Analysis Framework to Investigate Power-Failure Events and Their Causes

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***Abstract*—**This study aimed to address "How may location analytics enhance our understanding of power outages?" To answer the research question, we developed an analysis framework that the utility industry can use effectively to investigate power-failure events and their causes. Analysis revealed areas where power outage is statistically significant due to multiple causes. The GIS model presented in this study can help advance smart-grid reliability by, for example, elucidating a root cause of power failure, defining a solution for a blackout through data, or implementing a solution with continuous monitoring and management. In this study, we unveil the novel use of location analytics in enhancing understanding of power outages. Future work may involve connecting to virtually any type of streaming data feed and transforming GIS applications into frontline decision applications, showing power-outage incidents as they occur. GIS can be a major resource of assistance for electronic-inspection systems, to lower the duration of customer outages, improve crew response time, and reduce labor and overtime costs.

Keywords*—Location analytics, power-failure, GIS, Smart-grid*

I. INTRODUCTION AND PROBLEM DEFINITION

In a short time, electrical power has become a necessity of modern life. Our work, healthcare, leisure, economy, and livelihood depend on the constant supply of electrical power. Even a temporary power outage can lead to relative chaos, financial setbacks, and possible loss of life. U.S. cities dangle on electricity, and without a constant supply from the power grid, pandemonium would ensue. Power outages can be especially tragic when they endanger life-support systems in hospitals and nursing homes or systems in synchronization facilities such as in airports, train stations, and traffic control. The economic cost of power interruptions to U.S. electricity consumers is $79 billion annually in damages and lost economic activity [1]. In 2017, Lawrence Berkeley National Laboratory provided an update, estimating power-interruption costs have increased more than 68% per year since their 2004 study [2].

Many reasons underlie current power failures. Among these reasons are severe weather, damage to electric transmission lines, shortage of circuits, and the aging of the power-grid infrastructure. Severe weather is the leading cause of power outages in the United States [3]. Last year, weather events as a whole cost U.S. utilities $306 billion: the highest figure ever recorded by the federal government [4].

The aging of the grid infrastructure is another noteworthy reason for power failures. In 2008, the American Society of Civil Engineers gave the U.S. power-grid infrastructure an unsatisfactory grade [5]. They stated in a report that the power-transmission system in the United States required immediate attention. Furthermore, the report mentioned that the U.S. electric-power grid is similar to those of third-world countries. According to the Electric Power Research Institute, equipment such as transformers controlling power transmission need to be replaced, as they have exceeded their expected lifespan considering the materials' original design [6].

Electrical outages have three main causes: (1) hardware and technical failures, (2) environment-related, and (3) human error [7]. Hardware and technical failures are due to equipment overload, short circuits, brownouts, and blackouts, to name a few [8–10]. These failures are often attributed to unmet peak usage, outdated equipment, and malfunctioning back-up power systems. Environment-related causes for power outages comprise weather, wildlife, and trees that come into contact with power lines. Lightning, high winds, and ice are common causes of weather-related power interruptions. Also, squirrels, snakes, and birds that come in contact with equipment such as transformers and fuses can cause equipment to momentarily fail or shut down completely [8]. As for the third main cause for electrical outages, human error, the Uptime Institute estimated that human error causes roughly 70% of the problems that plague data centers. Hacking can be included in the human-error category [11].

Analytics have been a popular topic in research and practice, particularly in the energy field. The use of analytics can help advance Smart Grid reliability through, for example, elucidating a root cause of power failure, defining a solution for a blackout through data, or implementing a solution with continuous monitoring and management. In this research paper, we aim to unveil the novel use of location analytics to investigate power-failure events and their causes. As the objective in this research is to advance smart-grid reliability, this paper specifically explores location analytics to offer a spatially enhanced predictive model for power outages.

II. DATA SELECTION AND METHODOLOGY

The Electric Power Research Institute's (EPRI's) data repository includes the primary datasets we used to conduct this analysis. The data sets include data from advanced metering systems, supervisory control and data acquisition systems, GIS, outage-management systems, distribution management systems, asset-management systems, work-management systems, customer-information systems, and intelligent electronic-device databases. Access to datasets was provided as part of EPRI's data-mining initiative; the initiative provides a test bed for data exploration and innovation and seeks to solve major challenges faced by the utility industry [12].

