

Predicting Real Estate Sales Using Machine Learning and Spatial Dependence

Boosting ML Predictive Accuracy Using Spatial Lags

By

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1 Introduction

Income inequality may be one of the most pressing challenges of our time, yet, its causes remain unclear. What is clear is that, increasingly, the places where people live “over time are becoming more segregated by income, due in part to macro-level increases in income inequality” (Zuk 2015). Income inequality has many dimensions: social, economic, political, philosophical. But one key dimension remains under-explored despite its potential for positive impact: geo-spatial. The locations where people live (by choice or not) have a dramatic impact on their quality of life and ability to progress. Yet, many who are displaced by gentrification find themselves in self-reinforcing cycles of displacement and poverty.

Researchers at the Urban Institute (Solomon Greene and Lei 2016) recently identified the socio-economic phenomenon of “Economic Exclusion” as a direct cause of income inequality in the US. “Economic Exclusion” can be defined as follows: vulnerable populations—disproportionately communities of color, immigrants, refugees, and women—who are physically displaced by local economic prosperity can enter into a gradual cycle of diminished access to good jobs, good schools, health care facilities, public spaces and other physically proximate benefits. Diminished access leads to more poverty, which leads to more displacement. Such self-reinforcing poverty gradually exacerbates income inequality over the course years and even generations.

One practical way to combat Economic Exclusion is to focus on preventing displacement, i.e., the physical relocation of populations away from economic resources. As defined by Clay (1979), Displacement is the negative consequence of gentrification. Reliably predicting gentrification would be a valuable tool for preventing displacement at an early stage, however, such a task has proven difficult historically.

When an area experiences economic growth, increased housing demands and subsequent affordability pressures can lead to voluntary or involuntary relocation of low-income families and small businesses. Government agencies and nonprofits tend to intervene once displacement is already underway, and after-the-fact interventions can be costly and ineffective. As explained

by Solomon Greene and Lei (2016), there are several preemptive actions that can be deployed to stem divestment and ensure that existing residents benefit from new investments. Not unlike medical treatment, early detection is the key to success.

Consequently, in 2016, the Urban Institute put forth a call for research into the creation of “neighborhood-level early warning and response systems that can help city leaders and community advocates get ahead of neighborhood changes” (Solomon Greene and Lei 2016). This paper explores a technique to answer that call in part using free, open data and open-source software.

Many government agencies have already become competent at using predictive modeling to identify and address socio-economic challenges at the individual-level, ranging from prescription drug abuse to homelessness to recidivism (Ritter 2013). However, few, if any, examples exist of large-scale, systematic applications of data analysis to aid vulnerable populations experiencing displacement. This paper belongs to an emerging trend known as the “science of cities” which aims to use large datasets and advanced simulation and modeling techniques to understand urban patterns and how cities function (Batty 2013).

In this paper, we explore techniques that can dramatically boost the accuracy of existing gentrification prediction models. We use real estate transactions, both their occurrence (probability of sale) and their dollar amount (sale price per square foot) as a proxy for gentrification. We explain how this predictive technique may be applied to practically combat Economic Exclusion, a precursor and contributor to Income Inequality. The technique marries the use of machine-learning predictive modeling (using Random Forrest) with “spatial-lag” features typically seen in geographically-weighted regressions (GWR). We find that, while the addition of many new variables to a modeling data set can inhibit the models’ ability to generalize into the future, spatial-lag features 1) consistently outperform zip-code level aggregation features, and 2) outperform all models for specific types of properties in specific areas. We conclude that spatial-lag features, while computationally expensive, can be used to greatly increase the accuracy of spatially-conscious predictive models.

2 Literature Review

The literature review for this paper reviews the concept of Economic Displacement as it has been addressed in academia, primarily in relation to the study of gentrification. We also examine “mass appraisal techniques”, which are automated analytical techniques used for valuing large numbers of real estate properties. Finally, we will briefly examine the literary treatment of machine learning as it relates to the problem of predicting gentrification and/or Economic Displacement.

2.1 How Has Economic Displacement Been Addressed in the Past?

Economic Displacement has been intertwined with the study of gentrification since shortly after the latter became academically relevant in the 1960’s. The term “gentrification” was first used by Ruth Glass in 1964 to describe the “gentry” in low income neighborhoods in London. Gentrification was originally understood as a “tool of revitalization for declining neighborhoods” (Zuk 2015), however, in 1979 Phillip Clay made the distinction between two types of revitalization: “incumbent upgrading” and “gentrification”, noting that Economic Displacement was the negative consequence of the latter (Clay 1979). Today, the term has evolved to describe “a spatial organization and re-organization of human dwelling and activity” (Zuk 2015). Specific to cities, gentrification is thought of as “the transformation of a working-class or vacant area of the central city into middle-class residential or commercial use” (Lees 2008).

Studies of gentrification and displacement generally take two approaches in the literature: supply-side and demand-side, or “the flows of capital versus flows of people to neighborhoods”, respectively (Zuk 2015). Supply side arguments for gentrification tend to focus on “private capital investment, public policies, and public investments” (Zuk 2015), and are much more often the subject of academic literature on Economic Displacement. This kind of research

is more common because it has the advantage of being more directly linked to influencing public policy (as opposed to controlling the flows of people). According to Dreier (2004), public policies that have been negatively linked to Economic Displacement have been, among others, automobile-oriented transportation infrastructure spending and mortgage interest tax deductions for home owners. Others that have argued for supply-side gentification include Smith (1979), who stated that the return of capital from the suburbs to the city, or the “political economy of capital flows into urban areas” are what primarily drive both the positive and negative consequences of urban gentrification.

More recently, income inequality has been explored as a major consequence of Economic Displacement. Specifically, “higher compensation in the top quintile and the lack of jobs for the bottom quintile” (Reardon 2011); (Watson 2009). The concentration of wealth allows “certain households to sort themselves according to their preferences – and control local political processes that continue exclusion” (Reardon 2011). This results in a self-reinforcing feedback loop where wealthier households influence public policy toward their self interest. Gentrification prediction tools could be used to help break such feedback loops through early identification and intervention.

Many studies conclude that gentrification in most forms leads to exclusionary economic displacement, however, Zuk (2015) characterizes the results of many recent studies as “mixed, due in part to methodological shortcomings”. In this paper, we attempt to further the understanding of gentrification prediction by demonstrating a technique to better predict real estate sales in New York City.

2.2 A Review of Mass Appraisal Techniques

Much of the research on predicting real estate prices has been in service of creating mass appraisal models. Mass appraisal models are most commonly used by local governments for the purpose of collecting taxes from property owners. Mass appraisal models share many characteristics with predictive machine learning models, in that they are data-driven,

standardized methods that employ statistical testing (Eckert 1990). A variation on mass appraisal models are the “automated valuation models” (AVM), which use “often the same methodological framework of mass appraisal. . . a statistical model and a large amount of property data to estimate the market value of an individual property or portfolio of properties” (d’Amato 2017).

Scientific mass appraisal models date back to 1936 with the reappraisal of St. Paul, Minnesota (Silverherz 1936). Since that time, and accelerated with the advent of computers, much statistical research has been done relating property values and rent prices to various characteristics of those properties, including characteristics of their surrounding area. Multiple regression analysis (MRA) has been the most common set of statistical tools used in mass appraisal, including Maximum Likelihood, Weighted Least Squares, and the most popular, Ordinary Least Squares (OLS) (d’Amato 2017). The primary drawbacks of MRA techniques are “excessive multicollinearity among attributes” and “spatial autocorrelation among residuals” (d’Amato 2017). Another group of models that seek to correct for spatial dependence are known as Spatial Auto Regressive models (SAR), chief among them the Spatial Lag Model, which aggregates weighted summaries of nearby properties in order to create independent regression variables (d’Amato 2017).

S0-called “Hedonic” regression models seek to decompose the price of a good based on the intrinsic and extrinsic components. Koschinsky (2012) is a recent and thorough discussion of parametric hedonic regression techniques. Some of the variables included in Koschinsky’s models are derived from nearby properties, similar to the technique used in this paper, and these variables were found to be predictive. The real estate hedonic model as defined by Koschinsky describes the price of a property as:

$$P_i = P(S_i, N_i, L_i)$$

Where P_i represents the price of house i , which is a composite good comprised of a vector of structural characteristics S , a vector of social and neighborhood characteristics

N , and a vector of locational characteristics L . Specifically, the model calculates spatial lags on properties of interest using neighboring properties within 1,000 feet of a sale. The derived variables include characteristics like average age, quantity of poor condition homes, percent of homes with electric heating, construction grade, etc., within 1,000 feet of the property in question. Koschinsky found that in all cases, “the relation between a home’s price and the average price of its neighboring homes is characterized by positive spatial autocorrelation” meaning that homes near each other were typically similar to each other and priced accordingly. Koschinsky concluded that locational characteristics should be valued at least as much “if not more” than important structural characteristics.

