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Exponential Predictive Model of Excavation Damages on a Natural Gas Distribution Network Situated on Metropolitan Regions of São Paulo State – Brazil

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This study develops and demonstrates an exponential equation whose variables, Brazilian industrial quarterly GDP index and the total natural gas pipe length (transmission, distribution and external services) of a Brazilian distribution company, has the ability to predict the Absolut amount of third party excavation damages (annual monthly average value). With the use of the quarterly macroeconomic projection of Brazilian industry GDP and the company expansion scenarios is possible to simulate the amount excavation's damages and establish an adequate dimensioning of actions for the predicted scenario over the natural gas pipes inside metropolitan areas.

1. Introduction

The natural gas is pipe and delivered through an underground network for houses, residential, commerce buildings, industries and gas stations. Others companies of infrastructure uses underground pipes to deliver services as electricity, water, steam, communications, sewage, etc. Boosted by private and public resources that affect the GDP they performing excavations to maintain and expand these network systems. Maintenance actions are recognized as a risk factor (Okoh and Haugen, 2013), excavation damages are recognized together with internal and external corrosion as one of the most frequently causes of cost consequences in natural gas transmission and as the first in distribution pipeline infrastructures (Simonoff et al, 2009). The effects on structural building components due to gas pipelines incidents involving high-pressure transmission in urban areas received recently studies to model and predict their impact (Russo et al, 2014). There are well-identified causes and consequences but for occurrence predictions, only an exploratory study over excavation damages on pipes that identified the existence of cyclical forces that govern damage function (Rodrigues, 2012).

The focus of this study was to verify a correlation between the GDP resources level with the third party damage normalized by the network length (km) and develop a quantitative prediction model not in a time domain but a result of time independent variables.

2. Concession rules and the studied area

The Comgás, CG, was founded in 1872, and is a Brazil's distributor of piped natural gas with over 1 million of customers in residential, commercial and industrial segments over 80 municipalities in the São Paulo and Campinas metropolitan regions, and the regions of Santos and Paraiba Valley, 27% of Brazil's GDP comes from the CG concession area. As the distributing piped gas is a public service, it is subject to standards and requirements stated in the agreement signed with the concession authority, the Regulatory Agency of Sanitation and Energy of the State of São Paulo, ARSESP. (Comgás, 2018).

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3. Incident criteria used on this study

The criteria used in this study to register excavation damages on natural gas networks (pipes of transmission and distribution) are described and compared on Table 1 with the EGIG (European Gas Pipeline Incident Data Group criteria used to capture incidents with unintentional gas release on transmission's pipelines), (EGIG-Database, 2011).

Table 1: EGIG Incidents Criteria and CG Excavation Incidents Criteria.

Criteria	EGIG	CG
Must Lead to an Unintentional Gas Release	Yes	Yes
Not Lead to an Gas Release but need a pipe replacement	No	Yes
Natural Gas Transmission Pipelines	Yes	Yes
Natural Gas Distribution Pipelines	No	Yes
To be Onshore	Yes	Yes
Pipes made on Steel	Yes	Yes
Pipes made on Cast Iron	No	Yes
Pipes made on Polyethylene	No	Yes
To have a Maximum Operating Pressure Higher than 15 bar	Yes	Yes
To have a Maximum Operating Pressure Lower than 15 bar	No	Yes
To be located outside the Fences of Gas Installations	Yes	Yes
Incident Cause 1	Constr. defect /Mat. fail	No
Incident Cause 2	Hot tap made by error	No
Incident Cause 3	Other and unknown	Excavation
Incident Cause 4	Ground movement	No
Incident Cause 5	External Interface	No
Incident Cause 6	Corrosion	No
Primary Failure Frequency per	1.000 km.yr	1.000 km.mo
Moving Average, years	5	1

4. Time Series Data

4.1 Excavation Damages Data, Excavation Damage Index (EDI) and EDI $^{\text{Quarterly}}$

EDI is calculated as a moving average of the last 12 months (one year) of third party excavation damages data, divided by the pipe length in kilometres on the respective month multiplied by 1,000 applied as described on Eq(1), (DPPdb, 2018).

$$Excavation\ Damages\ Index, EDI = \left(\frac{Monthly\ Third\ Party\ Damages\ One\ Year\ moving\ average}{Monthly\ Network\ lengh,km}\right) x\ 1{,}000 \qquad (1)$$

An EDI $^{\text{Quarterly}}$ is calculate as an EDI average issued periodically every three months, described on Table 2.

