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RISK ASSESSMENT OF WATER DISTRIBUTION NETWORK FOR CAST IRON PIPES USING STATISTICAL MODELING TECHNIQUE

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Abstract - Water supply network are an integral part of the urban water infrastructure. These systems are capital-intensive in nature. Unfortunately, many water networks are undergoing aging hence deterioration takes place, which undermine their structural integrity. This results in failures of pipe network which need costly emergency repair works. To avoid such occurrences, risk assessment – is advocated as a better strategy to manage water supply system. This type of strategy can be achieved by implementing an infrastructure asset management system, which allows for the efficient operation, maintenance and rehabilitation of the water networks through informed and structured decision-making. In this research paper, 5 years historical data collected from Surat city and multiple regressions and Poisson regression model was developed for cast iron pipes using SPSS statistical software.

Key Words - C.I, IWA, MLR, PI, PRA

I. INTRODUCTION

Pipe bursts are a regular occurrence in water distribution systems. Bursts commonly occur when the residual strength of a deteriorated main becomes inadequate to resist the force imparted on it (1). The pipe bursts are commonly referred to also as breaks or failures and are linked to leaks when losses in water distribution networks are analysed (2). The deterioration of pipes can be classified into two categories (3): (a) structural deterioration, which reduces the pipe's structural resilience and its ability to withstand the various types of stresses imposed upon it; (b) functional deterioration of the pipe resulting in reduced hydraulic capacity and degradation of water quality. The consequence of pipe failures is not only an economic burden (repair and other costs), but it can also have significant social (e.g. service interruptions, traffic delays, etc.) and environmental (e.g. lost water and energy) impacts. A number of research projects have been recently undertaken with the goal of developing a Decision Support System for optimal asset management of water and wastewater systems (4). An integral part of these projects is the selection of Performance Indicators (PIs) and their integration into the decision making process (5). IWA best practice manuals (6) are often taken as a reference point for defining and selecting relevant PIs which are typically derived by modeling hydraulic behaviour and asset performance. Both types of models are based on the analysis of existing water supply data related to physical infrastructure and on the historical records of associated failure events.

II. STATE OF KNOWLEDGE

A survey of literature revealed that several techniques are being used in modeling the structural deterioration of water supply network. These techniques range from physical models to artificial intelligence-based and statistical-based models. These models can further be subdivided into pipe group and pipe-level models(7). An extensive amount of work on pipe rehabilitation and replacement has been published. The various algorithms developed have taken the form of non-linear, dynamic, heuristic and successive linear programming economic models, which assist decision-making based usually on historical statistics and cost information. In an early work Shamir & Howard (8) proposed a model, which estimates the optimal time for pipe replacement based on pipe breakage history and the cost for repairing and replacing pipes. Kettler and Goulter (9) identified a relationship between breakage rate and pipe diameter as well as a correlation between the number of pipe failures and pipe age. They proposed that improvements to pipe breakage or mechanical reliability may be achieved by selecting larger pipe diameters. Woodburn et al (10) presented a model for determining the minimum cost for rehabilitation, replacement or expansion of an existing network based on a combination of non-linear optimization and hydraulic simulation procedures. An explicit algorithm, implementing a graph theory approach, has been developed by (11). The algorithm is capable of handling widespread applications, associated with future planning, expansion and improvement of fluid distribution networks. Arulraj and Rao (12) proposed an optimality criterion called the significance index to rehabilitate existing networks.

