Reverse Engineering to Estimate Subsurface Utility Infrastructure Density for Financing Smart City Infrastructure

07/05/2023

NYU Center for Urban Science + Progress(CUSP).
Yutong Lan, Zihao Liu, Zihao Wu
Terri Matthews, Director, Town+Gown (@ NYC DDC)
Debra Leafer, Project Faculty Mentor
Keywords: Subsurface Density, NYC City Planning, Smart City
Github:
https://github.com/Zihao-Wu999/Reverse-Engineering-to-Estimate-Subsurface-Utility-Infrastructure-Density.git

Policy Implications or Recommendations:

1. **Optimizing land use planning to incorporate utilidor construction into urban planning and land use plans, enabling efficient utilization of underground space to support smart city development and sustainable infrastructure.**
2. **Support technological innovation and research by providing funding, establishing innovation centers, facilitating collaboration, and creating an innovation ecosystem to improve the design, construction, and operation of utilidors.**
3. **Modify NYSPSC tariffs for NYC utilities to address the utility pricing gap, including subsurface PROW value and negative direct burial externality costs, aiming to establish pricing levels that can adequately finance utilidor construction, operation, and maintenance while reshaping the decision-making approach of the regulatory regime.**

Executive Summary

The "Reverse Engineering to Estimate Subsurface Utility Infrastructure Density for Financing Smart City Infrastructure" report presents a methodology to estimate subsurface utility infrastructure density in New York City (NYC) in order to generate surface and subsurface densities by Community District. The goal is to provide a foundation to estimate a utility pricing gap within NYC, which can support the development of revenue sources for financing utilidors. Utilizing NYC Department of Finance PLUTO data and NYC Department of Transportation LION street geometry data, the capstone team developed a foundational analysis for this purpose.

The methodology employed an indirect approach by deriving underground infrastructure density through the ratio of building density to road area. Three open datasets were used: NYC 3D Model by Community District, PLUTO, and LION. The NYC 3D Model provides a surface density model of buildings in the city, while PLUTO offers building information based on tax lots. LION serves as a comprehensive dataset for analyzing the road infrastructure. Data verification and cross-data validation were conducted to enhance reliability.

Surface maps and bar graphs were generated to visualize subsurface density and rank district-level density and road areas. The densest subsurface districts were found to be in mid and lower Manhattan, while districts in Staten Island and Queens had larger road areas compared to other boroughs and later development. Additionally, surface density estimates were performed for Westchester and Nassau Counties for comparison purposes because some utility companies operate outside NYC in their service districts..

The primary objective of this project is to establish a foundation for financing utilidors, which require a combination of public and private funding. Three policy implications arise from the findings: optimizing land use planning to incorporate utilidor construction into urban planning, supporting technological innovation and research, and modifying NYSPSC traffic regulations to address the utility pricing gap. Alternative approaches, such as data enrichment, expert consultation, and model development, can be considered to mitigate the lack of direct subterranean data in estimating underground infrastructure density.

This report provides valuable insights and recommendations for estimating subsurface utility infrastructure density, paving the way for future financing strategies for utilidors and facilitating the development of smart city infrastructure in NYC.

Contents

1. Introduction

This capstone report investigates the density of subsurface utility infrastructure in densely populated New York City. The goal is to provide insights into the challenges faced by utilities in financing and implementing modern utilidors. By analyzing surface density to derive subsurface density, we lay the groundwork for future studies to identify revenue sources for utilidors. While our research focuses on infrastructure density and does not directly address financial aspects, it contributes to the discussion on navigating financial challenges and finding sustainable solutions for utilidor development. The report presents our methodology, data collection techniques, and analysis process. The findings have implications for financing and implementing subsurface utility infrastructure, emphasizing the importance of sustainable urban utility planning. The report serves as a valuable resource for stakeholders involved in urban utility management, aiming to create a more efficient and sustainable utility infrastructure system in New York City.

2. Problem Definition

The financing challenge for modern utilidor infrastructure in New York City hinders its implementation for utilities in dense urban areas. This project aims to estimate subsurface utility infrastructure densities using a 3D volumetric approach in NYC, as well as Westchester and Nassau Counties for comparison. However, limited data on subsurface infrastructure poses a major obstacle to estimating densities and identifying potential revenue sources.

To overcome data limitations, we assume subsurface infrastructure density mirrors surface density based on urban economics principles. Our objective is to estimate subsurface infrastructure density using NYC DCP surface density maps, USGS Lidar, and NYC DOT street geometry data. This will provide an initial estimate of density and help identify the utility pricing gap and revenue sources for financing utilidors.

By addressing data challenges and estimating subsurface infrastructure density, this project will offer valuable insights into financing and operating public-private utilidors in New York City. Successful implementation of modern utilidor infrastructure will benefit all residents and businesses by ensuring a reliable and sustainable infrastructure system.

3. Literature Review

The challenges of subsurface utility infrastructure in New York City's public rights-of-way (PROW) have hindered efficient planning and management. The concept of utilidors, multi-utility tunnels that eliminate the need for extensive street excavation, has emerged as a potential long-term solution. Economic models based on land price and distance patterns, as proposed by Alain Bertaud, can predict changes in urban densities, aiding utilidor implementation decisions.

Bertaud emphasizes the importance of a well-functioning labor market in cities, facilitating innovation and attracting diverse populations. Urban amenities such as symphonic orchestras, museums, and great restaurants, enabled by a thriving labor market, contribute to a vibrant urban life. Understanding the economic dynamics, including land prices and labor market dynamics, is crucial for utilidor financing and operation. Therefore we can set a hypothesis that subsurface infrastructure density should mirror surface density. In order to do that, developing a methodology to estimate the surface density and subsurface infrastructure density of NYC became a fundamental step to finance the subsurface utilidors.

Utilidors offer a solution to subsurface utility challenges in New York City's PROW. Economic models, influenced by Bertaud’s insights, help predict subsurface densities and inform utilidor implementation decisions. A well-functioning labor market and urban amenities drive innovation. Further research and pilot projects are needed for broader utilidor implementation.

In order to move forward in consideration of utilities based on this analysis, the evaluation of benefits and identification of potential locations for future utility tunnels represent a promising endeavor for enhancing urban infrastructure. Utility tunnels offer numerous advantages such as improved reliability, reduced disruptions, and enhanced urban design. However, challenges related to financing, planning, technical complexity, and stakeholder engagement must be carefully considered during the implementation process. The part 6 of 'Building Better Street' provides a foundation for the forthcoming report on estimating subsurface utility infrastructure density for financing smart city infrastructure, aiding decision-makers in developing strategies that harness the potential of existing utilidor systems in parts of Manhattan and the Bronx demonstrate their potential to optimize subsurface space. Feasibility studies and pilot projects are necessary to fully explore utilidors' benefits and develop the required tools and collaborations in building better streets and sustainable urban environments.

