Gas Distribution Businesses Opex Cost Function

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Multinet Gas

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EXECUTIVE SUMMARY

This report documents an econometric analysis of gas network real operating costs ('opex') as a function of outputs, fixed capital inputs and business environment factors. This econometric analysis is used to:

- test the hypothesis that line length is a significant determinant of opex; and
- quantify the elasticities of real opex with respect to each of the outputs and compare the magnitudes of the elasticities.

The study was undertaken at the request of Multinet Gas in relation to its Access Arrangement proposal for the period 2018 to 2022.

The study uses a database that includes 11 Australian and 3 New Zealand gas distribution businesses (GDBs). The data has two main sources. For 5 Australian GDBs the data was provided by the businesses in response to surveys prepared by Economic Insights. Data for the other GDBs in the sample was sourced from documents in the public domain. The sample periods differ between utilities, but in most cases includes historical data for the period from 1999 to 2015. The database includes a total of 234 observations. This sample is substantially larger than that available for previous econometric studies of the gas industry undertaken by Economic Insights.

The methodology for developing the econometric real opex cost function is to begin with a flexible functional form, the translog variable cost function, initially with three outputs (customer numbers, gas throughput and network length) and five other exogenous variables, and then undertake a specification search to derive a more parsimonious model. A number of different stochastic specifications are tested. The two main conclusions from the specification search are:

- A model with no second-order effects (ie, interactions and higher powers of the exogenous variables) is found to be preferable to any of the alternatives that include second-order effects.
- The random effects (RE) and stochastic frontier (SF) models are the only stochastic specifications found to be satisfactory.

For the purpose of making inferences about the significance of outputs as determinants of real opex, it is not essential to choose between the RE and SF models. Both are useful methods of estimating the real opex cost function of gas networks. The RE specification was used by Economic Insights to estimate the cost function for domestic telecommunications transmission capacity services (DTCS) on behalf of the Australian Competition and Consumer Commission (ACCC) for the purposes of its DTCS final access determination (Economic Insights 2015a). The SF specification method is widely used in cost function estimation, and was one of the two methods used by Economic Insights for the estimation of the gas network opex cost function in previous work for Jemena Gas Networks (Economic Insights 2014, 2015b).

The conclusions of this study in regard to the significance of outputs are as follows:

- gas throughput is not a statistically significant determinant of real opex;
- network length is a statistically significant determinant of real opex; and
- customer numbers are a statistically significant determinant of real opex.

The estimated elasticity of real opex with respect to customer numbers is 0.16 (RE) to 0.24 (SF), and the estimated elasticity with respect to network length is 0.41 (RE) to 0.43 (SF).

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1 INTRODUCTION

This report documents an econometric analysis of gas network real operating costs ('opex') as a function of outputs, fixed capital inputs and business environment factors. The study was undertaken at the request of Multinet Gas to assist in relation to its Access Arrangement proposal for the period 2018 to 2022. Its principal aims are to test whether network length should be regarded as an output of gas distribution businesses (GDBs), and hence a significant determinant of real opex, and to quantify the elasticities of real opex with respect to each of the outputs.

1.1 Scope

The scope of the study is to undertake econometric estimation of the opex cost function for natural gas distribution networks, including network length, customer numbers and gas throughput as outputs, and use that model to:

- test the hypothesis that line length is a significant determinant of opex; and
- quantify the elasticities of real opex with respect to each of the outputs and compare the magnitudes of the elasticities.

1.2 Previous relevant studies

This section briefly discusses relevant literature on the econometric estimation of cost functions for gas distribution businesses, particularly in Australia and New Zealand.

Cost function analysis of gas network businesses has a long history. In the United States, Barcella (1992) estimated the cost function of gas distribution businesses based on a sample of 50 companies over the period 1969-1988 using a translog specification. In the context of Australia and New Zealand, Pacific Economics Group (2001b, 2001a, 2001c) evaluated the opex performance of the three Victorian GDBs relative to that of US gas distribution utilities by estimating an econometric cost function model that explained the effect on a company's gas distribution cost of some measurable 'business conditions'. The parameters of the model were estimated by established statistical methods using data from a large sample of American investor–owned gas distribution utilities. The model was used to predict opex for the Australian utilities given the values for the (included) business conditions that the utilities faced. The business condition variables included input prices, the amount of outputs supplied and certain characteristics of the customer base and service territory. The model therefore controlled, among other things, for differences in realised scale economies. Cost performance was evaluated by comparing the Australian utilities' actual opex with those predicted by the model for an average US utility facing similar business conditions.

Economic Insights (2012) used econometric analysis of the total cost function for gas distribution businesses to assess the comparative efficiency of SP AusNet. This analysis was based on a sample of 9 Australian GDBs and 2 New Zealand GDBs using data sourced from the public domain to the maximum extent possible. Total cost function analysis takes into account opex and capital input trade–offs, price effects and controls for certain operating environment factors in the analysis of comparative cost efficiency. The study also developed econometric estimates of the variable or operating cost function and the parameters of this function were combined with forecasts of output and capital input levels to forecast SP AusNet's future GDB opex partial productivity growth rates. Such forecasts are used in the 'rate of change' formula for rolling forward opex allowances often used in the application of building blocks regulation (see ESC, 2008, pp. 224-250; AER, 2012, Appendix C).

Economic Insights (2014, 2015b) estimated an econometric variable cost function for Australian and New Zealand gas networks on behalf of Jemena Gas Networks. The econometric analysis utilised both stochastic frontier and feasible generalized least squares methods, and the models were used for both efficiency benchmarking and forecasting opex partial productivity. The two outputs used in that study were customer numbers and gas throughput. Customer density was also an important explanatory variable, measured by customer numbers per kilometre (km) of mains. Real opex was found to be negatively related to customer density, which implies a positive relationship between network length and real opex.

1.3 Approach

The analysis presented in this report is, broadly speaking, similar to that previously undertaken by Economic Insights, since it is based on the translog variable cost function specification. However, the specification search does not begin with simplified specifications previously developed. It begins with the full translog variable cost function and examines several methods of simplifying the model into a more parsimonious form. Alternative stochastic specifications are then tested.