Among the different studies carried out on deriving structural deterioration models, a preliminary distinction has to be made between physically based approaches and statistical methods (3). The former aim at describing the physical mechanisms underlying pipe failure and require data that is costly or impossible to obtain. The latter can be applied with variable input data quality and may be useful even when only limited data is available. For water distribution pipes, statistical models provide a cost-effective means of analysis. The water mains deterioration has traditionally been studied as a steady monotonic process affected by time-varying “noise” (3). Time-dependent factors can be random, cyclical (i.e. environmental conditions) or variable (i.e. operational factors), often resulting in a masking effect of the underlying ageing patterns, especially in small datasets. The effectiveness of analyzing these factors depends primarily on the accuracy of forecasting the time related phenomena (e.g. weather conditions) and on the planning horizon adopted (i.e. short-term vs. long-term rehabilitation). The majority of statistical models developed consider pipe age as the most important variable describing the time dependence of pipe breakage. Two important observations made by a number of researchers are: (a) age is not the only governing parameter of pipe breaks (13) and (b) pipes often need to be aggregated into homogeneous groups in order to conduct more effective analysis (8). In addition to age, pipe diameter was identified early on as a key factor affecting pipe failure rates (14). In particular, a strong inverse correlation was found between pipe diameter and failure rate (13). Studies examining metallic pipe behaviour (i.e. cast iron, ductile iron, etc.) have been carried out to establish the influence of pipe material on breakage rates (13). That performed on a real network by (15) revealed that a close dependence exists among pipe material, diameter and the year the pipe was laid.

III. METHODOLOGY

3.1 PRILIMINARY ANALYSIS

In the research, preliminary analysis was done using random dataset collected from south-west zone of Surat city. The purpose of the analysis is to predict the cast iron pipe failure using the Multiple Regression Analysis and Poission Regression Analysis. The Multiplt regression and Poisson regression models were developed for cast iron pipes using IBM SPSS Statistics 19 software and graphs were plotted in minitab software. The table below shows the summery of variables included in the analysis. Univariate analysis of each variable was performed to understand the variable in more detail. In order to perform the multiple regression analysis, the assumption of normality was tested for each variable. To conduct the normality test, probability-probability (P-P) Plot of variable was performed. The

Sr. No	Variable	Type	Measured Scale	
			Minimum	**Maximum**
1	Number of Leakages	Continuous	0	24
2	Diameter – mm	Continuous	75	1500
3	Depth – Meter	Continuous	1	3.50
4	Type of Traffic	Categorical	1	3
5	Pipe Material	Categorical	1	3
6	Age – Year since installed	Continuous	5	31
7	Operational Pressure	Continuous	1.5	3
8	C factor	Continuous	90	150
9	Pipe Thickness – mm	Continuous	6	18
10	Length of Pipe – m	Continuous	28	560

Table 1. Summary of variable used for pipe failure modeling

Probability-probability plot (P-P plot or percent plot) compares an empirical cumulative distribution function of a variable with a specific theoretical cumulative distribution function (e.g., the standard normal distribution function). If two distributions match, the points on the plot will form a linear pattern passing through the origin with a unit slope.

3.1.1 CORRELATION ANALYSIS

The correlation between two variables is a measure of the linear relationship between them. The correlation gives an indication of how well the two variables move together in a straight-line fashion. Two variables are highly correlated if they move well together. Correlation is indicated by the correlation coefficient. The coefficient can take any value in between -1, through 0, to 1. It is found that the number of leakages and other independent variables were having moderate correlations. Highest positive correlation is found between operational pressure and number of leakages (0.33). Pipe Thickness and Log of length are having moderate positive correlation with number of leakages. Majority of the correlation between number of leakages and other independent variables are found significant at 5 percent level of significance. The high degree of positive correlation was found between pipe thickness and diameter of the pipe (0.92). The Multiple regression and Poisson regression model were develop for C.I pipes using data set.

