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Patterns of waste generation: A gradient boosting model for short-term waste prediction in New York City

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ABSTRACT

Historical municipal solid waste (MSW) collection data supplied by the New York City Department of Sanitation (DSNY) was used in conjunction with other datasets related to New York City to forecast municipal solid waste generation across the city. Spatiotemporal tonnage data from the DSNY was combined with external data sets, including the Longitudinal Employer Household Dynamics data, the American Community Survey, the New York City Department of Finance's Primary Land Use and Tax Lot Output data, and historical weather data to build a Gradient Boosting Regression Model. The model was trained on historical data from 2005 to 2011 and validation was performed both temporally and spatially. With this model, we are able to accurately ($R2 > 0.88$) forecast weekly MSW generation tonnages for each of the 232 geographic sections in NYC across three waste streams of refuse, paper and metal/glass/plastic. Importantly, the model identifies regularity of urban waste generation and is also able to capture very short timescale fluctuations associated to holidays, special events, seasonal variations, and weather related events. This research shows New York City's waste generation trends and the importance of comprehensive data collection (especially weather patterns) in order to accurately predict waste generation.

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1. Introduction

With the rapid development of urban environments around the world, municipal waste generation is fast becoming one of the most pressing issues facing cities globally. Currently, at 3.3 million tons per day, the global production of waste is already becoming unmanageable, and this rate is expected to grow to 11 million tons per day by 2100 (Hoornweg et al., 2013). Given these trends, effective urban waste management systems are essential, and in order to provide these services in an environmentally sound and financially sustainable way, there is an urgent need for basic understanding of the amount and composition of the materials produced (Beigl et al., 2008; Rimaityte et al., 2012). Furthermore, forecasting waste generation becomes a critical aspect of urban waste management that provides city agencies the ability to optimize collection and disposal operations in the short term, as well as develop long-term strategies for disposal planning, policy development, and implementation of waste reduction programs (Chang and Lin, 1997). The goal of this research is to use historical municipal solid waste (MSW) data supplied by the New York City Department of Sanitation (DSNY) to forecast waste generation across the city.

2. Modeling of waste data

A variety of modeling methodologies have been used to forecast waste generation including the use of group comparison, correlation analysis, multiple regression analysis, input-output analysis, time-series analysis, and system dynamics modeling (Beigl et al., 2008). These models often focus on identifying the underlying relationship between variables that drive waste generation. For example, at the municipal level, Oribe-Garcia et al. (2015) identified urban morphology, tourism activity, level of education, and income as the most influencing factors leading to MSW generation while Daskalopoulos et al. (1998) used single regression analysis to link gross domestic product and related total consumer expenditure as strong correlating factors in waste generation at the country level. Navarro-Esbri et al. (2002) and Rimaityte et al. (2012) used traditional time-series approaches such as Autoregressive and

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Integrated Moving Average (ARIMA) and seasonal Autoregressive and Integrated Moving Average (sARIMA) to predict generation. Xu et al. (2013) disregarded demographic and socioeconomic factors and forecasted waste generation using a hybrid sARIMA model and grey system theory, a methodology to reveal the dynamic relationships in a system using differential equations that is derived from control theory in which the term grey describes the understanding of information in the system (a system is defined as "grey" if the information about the system is only partially known). Other approaches to model waste generation include Zade and Noori (2007) who used artificial neural networks to predict weekly waste generation in Tehran and Abbasi et al. (2012) who used partial least squares for feature selection and support vector machines to predict for the same area.

Our work builds upon these data-centric forecasting approaches in several ways. First, the close collaboration with the DSNY provided detailed information about citywide operations and the specific challenges faced by the agency. The agency's expert knowledge of the city's waste system was important for proper data organization and cleaning processes, including specific information about how source data was generated, as well as provided insight on and confirmation of preliminary analyses. Second, the breadth and depth of the historical data provided by the DSNY is unprecedented in urban waste forecasting studies. Not only is this dataset highly granular both temporally and spatially, it also spans a full ten-years that allows for robust statistical results and thorough model cross-validation. Finally, this research uniquely uses a Gradient Boosting Regression model for forecasting in both time and space for New York City.

3. Waste in NYC

Currently all of NYC's refuse is exported out of the city through a network of contract vendors. These vendors use a combination of long-haul trailer trucks (48%), trains (42%), and direct haul (10%). At present, 80% of the city's solid waste is disposed of in landfills located in New York, Pennsylvania, Ohio, South Carolina, Virginia, and Kentucky, and 20% is disposed of in waste-to-energy facilities in New York, New Jersey, Pennsylvania, and Connecticut. The operational budget for the DSNY in 2012 was $1.6 billion dollars (Kellerman and Gibbs, 2014).