4. Methodology

To estimate the underground infrastructure density in the absence of direct data, we adopted an indirect approach based on the research of Alain Bertaud in his book "Order Without Design" (Cambridge: MIT Press, 2018). Following his methodology, we aimed to establish a relationship between building density and road area to create a ratio that reflects underground infrastructure density. Thus, our methodology involved obtaining surface building density and surface road area for New York City and using the ratio of density to area as a proxy for underground density.

To begin, we collected data on surface building density across New York City. This information was obtained from reliable sources, such as the New York City Department of City Planning (DCP) or other relevant agencies. Additionally, we acquired data on surface road area, which was obtained from LION that was provided by the New York City Department of Transportation (DOT).

Subsequently, we calculated the ratio of building density to road area for each specific geographic area of interest which is the community by district, the smallest geographical area in NYC. This ratio served as an indicator of underground infrastructure density, assuming a correlation between surface building density and subsurface infrastructure density.

To analyze the data's policy implications and research value, we employed visualization tools throughout the process. Using administrative district planning boundaries in New York City, we conducted city-wide and district-level visual analyses. These visualizations provided insights into the spatial patterns and variations in underground infrastructure density across different areas, enabling us to draw meaningful conclusions.

In summary, our methodology involved deriving underground infrastructure density through an indirect approach that utilized the ratio of building density to road area.

By analyzing the data and employing visualization techniques, we aimed to uncover the policy implications and research significance embedded within the dataset.

5. Data

In this study, we used three open datasets from NYC: NYC Department of City Planning (DCP) 3D Models by Community District, NYC Department of Finance (DOF) PLUTO dataset and NYC Department of Transportation (DOT) LION-related dataset. Information about the datasets will be described in detail below. The relevant processing criteria and cleaning principles of the datasets are available at the project's website.

5.1. Data Collection

5.1.1 NYC DCP surface density maps

The DCP 3D Model by Community District is an openly accessible surface density model that encompasses all the buildings present in New York City as of 2014(NYC 3D Model, 2018). This model is derived from DOITT's 2014 aerial survey, which offers comprehensive information about the roof structures of buildings, including intricate details for specific iconic structures. DCP also divided the model into the City's 59 Community Districts and enriched each CD with base layers, including lots, streets, parks, and rail lines. This dataset is a 3D model, meaning that this dataset is completed by spatial modeling. It contains spatial information such as the outline and height of each building. It is compatible with rhino software. We had planned to use the DCP 3D Model by Community District dataset to calculate NYC's surface density. But, due to the large amount of building information contained in this data set and the need to use Rhino, we could not process it in bulk. Instead, we used DOF PLUTO data to estimate surface density, but we selected some buildings from the DCP data to compare with the PLUTO methodology to ensure the accuracy of our research.

5.1.2 PLUTO data set

PLUTO is a building dataset provided by the DOF. It provides building information of the area based on each tax lot, including building area, lot size, building age and other information(NYC PLUTO, 2023). The dataset can be opened and processed with ArcGIS Pro. The dataset also includes tags for each of New York's 59 Community Districts, which will ensure that the data is analyzed at the overall and district level. By visualizing this dataset, we obtained a surface building density map, which helped us understand the distribution of building density in New York City and create surface density ratios .

5.1.3 LION data set

LION is a comprehensive dataset that offers a single line representation of the streets in New York City(NYC LION, 2023). It encompasses various crucial information such as address ranges, road distribution, length, and width. With its compatibility with ArcGIS Pro, we leveraged the LION dataset to obtain and visualize essential details about the road network in the 59 diverse boroughs of New York to calculate the road surface area.

5.2 Data Cross Validation

In order to validate and enhance the reliability of our project, we conducted cross-data validation using the PLUTO and DCP 3D model datasets. First, we calculated the density of buildings in specific areas and compared the results from both datasets using statistical tests. Second, we visually compared the building shapes within these areas from top-view and 3D perspectives. These validation approaches provided a comprehensive assessment of data consistency and accuracy, ensuring the robustness of our findings. The formulae and results for the two data sets are shown in the Appendix.

5.2.1 Calculation Validation

We initially computed the building density in six districts of Brooklyn using DCP data. Given the differing units of the PLUTO and DCP 3D model datasets, we standardized the calculated results. Subsequently, we visualized the normalized density values from both datasets by plotting them together in a bar graph. The resulting graph depicts the comparison between the two datasets' calculations.

Despite the visual similarity of the bar graphs, we conducted a statistical validation using the Kolmogorov-Smirnov Test. The test yielded a p-value of 0.93, indicating that we cannot reject the null hypothesis. Therefore, we conclude that the two datasets follow the same distribution. This statistical validation provides further evidence supporting the consistency and reliability of the PLUTO and DCP 3D model datasets in terms of building density calculations.

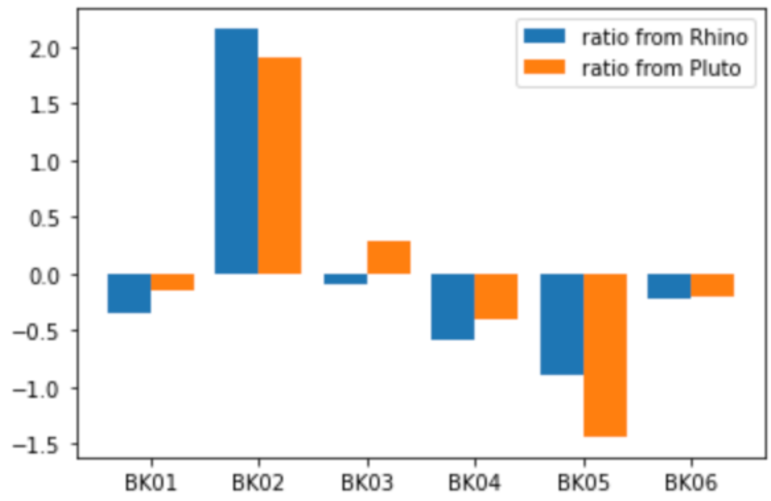


Figure 2.

5.2.2 Visualization Validation

We constructed 3D building models for a selection of buildings from both datasets to compare their heights and shapes. We conducted a visual examination of the models from both frontal and top views to assess their similarity. Upon observation, it is evident that there is a notable resemblance between the buildings from both datasets, irrespective of the viewing angle (top view or frontal view). These findings indicate a high degree of similarity in terms of building heights and overall shapes between the PLUTO and DCP 3D model datasets.

Figure3.