As recently as 2015, much research has dealt with mitigating the drawbacks of MRA, including the use of multi-level hierarchical models. Fotheringham (2015) explored the combination of Geographically Weighted Regression (GWR) with time-series forecasting to predict home prices over time. GWR is a variation on OLS that allows for “adaptive bandwidths” of local data to be included, i.e., for each estimate, the number of data points included varies and can be optimized using cross-validation.

2.3 A Review of Machine Learning Applied to Predicting Gentrification

Both Mass Appraisal techniques and Automated Valuation Modeling seek to predict real estate prices using data and statistical methods, however, traditional techniques typically fall short. This is because property valuation is inherently a “chaotic” process that does not lend itself to binary or linear analysis (Zuk 2015). The value of any given property is a complex combination of perceived value and speculation. The value of any building or plot of land belongs to a rich network where decisions about and perceptions of neighboring properties influence the final market value. Guan et al. (2014) compared traditional MRA techniques to alternative “data mining techniques” resulting in “mixed results”. However, as Helbich (2013) states, hedonic pricing models “can be improved in two ways: (a) Through novel estimation

techniques, and (b) by ancillary structural, locational, and neighborhood variables on the basis of Geographic Information System (GIS)". Recent research generally falls into these two buckets: better analysis algorithms and/or better data.

In the "better data" category, researchers have been striving to introduce new independent variables to increase the accuracy of predictive models. Dietzell (2014) successfully used internet search query data provided by Google Trends to serve as a sentiment indicator and improve commercial real estate forecasting models. Pivo and Fisher (2011) examined the effects of walkability on property values and investment returns. Pivo found that on a 100-point scale, a 10-point increase in walkability increased property investment values by up to 9%.

Research into better prediction algorithms do not necessarily happen at the exclusion of "better data". For example, Fu (2014) created a prediction algorithm, called "ClusRanking", for real estate in Beijing, China. ClusRanking first estimates neighborhood characteristics using taxi cab traffic vector data, specifically as they relate to accessibility to "business areas". Then, the algorithm performs a rank-ordered prediction of investment returns segmented into five categories. Similar to Koschinsky (2012), though less formally stated, Fu (2014) thought of a property's value as a composite of individual, peer and zone characteristics. In the predictive model, Fu includes characteristics of the neighborhood (individual), the values of its nearby properties (peer), and the prosperity of the affiliated latent business area (zone) based on taxi cab data (Fu 2014).

Several other recent studies compare various "advanced" statistical techniques and algorithms either to other advanced techniques or to traditional ones. Most studies conclude that the advanced, non-parametric techniques outperform traditional parametric techniques, while several conclude that the Random Forest algorithm is particularly well-suited to predicting real estate values.

Kontrimasa (2011) compares the accuracy of linear regression against the SVM technique and found the latter to outperform. Scherthanner H. (2016) compared traditional linear

regression techniques to several techniques such as krigging (stochastic interpolation) and Random Forest. They concluded that the more advanced techniques, particularly random forest, are sound and more accurate when compared to traditional statistical methods. Antipov and Pokryshevskaya (2012) came to a similar conclusion about the superiority of Random Forest for real estate valuation after comparing 10 algorithms: multiple regression, CHAID, Exhaustive CHAID, CART, 2 types of k-Nearest Neighbors, Multilayer Perceptron neural network (MLP), Radial Basis Function neural network (RBF)), Boosted Trees and finally Random Forest.

Guan et al. (2014) compared three different approaches to defining spatial neighbors: a simple radius technique, a k-nearest neighbors technique using only distance and a k-nearest neighbors technique using all attributes. Interestingly, the location-only KNN models performed best, although by a slight margin. Park (2015) developed several housing price prediction models based on machine learning algorithms including C4.5, RIPPER, Naive Bayesian, and AdaBoost. By comparing the models' classification accuracy performance, the experiments demonstrate that the RIPPER algorithm, based on accuracy, consistently outperformed the other models in the performance of housing price prediction. Rafiei (2016) employed a restricted boltzmann machine (neural network with back propagation) to predict the sale price of residential condos in Tehran, Iran, using a non-mating genetic algorithm for dimensionality reduction with a focus on computational efficiency. The paper concludes that two primary strategies help in this regard: weighting property sales by temporal proximity (sales which happened closer in time are more alike), and also using a learner to accelerate the recognition of important features. The paper compares this technique to several other common neural network approaches and finds that while not necessarily the only way to get the best answer, it is the fastest way to get to the best answer.

Finally, it should be noted that many studies, whether exploring advanced techniques, new data, or both, rely on aggregation of data by some arbitrary boundary. For example, Turner and Snow (2001) predicted gentrification in the Washington, D.C. metro area by

ranking census tracts in terms of development. Chapple (2009) created a gentrification “early warning system” by identifying low income census tracts in central city locations. Barry Bluestone & Chase Billingham (2010) analyzed 42 census block groups near rail stations in 12 metro areas across the United States, studying changes between 1990 and 2000 for neighborhood socioeconomic and housing characteristics. All of these studies, and many more, relied on aggregation of data at the census-tract or census-block level. In contrast, this paper compares boundary-aggregation techniques (specifically, aggregating by zip codes) to spatial-lag techniques and finds the spatial lag techniques to generally outperform.

3 Methodology

Our goal is to compare the use of spatial lags as features in a machine learning predictive model against traditional feature engineering techniques. We created three modeling data sets:

- Base modeling data
- Zip Code modeling data
- Spatial Lag modeling data

The second and third modeling datasets are variations of the first, using competing feature engineering techniques to extract value from the data. In addition to measuring performance across three datasets, we also create 2 predictive models for each modeling data set, using a different outcome variable for each:

- 1) **Probability of Sale** The probability that a given property in New York City will sell in a given year
- 2) **Amount of Sale (\$)** Given that a property sells, how much is the sale value?

There will be six predictive models built in total, as shown in Table 3.1. To accomplish this, we combine three open-source data repositories provided by New York City via nyc.gov and data.cityofnewyork.us. Our base modeling data set includes all building records and

Table 3.1: Six Predictive Models

#	Model	Model Type	Data	Outcome Var	Outcome Type	Eval Metric
1	Probability of Sale	Classification	Base	Building Sold	Binary	AUC
2	Probability of Sale	Classification	Zip Code	Building Sold	Binary	AUC
3	Probability of Sale	Classification	Spatial Lags	Building Sold	Binary	AUC
4	Sale Price	Regression	Base	Sale Price per SF	Continuous	RMSE
5	Sale Price	Regression	Zip Code	Sale Price per SF	Continuous	RMSE
6	Sale Price	Regression	Spatial Lag	Sale Price per SF	Continuous	RMSE

associated sales information from 2003-2017.

Following the creation of the base modeling data, we create two additional data sets through feature engineering: a “Zip Code features” data set and a “Spatial Lag features” data set. The primary goal of this study is to compare the predictive power of the spatial lags vs. the base and zip code features.

3.1 Data

The New York City government makes available an annual data set which describes all tax lots in the five boroughs. The Primary Land Use and Tax Lot Output data set, known as PLUTO, contains a single record for every tax lot in the city along with a number of building and tax-related attributes such as Year Built, Assessed Value, Square Footage, number of stories, and many more. At the time of this writing, NYC has made this data set available for all years between 2002-2017, excluding 2008. For convenience, we also exclude the 2002 data set from our analysis because corresponding sales information is not available for that year. Importantly for our analysis, the latitude and longitude of the tax lots are also made available, allowing us to locate in space each building and to build geospatial features from the data.

Ultimately, we are interested in sales transactions—both frequency, and amount. Sales transactions are also made available by the New York City government, known as NYC Rolling Sales Data. At the time of this writing, sales transactions are available for the years 2003-2017. The sales transactions data contains additional data fields describing time,

place, and amount of sale as well as additional building characteristics. Crucially, the sales transaction data does not include geographical coordinates, making it impossible to perform geospatial analysis without first mapping the sales data to PLUTO.

Prior to mapping to PLUTO, the sales data must first be transformed to include the proper mapping key. New York City uses a standard key of Borough-Block-Lot to identify tax lots in the data. For example, 31 West 27th Street is located in Manhattan, on block 829 and lot 16, therefore, its Borough-Block-Lot (BBL) is 1_829_16 (the 1 represents Manhattan). The sales data contains BBL's at the building level, however, the sales transactions data does not appropriately designate condos as their own BBL's. Mapping the sales data directly to the PLUTO data results in a mapping error rate of 23.1%. Therefore, the sales transactions data must first be mapped to another data source, the NYC Property Address Directory, or PAD, which contains an exhaustive list of all BBL's in NYC. Once the sales data is combined with PAD, the data can be mapped to PLUTO with an error rate of 0.291%.