To ensure comparability with earlier studies and to ensure that the sample is as large and broad as possible, this econometric study uses a database that includes 11 Australian and 3 New Zealand gas distribution businesses (GDBs). The data has two main sources. For 5 Australian GDBs the data was provided by the businesses in response to surveys prepared by Economic Insights. These GDBs include Australian Gas Networks (AGN) South Australia (SA), AGN Victoria, Jemena, Multinet and AusNet Services. Data for the other GDBs in the sample was sourced from documents in the public domain. The sample periods differ between utilities, but in most cases includes historical data for the period from 1999 to 2015. In a relatively small number of cases, forecast data from final regulatory determinations are also included, primarily because several of the smaller GDBs in the sample are no longer subject to price regulation, and up-to-date statistical information is no longer available for them. The data includes revenue, throughput, customer numbers, distribution pipeline length, opex, capex and regulatory asset value. In some cases missing observations were estimated based on growth rates for the variable or a related variable before and after the missing year. The database includes a total of 234 observations. This sample is substantially larger than that available for previous econometric studies of the gas industry undertaken by Economic Insights.

1.4 Outline of the report

Chapter 2 of this report documents the dataset, including the GDBs, time periods and variables used in the study, and it explains the econometric methodologies, including the specification of the variable cost function, the alternative stochastic specifications, and the methods, criteria and tests used for model selection.

Chapter 3 presents the results of the analysis of the real opex cost function of Australasian GDBs. It summarises the results of 'stage 1' of the analysis, fully documented in Appendix A, in which a 'general-to-specific' approach is used to derive a parsimonious econometric model. It then presents the results of 'stage 2' of the analysis which, using the parsimonious model, tests alternative stochastic specifications and some further simplifications. Tests are used to address the central questions of this study.

Lastly, chapter 4 summarises the main conclusions of this study.

2 METHODOLOGY & DATA

This section describes the data and the economic and econometric methodologies used in the study. Section 2.1 describes the data sources and the variables used. Section 2.2 describes the functional form used for the variable cost function, and alternative stochastic specifications. Section 2.3 discusses the strategy selecting a preferred parsimonious model.

2.1 Data

2.1.1 Sources

The analysis make use of the Economic Insights dataset for Australian and New Zealand gas distribution businesses, which includes the following gas distribution businesses (GDBs):

- in Australia: AGN Albury, AGN Vic, Multinet, AusNet, AGN SA, AGN Qld, Allgas, AGN Wagga, Jemena, ActewAGL, ATCO; and
- in New Zealand: Powerco, Vector and GasNet.

All of these GDBs are included in the sample in this study.[1] The data represents yearly observations, and details of the sample are shown in Table 2.1. GDBs differ in whether their reporting years end in June or December, or in some cases, March or September. Some have changed their reporting years during the period studied. Overall, there are 234 observations, or approximately 17 observations per GDB on average. Data for most of the Australian GDBs in the study are publicly available for the period 1999 to 2015. However, there are fewer consistent observations publicly available for the New Zealand GDBs, reflecting the impact of mergers, asset sales and industry restructuring. Some of the smallest Australian GDBs are no longer subject to price regulation, and the data for these GDBs supplemented by forecasts.

The data for AGN Vic, AusNet, AGN SA, Jemena and Multinet Gas are drawn from confidential survey data provided by those businesses for the purposes of productivity analysis. Two years of survey data is used for AGN Qld also. All of the remaining data has been sourced from public documents such as regulator final decisions, Assess Arrangement Information, asset management plans, statutory information disclosure and/or company Annual Reports. The public domain data source used for the New Zealand GDBs is the Information Disclosure Data filings required by the Gas (Information Disclosure) Regulations 1997. For Australian GDBs, we have used the final approval information, where possible, as we consider that it is the most consistent and objective source of information available. In some cases the data represents official forecasts made by regulators. As detailed in Table 2.1, these represent only a small proportion of the observations.

The data used for the Australian GDBs covers only the regulated activities. Data relating to large industrial users whose supply is not regulated are not included. Inclusion of this data would require access to information not generally in the public domain and has been beyond the scope and timeframe of this study.

[1] In previous studies some of the smaller GDBs (particularly GasNet and AGN Wagga) were excluded for econometric analysis, due to their small size.

Table 2.1: **Summary of data sample**

GDB	*Actuals*	*Forecasts*	*Notes*	*# obs*
AGN Albury	1999–2012	2013-2017		19
AGN Vic	1998–2015	.		18
Multinet	1998–2015	.		18
AusNet	1998–2015	.		18
AGN SA	1998/99–2014/15	.		17
AGN Qld	1998/99–2010/11	2011/12–2015/16		18
Allgas	1999/00–2010/11	2011/12–2015/16		17
AGN Wagga	1999–2009/10	2010/11–2014/15	Calendar years to 2005. Six months to June 2006 annualised. Financial years thereafter.	17
Jemena	1998/99–2013/14	.		16
ActewAGL	1998/99–2014/15	2015/16		18
ATCO	2000–2013/14	2014–2015	Calendar years to 2009. Six months to June 2010 annualised. Financial years to 2013/14. Six months to Dec 2014 annualised. Calendar years thereafter. One additional observation generated by annualisation.	17
Powerco (NZ)	2003/04–2014/15	.	Years ending March to 2012. Years ending September thereafter. One additional observation generated by annualising 6 months ended Sep 2012.	13
Vector (NZ)	2004/05–2014/15	.		11
GasNet (NZ)	1998/99–2014/15	.		17

All cost data were first converted to nominal terms (where necessary) using the All Groups Consumer Price Index in Australia and the equivalent in New Zealand. The nominal series were then converted to real series in (calendar year) 2010 dollars using the same price indexes. The New Zealand data were then converted to Australian dollars using the OECD (2014) purchasing power parity for 2010. Purchasing power parities are the rates of currency conversion that eliminate differences in international price levels and are commonly used to make comparisons of real variables between countries.

2.1.2 Variables

The following variables are used in the analysis:

- Dependent variable: Constant price opex (in 2010$)
- Outputs:
  - Customer numbers
  - Gas throughput (TJ)
  - Network length (km)
- Fixed inputs:
  - Capital services (measured by constant price asset value) (in 2010$)
- Technological change
  - Time trend variable (the quarter in which each yearly observation ends, where quarters are measured as sequential integers with 2014:q2 = 0)
- Operating environment factors:
  - Load factor (average TJ per day / maximum daily demand)
  - Proportion of total mains length not made of cast iron or unprotected steel (proxy for network age)
  - Number of city gates (proxy for service area dispersion)
  - Tariff customer-class gas volumes / total gas volumes.