Georgia Spatial Data Infrastructure and the Georgia GIS Clearinghouse are the data sources for the monthly temperature and precipitation data we employed in this study. As for storm events and storm details, the data source is the National Oceanic and Atmospheric Administration website (NOAA). The link to the NOAA Storm-Events Database is https://www.ncdc.noaa.gov/stormevents/.

The first step of the project methodology was to load data files from EPRI's Data Repository along with weather data to ArcGIS. Using the ArcMap ModelBuilder tool, we designed three models to spatially join the 48 map layers of weather data (from the Georgia Spatial Data Infrastructure and the Georgia GIS Clearinghouse website) with the outage map layer. Data exploration and correlational analysis were conducted in SPSS and GeoDa software. The final step was to run an optimized hot-spot and emerging-hot-spot analysis in ArcGIS.

We developed the following framework (see Figure 1) to guide the investigation and illustrate the various levels of analysis. Based on Level 1 of spatial-analysis Framework 1, we used the ArcGIS Optimized Hot Spot Analysis tool to generate a map of statistically noteworthy hot and cold spots using the Getis-Ord Gi* statistic.[1] Because we did not identify an analysis field, this tool assessed the characteristics of the input feature class (power-outage events) to produce optimal results [13].

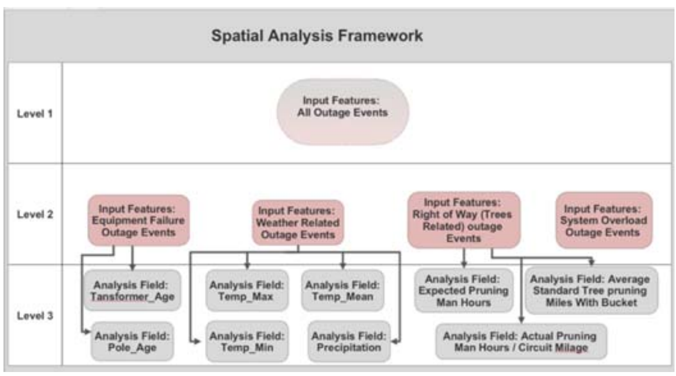

Fig. 1. Spatial-Analysis Framework 1.

In addition, we developed spatial-analysis Framework 2 (see Figure 2) to further illustrate Level 4 of the analysis. In this case, we identified "Transformer Age" for the analysis field, as our intent was to analyze all types of outage events associated with transformer age.

III. Analysis and Results

Figures 3 and 4 were the outcome of the initial power-outage-events data-exploration analyses.

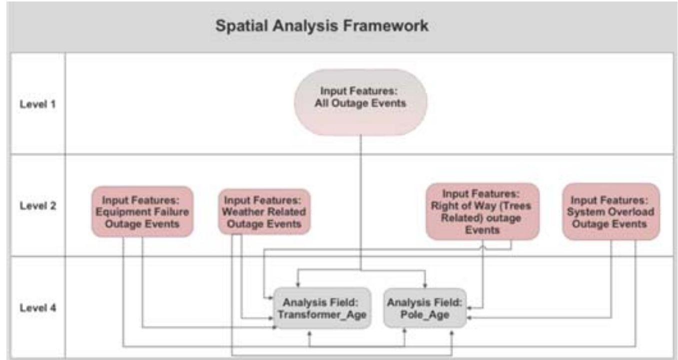

Fig. 2. Spatial-analysis Framework 2.