After the Sales Transactions data has been mapped to PAD, it can then be mapped to PLUTO. The sales data is normalized and filtered so that only BBL's with less than or equal to 1 transactions in a year occur. The final data set is an exhaustive list of all tax lots in NYC for every year between 2003-2017, whether that building was sold, for what amount, and several other additional variables.

Only building categories of significant interest are included in the data. The included building types are displayed in Table 3.2.

The data is further filtered to include only records with equal to or less than 2 buildings per tax lot. The global filtering of the data set reduces the base modeling data from 12,012,780 records down to 8,247,499.

Table 3.2: Building Category Codes

Category	Description
A	ONE FAMILY DWELLINGS
B	TWO FAMILY DWELLINGS
C	WALK UP APARTMENTS
D	ELEVATOR APARTMENTS
F	FACTORY AND INDUSTRIAL BUILDINGS
G	GARAGES AND GASOLINE STATIONS
L	LOFT BUILDINGS
O	OFFICES

3.2 Feature Engineering

3.2.1 Base modeling data

The base modeling data set is enhanced to include additional features. A summary table of the additional features are presented in Table 3.3. A binary variable is created to indicate whether a tax lot has a building on it (i.e., whether it is an empty plot of land or not). In addition, building types are quantified by what percent of the square footage belongs to the major property types: Commercial, Residential, Office, Retail, Garage, Storage, Factory and Other.

Importantly, two variables are created from the Sales Prices: A price-per-square-foot figure (“Last_Sale_Price”) and a total Sale Price (“Last_Sale_Price_Total”). Sale Price per Square foot eventually becomes the outcome variable in one of the predictive models, even though it is referred to as Sale Price. Further features are derived which carry forward the previous sale price of a tax lot, if there is one, through successive years. Previous Sale Price is then used to create Simple Moving Averages (SMA), Exponential Moving Averages (SMA), and percent change measurements between the moving averages. In total, 69 variables are input to the feature engineering process and 92 variables are output. The final base modeling data set is 92 variables by 8,247,499 rows.

Table 3.3: Base Modeling Data Features

Feature	Min	Median	Mean	Max
has_building_area	0	1.00	1.00	1.00
Percent_Com	0	0.00	0.16	1.00
Percent_Res	0	1.00	0.82	1.00
Percent_Office	0	0.00	0.07	1.00
Percent_Retail	0	0.00	0.04	1.00
Percent_Garage	0	0.00	0.01	1.00
Percent_Storage	0	0.00	0.02	1.00
Percent_Factory	0	0.00	0.00	1.00
Percent_Other	0	0.00	0.00	1.00
Last_Sale_Price	0	312.68	531.02	62,055.59
Last_Sale_Price_Total	2	2,966,835.00	12,844,252.00	1,932,900,000.00
Years_Since_Last_Sale	1	4.00	5.05	14.00
SMA_Price_2_year	0	296.92	500.89	62,055.59
SMA_Price_3_year	0	294.94	495.29	62,055.59
SMA_Price_5_year	0	300.12	498.82	62,055.59
Percent_Change_SMA_2	-1	0.00	685.69	15,749,999.50
Percent_Change_SMA_5	-1	0.00	337.77	6,299,999.80
EMA_Price_2_year	0	288.01	482.69	62,055.59
EMA_Price_3_year	0	283.23	471.98	62,055.59
EMA_Price_5_year	0	278.67	454.15	62,055.59
Percent_Change_EMA_2	-1	0.00	422.50	9,415,128.85
Percent_Change_EMA_5	-1	0.06	308.05	5,341,901.60

3.2.2 Zip Code Modeling Data

The first of the two comparative modeling data sets is the Zip Code modeling data. Using the base data as a starting point, several features are generated to describe characteristics of the zip code where the tax lot resides. A summary table of the Zip code level features is presented in 3.4.

In general, the base model data features are aggregated to a zip code level and attached to the individual observations, including SMA and EMA calculations. Additionally, a second set of features are added, denoted as “bt_only”, which filter only for tax lots of the same building type. In total, the Zip code feature engineering process inputs 92 variables and outputs 122 variables.

3.2.3 Spatial Lag modeling data

Spatial lags are variables created from physically proximate observations. For example, taking the average building age from all buildings within 100 meters of the tax lot in question would be a spatial lag. Creating spatial lags presents both advantages and disadvantages in the modeling process. Spatial lags allow for much more fine-tuned measurements of a building’s surrounding area. Knowing the average sale price of all buildings within 500 meters of a building can be much more informative than knowing the sale prices of all buildings in the same zip code. However, building spatial lags is computationally expensive.

To build spatial lags for all 8,247,499 observations in our modeling data, we created a spatial indexing technique that greatly speeds up the process by allowing for parallelization of the point-in-polygon operations. Since tax lots rarely if ever move, we first reduced the indexing task to 514,124 unique points (the number of unique tax lots in New York City). Then, for each building, we calculated and cached every other tax lot within 500 meters of that building. The result was an origin-destination relationship graph that connected each tax lot to its surrounding tax lots. This process is illustrated in Figure 3.2.

A spatial indexing task takes the form of a point-in-polygon operation. As defined by

Table 3.4: Zip Code Modeling Data Features

Feature	Min	Median	Mean	Max
Last Year Zip Sold	0.00	27.00	31.14	112.00
Last Year Zip Sold Percent Ch	-1.00	0.00	Inf	Inf
Last Sale Price zip code average	0.00	440.95	522.87	1,961.21
Last Sale Price Total zip code average	10.00	5,312,874.67	11,877,688.55	1,246,450,000.00
Last Sale Date zip code average	12,066.00	13,338.21	13,484.39	17,149.00
Years Since Last Sale zip code average	1.00	4.84	4.26	11.00
SMA Price 2 year zip code average	34.31	429.26	501.15	2,092.41
SMA Price 3 year zip code average	34.31	422.04	496.47	2,090.36
SMA Price 5 year zip code average	39.48	467.04	520.86	2,090.36
Percent Change SMA 2 zip code average	-0.20	0.04	616.47	169,999.90
Percent Change SMA 5 zip code average	-0.09	0.03	341.68	113,333.27
EMA Price 2 year zip code average	30.77	401.43	479.38	1,883.81
EMA Price 3 year zip code average	33.48	419.11	479.95	1,781.38
EMA Price 5 year zip code average	29.85	431.89	472.80	1,506.46
Percent Change EMA 2 zip code average	-0.16	0.06	388.90	107,368.37
Percent Change EMA 5 zip code average	-0.08	0.07	326.17	107,368.38
Last Sale Price bt only	0.00	357.71	485.97	6,401.01
Last Sale Price Total bt only	10.00	3,797,461.46	11,745,130.56	1,246,450,000.00
Last Sale Date bt only	12,055.00	13,331.92	13,497.75	17,149.00
Years Since Last Sale bt only	1.00	4.78	4.30	14.00
SMA Price 2 year bt only	0.00	347.59	462.67	5,519.39
SMA Price 3 year bt only	0.00	345.40	458.50	5,104.51
SMA Price 5 year bt only	0.00	372.30	481.09	4,933.05
Percent Change SMA 2 bt only	-0.55	0.03	600.10	425,675.69
Percent Change SMA 5 bt only	-0.33	0.02	338.15	188,888.78
EMA Price 2 year bt only	0.00	332.98	442.79	5,103.51
EMA Price 3 year bt only	0.00	332.79	443.02	4,754.95
EMA Price 5 year bt only	0.00	340.57	436.70	4,270.37
Percent Change EMA 2 bt only	-0.47	0.06	377.17	254,462.97
Percent Change EMA 5 bt only	-0.34	0.06	335.17	178,947.30

Huang (1996), point-in-polygon is defined as “with a given polygon P and an arbitrary point q , determine whether point q is enclosed by the edges of the polygon.” Given that, for every point q_i in our dataset, we need to determine whether every other point q_i falls within a given radius. This means that the time-complexity of our operation, without pre-processing, can be approximated as:

$$O(N)^{N-1}$$

Despite having reduced the search space to $N = 514,124$, having the number of operations approaching N^N is infeasible from a computation and time standpoint. To overcome this, we add a pre-processing step of gridding the data and parallelizing the operation, allowing us to significantly reduce the time required. The gridded spatial indexing process is outlined in Algorithm 1.