Data for the outputs and inputs are reasonably complete in the dataset, although in some instances missing observations were estimated based on growth rates for the variable or a related variable before and after the missing year. In a number of cases adjustments were made to ensure the data related to comparable activities and measures (eg, unaccounted for gas allowances for non–Victorian GDBs have been excluded to put those GDBs on a comparable basis with Victorian reporting). Data coverage of some of the business environment variables is less complete — especially with regard to load factors for Victorian GDBs. Interpolation or extrapolation are used where necessary.

While every effort has been made to make the publicly available data used in this study as consistent as possible, the limitations of currently available public domain data need to be recognised. These include somewhat different coverage of activities and definitions of variables reported both across jurisdictions and over time as regulators have changed reporting requirements.

2.2 Model specification

The ultimate functional specification of the preferred model(s) is derived through a specification search. The methods and criteria used in the search are discussed in section 2.3. This section discusses the initial functional specification and the alternative stochastic specifications.

2.2.1 Variable cost function

The functional specification is initially based on the translog variable cost function, in which the variables are in log form. The exogenous variables enter the model directly (hereafter 'primary variables') as well as through interaction and higher-order terms (together 'second-order effects'). The translog variable cost (VC) function has the following form (in full):

(1) $$\ln VC = a_0 + c_1 \ln K + \sum_h a_h \ln N_h + \sum_j \theta_j \ln Y_j + \sum_l b_l \ln P_l + c_2 (\ln K)^2$$

$$+\frac{1}{2}\sum_h \sum_i a_{hi} \ln N_h \ln N_i + \frac{1}{2}\sum_j \sum_k \theta_{jk} \ln Y_j \ln Y_k + \frac{1}{2}\sum_l \sum_m b_{lm} \ln P_l \ln P_m$$

$$+\sum_l \sum_j d_{lj} \ln P_l \ln Y_j + \sum_l \sum_h e_{lh} \ln P_l \ln N_h + \sum_j \sum_h f_{jh} \ln Y_j \ln N_h$$

$$+\sum_h g_{Nh} \ln N_h \ln K + \sum_j g_{Yj} \ln Y_j \ln K + \sum_l g_{Pi} \ln P_l \ln K + a_t t + \varpi$$

where:

- Y_j and Y_k are the quantities of outputs j and k; where $j,k = 1, 2, \dots J$;
- P_l and P_m are the prices of variable inputs l and m where $l,m = 1, 2, \dots L$;
- N_h and N_i are operating environment factors h and i; where $h,i = 1, 2, \dots H$;
- K is a service flow measure of fixed capital;[2]
- t is a measure of time and reflects the principle that, all else unchanged, costs decrease marginally each year due to technical change; and
- ϖ is a stochastic term that reflects the combined influence of all other influences on variable cost.

Regularity conditions derived from economic theory can be imposed on this function, which can greatly reduce the number of parameters that need to be estimated. These restrictions include: symmetry of certain parameters of interaction terms ($\theta_{jk} = \theta_{kj}$, $b_{lm} = b_{ml}$) and linear homogeneity in input prices.

In this application there are only two inputs, capital and real opex, and capital inputs are fixed. There is only one input price to consider, namely the deflator of opex, P. Linear homogeneity in input prices implies that equation (1) can be simplified as follows:

(2) $$\ln(VC/P) = a_0 + c_1 \ln K + \sum_h a_h \ln N_h + \sum_j \theta_j \ln Y_j + c_2 (\ln K)^2$$

$$+\frac{1}{2}\sum_h \sum_i a_{hi} \ln N_h \ln N_i + \frac{1}{2}\sum_j \sum_k \theta_{jk} \ln Y_j \ln Y_k + \sum_j \sum_h f_{jh} \ln Y_j \ln N_h$$

[2] This refers to the annual capital input quantity. Due to its durable nature, capital has two distinct economic characteristics, as a source of capital services in production and as a store of wealth. Measures of these characteristics will often be different, and the appropriate measure depends on the analytical context. Wealth measures of capital are more commonly available, and in some circumstances may be used as a proxy measure of capital services (as is the case in this study).

$$+\sum_h g_{Nh}\ln N_h \ln K + \sum_j g_{Yj}\ln Y_j \ln K + a_t t + \varpi$$

By reason of all of the interaction and higher-order terms, if there are *N* original exogenous variables, including the outputs, fixed capital and business environment variables, there will be ((*N*+1)/2 + 1)*N* + 2 coefficients to be estimated including the constant and the time-trend coefficient. For example, 8 exogenous variables would imply 46 coefficients to be estimated. This is a large number of parameters to estimate relative to the sample size, and it can give rise to multicollinearity, which can affect the interpretation of the coefficients.

The identification of the parameters of interest may be improved by reducing the model to a more parsimonious form. This is carried out using a transparent set of criteria for iterative model simplification to derive a preferred model or models. That said, where there is a large number of parameters to estimate, there can be an extremely large number of combinations to test for simplifying the model, and when there is a high degree of multicollinearity, this can confound the model simplification process. In these circumstances it is also common practice to impose *a priori* restrictions on functional specification to reduce the size of the model and to simplify the specification search.

2.2.2 Stochastic specifications

The stochastic specification is another important aspect of the theoretical model underlying the econometric specification. Two of the issues to consider are the possibility of that some businesses are not fully efficient, and also the possibility of 'unobserved heterogeneity' among the businesses in the sample.

Inefficiency: A cost function represents the minimum cost that a business can achieve with given technology, input prices and the levels of outputs. In theory the minimum cost is an ideal or frontier, which may not be realised by all businesses, and businesses may differ in the degree to which they minimise cost. That is, they may differ in their degrees of efficiency, and the measurement of their differing degrees of efficiency is often an objective of analysis.

Unobserved heterogeneity: Although the explanatory variables of the model ideally represent all of the important determinants of the dependent variable, there will always be a range of lesser determinants not explicitly taken into account, and their combined effect is reflected in the random disturbance term. That said, in some circumstances there may be important variables that are unmeasured or not known, and hence omitted, which may systematically affect the ability of different GDBs to transform inputs into output. Influences of this kind can give rise to "unobserved heterogeneity' between the businesses in the sample.