In 2007, NYC Mayor Michael Bloomberg launched PlaNYC that established the goal of diverting 75% of the city's solid waste from landfills by 2030 (Bloomberg, 2006). To achieve this goal, the DSNY established a pilot organic collection program to capture food scraps, yard clippings and soiled paper that serviced 100,000 homes and 40% of NYC schools as well as enhanced drop-off programs for diverting other waste including textiles, e-waste and household hazardous materials. The recycling program was expanded in 2013 as a result of the construction of a new state-of-the art facility which allowed the collection of all rigid plastics for recycling.

In 2015, Mayor de Blasio announced the OneNYC plan that, among other initiatives, sets a citywide goal of 90% reduction of waste disposed in landfills by 2030 (de Blasio, 2015). To achieve this goal, the city aims to expand its organics collection program to the entire city, create a single-stream recycling program to enhance curb-side collection, expand the recycling program to include New York City Housing Authority buildings, reduce the use of non-compostable wastes (plastic bags) and initiate zero waste programs in NYC schools.

3.1. DSNY data

To manage the waste generated by NYC's ~8.4 million inhabitants, DSNY employs over 7000 sanitation workers, servicing 59 community districts. In total, 12,000 tons of residential refuse and recycling is produced in the city each day. The agency's purview includes collection of waste from city residents, public agencies and not-for-profit organizations as well as street cleaning and snow clearing mandates. DSNY collects ~25% of the total waste produced in NYC. The remaining 75% is handled by private haulers and includes commercial/business waste, construction and demolition waste, and industrial waste.

DSNY provides bi-weekly or tri-weekly MSW collection services throughout the city as well as recycling collection once per week. NYC residents are required to separate recyclables into two separate bins, one comprised of metal, glass and plastic (MGP) and the other with mixed cardboard and paper. The city's recycling program began in 1989 though it was suspended for two years from 2002 to 2004.

3.2. Data collection

The waste collection data provided by DSNY spans more than a decade, from July 2003 to January 2015. Each record in this dataset contains the collection information for a single truck. Specifically, each record holds a unique truck ID, the collected tonnage inferred by weighing the truck, the time the truck was weighed, the type of material collected (refuse, metal/glass/plastic, paper), and the geospatial area from which the waste was collected (DSNY uses 232 geographies across NYC's five boroughs that are referred to as sections).

Fig. 1 shows the total weekly collection tonnage integrated across all sections of the city for both refuse and recycling. There are clear temporal patterns at multiple timescales. For example, strong seasonality is apparent with higher waste generation rates during the summer and lower generation rates during the winter. This observation is consistent with previous research (Korhonen and Kaila, 2015; Denafas et al., 2014). A decreasing trend in refuse generation can also be identified: in 2005, the average weekly refuse generation was approximately 60,000 tons, which has slowly declined to 48,000 tons per week in 2014 despite an increasing urban population. This overall decline in waste generation is in part due to the effects of the recession in 2008 as well as reduced product size and packaging (Garcia, 2014). New York City's recycling program initiated in 2004 and has maintained an average recycling rate of 17%.

In January of 2011, a winter storm produced 20 in. of snow resulting in a significant aberration in waste collection, visible by the sharp increase and decrease in tonnage. The snowfall paralyzed the city's means of transportation and left vehicles abandoned roadside reducing DSNY's ability to clear snow. Subsequently, waste collection was delayed across the city. This interruption is visible in the sharp decline in tonnage during the event and an increase in tonnage following the event when DSNY began collecting refuse and recycling that accumulated during snow clearing operations.

Recycling rates vary across DSNY collection sections. Fig. 2 shows the distribution of daily per capita waste generation that highlights a narrow distribution for the refuse stream ranging from 1 lb to 2.5 lb, while the paper and MGP recycling streams show a much larger distribution. Clarke and Maantay (2006) suggest that the variance in recycling rates in New York City are strongly correlated to four variables including percentage of persons below the poverty level, percentage of households headed by a single female with children, percentage of adults without a high school diploma and the percent of minority population.

4. Methods

Figs. 1 and 2 demonstrate that there is tremendous complexity in the data gathered by DSNY, though there are also clear patterns

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