Table 2: Excavation Damages Index, EDI $^{\text{Quarterly}}$.

Year	Q1	Q2	Q3	Q4
2003	2,211	2,485	2,543	2,557
2004	2,714	2,691	3,121	2,832
2005	2,665	2,576	1,944	1,966
2006	1,843	1,743	1,887	2,017
2007	2,125	2,271	2,338	2,506
2008	2,517	2,368	2,240	1,975
2009	1,941	2,047	2,092	2,313
2010	2,520	2,506	2,720	2,882
2011	2,900	3,227	3,560	3,792
2012	3,973	3,892	3,734	3,439
2013	3,179	3,162	3,069	3,167
2014	3,384	3,554	3,634	3,550
2015	3,220	2,878	2,535	2,319
2016	2,218	2,117	2,049	2,027
2017	2,003	1,997	2,033	1,953

4.2 Brazilian Quarterly GDP (seasonally adjusted data - Industry total) and GDP $^{\text{Industry Quarterly moving average}}$

The Brazilian Industry Quarterly GDP (data seasonally adjusted) represent the industry contribution to the total Brazilian GDP, index formatted (1995=100), (BCB-SGS, 2018). A GDP $^{\text{Industry Quarterly moving average}}$ is calculate as an GDP moving average of the last four quarters (one year) described on Table 3.

Table 3: Brazilian Quarterly GDP $^{\text{Industry Quarterly moving average}}$

Year	Q1	Q2	Q3	Q4
2003	108	108	108	108
2004	110	113	115	117
2005	118	120	120	120
2006	120	120	121	122
2007	123	126	128	130
2008	132	133	136	135
2009	131	129	127	129
2010	133	137	140	142
2011	143	145	147	148
2012	148	147	147	146
2013	146	147	149	150
2014	151	150	148	147
2015	146	144	142	139
2016	136	135	134	133
2017	133	132	132	133

5. Methodology

5.1 Changes identification on studied period, January 2002 until May 2014.

Excavation damages have been registered since 2002, the Damage Prevention Program (DPP) started to be implemented by January 2004 and was consolidated as is today at September 2005. As DPP does have, a direct influence on the excavation damages were discarded all the data before September 2005 for this analysis.

5.2 Correlation Test between EDI $^{\text{Quarterly}}$ and Brazilian Monthly GDP $^{\text{Industry Quarterly moving average}}$

Starting on Q4 2005 until Q4 2017 a correlation test applied between the data on table 2 and table 3 resulted a value of 0.874. The positive sign imply there is a direct dependence and the absolute value greater than 0.80 that there is a high correlation, (Franzblau, 1958).

5.3 Politics and Economic scenarios characterization

There are four Brazilian politics and economics cycles represented by four terms of office whose periods are from (Jan 2003; Dec 2006), (Jan 2007; Dec 2010), (Jan, 20011; Dec 2014), and (Jan 2015: Dec 2018) as in Figure 1.

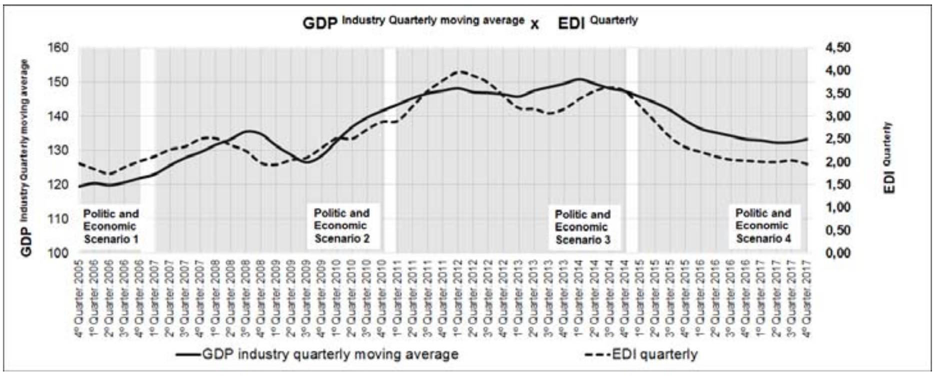


Figure 1: Brazil GDP Industry Quarterly moving average and EDI Quarterly inside Politics and Economics Scenarios.