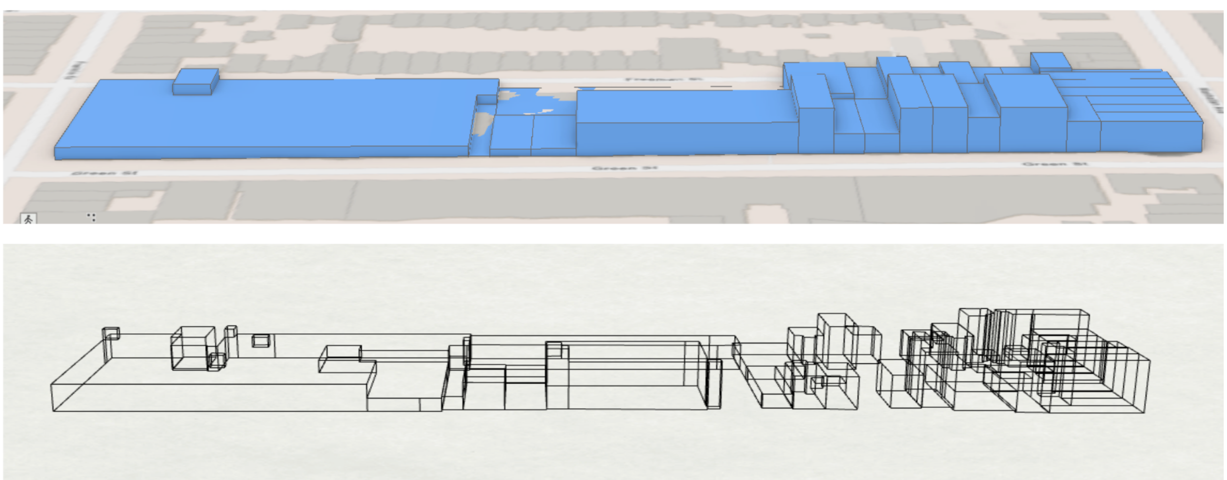


Figure4.

6 Risk Mitigation

Lack of direct underground infrastructure data for calculating the underground infrastructure density in New York is one of the primary risks in our endeavor. This restriction introduces uncertainty and possible bias into our estimations. To mitigate this risk, the following strategies will be implemented.

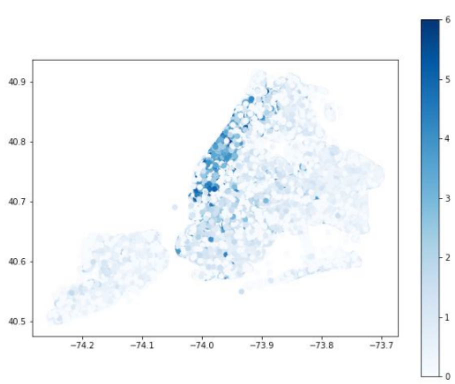
Data Verification: We verified the accuracy and dependability of the building density and road surface area data utilized in our analysis by comparing the provided data with information on known underground infrastructure or other reliable data sources. We were assured a certain degree of consistency between the data sources so that we had confidence in the accuracy of our estimates.

Sensitivity Analysis: Conducting a sensitivity analysis allowed us to assess the impact of variations in building density and road surface area on the estimation of underground infrastructure density. We can determine the robustness and sensitivity of our results by simulating or adjusting the densities at various levels. This analysis will shed light on how variations in input data impact the estimation as a whole.

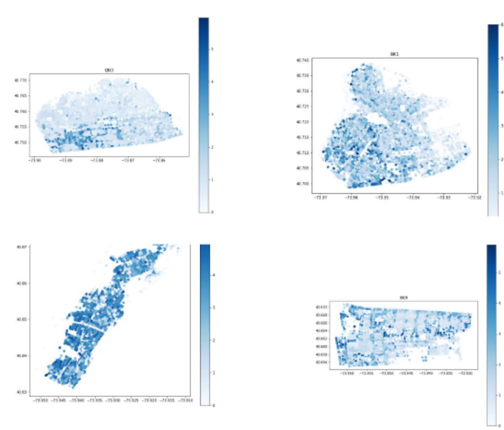
By implementing these risk mitigation strategies, we avoided the limitations caused by the lack of direct underground data. These measures improved the dependability, robustness, and precision of our estimates, allowing us to draw more meaningful conclusions about the underground infrastructure density in New York.

7 Findings

The PLUTO data sets contain the detailed information of buildings in NYC. Hence, by implementing the surface building information in both Python and ArcGIS Pro, we derived the following maps, where each building on the map appears as a point and the color and size represents its density.



New York city



59 Districts

Figure5. Map of surface buildings of whole city and 59 districts in python

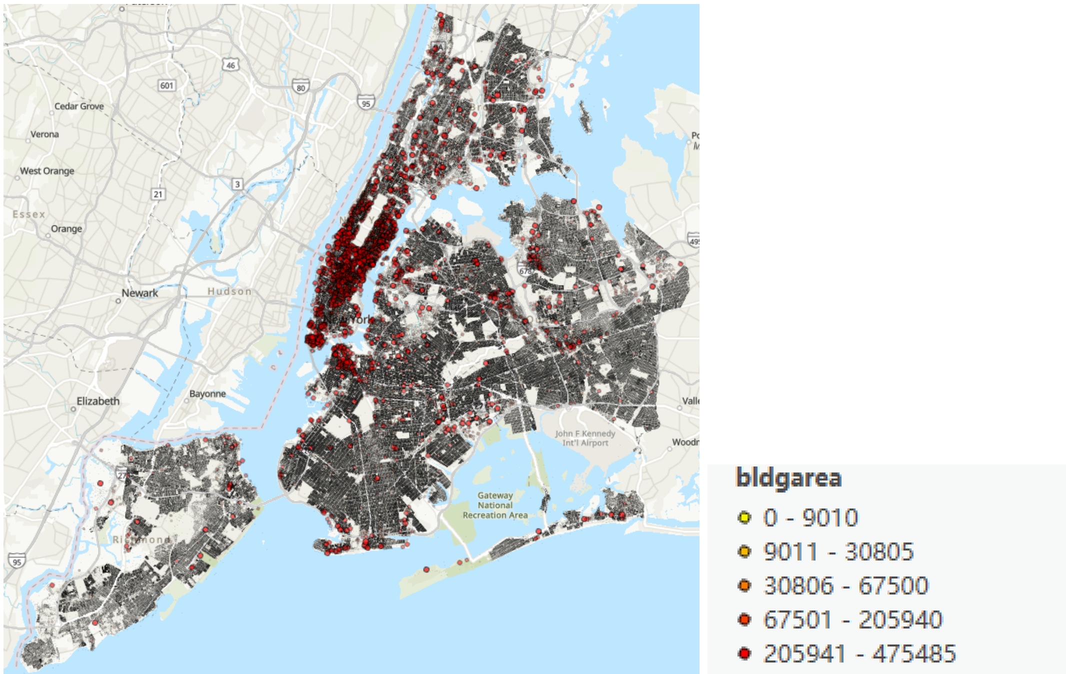


Figure6. Map of surface buildings of whole city and 59 districts in ArcGIS Pro

It is clearly shown in Figure 6 that most red and clear buildings lie in the area of Manhattan. However, as we expected before, it is difficult to figure out other useful information since the map appears a bit chaotic.

