers were instrumental in rebuilding cities, bridges, and transportation networks, and explored designs that could withstand natural disasters and provide long-term durability. The focus still remained on *safety* and *economics*. More recently, rapid urbanization in the late twentieth and early twenty-first centuries has increased the need for public services, giving rise to environmental awareness and a shift towards sustainability and *livability*. During this time, social equity awareness has influenced not only societal perceptions, but also emphasized the imperative social capital and benefits provided by our engineered and built spaces. These powerful social waves have underlined the essential role of civil engineering in fostering social capital and human-centered benefits, calling for design approaches that promote social interaction, unity, inclusively, cohesion, and access to essential services and facilities. As civil engineers are faced with doing more with less, we look to public facilities and see the line between architecture, urban design, and civil engineering becoming blurred. How can we introduce engineering perspectives into the design and management of parks and public open spaces to augment traditional architecture and urban design approaches to better ensure that they can operate to meet the needs of the communities that rely on them?

Main takeaway: The role of the civil engineer has evolved throughout history in response to societal needs. There is an emerging need for a focus on the design and management of public open spaces and essential facilities in coordination with local operators and the communities who stand to benefit from these spaces.

Introduction and Motivation

Social infrastructure is an essential class of infrastructure that supports social interaction and contributes to community well-being. Common examples include parks, community centers, libraries, public markets, and transit hubs, just to name a few. In the United States, deliberate investment in social infrastructure grew in the mid-nineteenth century in part to address the strong social stratifications emerging from immigration. For example, Frederick Olmsted designed Central Park to encourage the co-mingling of social classes in one recreational space. Today, social infrastructure plays a major role in supporting societal quality of life by offering space for recreation and social interaction while simultaneously reinforcing community resilience, economic prosperity, and improved public health. Social infrastructure advances community resilience by building the social capital essential for community members to support one another during crisis. Social infrastructure is also a driver of economic activity including raising the value of property in close proximity to social infrastructure assets. Some assets like parks and community markets also drive capital and operational spending resulting in the creation of jobs and businesses that benefit communities. Finally, social infrastructure improves community health. For example, the obesity rate in communities is inversely proportional to the spatial density of public recreational spaces. Public green spaces also alleviate urban heat island effects and improve air quality in urban neighborhoods, benefitting residents with chronic illnesses. Social infrastructure also offers spaces where communities create support networks. For example, during the COVID-19 pandemic, many communities relied on parks and other green spaces to support outdoor activity and social interaction that improved their health.

Social infrastructure and its role in supporting community well-being is under stress in many parts of the United States. Public underinvestment in infrastructure including social infrastructure is a serious national issue. In parts of the country where there have been significant declines in population and tax revenues (e.g., Detroit, Cleveland, Pittsburgh, St. Louis), the negative impacts of underinvestment in social infrastructure are especially observable. The 1995 heat wave in Chicago is a poignant example; the absence of social infrastructure in some areas kept the elderly isolated, resulting in those areas having the highest mortality rates. Underinvestment also raises complex questions centered on the social equity of infrastructure investments. For example, underinvestment disproportionately impacts communities below the poverty line because social infrastructure offers one of the most affordable forms of leisure and social gathering available. Given its importance, there is an urgent need to advance scientific understanding of social infrastructure function and to quantify community benefits. Doing so allows communities to prioritize investments in social infrastructure with the aim of more equitable outcomes.

Goals and Objectives

The overarching goal of this project is the advancement of smart & connected community solutions to rigorously assess the performance of social infrastructure (specifically, parks) and to create multi-stakeholder frameworks that can lead to equitable social infrastructure design. As compared to physical infrastructure (e.g., roads, grids), social infrastructure has not been as extensively studied, leading to gaps in knowledge in how people use and benefit from public spaces. This project aims to urban sensing technologies to quantitatively model user behaviors, including the social interactions social infrastructure spaces support. We envision ultimately integrating longitudinal survey data to measure community perceptions of the social capital derived from social infrastructure. Predictive modeling of the social interactions and use supported by public spaces would ultimately empower a multi-stakeholder design framework. The framework aims to improve equitable access to the benefits derived from social infrastructure investments. The project utilizes community parks as the primary platform for exploring the scientific questions posed because they offer a rich set of unstructured social interactions to study. However, the implications of the research on other social infrastructure types could also be explored by considering community markets, Open Streets, etc. The key project objectives are:

- Thrust 1: Create a predictive modeling framework that uses machine learning to measure and predict how people use public spaces using privacy-preserving sensor data for quantitative assessment of space use.
- Thrust 2: Integrate longitudinal survey instruments with quantitative data from sensing to define and track broad community benefits from investments in social infrastructure assets.
- Thrust 3: Develop a multi-stakeholder governance framework based on data to continuously empower stakeholder (i.e., City of Pittsburgh, Pittsburgh Parks Conservancy) knowledge, trust and agency in the design and management of social infrastructure.
- Thrust 4: Study and validate the data-driven governance framework in Pittsburgh primarily focusing on Mellon Park.