5.4 Annually Exponential Model and Coefficient of Determination

Organized as an annual average, the data between 2006 until 2017, from Table 2 and Table 3 were listed in a growing GDP $^{\text{industrial annual average}}$'s order and due to the hypothesis of a direct dependence between them (EDI $^{\text{annual average}}$ as an exponential function of GDP $^{\text{industrial annual average}}$).

A natural logarithm applied over the EDI $^{\text{annual average}}$ to use the Tool of Excel's Data Analysis, Linear Regression, as on Table 4 and a linear regression applied as on Figure 2.

Table 4: GDP $^{\text{industrial annual average}}$, EDI $^{\text{annual average}}$ and ln (EDI $^{\text{annual average}}$), modelling table

Year	GDP $^{\text{industrial annual average}}$	EDI $^{\text{annual average}}$	ln(EDI $^{\text{annual average}}$)
2006	121	1,872	0,627
2007	127	2,310	0,837
2009	129	2,098	0,741
2017	133	1,997	0,691
2008	134	2,275	0,822
2016	135	2,103	0,743
2010	138	2,657	0,977
2015	143	2,738	1,007
2011	146	3,370	1,215
2012	147	3,759	1,324
2013	148	3,144	1,146
2014	149	3,530	1,261

As showed on Figure 2, an R Square of 0.83518 indicates that the model described by Eq (2), explains 84% of the variability of the ln (EDI $^{\text{annual average}}$) as response from GDP $^{\text{industrial annual average}}$ data around its mean value.

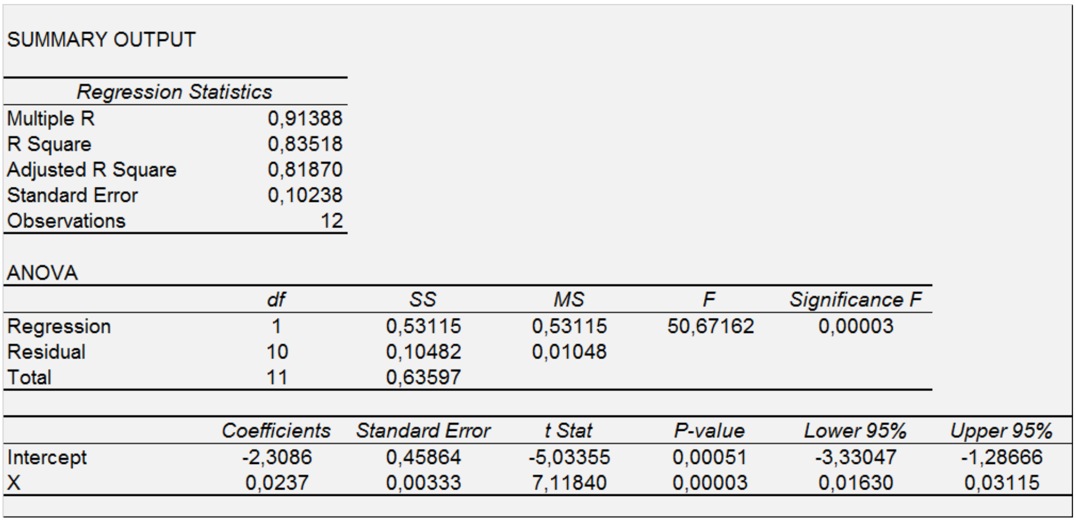
$$\ln(EDI \text{ annual average }) = -2.3086 + 0.0237\ x\ (GDP \text{ industrial annual average}) \tag{2}$$

Applying the e, on both sides of Eq (2)

$$EDI\ \text{ annual average} = \ e^{-2.3086}\ x\ e^{0.0237\ x\ GDP \text{ industrial annual average}} \tag{3}$$

Eq (4) represents the model, where EDI $^{\text{annual average}}$ is an Exponential function of GDP $^{\text{industrial annual average}}$ with 84% of R-Squared.