Thus, we aggregated the buildings by block, and got a block level surface density map in ArcGIS Pro where larger dots indicate a higher density in this block.

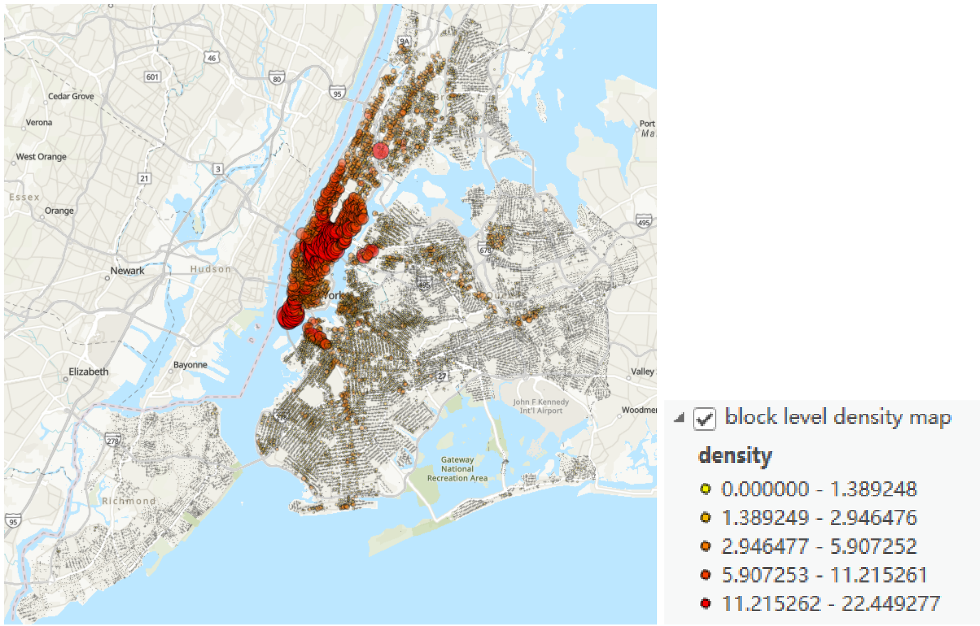


Figure7. Map of surface density of blocks in NYC

From this block level map of Figure 7, we can see the surface density distribution in NYC better. Mid and Lower Manhattan, as we have found before, appear as the most dense area in NYC. Furthermore, some areas in Long Island City and Downtown Brooklyn also show larger red points than any other area in their borough. The block level density map shows more information than the previous one.

Next, we conducted the aggregation by the community district of the buildings and get a district level density map together with a borough level density map. Still we found that the Mid and Lower Manhattan, Downtown Brooklyn still dominate the most dense areas in NYC, and Staten Island rank the lowest among them(see figure 8 & 9).