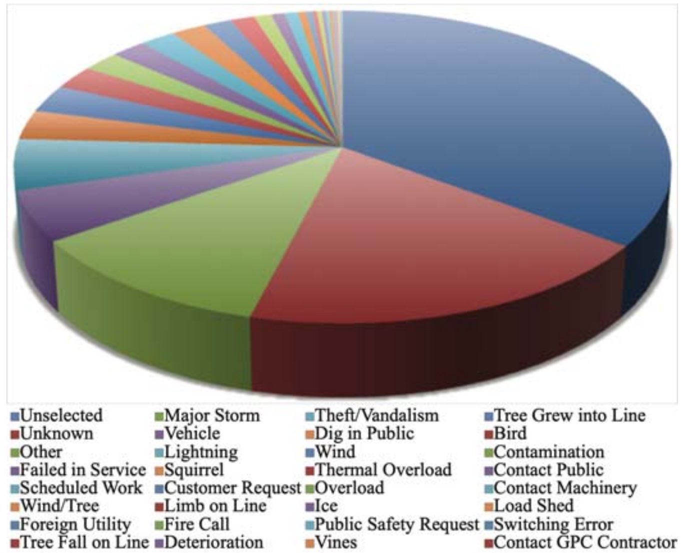

Fig. 3. Reported outage events percent count by cause.

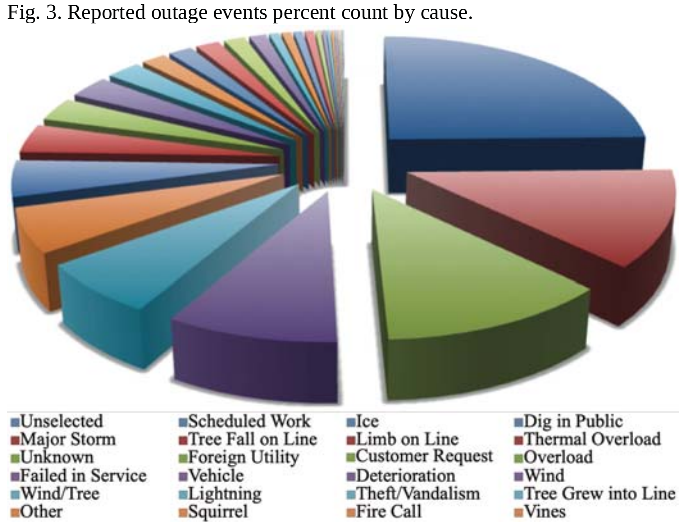

Fig. 4. Reported outage duration by cause.

Results of correlation analysis in SPSS indicated a strong positive correlation between variables, such as storm events and outage-event duration (Table 1). As expected, a storm event, precipitation, older poles, higher forestry expected pruning human hours, and higher levels of transformer age increased outage-event duration. A negative correlation between variables appeared between variables such as forestry management and outage-event customer calls. Amazingly, engaging in forestry management, having older poles, and

[1] The Getis-Ord Gi* statistic returned for each feature in the dataset is a *z*-score. For statistically significant positive *z*-scores, the larger the *z*-score, the more intense the clustering of high values (i.e., a hot spot). For statistically significant negative *z*-scores, the smaller the *z*-score, the more intense the clustering of low values (i.e., a cold spot). The Hot Spot Analysis tool calculates the Getis-Ord Gi* statistic for each feature in a dataset. The resultant *Z* score reveals where features with either high or low values cluster spatially. This tool works by looking at each feature in the context of neighboring features. A feature with a high value is of interest.

having lower levels of actual pruning human hours/circuit mile decreases the number of outage-event customer calls.

Based on ArcGIS average-nearest-neighbor analyses reports, observed mean distance is largest between system-overload outage events (727 meters) compared to weather-related events (171 meters), equipment failure (207 meters), and right-of-way outage events (210 meters). Weather-related outage showed the shortest mean distance between events. A clustered pattern appeared for all four outage-event types. Additionally, based on analysis results, these clustered patterns could be the result of random chance in less than 1%. Figure 5 illustrates the results summary, considering the different input feature used in the analysis.

Analysis results in ArcGIS show that right-of-way (trees-related) outages had the highest number of locations with hot trends (259 total count of locations) compared to weather-related outages (160 locations), equipment-failure outages (129 locations), and system-overloads (27 count of locations with hot trends). Thus, a utility company can use this intelligence to reduce the risk of power outages and plan accordingly.