The stochastic specifications discussed in this section differ in terms of which of these effects they seek to measure and how they do so. The approaches discussed are: the random effects and fixed effects models, and two different approaches to stochastic frontier analysis. Random effects and fixed effects estimation refers to particular methods of panel data analysis which seek to identify a time-constant unobserved effect for each panel group (here GDB). Stochastic frontier models seek to identify an efficiency frontier, based on best practice among the firms in the sample, and each firm may be closer or further from the frontier, hence there is a firm-specific inefficiency.

In the random effects (RE) model, the stochastic term has the following specification:

(3)
$$\varpi_{it} = u_i + \varepsilon_{it}$$
$$u_i \sim N(0, \sigma_u^2)$$
$$\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$$

where i is the indicator for the panel group variable (GDB) and t is the indicator for time period, and: ε_{it} is a normally distributed random variable which has a unique value for each observation, and u_i is a normally distributed random variable which has a unique value for each GDB. The values of u_i are usually interpreted as the effect of unobserved business environment factors that cause firm-specific heterogeneity.

The fixed effects (FE) model differs from the random effects model in that u_i is not a stochastic variable, but instead a set of parameters to be estimated, subject to at least one u_i being equal to zero (since the model has an intercept, a_0). Essentially, this means that each GDB has a unique intercept, and the stochastic element is $\varpi_{it} = \varepsilon_{it}$. Differences between the intercepts of GDBs may be interpreted as either due to unobserved business environment factors that cause firm-specific heterogeneity, or due to differences in GDB efficiency, or both.

In what is perhaps the most standard stochastic frontier (SF) model, the stochastic specification is:

(4)
$$\varpi_{it} = v_i + \varepsilon_{it}$$
$$v_i \sim N^+(\mu, \sigma_v^2)$$
$$\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$$

where: ε_{it} is a normally distributed random variable which has a unique value for each observation, and v_i is a strictly positive random variable which, as shown, has a truncated normal distribution with mean μ, and has a unique value for each GDB. In the models presented here the restriction $\mu = 0$ is imposed, so that v_i has a half-normal distribution. The values of v_i are usually interpreted as measures of the inefficiency of each GDB relative to the efficient frontier (ie, best practice).

A number of more flexible and more complicated SF specifications are available, most of which involve either: (a) different distributions adopted for v_i; or (b) allowing the parameters μ, σ_v^2 and σ_ε^2 to be functions of the same or other exogenous variables (see Kumbhakar and Lovell 2000; Greene 2008; Belotti et al. 2012). In our appraisal, the extensions of this kind that have been tested with the present dataset do not improve on the simple model described by (4) with $\mu = 0$.

An alternative approach to stochastic frontier analysis is Greene's 'true' random effects model (TRE), which has the following stochastic specification:

(6)
$$\varpi_{it} = u_i + v_i + \varepsilon_{it}$$

$$u_i \sim N(0, \sigma_u^2)$$
$$v_i \sim N^+(\mu, \sigma_v^2)$$
$$\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$$

where: ε_{it} is a normally distributed random variable which has a unique value for each observation, and v_i is a strictly positive random variable which here has a truncated-normal distribution and has a unique value for each GDB. Again we assume $\mu = 0$, so that v_i has a half-normal distribution The interpretation of u_i in this model is the same as for the RE model and the interpretation of v_i is the same as for the SF model.

The TRE model has limitations as a method of measuring firm-specific inefficiency because "all time-invariant unobserved heterogeneity is ruled out from the inefficiency component" (Belotti et al. 2012, p.7). This limitation of the TRE model (and the related 'true' fixed effects model) is explained by Agrell et al (2013, p.8):

> Assuming that physical network and environmental characteristics do not vary considerably over time and that the inefficiency is time-varying, these models help to separate unobserved time-invariant effects from efficiency estimates. However, if inefficiency is persistent over time, these models underestimate the inefficiency systematically, e.g. if managers take wrong decisions in every period or make the same mistakes again and again, the corresponding consequences in terms of inefficiency are detected as time–invariant unit–specific heterogeneity and not as inefficiency. As noted in Greene (2008), the 'truth' doubtless lies somewhere between the two strong assumptions.

This study is focussed on measuring the elasticities of variable cost with respect to each of the outputs and other exogenous variables, rather than measuring firm-specific inefficiency.

2.3 Processes for developing preferred models

2.3.1 Estimation strategy

The overall modelling strategy is to begin by estimating the full variable cost function shown in equation (2), and then testing various simplifications to this model. Both the random effects and fixed effects models are used in this stage of the analysis. In addition to testing some *ad hoc* simplifications, we also use the *genspec* user-written Stata routine to assist to identify appropriate simplifications to the specification (Clarke 2014). The overall modelling strategy takes a "general-to-specific" approach. This process will be referred to as 'stage 1' and is documented in Appendix A and summarised in section 3.1.1.

The preferred simplified model obtained through in the 'stage 1' process forms the basis against which some further simplifications are compared. As part of this comparison a wider set of stochastic assumptions are tested including the stochastic frontier (SF) and 'true' random effects (TRE) models. This part of the analysis will be described as 'stage 2' and the results are presented in section 3.1.2.

2.3.2 Presentation of results

In the results presented in the tables in section 3 and Appendix A, the variable descriptors have the following meanings:

- x1 = log customer numbers;
- x2 = log gas throughput (TJ)
- x3 = log network length (km)
- x4 = log capital stock (2010$)
- x5 = log load factor
- x6 = log proportion of mains *not* cast iron or unprotected steel
- x7 = log number of city gates
- x8 = log tariff class customer share of total gas throughput.

An interaction term between, say, variable x1 and variable x3, is denoted x13. A squared term, such as: 0.5*x4^2, is denoted x44. T-statistics are presented in brackets underneath each estimated parameter, and the significance of parameters is indicated by the use of asterisks.

For each model presented in this report, including those in Appendix A, the following statistics are also presented:

- a goodness-of-fit measure: the Bayesian Information Criterion (BIC) — a measure which penalises models with more parameters;
- a test for the normality of residuals: the p-value of the Doornik-Hansen statistic;
- a measure of the degree of multicollinearity between the explanatory variables: the average variance inflation factor (VIF);
- joint parameter significance tests for each primary variable and its associated second-order effects (only for models with second-order effects);
- elasticities of variable cost with respect to each primary variable (taking into account the second-order effects), and the standard errors of the elasticity estimates. In models that have no second-order effects these elasticities are given by the coefficients on the primary variables.