Algorithm 1 Gridded Spatial Indexing

```

1: for each grid partition  $G$  do
2:   Extract all points  $G_i$  contained within partition  $G$ 
3:   Calculate convex hull  $H(G)$  such that the buffer extends to distance  $d$ 
4:   Define Search space  $S$  as all points within Convex hull  $H(G)$ 
5:   Extract all points  $S_i$  contained within  $S$ 
6:   for each data point  $G_i$  do
7:     Identify all points in  $S_i$  that fall within  $abs(G_i + d)$ 
8:   end for
9: end for

```

Each partition of the data is married with a corresponding search space S , which is the convex hull of the partition space buffered by the maximum distance d . In our case, we are buffering the search space by 500 meters, since we are interested in identifying all points within 500 meters of all other points. By gridding the data, we are able to reduce the search-space for each operation by an arbitrary number of partitions G . This improves the base run-time complexity to:

$$O(N)^{\frac{N-1}{G}}$$

By making G arbitrarily large (bounded by computational resources only), we can reduce runtime substantially. Furthermore, binning the operations into grids allows us to parallelize the computation, substantially reducing the overall run time. Figure 3.1 shows a comparison of run times between different spatial indexing procedures. Note how the sequential Grid method starts out as slower than the basic Point-in-polygon technique due to pre-processing overhead, but wins out in terms of speed as complexity increases

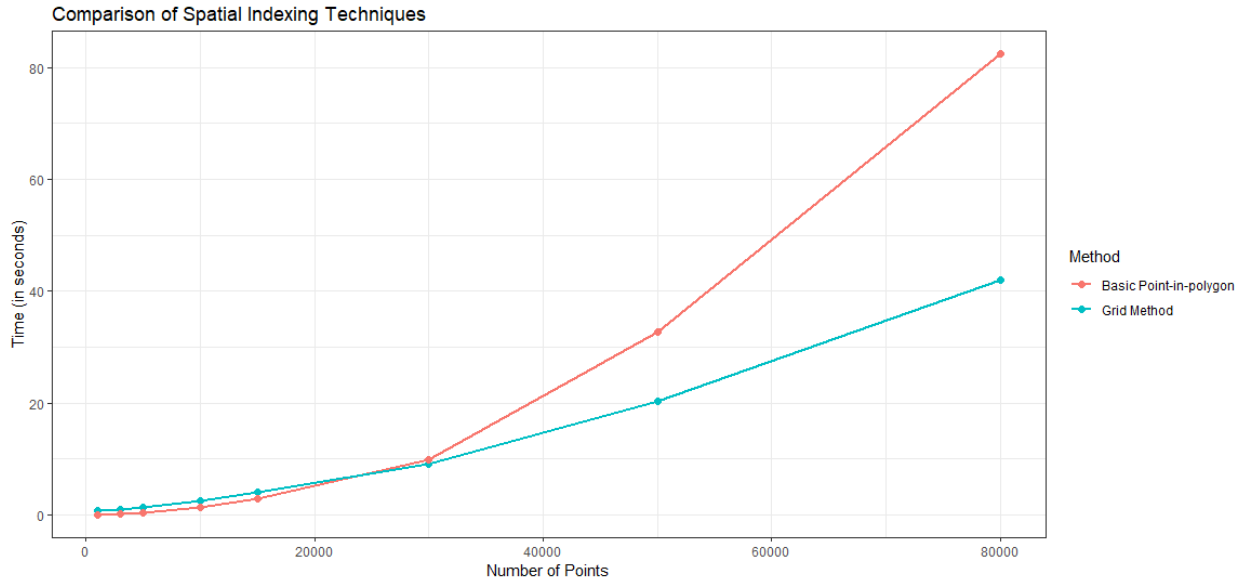


Figure 3.1: Spatial Index Time Comparison

Next, we used the spatial index to create spatial lag features. One advantage of using spatial lags is the rich number of potential features which can be engineered. Spatial lags can be weighted based on a distance function, e.g., physically closer observations can be given more weight. For our modeling purposes, we created two sets of features: distance weighted features (denoted with a `"_dist"` in Appendix A Table 6.1) and simple average features (denoted with `"_basic"` in Appendix A Table 6.1). SMA and EMA as well as percent changes were also calculated. Temporal and spatial derivatives of the Spatial Lag features presented in Table 3.5 were also added to the model, including: variables weighted by euclidean distance (`"dist"`), basic averages of the spatial lag radius (`"basic mean"`), Simple Moving Averages

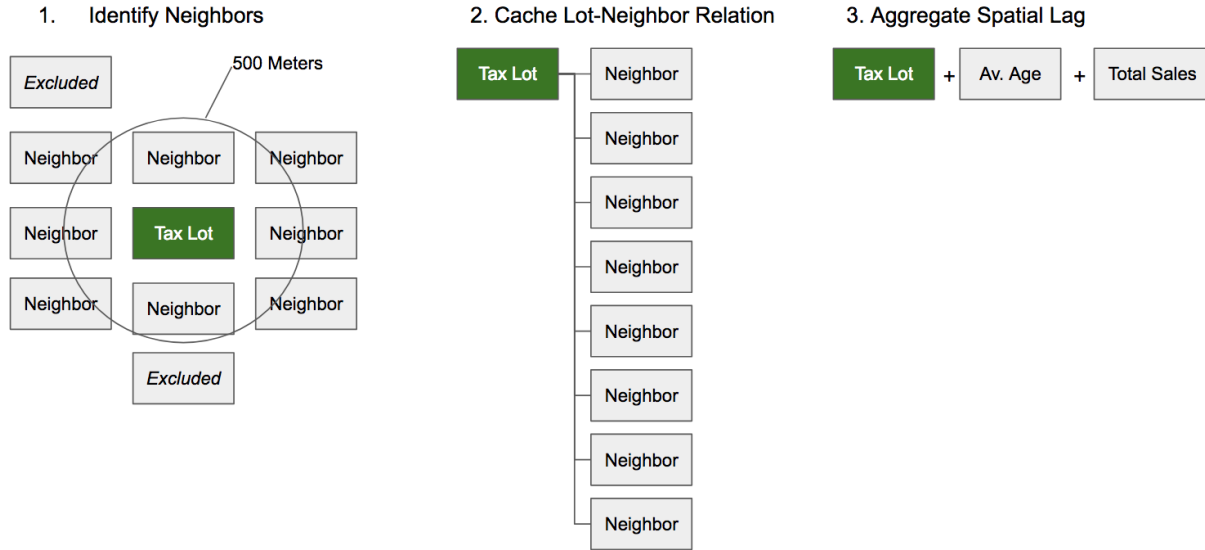


Figure 3.2: Spatial Lag Feature Creation Process

(“SMA”) for 2 years, 3 years and 5 years, exponential moving averages (“EMA”) for 2 years, 3 years and 5 years, and year-over-year percent changes for all variables (“perc change”). In total, the spatial lag feature engineering process input 92 variables and output 194 variables. A summary of the Spatial Lag features are presented in Appendix A Table 6.1.

3.3 Outcome Variables

The final step in creating the modeling data is to define the outcome variables. For our purposes, we create two dependent variables:

- 1) **Sold.** whether a tax lot sold in a given year. Used in the Probability of Sale classification model.
- 2) **Sale Price.** The price-per-square foot associated with a transaction, if a sale took place. Used in the Sale Price Regression model.

Table 3.6 describes the distributions of both outcome variables:

Table 3.5: Summary of Spatial Lag Features (See Appendix A for full list)

Spatial Lag Features
Radius Total Sold In Year
Radius Average Years Since Last Sale
Radius Res Units Sold In Year
Radius All Units Sold In Year
Radius SF Sold In Year
Radius Total Sold In Year sum over 2 years
Radius Average Years Since Last Sale sum over 2 years
Radius Res Units Sold In Year sum over 2 years
Radius All Units Sold In Year sum over 2 years
Radius SF Sold In Year sum over 2 years
Radius Total Sold In Year percent change
Radius Average Years Since Last Sale percent change
Radius Res Units Sold In Year percent change
Radius All Units Sold In Year percent change
Radius SF Sold In Year percent change
Radius Total Sold In Year sum over 2 years percent change
Radius Average Years Since Last Sale sum over 2 years percent change
Radius Res Units Sold In Year sum over 2 years percent change
Radius All Units Sold In Year sum over 2 years percent change
Radius SF Sold In Year sum over 2 years percent change

Table 3.6: Distributions for Outcome Variables

	Sold	Sale Price per SF
Min.	0.00	0.0
1st Qu.	0.00	163.5
Median	0.00	375.2
Mean	0.04	644.8
3rd Qu.	0.00	783.3
Max.	1.00	83,598.7

3.4 Algorithm

Previous works (see: Antipov and Pokryshevskaya (2012); also Schernthanner H. (2016)) have found the Random Forest algorithm (Breiman 2001) suitable to prediction tasks involving real estate. While algorithms exist that may marginally outperform Random Forest in terms of predictive accuracy (such as neural networks and functional gradient descent algorithms), Random Forest is highly scalable and parallelizable, and therefore a natural choice for comparing different feature engineering strategies. For these reasons and more outlined below, we select Random Forrest as the primary algorithm for comparrison in this paper.