3.2 MULTIPLE LINEAR REGRESSION ANALYSIS

The table below shows the summery of coefficients. It can be seen that majority of the coefficients were found insignificant (Only three variables are significant) at 5 percent level of significance. The model suggests the R square for the regression was 0.418 and ANOVA (F= 17.062) was also significant (0.000) indicating the regression model is valid and the independent variables are explaining 41.8 percent of variance in dependent variable Number of leakages. The Regression equation is written as below.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.646[a]	.418	.393	1.109

Table 2. Model Summary multiple regression

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	188.828	9	20.981	17.062	.000[a]

	Residual	263.154	214	1.230		
	Total	451.982	223			

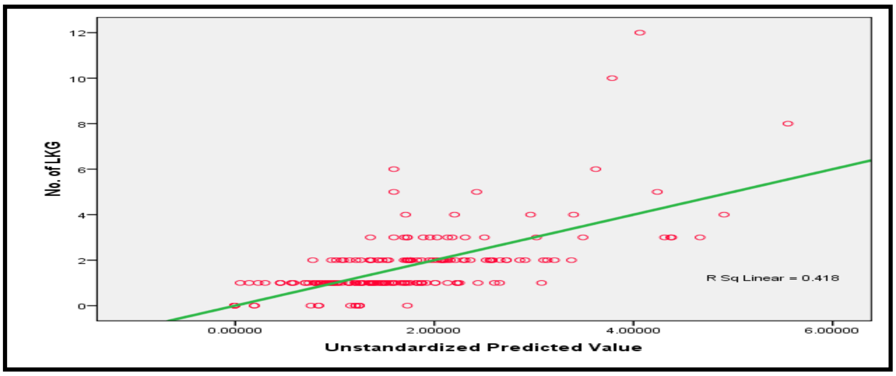
Table 3. Anova for Multiple regression analysis

Number of Leakages = 21.663 - 0.005(Diameter) +0.493 (Depth) – 0.136(Age)+ 2.226 (operational Pressure) – 0.254 (C factor) – 0.373 (Pipe Thickness) + 4.161 (Log Length) -2.436 (Low Traffic) – 1.272 (Medium Traffic) + e

Table 4. Summary table for Multiple regression coefficient

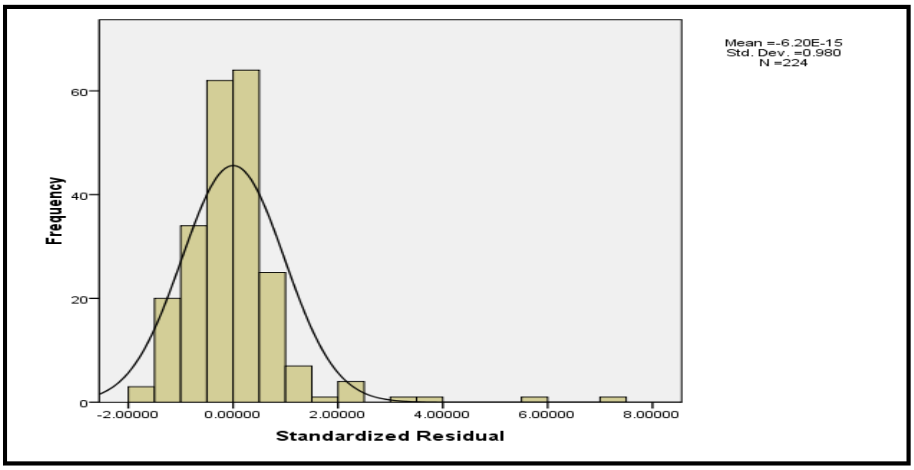
The chart below shows the scatter plot of predicted value and number of leakages. As R square value of 0.418 shows that the model is moderately fit to data and predictability of the model is moderate.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	21.663	33.617		.644	.520
	Diameter	-.005	.003	-.500	-1.827	.069
	Depth (m)	.493	.511	.184	.965	.335
	Age	-.136	.219	-.609	-.622	.535
	Operational pressure	2.226	.520	.502	4.282	**.000**
	C-factor	-.254	.294	-.845	-.862	.390
	Pipe thickness (mm)	-.373	.248	-.309	-1.506	.134
	Low_Traffic	-2.436	1.041	-.558	-2.339	**.020**
	Moderate_Traffic	-1.272	1.023	-.282	-1.243	.215
	Log_Lenght	4.161	.679	.440	6.127	**.000**