2.3.3 Methods of evaluating models

When evaluating alternative models we have regard to diagnostic statistics (including goodness of fit, normality of the residuals, and indicators of the degree of multi-collinearity) and also have regard to the consistency with theoretical priors of the signs and values of the elasticities of variable cost with respect to the primary effects. Where appropriate, specific hypothesis tests are carried out to assist model selection.

Among the diagnostic statistics:

- lower values of the BIC represent a better fit,[3] and differences of about 10 points are considered significant;
- a p-value > 0.05 for the Doornik-Hansen statistic indicates that the null hypothesis that the residuals are *not* normally distributed can be rejected;
- a significant degree of multicollinearity is usually indicated by VIF > 10.

The elasticities of variable cost with respect to each primary exogenous variable are examined for compliance with economic theory or reasonable expectations of the behaviour of the gas network variable cost function. The following are our expectations:

- elasticities of variable cost with respect to each of the outputs (x1, x2, x3) should be either positive or insignificant;
- the sum of the output elasticities should be less than one (economies of scale);
- the elasticity of variable cost with respect to the capital stock (x4) should be positive and usually less than or equal to one;
- the elasticity with respect to the load factor (x5) should be negative because a small load factor implies a more peaked demand, and a more peaked demand may require more capacity (eg, higher pressures) per unit of output than a network with a less peaked demand;
- the elasticity with respect to the proportion mains not made of cast iron or unprotected steel (x6) should be negative because older mains require higher maintenance;
- the elasticity with respect to the number of city gates (x7) should be positive because more inputs may be needed to maintain a more geographically dispersed network.

In Appendix A, statistical hypothesis tests are used to test whether GDB-specific effects, as implied in the fixed and random effects model, are significant whether ordinary least-squares (OLS) estimation should be preferred. A test is also employed to determine whether the fixed effects model outperforms the random effects model. These tests further assist to eliminate some modelling approaches.

[3] ie, a larger absolute value of a negative BIC is a better fit.

3 RESULTS

This section reports the results obtained for a sequential process of model selection. The first stage of this process is limited to using fixed effects and random effects panel data models. This is documented in section 3.1.1. The second stage involves further refining the simplified model, taking into account alternative stochastic specifications, to obtain a preferred model or models. This is documented in section 3.1.2. Using the preferred model(s), the central questions of the study relating to the outputs that are found to be significant determinants of real opex are then addressed in section 3.2. Section 3.3 makes some observations relevant if using the model to derive forecasts of opex.

3.1 Econometric Results

3.1.1 Stage 1 results summary

In the 'stage 1' specification search various specifications are tested using the random effects (RE) and fixed effect (FE) panel data models. Some of the simplifications are *a priori* restricted forms. The *genspec* user-written Stata routine is also used to assist to find parsimonious functional forms (Clarke 2014). This routine carries out a formal "general-to-specific" search algorithm.

Although the *genspec* routine represents a useful technique, this method has two important shortcomings in the present application. First, the routine does not allow some variables to be fixed in the specification. For example, a preference for the inclusion of primary effects over second-order effects cannot be imposed in this routine. Second, the routine searches for the model with the best fit, ignoring multicollinearity. However, a model in which mulitcollinearity is less severe may be preferred in the present context, even if some goodness-of-fit must be sacrificed.

An alternative model simplification routine for global search regression (*gsreg*) was tested (Gluzmann and Panigo 2015). This is a powerful method, which does not ignore issues such as multicollinearity. However, computer resources limit the number of coefficients to be estimated, given the exponential multiplication of possible alternative specifications as the number of right-hand-side variables increases.

The analysis presented in Appendix A indicates that the RE model with no second-order effects is the best of the models tested. Among the RE models, all of the specifications that included second-order effects had deficiencies, including:

- excessive degrees of multicollinearity
- most are inconsistent with expectations of elasticity signs, such as negative elasticities with respect to customer numbers.

The RE model with no second-order effects met the elasticity sign expectations, had acceptable levels of multicollinearity and satisfied the test of normality of residuals.

The FE models have better goodness-of-fit (since they are less restricted) but are less able to identify the parameters of interest. All of the FE models that included second-order effects had similar deficiencies to the corresponding RE models and were similarly rejected. However, the FE model with no second-order effects was not considered satisfactory because none of the elasticities of cost with respect to the outputs were statistically significant.

Using the simpler model specification with no second order effects, the following results are obtained using hypothesis test statistics (see Appendix A for details):

- an F-test is used to compare the FE model to ordinary least squares (OLS) regression and shows that the GDB-specific effects are jointly significant. The OLS model is rejected when compared to the FE model;
- a Hausman test is used to compare the RE model against the FE model and shows that the null hypothesis that the GDB-specific effects are adequately modelled as random effects cannot be rejected. This supports the simpler RE model against the FE model;
- a Breush-Pagan Lagrange-Multiplier (LM) test of the significance of the random effects rejects the null hypothesis that v_i are all equal to zero. This test suggests that the RE model is preferred to the OLS model because the random effects are jointly significant.

The stage 1 analysis set out in Appendix A thus concludes that a simple model specification which has no second order effects is preferred to the specifications that include second-order effects, and that the RE model is strictly preferred to the FE and OLS models. The RE model with only primary variables represents the starting point of the ‘stage 2’ analysis.

3.1.2 Stage 2 results

This section explores some narrower changes to the simple RE model obtained from the ‘stage 1’ analysis. These changes involve removing some variables that are insignificant, and testing the stochastic frontier (SF) and the ‘true’ random effects (TRE) models. These models are shown in table 3.1. Because there are no second-order effects in these models, the elasticities are the estimated coefficients.

Model (1.1) of Table 3.1 reproduces model (4) of Table A.1 in Appendix A. Models (2.1) and (3.1) present corresponding models using the SF and TRE stochastic specifications. It is apparent from comparing these three models that they are all very similar. The differences in stochastic specification between RE, SF and TRE make very little difference in this case.

Models (1.2) and (1.3) are simplifications to model (1.1). Model (1.2) removes gas throughput (x2), and model (1.3) removes both gas throughput and the number of city gates (x7). Removing these two variables has a small but beneficial effect on the RE model. The coefficients on the time variable (technology change) and customer numbers are better identified, with the former becoming significant at $\alpha = 0.05$ and the latter becoming significant at $\alpha = 0.1$. The goodness-of-fit, indicated by the BIC, is also significantly improved. Most of these observations are also true when comparing models (2.2) and (2.3) to model (2.1), and when comparing models (3.2) and (3.3) to model (3.1). Thus the simplest of the model specifications — that is models (1.3), (2.3) and (3.3) — appear to be superior to the other models shown.