In this instance, we identified trees/forestry that need pruning to be the leading cause of outages and identified the 259 locations with hot trends. These 259 locations include the 40 consecutive locations with a single uninterrupted run of statistically significant hot spots. The utility company can use this information to reduce the risk of wildfires and keep customers safe. The electric utility would accelerate its vegetation-management work and prioritize tree-pruning fieldwork to address these 40 consecutive locations first. Also, considering the availability of weather forecasts, this analysis can help a utility firm prepare, should it anticipate a storm.

TABLE 1. CORRELATION RESULTS

	1	2	3	4	5	6	7	8	9	10	11	12
2	0.09^{**}	1.00										
3	0.08^{**}	0.01	1.00									
4	-0.13^{**}	0.01	0.14^{**}	1.00								
5	0.08^{**}	0.00	-0.06^{**}	-0.37^{**}	1.00							
6	0.01	-0.02^{**}	-0.01	0.00	-0.03^{**}	1.00						
7	0.01^{**}	0.00	0.00	0.00	-0.02^{**}	0.77^{**}	1.00					
8	0.01^{**}	0.00	0.00	0.00	-0.02^{**}	0.81^{**}	0.96^{**}	1.00				
9	0.01^{**}	0.00	0.00	0.00	-0.02^{**}	0.81^{**}	0.96^{**}	1.00	1.00			
10	0.01^{**}	0.00	0.00	0.00	-0.02^{**}	0.81^{**}	0.96^{**}	1.00^{**}	1.00	1.00		
11	0.01^{*}	-0.01^{**}	-0.01	-0.01^{**}	-0.02^{**}	0.91^{**}	0.85^{**}	0.79^{**}	0.79^{**}	0.79^{**}	1.00	
12	0.01^{*}	0.01^{**}	0.01^{**}	0.00	0.02^{**}	-0.13^{**}	-0.11^{**}	-0.12^{**}	-0.12^{**}	-0.12^{**}	-0.11^{**}	1.00
13	0.02^{**}	-0.01^{**}	0.02^{**}	-0.01^{**}	0.03^{**}	0.02^{**}	0.04^{**}	0.03^{**}	0.03^{**}	0.03^{**}	0.03^{**}	-0.03^{**}

Note. 1. Outage-event duration; 2. Outage-event customer calls; 3. Storm event (1 = yes); 4. Temperature (mean); 5. Precipitation; 6. Forestry management (1 = yes); 7. Forestry expected pruning human hours; 8. Average standard tree-pruning miles with bucket; 9. Average mechanical tree-pruning miles; 10. Average climbing-tree-pruning miles; 11. Actual pruning human hours/circuit mile; 12. Transformer age; 13. Pole age; $^{*}p < .05$; $^{**}p < .01$, two-tailed tests.

Priority should be given to staging equipment and restoration workers at those 160 locations with weather-related hot trends in the event of a storm.

IV. CONCLUSION

This study aimed to address "How may location analytics enhance our understanding of power outages?" To answer the research question, we developed an analysis framework that the utility industry can use effectively to investigate power-failure events and their causes. The GIS model presented in this study can help advance smart-grid reliability by, for example, elucidating a root cause of power failure, defining a solution for a blackout through data, or implementing the solution with continuous monitoring and management. In this study, we unveiled the novel use of location analytics in enhancing understanding of power outages.

One limitation of this research is that we used pole-age data as a proxy for infrastructure age and the rest of equipment data. Future research should include analysis in ArcGIS Pro, which is ESRI'S next-generation desktop GIS product that provides professional 2D and 3D mapping and added tools to advance visualization, analytics, and imaging. Also, ArcGIS GeoEvent Server is another tool to accommodate the multiple streams of data flowing continuously through filters and processing steps one may define. Thus, identifying failures on the network by performing real-time analytics on streams of data can become feasible. Future work may involve connecting to virtually any type of streaming data feed and transforming GIS applications into frontline decision applications, showing power-outage incidents as they occur.

From this research, we conclude that GIS offers a solution to analyze the electric-grid distribution system. Our model provides evidence that GIS can perform the analysis to investigate power-failure events and their causes. If additional funds and data are made available, one can expand on this analysis, build an ArcMap source code, and create a custom solution for the utility industry to control and forecast power outages. GIS can be a major resource of assistance for electronic-inspection systems, to lower the duration of customer outages, improve crew-response time, and reduce labor and overtime costs.