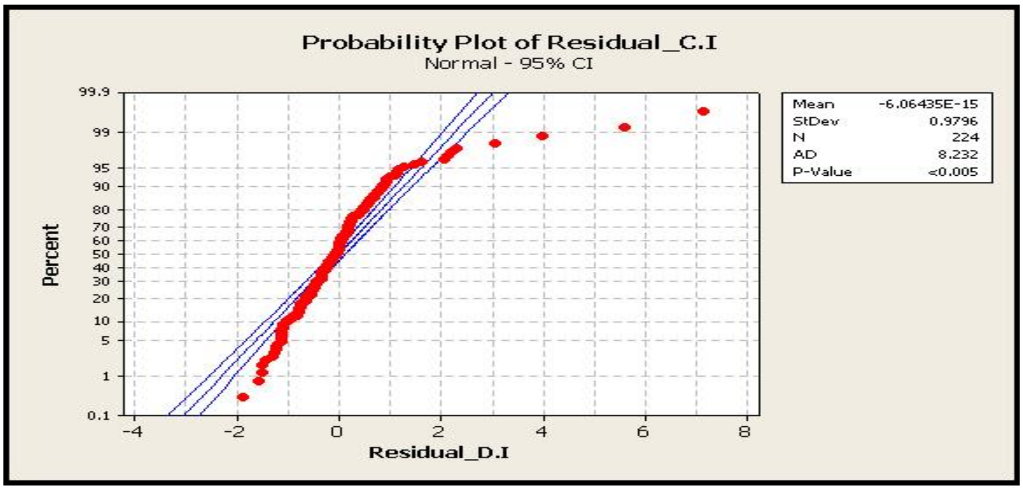


Graph 1. Scatter plot no. of leakage Vs Unstandardized predicted value

3.2.1 CHECKING THE ASSUMPTION OF M.L.R (.RESIDUAL ANALYSIS)



Graph 2. Histogram – Std. Residual

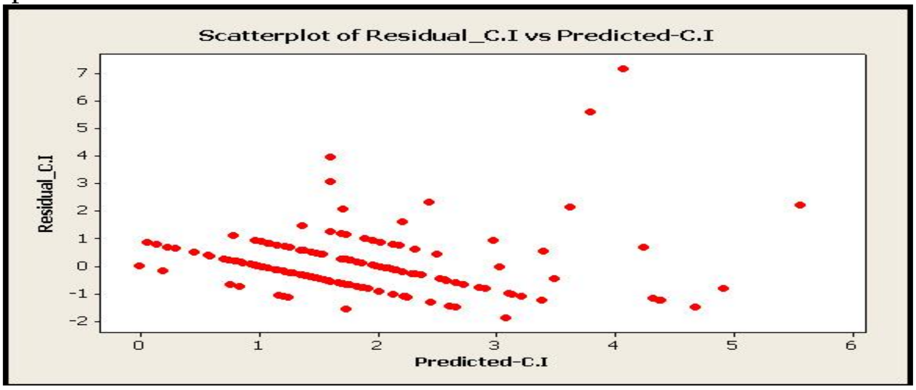


Graph 3. Probability-Probability Plot – Standard Residual

The analysis of regression residuals is an important tool for determining whether the assumptions of the multiple regression model are met. Under the assumptions of the regression model, the population errors *are* normally distributed with mean zero and standard deviation sigma. As a result, the errors divided by their standard deviation should follow the standard normal distribution: The chart below shows the histogram and P-P plot of Standardized Residuals. It can be clearly seen from the graph that the standardized residuals are not normally distributed violating the assumption of Multiple Regression Analysis.