Both the RE and SF models appear to be valid models. Neither outperforms the other significantly in terms of goodness-of-fit. The TRE model includes both the RE and SF effects, and in these models the parameter σ_v is not significantly different from zero, which suggests that when random effects are included in the model, the one-sided inefficiency effects are not significant. This tends to suggest that in this sample, there is not a large one-sided inefficiency effect. The similarities of the SF model to the RE model indicate that most GDBs in the sample are close to the efficiency frontier and only a relatively small number are significantly different from the frontier. This may be why the one-sided inefficiency effect is insignificant in the TRE model. The TRE model is not significantly different from the RE model, and this seems to reflect a general limitation of the TRE model. Hence, we focus on the RE and SF models in section 3.2.

3.2 Inference

For the purpose of making inferences about the appropriate outputs to be considered as drivers of real opex, it is not essential to choose between the models (1.3) and (2.3), the simplest RE and SF models respectively. The essential conclusions are as follows:

- The t-statistics on variable x2 (gas throughput) in models (1.1) and (2.1) (where gas throughput is included) are much smaller than the critical value of 1.96 (when $\alpha = 0.05$, or 95 per cent confidence), which indicates that gas throughput is not a statistically significant determinant of real opex.
- The t-statistics on variable x3 (network length) in the preferred models (ie, models (1.3) and (2.3)) are much larger than 1.96, which strongly indicates that network length is a statistically significant determinant of real opex.
- The t-statistics on variable x1 (customer numbers) in model (1.3) and (2.3) are 1.80 and 2.76 respectively. The first of these is significant at $\alpha = 0.1$ (or 90 per cent confidence) and the second is significant at $\alpha = 0.01$ (or 99 per cent confidence). These results support a conclusion that customer numbers are a statistically significant determinant of real opex.

The estimated elasticity of real opex with respect to customer numbers is 0.16 (RE) to 0.24 (SF). The estimated elasticity with respect to network length is 0.41 (RE) to 0.43 (SF). The sum of these parameters (a measure of economies of scale) is 0.57 (RE) to 0.67 (SF). The estimated elasticities of real opex with respect to the other exogenous variables are:

- *Fixed capital inputs*: 0.38 (SF) to 0.46 (RE);
- *Load factor*: –0.38 (SF) to –0.42 (RE);
- *Proportion of mains not cast iron or unprotected steel*: –0.32 (SF) to –0.41 (RE);
- *Tariff class customer share of total gas throughput*: –0.33 (SF) to –0.34 (RE).

Table 3.1: **Random effects models with 2 or 3 outputs**

	Random effects model			*Stochastic frontier model*			*'True' random effects model*		
Var	(1.1)	(1.2)	(1.3)	(2.1)	(2.2)	(2.3)	(3.1)	(3.2)	(3.3)
t	-0.0014	-0.0013	-0.0013	-0.0016	-0.0016	-0.0016	-0.0014	-0.0013	-0.0013
	(1.82)	(1.96)*	(1.98)*	(2.35)*	(2.56)*	(2.61)**	(0.72)	(0.74)	(0.73)
x1	0.1961	0.1713	0.1609	0.2420	0.2473	0.2429	0.2272	0.1941	0.1896
	(1.56)	(1.91)	(1.80)	(2.18)*	(2.96)**	(2.76)**	(0.94)	(1.69)	(1.58)
x2	-0.0229	.	.	0.0056	.	.	-0.0297	.	.
	(0.28)			(0.07)			(0.20)		
x3	0.3784	0.3817	0.4109	0.4042	0.4023	0.4314	0.3433	0.3525	0.3792
	(3.14)**	(3.15)**	(3.62)**	(3.34)**	(3.40)**	(3.66)**	(2.05)*	(2.39)*	(2.81)**
x4	0.4654	0.4655	0.4613	0.3812	0.3825	0.3754	0.4755	0.4733	0.4667
	(4.70)**	(4.66)**	(4.61)**	(4.00)**	(4.10)**	(4.04)**	(2.59)**	(2.58)**	(2.61)**
x5	-0.4529	-0.4534	-0.4221	-0.3927	-0.3934	-0.3838	-0.4084	-0.4086	-0.3594
	(2.76)**	(2.76)**	(2.67)**	(2.62)**	(2.64)**	(2.60)**	(1.60)	(1.43)	(1.26)
x6	-0.4306	-0.4385	-0.4055	-0.3548	-0.3567	-0.3232	-0.4201	-0.4269	-0.3996
	(2.20)*	(2.25)*	(2.15)*	(1.85)	(1.88)	(1.77)	(1.48)	(1.57)	(1.39)
x7	0.0188	0.0179	.	0.0196	0.0204	.	0.0181	0.0169	.
	(0.66)	(0.63)		(0.64)	(0.73)		(0.67)	(0.62)	
x8	-0.3359	-0.3287	-0.3391	-0.3135	-0.3158	-0.3301	-0.3166	-0.3120	-0.3246
	(3.33)**	(3.36)**	(3.51)**	(3.13)**	(3.32)**	(3.54)**	(2.22)*	(2.15)*	(2.24)*
cons	-5.6878	-5.6292	-5.6650	-6.2917	-6.2980	-6.4000	-5.8171	-5.7467	-5.8322
	(9.27)**	(9.67)**	(9.75)**	(13.21)**	(13.48)**	(14.18)**	(5.40)**	(6.04)**	(6.10)**
σ_u	0.0961	0.0985	0.1009	.	.	.	0.0943	0.0976	0.1021
	(4.01)**	(4.30)**	(4.42)**				(2.89)**	(2.82)**	(2.37)*
σ_v	.	.	.	0.1590	0.1583	0.1613	0.1164	0.0953	0.1154
				(2.00)*	(2.06)*	(2.09)*	(0.51)	(0.42)	(0.72)
σ_ε	0.1492	0.1490	0.1490	0.1492	0.1493	0.1493	0.1314	0.1371	0.1313
	(20.77)**	(20.87)**	(20.90)**	(10.47)**	(10.49)**	(10.50)**	(1.67)	(2.11)*	(2.25)*
N	234	234	234	234	234	234	234	234	234
BIC	-131.8798	-137.2602	-142.3295	-133.6499	-139.1000	-144.0374	-127.9719	-133.2998	-138.3415
DH (p)	0.8342	0.8319	0.8338	0.9318	0.9251	0.8628	0.6513	0.7214	0.6406
VIF	27	22	23	27	22	23	27	22	23

Note: T-statistics in parentheses. * $p<0.05$; ** $p<0.01$.