Random Forest can be used for both classification and regression tasks, both of which we undertake in this paper. The Random Forest algorithm works by generating a large number of independent classification or regression decision trees and then employing majority voting (for classification) or averaging (for regression) to generate predictions. Over a data set of N rows by M predictors, a bootstrap sample of the data is chosen ($n < N$) as well as a subset of the predictors ($m < M$). Individual decision/regression trees are built on the n by m sample. Because the trees can be built independently (and not sequentially, as is the case with most functional gradient descent algorithms), the tree building process can be executed in parallel across an arbitrary number of computer cores. With a sufficiently large number of cores, the model training time can be significantly reduced. This provides a highly accurate, robust prediction model that avoids many of the drawbacks of traditional parametric techniques, such as OLS.

The primary advantages to using Random Forest with real estate data are:

1. Can handle an arbitrarily large number of variables while avoiding the curse of dimensionality associated with regression techniques. Increasing the number of predictors in a multiple regression can quickly lead to over-fitting.
2. Can accommodate categorical variables with many levels. Real estate data often contains information describing the location of the property, or the property itself, as one of a large set of possible choices, such as neighborhood, county, census tract,

district, property type, and zoning information. Because factors need to be recoded as individual dummy variables in the model building process, factors with many levels will quickly encounter the curse of dimensionality in multiple regression techniques.

3. Appropriately handles missing data. Predictions can be made with the parts of the tree which are successfully built, and therefore, there is no need to filter out incomplete observations or impute missing values. Since much real estate data is self reported, incomplete fields are common in the data.
4. Robust against outliers. Because of bootstrap sampling, outliers appear in individual trees less often, and therefore, are reduced in terms of importance. Real estate data, especially with regards to pricing, tends to contain outliers. For example, the dependent variable in one of our models, Sale Price (see: Table 7), shows a clear divergence in median and mean, as well as a maximum significantly higher than the third quartile.
5. Can recognize non-linear relationships in data, which is useful when modeling spatial relationships.
6. Is not affected by co-linearity in the data. This is highly valuable as real estate data can be highly correlated.
7. The algorithm can be parallelized and is relatively fast compared to neural networks and functional gradient descent algorithms.

To run the model, we have chosen the `h2o.randomForest` function from the `h2o` R open source library. The `h2o` implementation of the Random Forest algorithm is particularly well-suited for high parallelization. For more information, see: <https://www.h2o.ai/>.

3.4.1 Data Validation

The goal of the predictive models are to be able to successfully predict both the probability and amount of real estate sales into the near future. As such, our models will use out-of-time validation to assess performance. As shown in Figure 3.3 The models will be trained using data from 2003-2015. 2016 modeling data will be used during the model training process

as cross-validation data. Finally, we will score our model using 2017 as a held-out sample. Using out-of-time validation should ensure that the models generalize well into the immediate future.

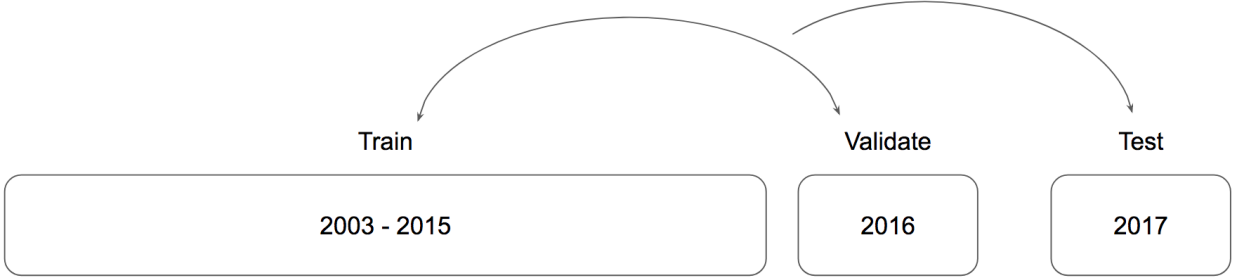


Figure 3.3: Out-of-time validation

3.5 Variable Selection

For ease of processing and to improve the ability of the model to generalize into the future, a variable selection step is added to the modeling process. A Random Forest model is first trained on a 1% sub-sample of the modeling data. Variable importance of the resulting model is calculated using the technique proposed by Friedman (2001), i.e., for a collection of decision trees $[T_m]_1^m$:

$$\hat{I}_j^2 = \frac{1}{M} \sum_{m=1}^M \hat{I}_j^2(T_m)$$

Where influence I for variable j is calculated as the sum of corresponding improvements in squared-error for node tree T . After calculating variable importance for the model data subset, the variables are rank-ordered by descending importance. Variables which account for 80% of the total variable importance are chosen to advance to the model training round on the full modeling data sets.

3.6 Evaluation Metrics

We have chosen evaluation metrics that will allow us to easily compare the performance of the models against other models with the same outcome variable. The classification models (Probability of Sale) will be compared using Area Under the ROC Curve (AUC). The regression models (Sale Price) will be compared using Root Mean Squared Error (RMSE). Both evaluation metrics are common for their respective outcome variable types, and as such will be useful for comparing within model-groups.

3.6.1 Area Under ROC Curve (AUC)

A classification model typically outputs a probability that a given row in the data belongs to a group. In the case of binary classification, the value falls between 0 and 1. There are many techniques for determining the cut off threshold for classification; a typical method is to assign anything above a 0.5 into the “1” or positive class. An ROC curve (receiver operating characteristic curve) plots the True Positive Rate vs. the False Positive rate at different classification thresholds; it is a measurement of the performance of a classification model across all possible thresholds, and therefore sidesteps the need to arbitrarily assign a cutoff.

Area Under the ROC Curve, or AUC measures the entire two-dimensional area underneath the ROC curve. It is the integration of the curve from (0,0) to (1,1), defined as $AUC = \int_{(0,0)}^{(1,1)} f(x)dx$.

AUC provides a relatively standard measure of performance across all possible classification thresholds, and can be interpreted as the probability that the model ranks a random positive example more highly than a random negative example. A value of 0.5 represents a perfectly random model, while a value of 1.0 represents a model that can perfectly discriminate between the two classes. AUC is useful for comparing classification models against one another because they are both scale and threshold-invariant.

One of the drawbacks to AUC is that it does not describe the trade-offs between false

positives and false negatives. In certain circumstances, a false positive might be considerably less desirable than a false negative, or vice-versa. For our purposes, we rank false positives and false negatives as equally undesirable outcomes.

3.6.2 Root Mean Squared Error

The Root Mean Squared Error (RMSE) is a common measurement of the differences between values predicted by a regression model and the observed values. It is formally defined as $RMSE = \sqrt{\frac{\sum_1^T (\hat{y}_t - y_t)^2}{T}}$, where \hat{y} represents the prediction and y represents the observed value at observation t .

Lower RMSE scores are typically more desirable. An RMSE value of 0 would indicate a perfect fit to the data. RMSE can be difficult to interpret on its own, however, it is useful for comparing models with similar outcome variables. In our case, the outcome variables (Sales Price per Square Foot) are consistent across modeling data sets, and therefore can be reasonably compared using RMSE.

4 Results

4.1 Sale Price Model

Using Root Mean Squared Error (RMSE) as an evaluation metric of predictive power, we find that the Spatial Lag modeling features consistently outperform the Zip Code features, while the Base modeling data tends to outperform both, as shown in the following Table (lower RMSE is better):

Interestingly, both the Spatial Lag modeling data and the Zip Code modeling data are extensions of the Base data, yet the Base data tends to generalize to the hold-out data sets better. From this, we make two observations:

- 1) Building characteristic data, which largely comprises the Base modeling data, are the most important for predicting building sale price per foot

Table 4.1: Sale Price Model RMSE For Validation and Test Hold-out Data

type	base	zip	spatial lag
Validation	280.6314	297.9717	286.2295
Test	287.8305	300.6031	297.9202

- 2) The Zip Code and Spatial Lag models are suffering from over-fitting of the data, which is limiting their ability to generalize to the hold-out samples.

It is possible that the over-fitting issue could be corrected through hyper-parameter tuning of the algorithms, as well as implementing stricter variable selection. Despite this, we can still safely conclude that the Spatial Lag features are superior to the Zip Code features in terms of predictive power.