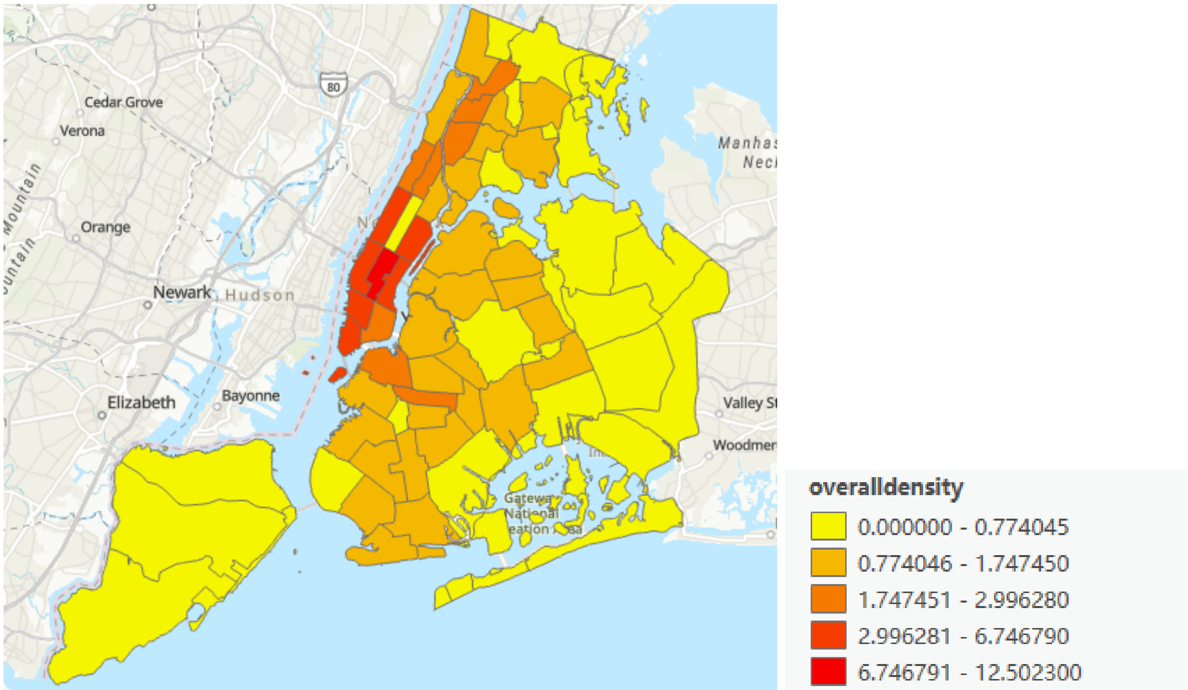


Figure8. Map of surface density of districts in NYC

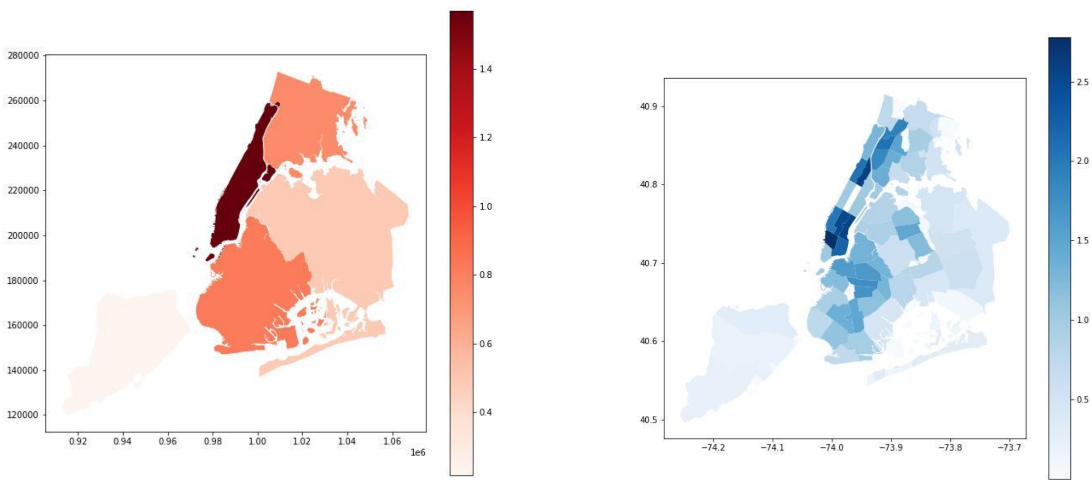


Figure9. District and borough surface building density distribution map in Python

Meanwhile, a bar graph of surface density map (figure 10) is shown below indicating the distribution of density by community district level of New York City.

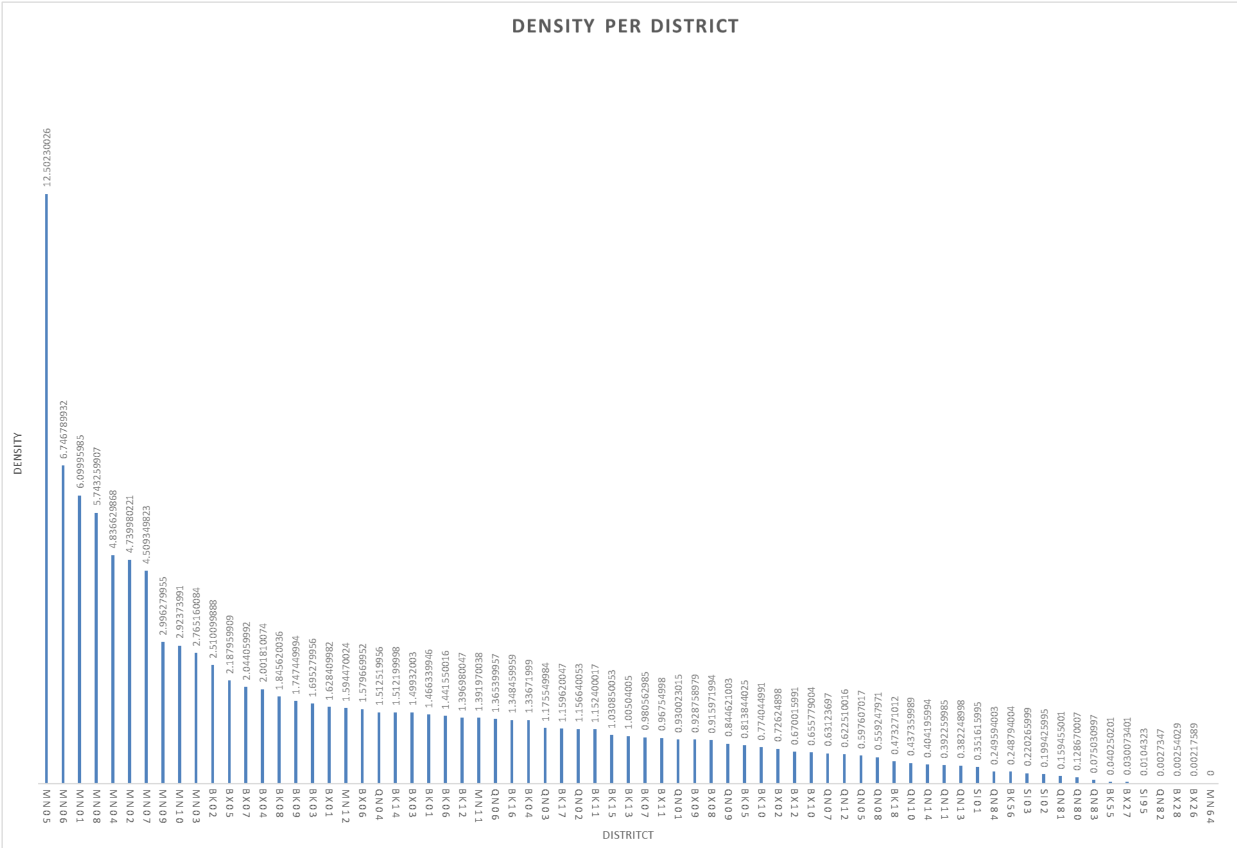


Figure10. Bar graph of district level density

From Figure 10, it is clear that Manhattan CD05 and Manhattan CD06 rank first and second in surface density respectively among the all districts, and it is not until the eleventh ranking that a district in another borough(Brooklyn CD02) appears.

Then, we extracted data from the LION data set and calculated the road surface area by multiplying the number of road lanes, road length and road width. The following maps (figure 11) reveal the result of this step in bar plot and in maps respectively.