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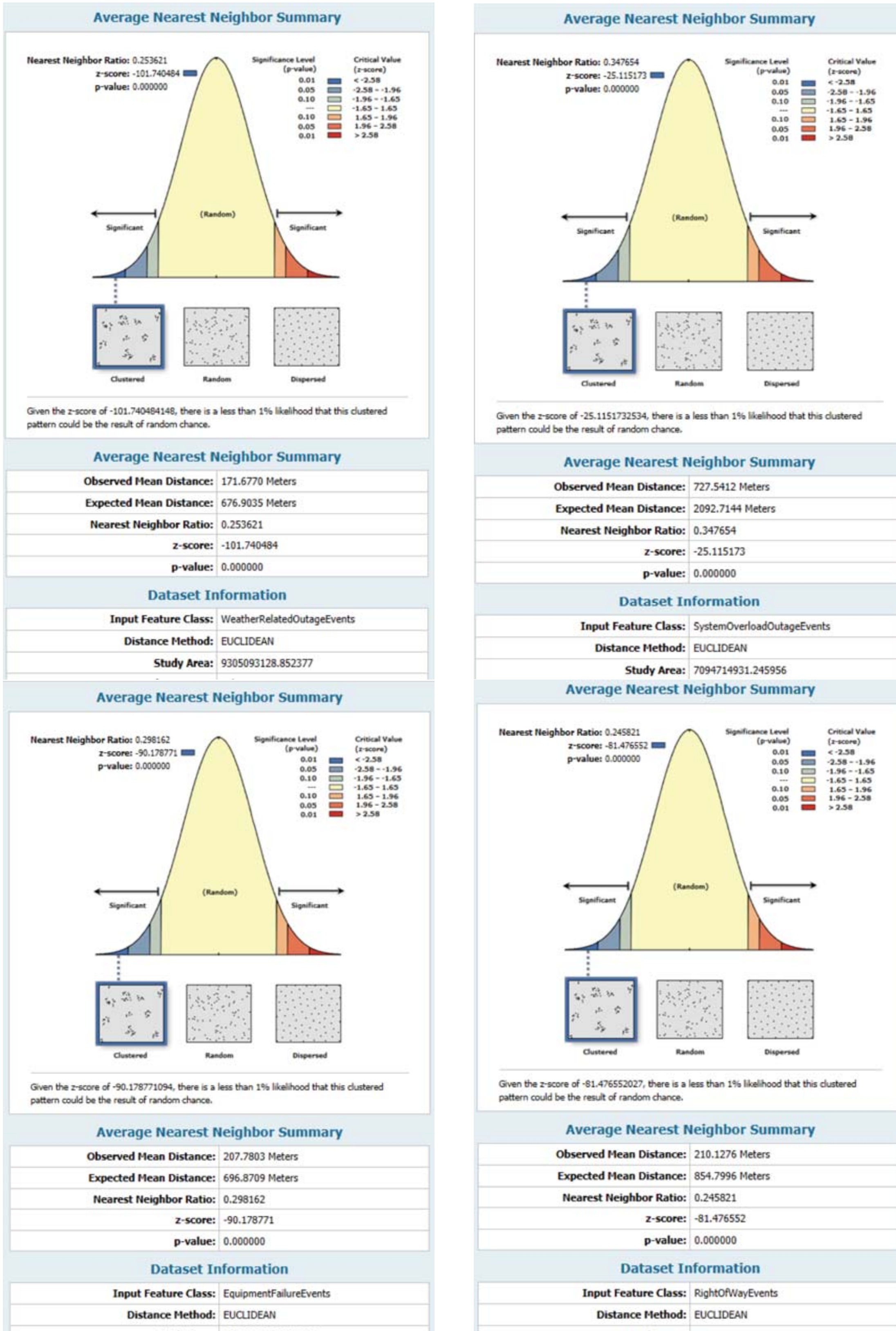

Figure 5. ArcGIS average-nearest-neighbor analyses results.