Taking a closer look at the data, we find that the models have varying performance across Building Types and Boroughs. Figure 4.1 shows RMSE by Model, faceted by Borough across the y-axis and Building Type across the x-axis (See Table 2 for a description of building type codes).

We make the following observations from Figure 4.1:

- The Spatial Lag modeling data outperforms both Base and Zip Code in 6 cases, notably for Type A buildings (One Family Dwellings) and Type L buildings (Lofts) in Manhattan as well as Type O Buildings (Office) in Queens
- It is generally harder to predict sale prices in Manhattan than other Boroughs
- The “residential” building Types A (One Family Dwellings), B (Two Family Dwellings), C (Walk Up Apartments) and D (Elevator Apartments) have generally lower RMSE scores compared to the non-residential types

If we rank the models by performance for each Borough, Building Type combination, we find that the Spatial Lag models outperform the Zip Code models in 72% of cases. Table 9

Table 4.2: Sale Price Model Rankings, RMSE by Borough and Building Type

Model Rank	1	2	3	Average Rank
Base	22.2%	9.3%	1.9%	1.39
Spatial Lag	5.6%	18.5%	9.3%	2.11
Zip	5.6%	5.6%	22.2%	2.50

Table 4.3: Probability of Sale Models AUC

Model AUC	Base	Zip	Spatial Lag
Validation	0.832	0.8292	0.8287
Test	0.830	0.8246	0.8279

shows the average ranking by model type as well as the percent distribution by model type across rankings.

4.2 Probability of Sale Model

Similar to the results found in the Sale Price models, using Area Under the ROC Curve (AUC) as an evaluation metric, we find the Spatial Lag model performs better on the hold-out validation data compared to the Zip Code modeling data, as shown in Table 10. The Base Modeling data continues to outperform the Spatial Lag and Zip Code modeling data overall, however, when broken down by Borough and Building Type, some interesting patterns emerge.

Looking at the predictions by the models made on the 2017 validation hold-out data, we see the Spatial Lag model performs best of any model for three out of five Boroughs: Manhattan, Bronx and Staten Island (Table 11).

Figure 4.2 shows a breakdown of model AUC faceted along the x-axis by Building Type

Table 4.4: Probability of Sale Models AUC by Borough

Model	BK	BX	MN	QN	SI
Base	0.8309	0.8288	0.7926	0.8338	0.8336
Zip	0.8234	0.8215	0.7796	0.8283	0.8281
Spatial Lag	0.8257	0.8312	0.8031	0.8327	0.8348

Table 4.5: Distribution and Average Model Rank for Probability of Sale by AUC across Borough and Building Types

Model Rank	1	2	3	Average Rank
Base	16.2%	12.0%	5.1%	2.22
Spatial Lag	11.1%	13.7%	8.5%	2.09
Zip	6.0%	7.7%	19.7%	1.69

and along the y-axis by Borough. The coloring indicated by how much a model's AUC diverges from the cell average.

We make the following observations about Figure 4.2:

- The Spatial Lag model outperforms all other models for Elevator Buildings (Type D), particularly in the Bronx
- The Probability of Sale model tends to perform poorly in Manhattan vs. other Boroughs
- However, the Spatial Lag model performs well in Manhattan for the residential building types (A, B, C and D)

If we rank model the probability models' performance for each Borough and Building Type, we see that the Spatial Lag models consistently outperform the Zip Code models, as shown in Table 12.

5 Conclusions and Future Research

5.1 Future Research

This research has shown that spatial-lag features can be worthwhile additions to machine learning predictive models in certain circumstances. There are several areas that could be further explored regarding spatial lag features, some of which are mentioned below.

First, it became apparent in the research that generalization was a problem for the models overall, likely due to overfitting of the training data. Further research into proper variable selection could be one remedy for such issues.

Additionally, the spatial lag features seemed to perform best for outer boroughs (non-Manhattan) and for smaller, residential building types. One possible explanation for this is that these types of assets are considerably more numerous and homogenous. It is possible that a 500 meter radius, which was arbitrarily chosen, works best for this type of asset. Fotheringham (2015) used an “Adaptive Bandwidth” technique to adjust the spatial lag radius based on cross-validation. research into applying a similar technique to this research could be valuable.

Finally, this research aimed to predict real estate transactions 1 year into the future. While this is a promising start, 1-year of lead time may not be sufficient to respond to growing gentrification challenges. In addition, modeling at the annual level could be improved to quarterly or monthly, given that the sales data contains date information down to the day. To make this system practical for combatting displacement, it may be helpful to predict at a more granular level and further into the future.

5.2 Conclusion

Gentrification is largely beneficial to societies and communities, however, the downside should not be overlooked. Displacement causes Economic Exclusion, which over time can contribute to rising Income Inequality. Combatting displacement allows communities to

benefit from gentrification without suffering the negative consequences. One way to practically combat displacement is to predict gentrification, which this paper has attempted to do.

Spatial lags, typically seen in geographically weighted regression, were employed successfully to enhance the predictive power of machine learning models. The features suffered in some areas due to modeling and data shortcomings, but overall we found that spatial lags outperform zip-code level aggregations, and perform quite well for specific asset types and geographic locations, particularly residential buildings outside of Manhattan.

While this research is not intended to serve as a full early-warning system for gentrification and displacement, it is a step in that direction. More research is needed to help address the challenges faced by city planners and governments trying to help incumbent residents reap the benefits of local investments. Income inequality is a complicated and grave issue of our time, but new tools and techniques to inform and prevent give a hope for a more equitable future.

6 Appendix A: List of Spatial Lag Features

References

- Almanie, R.; Lor, T.; Mirza. 2015. “Crime Prediction Based on Crime Types and Using Spatial and Temporal Criminal Hotspots.” *International Journal of Data Mining & Knowledge Management Process (IJDKP)* 5 (4).
- Antipov, Evgeny A., and Elena B. Pokryshevskaya. 2012. “Mass Appraisal of Residential Apartments: An Application of Random Forest for Valuation and a Cart-Based Approach for Model Diagnostics.” *Expert Systems with Applications*.
- Barry Bluestone & Chase Billingham, Stephanie Pollack &. 2010. “Maintaining Diversity in America’s Transit-Rich Neighborhoods: Tools for Equitable Neighborhood Change.” *New England Community Developments, Federal Reserve Bank of Boston*, 1–6.
- Batty, Michael. 2013. “The New Science of Cities.” *MIT Press*.
- Breiman, L. 2001. “Random Forests.” *Machine Learning* 45 (1): 5–32.
- Chapple, Karen. 2009. “Mapping Susceptibility to Gentrification: The Early Warning Toolkit.” *Berkeley, CA: Center for Community Innovation*.
- Chapple, Miriam, Karen; Zuk. 2016. “Forewarned: The Use of Neighborhood Early Warning Systems for Gentrification and Displacement.” *Cityscape: A Journal of Policy Development and Research* 18 (3).
- Clay, Phillip L. 1979. *Neighborhood Renewal: Middle-Class Resettlement and Incumbent Upgrading in American Neighborhoods*. Lexington Books.
- d’Amato, Tom, Maurizio; Kauko, ed. 2017. *Advances in Automated Valuation Modeling*. Springer International Publishing.
- Dietzell, Nicole; Schäfers, Marian Alexander; Braun. 2014. “Sentiment-Based Commercial Real Estate Forecasting with Google Search Volume Data.” *Journal of Property Investment & Finance*, 32 (6): 540–69.
- Dreier, John; Swanstrom, Peter; Mollenkopf. 2004. *Place Matters: Metropolitcs for the*