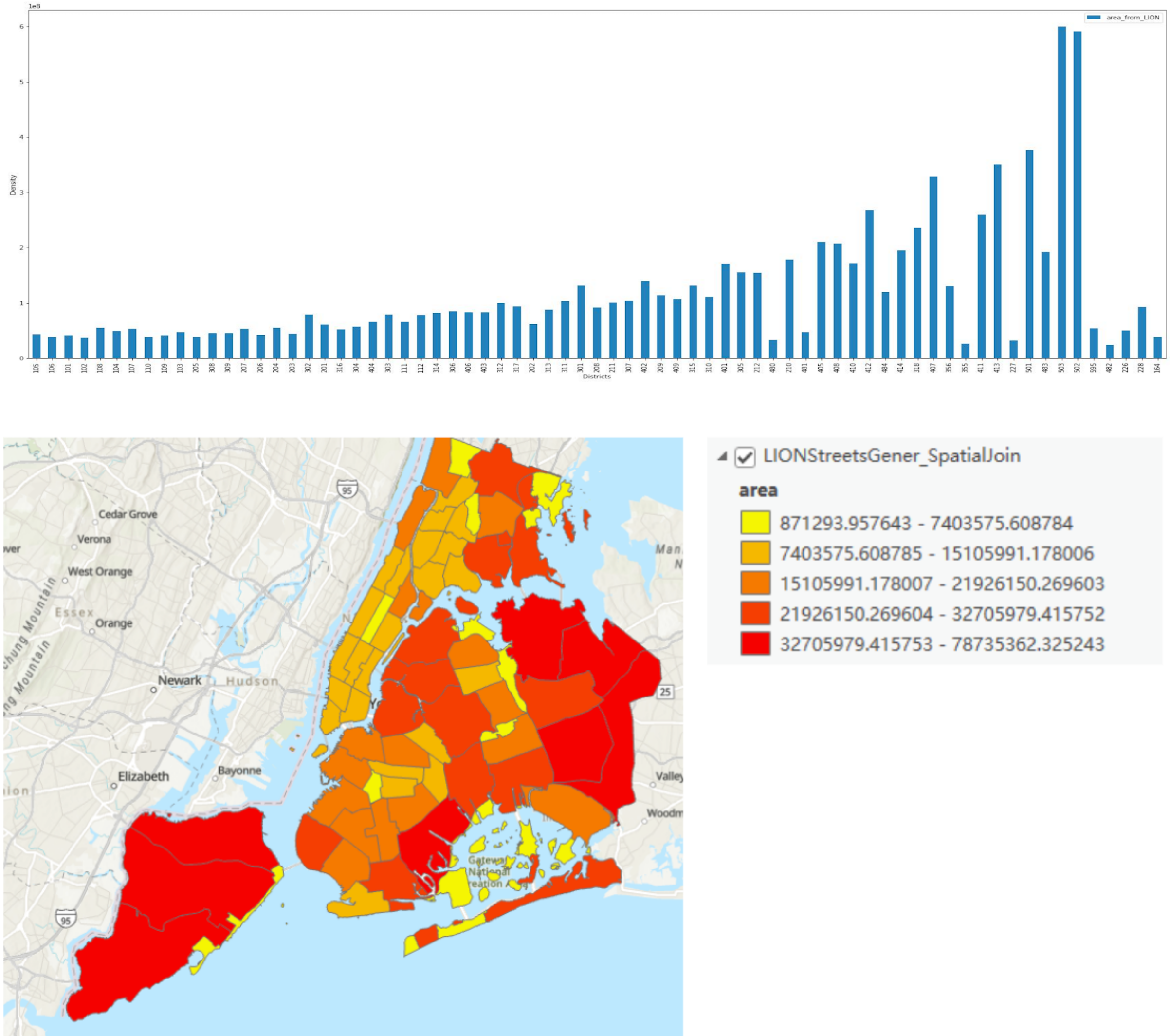


Figure 11.Road area map by bar chart and district view

Without surprise, the districts in Staten Island and Queens usually have larger road areas since the districts themselves are much larger than other districts in Manhattan.
Finally, by the formula:

$$Subsurface\_Density = \frac{Surface\_Density}{Road\_Area}$$

Figure12. Subsurface density formula

We calculated the subsurface density by dividing the surface density by its road area. The final map and bar graph are shown below:

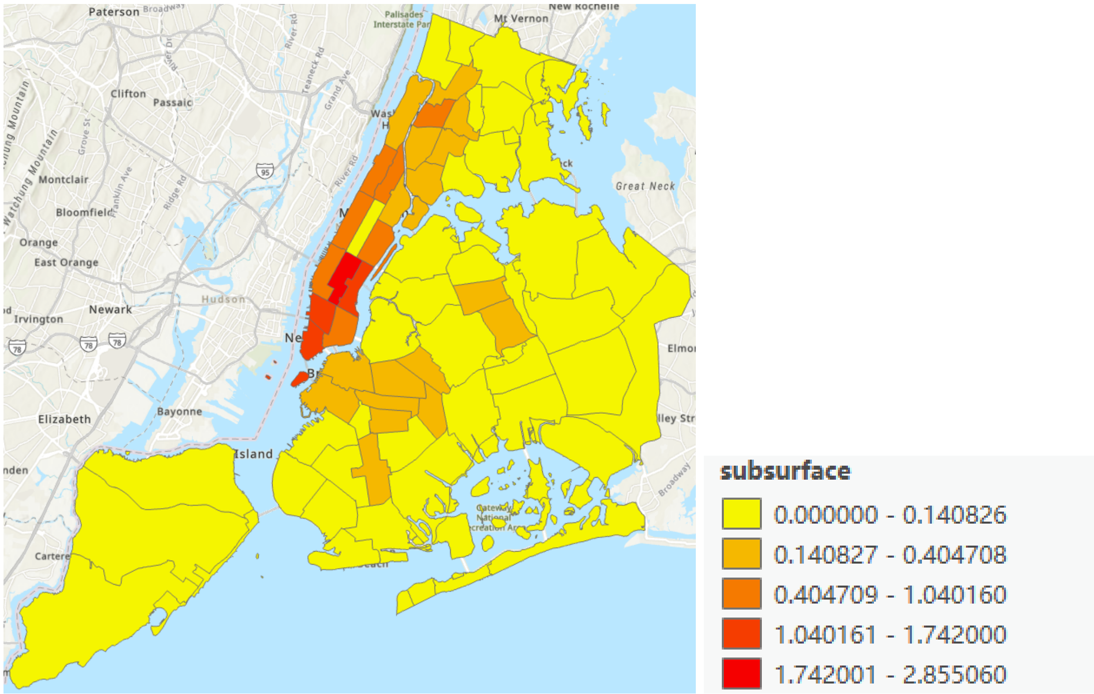
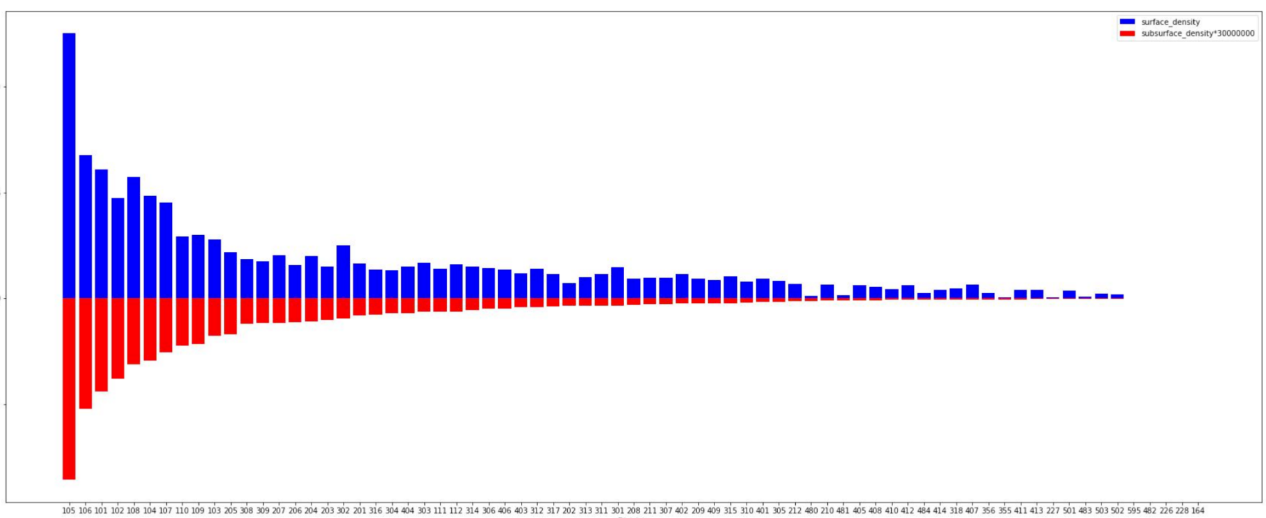