4 CONCLUSIONS

This report documents an econometric analysis of gas network real operating costs ('opex') as a function of outputs, fixed capital inputs and business environment factors. The dataset includes 14 gas distribution businesses in Australia and New Zealand, with approximately 17 observations per GDB on average. The specification of the real opex cost function is initially based on the translog variable cost function, and three outputs are initially included in the model — customer numbers, gas throughput and network length — and five other exogenous variables. A specification search is undertaken to derive a more parsimonious model, and a model with no second-order effects (ie, interactions and higher powers of the exogenous variables) is found to be preferable to any of the alternatives that include second-order effects. The key models that are tested using this simpler specification are the random effects (RE) model, the stochastic frontier (SF) model and the 'true' random effects (TRE) model. Among these the RE and SF models both appear to be valid.

For the purpose of making inferences about the significance of outputs as determinants of real opex, it is not essential to choose between these two models. The essential conclusions in regard to the significance of outputs are as follows:

- gas throughput is not a statistically significant determinant of real opex;
- network length is a statistically significant determinant of real opex; and
- customer numbers are a statistically significant determinant of real opex.

The estimated elasticity of real opex with respect to customer numbers is 0.16 (RE) to 0.24 (SF), and the estimated elasticity with respect to network length is 0.41 (RE) to 0.43 (SF).

We consider both the RE and SF models to be useful methods of estimating the real opex cost function of gas networks. The random effects method was used by Economic Insights to estimate a cost function for domestic telecommunications transmission capacity services (DTCS) on behalf of the Australian Competition and Consumer Commission (ACCC) for the purposes of its DTCS final access determination (Economic Insights 2015a). The stochastic frontier method is widely used in cost function estimation, and was one of the two methods used by Economic Insights for the estimation of the gas network opex cost function in previous work for Jemena Gas Networks (Economic Insights 2014, 2015b).

APPENDIX A: SPECIFICATION SEARCH

This appendix provides details of the initial steps of the specification search. This includes testing of the full translog variable cost model, which has many parameters, and testing various approaches to simplifying that model. In this process, two types of models are tested, the random effects model and the fixed effects model. These are widely used specifications for panel data, and provide sufficient guidance for developing a more parsimonious model. These two approaches are then evaluated using the following considerations:

- tests statistics for goodness-of-fit, normality of errors and degree of multicollinearity;
- expectations of significance of key coefficients and their signs
- hypothesis tests designed for making choices between the fixed and random effects specifications.

A.1 Random effects models

Table 3.1 shows the estimation of the random-effects (RE) model with three outputs. The models shown in columns (1) to (4) were estimated using Stata's *xtreg* routine (*mle* option). The specification of model (5) was derived using the user-written *genspec* routine for model simplification, and was then re-estimated using *xtreg* to obtain comparable goodness-of-fit statistics (the coefficients are the same although t-statistics reported here differ slightly from those reported by the genspec routine). Table 3.2 shows joint parameter significance tests and elasticity estimates associated with each of the primary variables.

Table 3.1: **Random effects models with 3 outputs - Estimates**

Var	(1)	(2)	(3)	(4)	(5)
t	-0.0028	-0.0024	-0.0008	-0.0014	
	(2.60)**	(2.60)**	(0.78)	(1.82)	
x1	3.5644	17.1063	7.8773	0.1961	5.9823
	(1.06)	(7.02)**	(3.04)**	(1.56)	(7.85)**
x2	1.8737	-4.2358	-0.5455	-0.0229	
	(0.93)	(3.00)**	(0.45)	(0.28)	
x3	-9.5132	-10.5559	-1.0868	0.3784	-10.5407
	(2.11)*	(3.48)**	(0.42)	(3.14)**	(9.91)**
x4	0.4064	-4.5235	-3.6067	0.4654	
	(0.12)	(1.89)	(1.31)	(4.70)**	
x5	13.0964	-1.6753	-0.2910	-0.4529	
	(2.10)*	(0.76)	(1.51)	(2.76)**	
x6	6.9298	-9.4468	-0.1172	-0.4306	
	(0.67)	(2.17)*	(0.47)	(2.20)*	
x7	1.3583	1.4656	-0.0092	0.0188	4.1614
	(1.09)	(3.15)**	(0.24)	(0.66)	(13.08)**
x8	7.0038	-3.4893	-0.1569	-0.3359	6.0658
	(1.60)	(2.70)**	(1.39)	(3.33)**	(7.27)**
x11	0.0562	-2.4036	-0.1898		
	(0.07)	(3.56)**	(0.29)		
x12	-1.2298	0.2096	-1.5900		-0.9889
	(2.76)**	(0.53)	(4.70)**		(8.05)**
x13	-0.8588	0.2372	0.4670		-1.1861
	(1.11)	(0.36)	(0.70)		(4.98)**
x14	2.4390	1.9319	0.9781		2.2592
	(6.50)**	(5.81)**	(2.12)*		(11.03)**