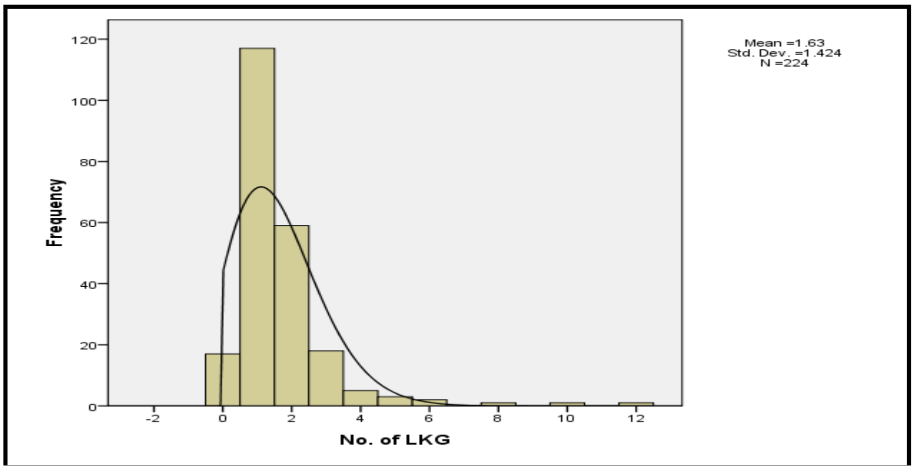
3.2.2 ERROR TERM HAS CONSTANT VARIANCE

The second important assumption of Multiple Regression Analysis is Error term has constant variance for all levels of the predictor variables. To check this assumption, the scatter plot of Predicted value Vs Residuals is shown below. The graph clearly suggests that the error term do not have constant variance. The variance is increases as the number of predicted value increases. After checking the important assumptions of Multiple Regression Analysis, it can be concluded that the model is moderately fit for data. There is violation of assumptions of Multiple Regression Analysis and majority of the independent variables were found insignificant. Hence an alternative approach can be used to predict the number of leakages of C.I Pipe.



Graph 4. Scatter plot – Residual Vs Predicted

3.3 POISSION REGRESSION ANALYSIS



Graph 5. Histogram and fitted curve

The graph above shows the histogram and fitted Poisson curve. The fitted curve indicates that the distribution of number of leakages is more fitted to Poisson distribution as compared to normal distribution.

3.3.1 MODEL FIT

	Value	df	Value/df
Deviance	118.530	214	.554
Scaled Deviance	118.530	214	
Pearson Chi-Square	128.149	214	.599
Scaled Pearson Chi-Square	128.149	214	
Log Likelihood[a]	-303.555		
Akaike's Information Criterion (AIC)	627.109		
Finite Sample Corrected AIC (AICC)	628.142		
Bayesian Information Criterion (BIC)	661.226		
Consistent AIC (CAIC)	671.226		

Table 5. Goodness of fit for Poisson regression analysis

The value of Deviance and Pearson Chi-square of 0.554 and 0.599 suggests under dispersion in data. Generally value below 1 indicates under dispersion and above 1 indicates over dispersion.

Likelihood Ratio Chi-Square	df	Sig.
89.998	9	.000

Table 6. Omnibus test for Poisson regression analysis

The omnibus test suggests that with 9 degree of freedom, the calculated chi- Square value is 89.998. The p-Value of 0.000 suggests that the model is valid.

B - These are the estimated Poisson Regression coefficients for the model. The response variable is a count variable, and Poisson regression models the log of the expected count as a function of the predictor variables.

Exp(B): These are the estimated Exponential Beta Poisson Regression coefficients for the model. Value