Table 6.1: Appendix A: All Spatial Lag Features

Feature	Min	Median	Mean	Max
Radius_Total_Sold_In_Year	1.00	20.00	24.00	201.00
Radius_Average_Years_Since_Last_Sale	1.00	4.43	4.27	14.00
Radius_Res_Units_Sold_In_Year	0.00	226.00	289.10	2,920.00
Radius_All_Units_Sold_In_Year	0.00	255.00	325.94	2,923.00
Radius_SF_Sold_In_Year	0.00	259,403.00	430,891.57	8,603,639.00
Radius_Total_Sold_In_Year_sum_over_2_years	2.00	41.00	48.15	256.00
Radius_Average_Years_Since_Last_Sale_sum_over_2_years	2.00	9.25	8.70	26.00
Radius_Res_Units_Sold_In_Year_sum_over_2_years	0.00	493.00	584.67	3,397.00
Radius_All_Units_Sold_In_Year_sum_over_2_years	1.00	555.00	660.67	4,265.00
Radius_SF_Sold_In_Year_sum_over_2_years	2,917.00	580,947.00	872,816.44	14,036,469.00
Radius_Total_Sold_In_Year_percent_change	-0.99	0.00	0.27	77.00
Radius_Average_Years_Since_Last_Sale_percent_change	-0.91	0.13	0.26	8.00
Radius_Res_Units_Sold_In_Year_percent_change	-1.00	-0.04	Inf	Inf
Radius_All_Units_Sold_In_Year_percent_change	-1.00	-0.04	Inf	Inf
Radius_SF_Sold_In_Year_percent_change	-1.00	-0.02	Inf	Inf
Radius_Total_Sold_In_Year_sum_over_2_years_percent_change	-0.96	-0.03	0.03	15.00
Radius_Average_Years_Since_Last_Sale_sum_over_2_years_percent_change	-0.72	0.12	0.17	2.50
Radius_Res_Units_Sold_In_Year_sum_over_2_years_percent_change	-1.00	-0.04	Inf	Inf
Radius_All_Units_Sold_In_Year_sum_over_2_years_percent_change	-0.99	-0.04	0.12	84.00
Radius_SF_Sold_In_Year_sum_over_2_years_percent_change	-0.98	-0.04	0.18	361.55
Percent_Com_dist	0.00	0.04	0.07	0.56
Percent_Res_dist	0.00	0.46	0.43	0.66
Percent_Office_dist	0.00	0.01	0.03	0.48
Percent_Retail_dist	0.00	0.02	0.02	0.09
Percent_Garage_dist	0.00	0.00	0.00	0.27
Percent_Storage_dist	0.00	0.00	0.01	0.26
Percent_Factory_dist	0.00	0.00	0.00	0.04
Percent_Other_dist	0.00	0.00	0.00	0.09
Percent_Com_basic_mean	0.00	0.04	0.07	0.54
Percent_Res_basic_mean	0.00	0.46	0.43	0.66
Percent_Office_basic_mean	0.00	0.01	0.03	0.44
Percent_Retail_basic_mean	0.00	0.02	0.02	0.08
Percent_Garage_basic_mean	0.00	0.00	0.00	0.29
Percent_Storage_basic_mean	0.00	0.00	0.01	0.23
Percent_Factory_basic_mean	0.00	0.00	0.00	0.03
Percent_Other_basic_mean	0.00	0.00	0.00	0.04
Percent_Com_dist_perc_change	-0.90	0.00	0.00	6.18
Percent_Res_dist_perc_change	-0.50	0.00	0.03	36.73
Percent_Office_dist_perc_change	-1.00	0.00	Inf	Inf
Percent_Retail_dist_perc_change	-0.82	0.00	Inf	Inf
Percent_Garage_dist_perc_change	-1.00	0.00	Inf	Inf
Percent_Storage_dist_perc_change	-1.00	-0.01	Inf	Inf
Percent_Factory_dist_perc_change	-1.00	0.00	Inf	Inf
Percent_Other_dist_perc_change	-1.00	0.00	Inf	Inf
SMA_Price_2_year_dist	0.00	400.01	496.30	3,816.57
SMA_Price_3_year_dist	0.00	396.94	492.00	3,816.57
SMA_Price_5_year_dist	8.83	425.55	515.29	3,877.53
Percent_Change_SMA_2_dist	-0.13	0.03	552.33	804,350.67
Percent_Change_SMA_5_dist	-0.09	0.02	317.46	322,504.58
EMA_Price_2_year_dist	0.00	378.63	475.54	3,431.17
EMA_Price_3_year_dist	8.83	382.25	476.05	3,296.46
EMA_Price_5_year_dist	7.88	386.34	468.91	2,813.34
Percent_Change_EMA_2_dist	-0.09	0.06	346.51	480,829.57
Percent_Change_EMA_5_dist	-0.02	0.06	303.55	273,458.42
SMA_Price_2_year_basic_mean	0.02	412.46	496.75	2,509.79
SMA_Price_3_year_basic_mean	0.02	409.00	492.43	2,509.79
SMA_Price_5_year_basic_mean	17.16	443.34	515.67	2,621.01
Percent_Change_SMA_2_basic_mean	-0.13	0.04	543.51	393,749.99
Percent_Change_SMA_5_basic_mean	-0.09	0.03	312.46	157,500.00
EMA_Price_2_year_basic_mean	0.02	390.30	475.96	2,259.21
EMA_Price_3_year_basic_mean	11.39	393.25	476.45	2,136.36
EMA_Price_5_year_basic_mean	15.30	402.06	469.09	1,848.27
Percent_Change_EMA_2_basic_mean	-0.09	0.06	340.89	235,378.24
Percent_Change_EMA_5_basic_mean	-0.02	0.06	296.78	133,547.59

Twenty-First Century. University Press of Kansas.

Eckert, J. K. 1990. *Property Appraisal and Assessment Administration*. Chicago, IL.: International Association of Assessing Officers.

Fotheringham, R; Yao, A.S.; Crespo. 2015. “Exploring, Modelling and Predicting Spatiotemporal Variations in House Prices.” *The Annals of Regional Science* 54.

Friedman, Jerome H. 2001. “Greedy Function Approximation: A Gradient Boosting Machine.” *The Annals of Statistics* 29 (5): 1189–1232.

Fu, Yanjie; et al. 2014. *Exploiting Geographic Dependencies for Real Estate Appraisal: A Mutual Perspective of Ranking and Clustering*. Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery; data mining.

Geltner, David, and Alex Van de Minne. 2017. “Do Different Price Points Exhibit Different Investment Risk and Return Commercial Real Estate.” Real Estate Research Institute.

Guan, Jian, Donghui Shi, Jozef M. Zurada, and Alan S. Levitan. 2014. “Analyzing Massive Data Sets: An Adaptive Fuzzy Neural Approach for Prediction, with a Real Estate Illustration.” *Journal of Organizational Computing and Electronic Commerce* 24 (1). Taylor & Francis: 94–112. <https://doi.org/10.1080/10919392.2014.866505>.

Helbich, et al., Marco. 2013. “Boosting the Predictive Accuracy of Urban Hedonic House Price Models Through Airborne Laser Scanning.” *Computers, Environment and Urban Systems* 39: 81–92.

Huang, Chong-Wei. 1996. “On the Complexity of Point-in-Polygon Algorithms.” *Computers and Geosciences* 23.

Johnson, Ken, Justin Benefield, and Jonathan Wiley. 2007. “The Probability of Sale for Residential Real Estate.” *Journal of Housing Research* 16 (2): 131–42. <https://doi.org/10.5555/jhor.16.2.0234g75800h5k8x6>.

Kontrimasa, Antanas, Vilius; Verikasb. 2011. “The Mass Appraisal of the Real Estate by Computational Intelligence.” *Applied Soft Computing*.

Koschinsky, J. et al. 2012. “The Welfare Benefit of a Home’s Location: An Empirical Comparison of Spatial and Non-Spatial Model Estimates.” *Journal of Geographical Systems* 10109.

Lees, Tom; Wyly, Loretta; Slater. 2008. “Gentrification.” *Growth and Change* 39 (3): 536–39. <https://doi.org/10.1111/j.1468-2257.2008.00443.x>.

Miller, J.; Aspinall, J.; Franklin. 2007. “Incorporating Spatial Dependence in Predictive Vegetation Models.” *Ecological Modelling* 202 (3): 225–42.

Park, Jae Kwon, Byeonghwa; Bae. 2015. “Using Machine Learning Algorithms for Housing Price Prediction: The Case of Fairfax County, Virginia Housing Data.” *Expert Systems with Applications* 42 (6): 2928–34.

Pivo, Gary, and Jeffrey D. Fisher. 2011. “The Walkability Premium in Commercial Real Estate Investments.” *Real Estate Economics* 39 (2): 185–219. <https://doi.org/10.1111/j.1540-6229.2010.00296.x>.

Quintos, Carmela. 2013. “Estimating Latent Effects in Commercial Property Models.” *Journal of Property Tax Assessment & Administration* 12 (2).

Rafiei, Hojjat, Mohammad Hossein; Adeli. 2016. “A Novel Machine Learning Model for Estimation of Sale Prices of Real Estate Units.” *Journal of Construction Engineering and Management* 142 (2).

Reardon, Kendra, Sean F.; Bischoff. 2011. “Income Inequality and Income Segregation.” *American Journal of Sociology*.

Ritter, Nancy. 2013. “Predicting Recidivism Risk: New Tool in Philadelphia Shows Great Promise.” *National Institute of Justice Journal* 271.

Schernthanner H., Gonschorek J., Asche H. 2016. “Spatial Modeling and Geovisualization of Rental Prices for Real Estate Portals.” *Computational Science and Its Applications* 9788.

Silverherz, J. D. 1936. “The Assessment of Real Property in the United States.” *Albany: J.B. Lyon Co. Printers*.