$$EDI \text{ annual average} = \ 0.0994\ x\ e^{0.0237\ x\ GDP \text{ industrial annual average}} \tag{4}$$



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,91388
R Square	0,83518
Adjusted R Square	0,81870
Standard Error	0,10238
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0,53115	0,53115	50,67162	0,00003
Residual	10	0,10482	0,01048		
Total	11	0,63597			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-2,3086	0,45864	-5,03355	0,00051	-3,33047	-1,28666
X	0,0237	0,00333	7,11840	0,00003	0,01630	0,03115

Figure 2: Regression data analysis for GDP $^{\text{industrial annual average}}$ vs. ln (EDI $^{\text{annual average}}$) from Table 4.

5.5 Model characteristics

Annually exponential model does have P-values smaller than (0.01), Figure 2, that can be interpreted of strength rejection the null hypothesis (H0) (University Of Alberta, 2016) and R Square that explains 84% of the variability of the ln (EDI $^{\text{annual average}}$) as response from GDP $^{\text{industrial annual average}}$ data around its mean value.

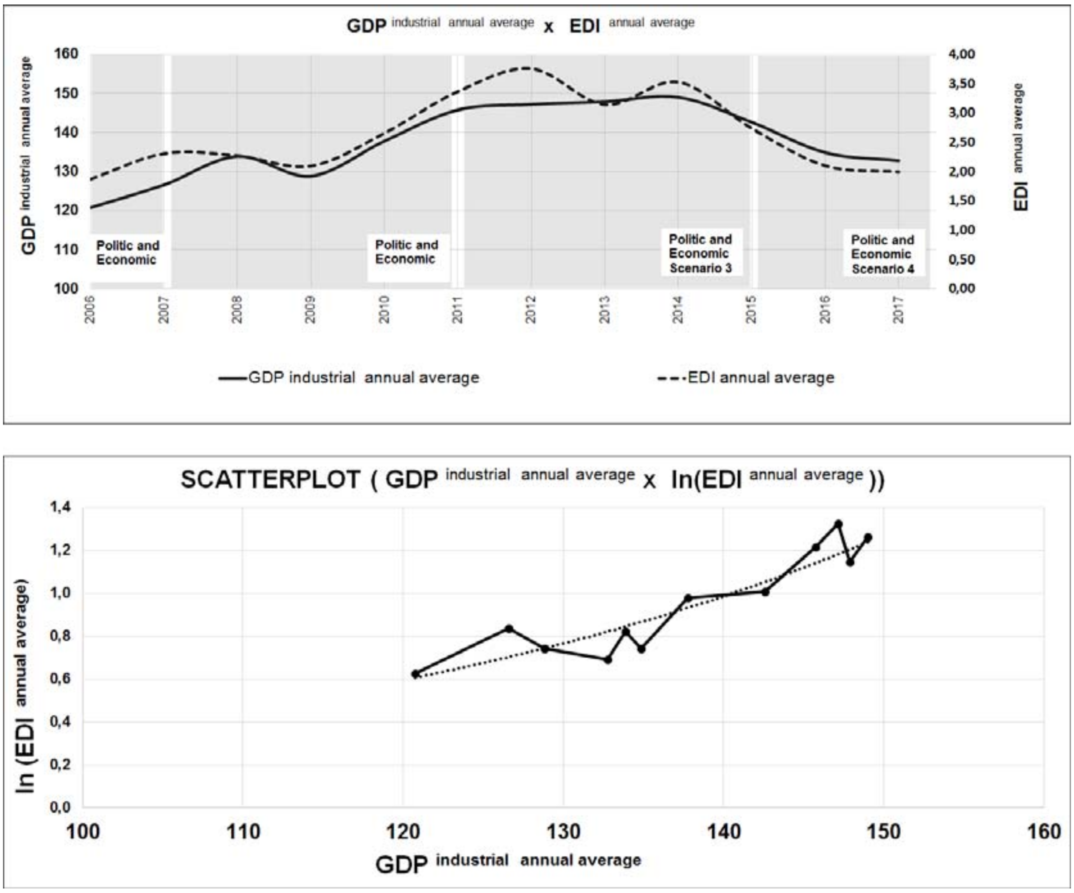


Figure 3: Annually Time Series and Scatterplot for GDP $^{\text{industrial annual average}}$ and ln (EDI $^{\text{annual average}}$).