Our team has been primarily focusing on Thrust 1 and Thrust 4. The predictive modeling framework in Thrust 1 is one of the most challenging parts of this project, and has consumed the majority of our time. Fortunately, with the gracious help of the Pittsburgh Parks Conservancy, we were able to install a network of privacy-preserving use sensors across Mellon Park to start collecting data in anticipation of completing the modeling framework and feeding this data into it. We will provide a brief overview of these two thrusts below.

Thrust 1 Updates

Cyber-physical systems (CPSs)—that is, sensing networks embedded within the built environment that have integrated and automated computing capabilities—have radically transformed engineering solutions over the last decade and garnered considerable attention, improving infrastructure performance through the combination of sensing, computing, and control. CPSs have even expanded to include human-in-the-loop control, where humans serve as operators or supervisors. While these paradigms have been wildly successful for the design and operation of physical systems decoupled from—or weakly coupled to—human social contexts, it is limiting to study physical systems in a vacuum, that is, without explicitly accounting for their interactions with the social systems they are designed to serve. While this is by no means a new notion, a unified approach to support such an integration remains elusive. Most notably, Agent-based Modeling (ABM) has been proposed to address limitations in accounting for human-centered attributes and goals. ABM supports the inclusion of individual-level representations and the modeling of emergent behavior. However, the parameterization of agents in ABM relies heavily on qualitative processes and assumptions that necessitate time-consuming and extensive engagement with communities and stakeholders. Even with this fine tuning, ABM is plagued by uncertainties and suffers from over fitting, particularly when translated to novel and unobserved design spaces.

This traditional approach, which has predominantly focused on optimizing the performance of *physical* infrastructure systems, has left many promising applications of CPSs to human-oriented systems—or cyber-physical-social infrastructure systems (CPSISs)—completely untouched and exacerbated inequities in community infrastructure. There are entirely unexplored social benefits derived from the built environment that have yet to be scientifically understood and exploited. For example, public open spaces (e.g., parks) are essential elements of urban infrastructure that offer opportunities for recreational and social activities, providing a meeting place for users to develop and maintain social ties and a sense of community. The quality, as opposed to quantity, of public open spaces holds greater influence on human psychology; well-designed spaces have the potential to enhance well-being, both mental and physical health, and socio-ecological benefits. Within housing complexes, the conviviality in the developments is either supported or hindered by the design of the houses. Additionally, the physical state and organization of school buildings significantly influences student health, cognitive abilities, and academic performance. These examples illustrate how the design and management of physical infrastructure can determine how well social capital is developed and social benefits are reaped. Despite the intimate coupling between social benefits and the design and management of physical infrastructure, there is no quantitative understanding of how to integrate and optimize *social* systems within CPS. To do so would engender—and provide the capabilities to quantitatively measure and achieve—an untrodden set of inquiries: How does the design and management of public open spaces improve sociability? How does the design and operation of buildings improve student productivity and classroom learning? How does the design and operation of maker spaces improve student collaboration and team building? How does the design and operation of prisons improve inmate rehabilitation?

To address this need, we propose that the CPS paradigm be radically altered such that physical infrastructure is controlled to meet social objectives (e.g., productivity, sociability, collaboration, well-being, accessibility). This transition necessitates an understanding of the social benefits derived from the built environment, novel taxonomization of human-human and human-infrastructure interaction, the responsible (i.e., privacy preserving) measurement of these interactions, modeling observed interactions for prediction, and actuation of the physical environment to promote desirable social outcomes. In this thrust, we are developing a modeling framework capable of measuring, modeling, and actuating social objectives within physical infrastructure systems.