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
(Intercept)	32.003	1.7638E1	-2.566	66.572	3.292	1	.070	7.920E13	7.681E-2	8.167E28
[Type of traffic=1]	-1.223	.5501	-2.301	-.145	4.946	1	.026	2.942E-1	1.001E-1	.865
[Type of traffic=2]	-.805	.5350	-1.854	.244	2.264	1	.132	4.471E-1	1.567E-1	1.276
[Type of traffic=3]	0[a]	.	.	.	.	.	.	1	.	.
Diameter	-.002	.0015	-.005	.001	1.561	1	.212	9.981E-1	9.952E-1	1.001
Depth (m)	.318	.2656	-.203	.838	1.430	1	.232	1.374E0	8.163E-1	2.312
Age	-.184	.1159	-.411	.043	2.521	1	.112	8.319E-1	6.628E-1	1.044
Operational pressure	1.032	.2422	.558	1.507	1.817 E1	1	.000	2.808E0	1.747E0	4.513
C factor	-.286	.1555	-.590	.019	3.371	1	.066	7.516E-1	5.541E-1	1.019
Pipe thickness mm	-.269	.1529	-.569	.030	3.106	1	.078	7.638E-1	5.660E-1	1.031
Length of pipe (m)	.008	.0013	.006	.011	3.749 E1	1	.000	1.008E0	1.006E0	1.011
Low_Traffic	0[a]	.	.	.	.	.	.	1	.	.
Moderate_Traffic	0[a]	.	.	.	.	.	.	1	.	.
(Scale)	.554[b]									

Table 7. Parameter Estimates Poisson regression

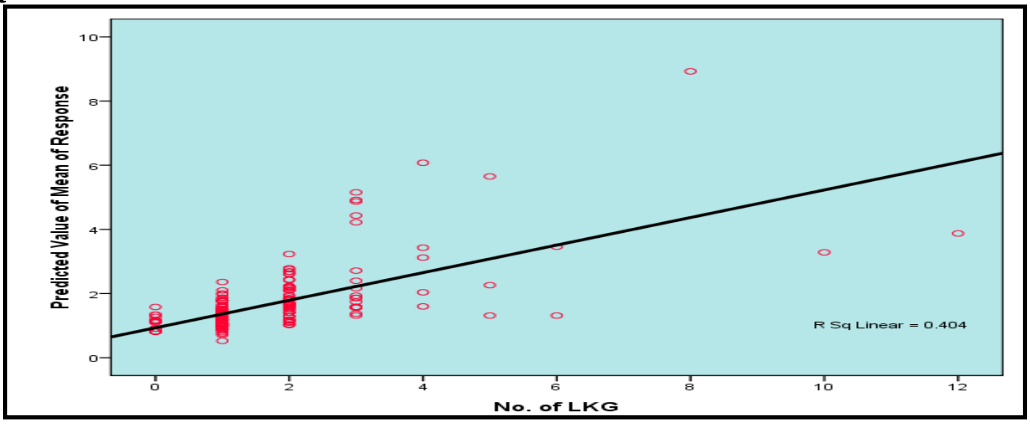
greater than 1 indicates Positive association between dependent variable and independent variable where as value less than 1 indicates negative association between two variables. In the analysis diameter, age, c factor and pipe thickness are negatively associated with number of leakages. Similarly other variables are positively associated with number of leakages.

Source	Type III Wald Chi-Square	df	Sig.
(Intercept)	1.764	1	.184
Typeoftraffic	5.493	2	.064
Diameter	.864	1	.353
Depthm	.792	1	.374
Age	1.396	1	.237
Operationalpressure	10.062	1	.002
Cfactor	1.867	1	.172
Pipethicknessmm	1.720	1	.190
Lengthofpipem	20.767	1	.000

Table 8. Tests of Model Effects Poisson regression

Number of leakages = exp (32.003 ***-0.002 (Diameter) + 0.318(Depth) - 0.184 (Age) + 1.032 (operational Pressure) - 0.286 (C factor) - 0.269 (Pipe Thickness) + 0.008 (Length) -1.223 (Low Traffic) - 0.805 (Medium Traffic) + e)***

3.3.2 ADEQUECY OF MODEL



Graph 6. Scatter plot – no of leakage vs predicted value

IV. CONCLUSION

To check the adequacy of the model, the graph of predicted value against the observed value is plotted . After comparing the R-square value for both the model, the value for Poisson Regression is 0.404 and than in the linear regression Model (R- Square – 0.418). Hence it can be concluded that the both model are giving almost same prediction. So both models provide same type of result while analyzing them material wise.

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