Figure13. Subsurface density map of 59 districts in NYC



*Notes: Negative values of y-axis have no meaning. The density is all positive. This is needed for graphing purposes.

Figure14. Comparison of subsurface and surface density by bar chart and district view

The results shown in Figure 13 & 14 indicate that the districts with the highest surface densities had the highest subsurface densities which means subsurface density reflects surface density , which confirms the hypothesis discussed above that subsurface infrastructure density should mirror surface density. This analysis provides a basis for looking at Nassau and Westchester Counties discussed below.

8 Other Analysis

8.1 Nassau and Westchester counties analysis

Private utility companies often operate in service areas outside NYC. We compared surface densities in NYC and two neighboring counties—Westchester and Nassau—to suggest that revenues generated from NYC operations are higher than revenues generated outside NYC for the same services to lay the groundwork for understanding the utility pricing gap. The utility pricing gap is the extent to which utilities' payments to NYC do not reflect the urban subsurface value (and negative externalities) and represents a potential revenue source to finance utilidor construction and operation costs. We conducted an analysis comparing the ratios of population density to area density in NYC and the two selected counties which are Nassau and Westchester. The chart presented below serves as a rough comparison of surface densities between NYC and these counties. As illustrated by Figure 16, there is a gap between the proportions of these two counties and the five boroughs of New York. This chart serves as a key component in establishing a foundation for evaluating the utility pricing gap.

We broadened the analysis of the relationship between population density, surface density, and subsurface infrastructure density. By exploring these factors, the potential revenue sources suggested by the utility pricing gap and required to finance utilidors can emerge.

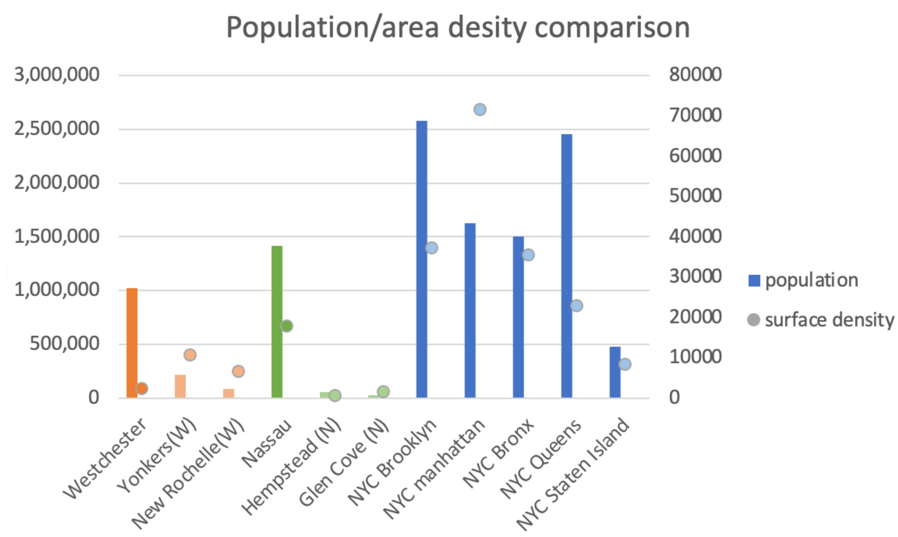


Figure15. Bar chart of population/area density comparison

8.2 Interactive heatmap

We created a heatmap on a real-time map that allows us to observe the distribution of buildings and select specific building types. This interactive map in figure 16 provides a visual representation of building density in different locations, allowing for a comprehensive analysis of spatial patterns. By utilizing this map, we can gain insights into the varying densities of different building types and easily compare their distribution across the area of interest. This visualization tool enhances our understanding of the built environment and facilitates more intuitive observations of building distribution.

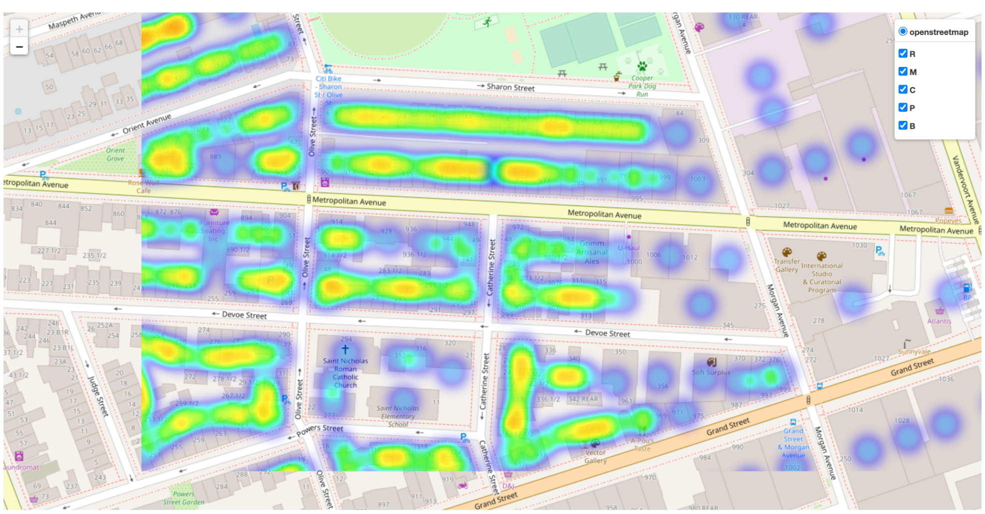


Figure16. Interactive heatmap of building density

9 Policy Recommendations(Long-term)

1) **Optimizing land use planning:** In order to build a smart city, it is important to optimize land use planning by fully utilizing underground PROW space. Planning for PROW subsurface is an important step for implementing utilidors to replace direct burial of infrastructure assets. It will also ensures the rational allocation and utilization of underground space to support smart city development and sustainable infrastructure.