The generalized CPSIS framework is illustrated in Figure 1. CPSIS represents the integration of physical and cyber realms, where the physical world encompasses both infrastructure systems *human actors*. The monitoring system captures data pertaining to the state of the infrastructure systems as well as the states of the individuals, storing this information in a sensor database. The sensor database, in conjunction with information models, serves as input for the computation engine, which processes the observations. The raw data undergoes analysis and is then utilized as input for an optimization algorithm within a recursive

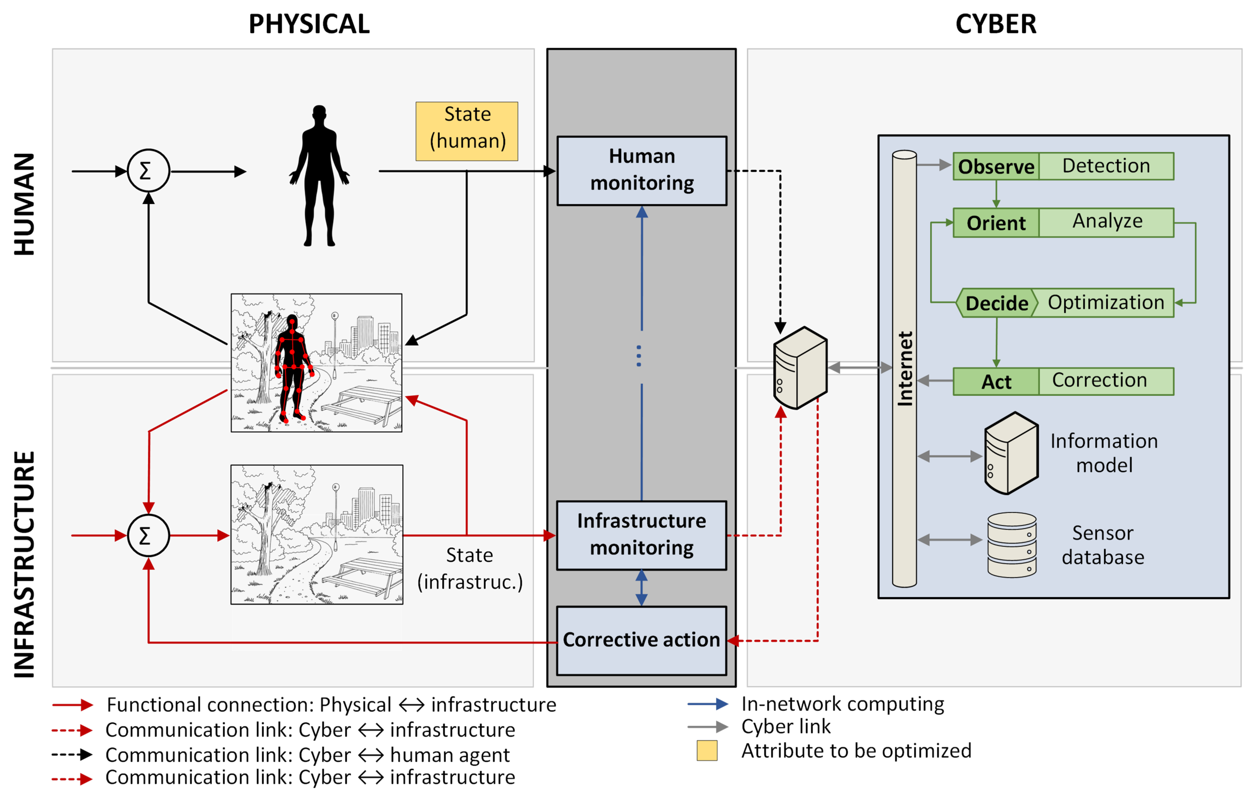

Figure 1: CPSIS framework for modeling human-human and human-infrastructure interaction.

loop, continuously refining the corrective actions until an acceptable optimization level is achieved. Subsequently, the corrective action is implemented in the physical world, resulting in changes to the state of the infrastructure systems. These changes consequently impact the state of the human actors and the associated social objectives.

Opening up the hood of the framework to provide some technical details, we are using multi-agent reinforcement learning to simulate goal-driven human behavior in the dynamic built environment (modeled after, say, Mellon Park). To train the agents (i.e., simulated humans) in the environment, we leverage imitation learning methods such as multi-agent generative adversarial imitation learning to extract the reward function purely from sensor data (i.e., sensor data collected from Mellon Park). Within the multi-agent simulation setting, the agents observe their environment and decide their actions with respect to the observations previously seen from sensor data. This enables us to model changes to the built environment (e.g., changes to Mellon Park) and see how those changes impact human behavior and choices.

Main takeaway: We are making great progress in the development of a simulation modeling framework capable of predicting how people will use and interact with the built environment. The model uses GIS information of the physical space and sensor data collected within the space as inputs, and produces human trajectories and interactions that result from changes to the GIS model as an output. This digital framework will enable stakeholders to test out "what-if" scenarios of investments they are considering.