Smith, Neil. 1979. “Toward a Theory of Gentrification a Back to the City Movement

by Capital, Not People.” *Journal of the American Planning Association* 45 (4). Routledge: 538–48. <https://doi.org/10.1080/01944367908977002>.

Solomon Greene, Molly Scott, Rolf Pendall, and Serena Lei. 2016. “Open Cities: From Economic Exclusion to Urban Inclusion.” *Urban Institute Brief*. Urban Institute Brief.

Turner, Margery Austin, and Christopher Snow. 2001. *Leading Indicators of Gentrification in D.c. Neighborhoods*.

Watson, Tara. 2009. “Inequality and the Measurement of Residential Segregation by Income in American Neighborhoods.” *Review of Income and Wealth*.

Zuk, Miriam; et al. 2015. “Gentrification, Displacement and the Role of Public Investment: A Literature Review.”

Sale Price Model Performance by Borough and Building Type

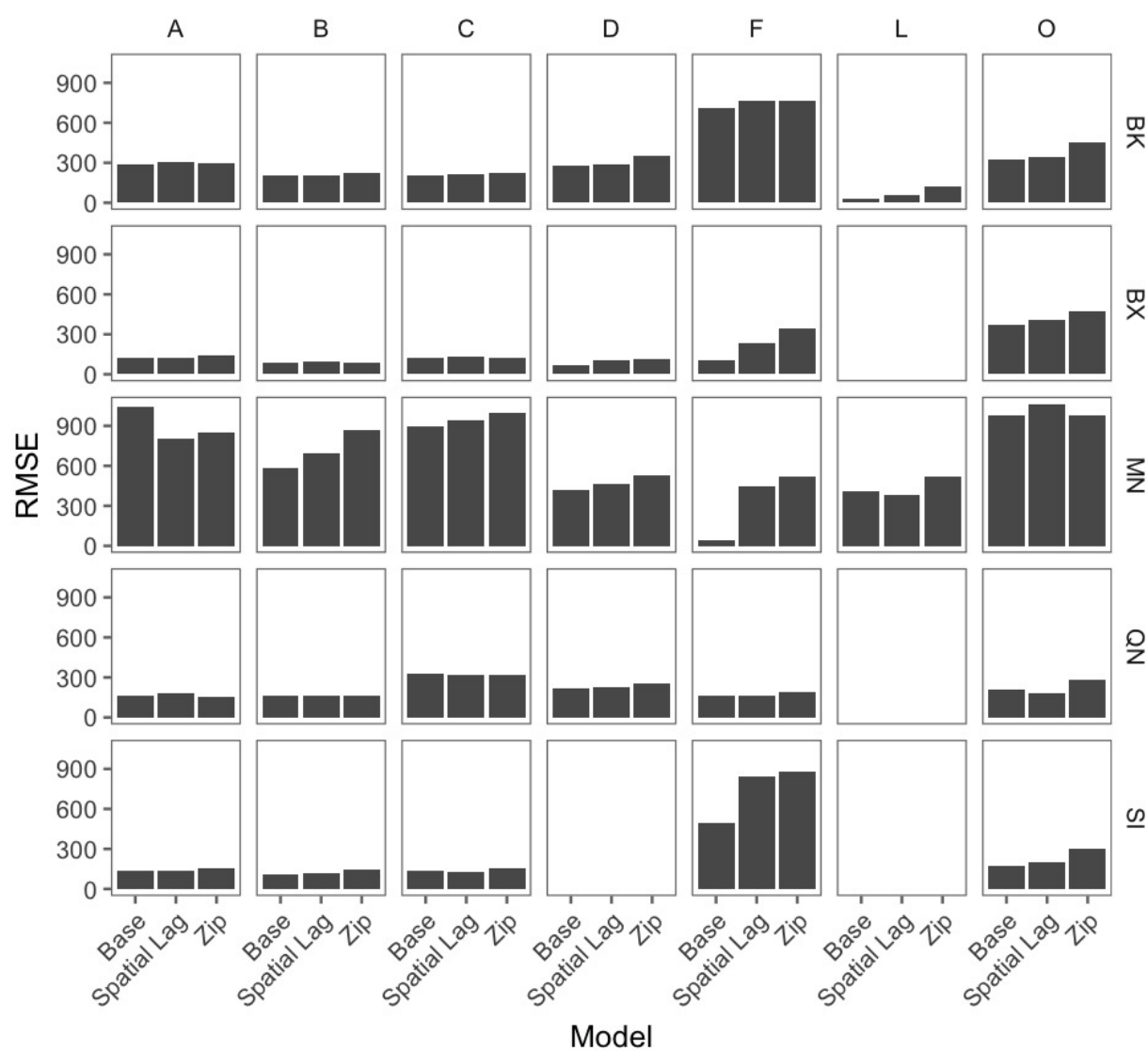


Figure 4.1: RMSE By Borough and Building Type

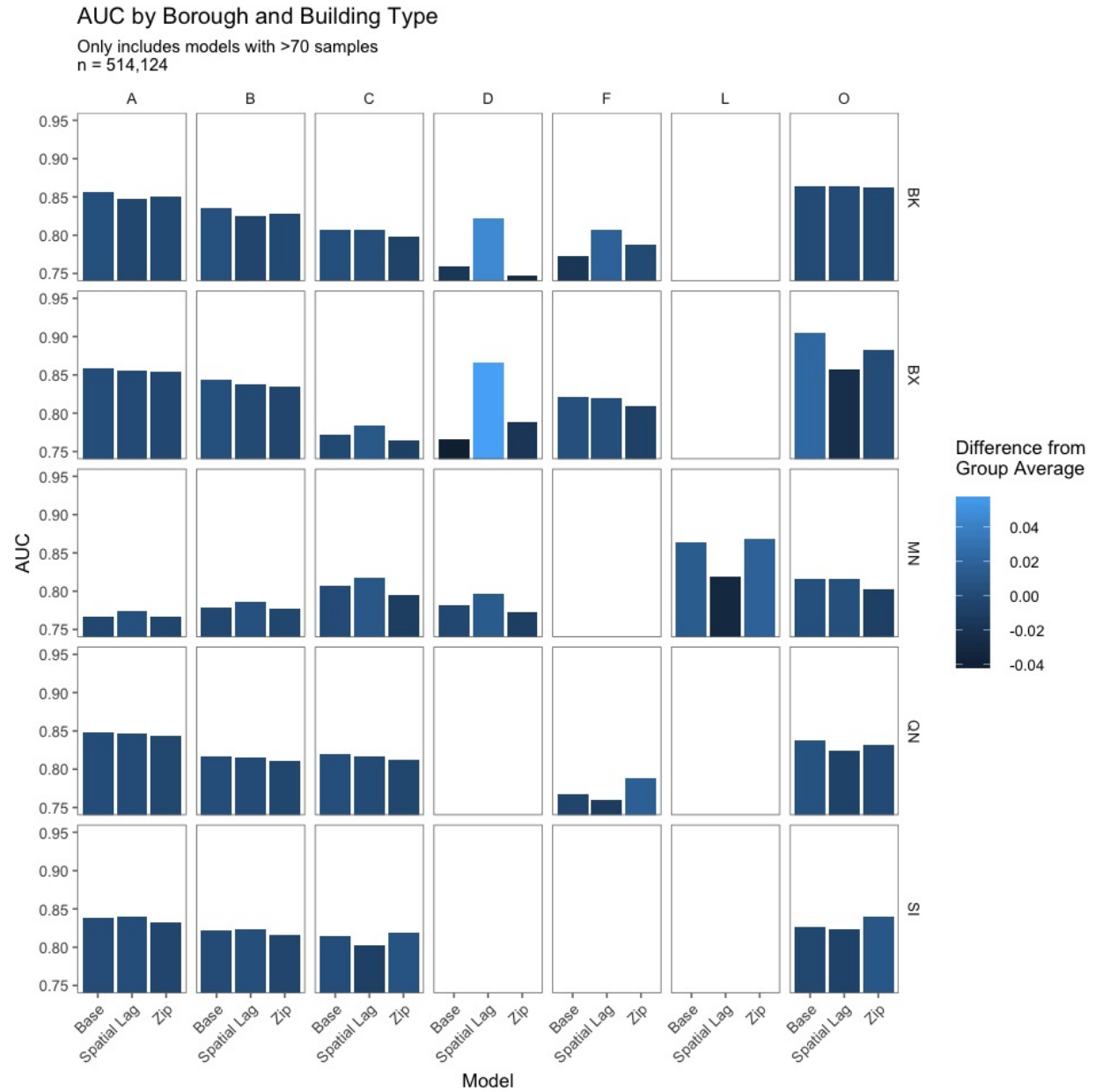


Figure 4.2: AUC By Borough and Building Type