2) **Support technological innovation and research:** Government—state and NYC—can encourage and support technological innovation and research to improve the design, construction, and operation of utilidors. This can include providing research and development funding, establishing innovation centers and laboratories, facilitating technology exchange and collaboration, and fostering a conducive innovation ecosystem. Texas Transportation Institute's Utility Engineering Program could be replicated in New York.

3) **Changing utility tariffs:** Financing utilidors will require identifying revenue sources for utilidor construction and operations, which will require modifying the tariffs of the New York State Public Service Commission (NYSPSC) for the utilities in New York City, perhaps based on the utility pricing gap discussed above, which encompasses the value of underground PROW and the costs associated with negative direct burial externalities. These revisions would aim to establish appropriate levels of pricing that can generate enough funds for the construction, operation, and maintenance of utilidors while also altering the decision-making approach of the regulatory regime.

10 Interactive Approaches

Given the absence of direct subterranean data in our project, we can propose alternative methods for estimating the underground infrastructure density in NYC:

1) **Data Enrichment:** Future researchers can seek out additional data sources that provide more precise information on underground infrastructure. This may necessitate collaborating with pertinent organizations or government departments tasked with maintaining such data. Future researchers can improve the accuracy and completeness of our estimates by incorporating their datasets.

2) **Expert Consultation:** Consulting domain experts or professionals familiar with New York's underground infrastructure can provide insightful information. Their expertise and experience can supplement our analysis by providing valuable information about the distribution and characteristics of subsurface infrastructure in the region.

3) **Model Development:** Building a model to estimate subsurface infrastructure density is an additional alternative method. Future researchers can construct a comprehensive model by considering factors such as population density, soil conditions, and proximity to transportation hubs. Combined with appropriate data acquisition and modeling techniques, this model can produce more accurate estimates.

By investigating these alternative methods, future researchers can mitigate the limitations caused by the lack of direct underground data. These strategies provide opportunities to integrate additional data sources, leverage expert knowledge, and employ modeling techniques to improve the accuracy and reliability of our estimates of underground infrastructure density in NYC.

11 Evaluation

Throughout the course of this project, we have been fortunate to receive invaluable feedback that significantly influenced our approach and overall outcomes. Notably, Terri Matthews, Director, Town+Gown: NYC provided valuable input by suggesting a comprehensive review of the project's history and the challenges we encountered while attempting to access DCP maps through ArcGIS Pro. This feedback proved instrumental in steering us towards alternative solutions and refining our methods. However, it is essential to acknowledge that the original project description did not entirely align with our experience during the project. Initially relying solely on the Rhino-based access to the DCP database to estimate underground infrastructure density proved to be time-consuming and inadequate, as it lacked the required level of detail. Consequently, we had to pivot and explore alternative data sources and methodologies.

In retrospect, we encountered challenges in accessing DCP maps through ArcGIS Pro, leading us to explore the use of PLUTO data as a viable alternative. Conducting pairwise comparisons with this data and incorporating Professor Debra Laefer's meaningful visualizations insights provided us with the correct research direction, ultimately contributing to the project's successful completion. This project has been an invaluable learning experience for our team. We learned to navigate and overcome obstacles in data acquisition and analysis. We also recognize the importance of refining project objectives to ensure alignment with the available data and resources.

In conclusion, the feedback and collaboration from various stakeholders, including Terri Matthews, Director, Town+Gown, Professor Debra Laefer, John Speroni, NYC DOT, Matthew Croswell, NYC DOP, and Sai Krishna Prathapaneni, CUSP Teaching Assistant, significantly enriched our project. Despite facing initial challenges, we successfully adapted our methods to achieve meaningful results. Our experiences in this project have equipped us with valuable skills and insights that will undoubtedly benefit future endeavors in the field of urban infrastructure analysis and planning.

12 Conclusion

We successfully achieved the project's primary objective by confirming our working hypothesis of the relation of surface density to subsurface infrastructure density and visualizing the subsurface utility infrastructure density in New York City. Additionally, we created visualizations for surface building density and road surface density at different levels, ranging from the city-wide scale to the district level. These visualizations provided valuable insights into the spatial distribution of infrastructure across the city.

Furthermore, we generated bar charts illustrating the surface and subsurface densities at the district level, laying the foundation for pricing and financing strategies in future research. By comparing the population-to-area ratio in Nassau and Westchester Counties with the five districts of New York City, we gained valuable insights for exploring pricing strategies. The interactive surface building density graph also offered a deeper understanding of surface density patterns.

In summary, our project successfully fulfilled its objectives, presenting a wide array of visualizations that shed light on the complex relationships between surface and subsurface infrastructure density. These visualizations provide essential data for policy analysis, pricing strategies, and potential financing solutions for the development of utilidors in dense urban environments.

13 Acknowledgements

This work was directly supported by capstone sponsor Debra Leafer and the NYU Center for Urban Science + Progress(CUSP).

14 References

Texas a&m transportation institute. (n.d.). TTI's Utility Engineering Program Helps Sponsors Avoid Unseen Expenses, Delays. https://tti.tamu.edu/researcher/ttis-utility-engineering-program-helps-sponsors-avoid-unseen-expenses-delays/

Kahn, A. (1988). *The Economics of Regulation: Principles and Institutions*. Cambridge: MIT Press.

Texas a&m transportation institute. (n.d.). Faster, Safer, Less Expensive Road Construction Through Utility Engineering. https://tti.tamu.edu/researcher/faster-safer-less-expensive-road-construction-through-utility-engineering/

Bertaud, A. (2018). Order without Design: Vol. pp. 7, 8. Cambridge: MIT Press.

NYC Department of City Planning. (2018, October). NYC 3D Model by Community District. https://www.nyc.gov/site/planning/data-maps/open-data/dwn-nyc-3d-model-download.page

NYC Department of City Planning. (2023, April). NYC PLUTO. https://www.nyc.gov/site/planning/data-maps/open-data.page#pluto

NYC Department of City Planning. (2023, May). LION Single Line Street Base Map. https://www.nyc.gov/site/planning/data-maps/open-data/dwn-lion.page

15 Appendix

APPENDIX A. CALCULATION OF ANALYSIS METRICS

Table 1 Cross validation data

Cross validation result						
Density from DCP 3D MODEL	36.81836569	65.73728729	39.77941479	34.1031122	30.61089658	38.41869853
Density from PLUTO	1.466339946	2.510099888	1.695279956	1.33671999	0.813844025	1.441550016

Figure 1 Cross validation density formula

$$Density = \frac{Volume}{Bottom\ area}$$

$$Density = \frac{Building\ area}{Lot\ area}$$