Thrust 4 Updates

Providing additional background on the sensors installed, park usage and associated health and performance metrics are measured directly using a low-power wireless sensing architecture developed by Katherine Flanigan. Each sensing node, called *Urbano* (from the Latin urbanus, "of or belonging to a city", derived from urbs, "city"), is an Internet of Things-(IOT) based technology that supports interoperability among diverse arrays of heterogeneous IoT devices, preserves privacy and trust among citizens, supports cloud-based analytics, and has a user-friend design. For example, discrete pedestrian counts (measured from passive infrared, or "PIR", sensors) are collected from distributed sensing nodes. Because *Urbano* nodes support low-power and low-cost sensing and use cellular communication to free nodes from fixed power sources (relying instead on small solar panels for solar harvesting), they can be deployed in under-resourced areas, enabling decision makers to make data-driven investments in neighborhoods that have historically been underserved. *In situ* data measured using *Urbano* nodes is transmitted to a cloud-based server and provides a wealth of information that will be used to characterize usage within the predictive modeling framework that is being developed in Thrust 1. More simply, this data can also be used to capture "before" and "after" data to quantify the impact of asset and infrastructure management decisions made by the City of Pittsburgh and Pittsburgh Parks Conservancy. We have this data ready to go for these stakeholders and would be happy to visualize the data as they see fit.

Figure 2: Sensing node deployment locations across the top (north of 5th Avenue) and bottom (south of 5th Avenue) halves of Mellon Park.

For this project, a network of eight sensing nodes (Figure 3) were installed across Mellon Park in Pittsburgh, PA. The only limitation of the size of the network was the availability of light poles (which are used for the installation to keep the sensing nodes out of reach). As requested by the City of Pittsburgh, each sensing node is accompanied by a lawn sign that provides information about the project, states the objective of the data collection, and lets users know that the data is full privacy preserving.

An extracted segment of data collected is presented in Table 1 to illustrate what the data looks like. The system starts operating by placing a "start" followed by a string of time in a new segment, which is updated every 15 minutes to address the energy-harvesting nature of urban sensing—we are able to differentiate the down time of the system by comparing the string of time in the previous section to the time of the first data in the next segment. For instance, the system is out of charge during January 3 and 4 in the example below. This can occasionally happen during the winter when there are overcast days for long stretches of time, e.g., a week. When users travel from left to right in front of the node at 2:36:54 pm on December 17, 2022, the capture is logged as: 'R, 12, 17, 2022, 14, 36, 54'. Whereas users traveling from right to left in front of the node at 10:23:8 am on July 4, 2023 would be documented as: 'L, 7, 4, 2023, 10, 23, 8' following the chronological order.

Even without being integrated into the prediction framework from Thrust 1, the data collected is able to provide a plethora of information: special events, the number of users, usage metrics such as time of data and length of stay, estimated user trajectories, and use of amenities such as bench usage, garbage can usage, just to name a few.

Special events, such as park maintenance, are detected when a considerable amount of thinly-spaced data is collected within a time frame, which indicates the frequent passing in front of the node. Removing possibilities of special events and system anomaly, the number of users in the park can be acquired by counting rows of data collected.

(a) (b) (c)

Figure 3: Examples of three of the eight sensing nodes installed at (a) Location 1, (b) Location 3, and (c) location 6.

Table 1: The first segment of sample pedestrian data estimates 6 users during 5:00 to 6:30 pm on January 2, 2023, and the second segment indicates a special event on January 4, 2023.

start	M	D	Y	H	M	S
1	3	2023	2	40	56	
L	1	2	2023	17	23	48
R	1	2	2023	17	48	33
L	1	2	2023	17	52	49
L	1	2	2023	18	5	12
L	1	2	2023	18	15	6
L	1	2	2023	18	39	52
start	M	D	Y	H	M	S
1	9	2023	13	25	37	
L	1	4	2023	11	23	48
R	1	4	2023	11	23	50
L	1	4	2023	11	23	53
L	1	4	2023	11	23	59
L	1	4	2023	11	24	3
L	1	4	2023	11	24	5

Main takeaway: We have been collecting usage data at Mellon Park continuously for eight months now. We are approximately 60% of the way through completing the predictive modeling framework that asses usage and predicts how usage will change given changes to the park layout. Once this framework is complete, we will be able to integrate the sensor data we are collecting. The more data we can continue to collect, the better!

What we request: (1) To maintain our relationship with the Pittsburgh Parks Conservancy and the City of Pittsburgh, and (2) continue to collect data until the modeling system is complete. At that time, we will be able to feed the collected data into the model to provide useful information discussed to the stakeholders. Now that the modeling framework and data collection are progressing, we would also like to start working more closely with the City of Pittsburgh and the Pittsburgh Parks Conservancy to best understand how they would like to benefit from the data, and to develop a user dashboard so that they can interface with the data in the most useful way possible.