Table 5: GDP $^{\text{industrial annual average}}$ vs. EDI $^{\text{annual average}}$, modelling table

Year	GDP $^{\text{industrial annual average}}$	EDI $^{\text{annual average}}$	EDI $^{\text{annual average}}$, model	Error$^{\wedge 2}$
2006	121	1,872	1,745	0,016
2007	127	2,310	2,003	0,094
2009	129	2,098	2,113	0,000
2017	133	1,997	2,320	0,105
2008	134	2,275	2,381	0,011
2016	135	2,103	2,437	0,111
2010	138	2,657	2,612	0,002
2015	143	2,738	2,929	0,036
2011	146	3,370	3,157	0,045
2012	147	3,759	3,264	0,245
2013	148	3,144	3,319	0,031
2014	149	3,530	3,409	0,015

5.6 Absolut third party damage (annual monthly average)

Multiplying on Eq (4) by the network length in kilometers, resulting in Eq (5).

$$\text{ABSOLUT Third Party Damage (annual monthly average)} \quad = ((Network\ Lenght, km)\ x\ (0.0994\ x\ e^{0.0237\ x\ GDP\ \text{industrial annual average}}))/1{,}000 \quad (5)$$

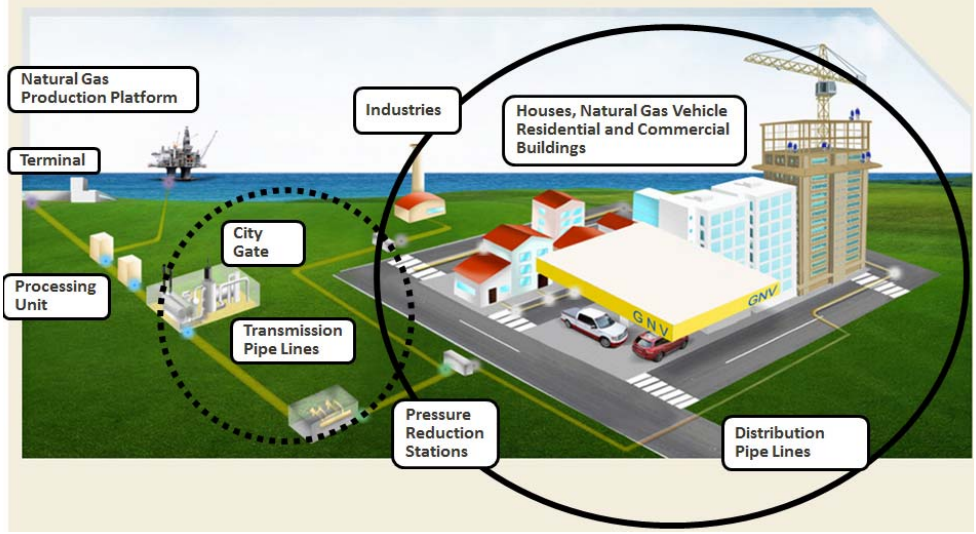


Figure 4: Area covered by the model, inside dashed and continuous lines (Figure adapted from CG, 2018).

6. Conclusions

The Classification's criteria of damages used on this study are able to capture a large variety of incidents in transmission and distribution network. This is possible due to the data utilized consider network's incidents with the full range of pressure, incidents with gas release, incidents with pipe replacement with or without gas release and incidents over three types of pipe material (cast iron, steel and polyethylene).

A positive correlation of 0.874 between the EDI $^{\text{Quarterly}}$ and the GDP $^{\text{Industry moving average}}$ indicate a high direct dependence of them. An exponential function with 84% of R-Squared indicates that the model described by Eq (5), explains 84% of the variability of the EDI $^{\text{annual average}}$ as response from of GDP $^{\text{industrial annual average}}$ data around its mean value. So using the Brazilian GDP $^{\text{industrial annual average}}$ macroeconomic projection and the company expansion scenarios, in kilometers of natural gas pipe, is possible to simulate the absolute number of third party excavation damages (annual monthly average) and establish an adequate dimensioning of actions for the predicted scenario.

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