Var	(1)	(2)	(3)	(4)	(5)
x22	2.0594	1.0442	1.6103		2.5977
	(5.51)**	(3.52)**	(6.07)**		(13.02)**
x23	0.5990	0.0761	1.1177		
	(1.29)	(0.19)	(2.81)**		
x24	-1.5246	-1.7657	-0.8294		-1.7559
	(4.23)**	(5.36)**	(2.52)*		(11.10)**
x33	2.5222	0.2779	-1.9816		4.1408
	(2.07)*	(0.28)	(1.75)		(6.24)**
x34	-1.5247	0.3868	0.2454		-1.5075
	(2.01)*	(0.64)	(0.34)		(4.70)**
x44	-0.3262	-0.7347	-0.2872		
	(0.49)	(1.27)	(0.45)		
x15	-0.8031	2.5132			
	(0.72)	(3.53)**			
x16	7.8028	5.9133			5.4678
	(2.60)**	(2.80)**			(5.93)**
x17	-0.0891	-0.2620			
	(0.38)	(1.23)			
x18	-0.3969	2.1022			
	(0.60)	(6.24)**			
x25	2.1783	-0.8622			1.5364
	(2.51)*	(1.10)			(3.69)**
x26	-1.3054	-2.1962			
	(1.59)	(3.51)**			
x27	-0.0288	0.4414			
	(0.18)	(3.05)**			
x28	2.3169	0.3421			2.2096
	(5.42)**	(1.17)			(13.41)**
x35	-4.2538	-2.4707			-2.1725
	(3.30)**	(2.73)**			(4.16)**
x36	-10.1527	-5.0106			-8.0491
	(2.91)**	(2.19)*			(5.99)**
x37	-0.7009	-0.3005			-1.3333
	(3.16)**	(1.98)*			(11.89)**
x38	-2.7054	-2.9926			-2.9250
	(3.69)**	(6.08)**			(13.86)**
x45	2.9532				0.9486
	(4.23)**				(3.67)**
x46	0.5955				
	(0.28)				
x47	0.7122				1.0672
	(4.18)**				(10.36)**
x48	0.4576				
	(0.81)				
x55	2.4978				
	(1.25)				
x56	6.7156				
	(1.80)				
x57	-1.3364				-0.6826
	(3.18)**				(5.13)**
x58	1.0794				
	(1.04)				
x66	6.5672				
	(2.81)**				
x67	-1.0901				
	(2.82)**				
x68	0.9359				
	(0.59)				
x77	0.1871				0.1283
	(3.15)**				(5.44)**
x78	-0.5569				
	(2.11)*				
x88	3.3539				3.6884
	(3.42)**				(10.97)**

Var	(1)	(2)	(3)	(4)	(5)
cons	11.9787	-29.0943	-30.1876	-5.6878	4.0092
	(0.91)	(3.46)**	(3.54)**	(9.27)**	(1.66)
sigma_u	0.0000	0.0000	0.1335	0.0961	0.0000
	(0.00)	(0.00)	(2.35)*	(4.01)**	(0.00)
sigma_e	0.0904	0.1098	0.1257	0.1492	0.0994
	(21.64)**	(21.63)**	(18.94)**	(20.77)**	(21.63)**
N	234	234	234	234	234
σ_u/σ_e	0.0000	0.0000	1.0621	0.6441	0.0000
BIC	-198.7402	-184.3799	-144.8413	-131.8798	-274.6211
LL	230.2978	184.9304	132.4292	98.6718	208.2297
DH (p)	0.7090	0.0202	0.4172	0.8342	0.5743
VIF	996,319	685,362	403,387	27	187,301

Note: T-statistics in parentheses. * $p<0.05$; ** $p<0.01$

Table 3.2: **Random effects models with 3 outputs – joint parameter significance tests and elasticity estimates**

Var	(1)	(2)	(3)	(4)	(5)
Joint test (p)					
x1 - all	0.0000	0.0000	0.0000	.	0.0000
- 2nd order	0.0000	0.0000	0.0000	.	0.0000
x2 - all	0.0000	0.0000	0.0000	.	0.0000
- 2nd order	0.0000	0.0000	0.0000	.	0.0000
x3 - all	0.0000	0.0000	0.0062	.	0.0000
- 2nd order	0.0000	0.0000	0.0040	.	0.0000
x4 - all	0.0000	0.0000	0.0000	.	0.0000
- 2nd order	0.0000	0.0000	0.0058	.	0.0000
x5 - all	0.0000	0.0000	.	.	0.0000
- 2nd order	0.0000	0.0000	.	.	0.0000
x6 - all	0.0000	0.0003	.	.	0.0000
- 2nd order	0.0000	0.0005	.	.	0.0000
x7 - all	0.0000	0.0000	.	.	0.0000
- 2nd order	0.0000	0.0000	.	.	0.0000
x8 - all	0.0000	0.0000	.	.	0.0000
- 2nd order	0.0000	0.0000	.	.	0.0000
Elasticities					
x1 - est	-0.3599	-0.3976	0.0667	0.1961	-0.4104
- se	(0.2145)	(0.1888)	(0.2035)	(0.1259)	(0.1435)
x2 - est	-0.1593	-0.0680	0.1887	-0.0229	0.0929
- se	(0.1165)	(0.1133)	(0.1217)	(0.0828)	(0.0515)
x3 - est	1.6067	1.0068	0.2826	0.3784	1.6559
- se	(0.2662)	(0.2181)	(0.2089)	(0.1205)	(0.1858)
x4 - est	-0.0412	0.4969	0.4457	0.4654	-0.3343
- se	(0.1752)	(0.1231)	(0.1690)	(0.0991)	(0.0969)
x5 - est	0.7473	-0.2664	-0.2910	-0.4529	0.7907
- se	(0.3390)	(0.2973)	(0.1925)	(0.1639)	(0.2204)
x6 - est	-0.2563	-1.1645	-0.1172	-0.4306	-0.9951
- se	(0.6191)	(0.2984)	(0.2501)	(0.1959)	(0.1396)
x7 - est	0.1921	0.0928	-0.0092	0.0188	0.1821
- se	(0.0550)	(0.0412)	(0.0381)	(0.0285)	(0.0248)
x8 - est	0.2843	0.2063	-0.1569	-0.3359	0.3047
- se	(0.1804)	(0.1572)	(0.1125)	(0.1008)	(0.0945)

In commenting on these models we have regard especially to the diagnostic statistics at the bottom of Table 3.1, and the elasticity estimates in Table 3.2.

Among the RE models shown in Table 3.1, model (5), which is produced by the *genspec* routine, has the best fit (measured by the lowest BIC), which is unsurprising since this routine is designed to find the specification with the lowest BIC. The full model in column (1) is the best fitting among the remaining models. The p-value associated with the Doornik-Hansen (DH) test for normality indicates that all of the models except model (2) satisfy the test for normally distributed residuals. The random GDB-specific effect only plays a role in models (3) and (4).

The test for multicollinearity used here is the average VIF. It shows that models (1), (2) (3) and (5) all have extremely severe multicollinearity. Multicollinearity makes interpretation of the coefficients and their standard errors difficult, and thus makes inference from the model problematic. Among these models only model (4) has an average VIF sufficiently low to be regarded as yielding reliable coefficient estimates.

The conclusions on multicollinearity are sufficient to reject all models except model (4), since inference is of central importance in this study. However, for completeness, the elasticities shown in Table 3.2 will be compared.

Models (1), (2) and (5) show negative elasticities for variable cost with respect to customer numbers which are significant at $\alpha = 0.05$ or $\alpha = 0.1$, which is inconsistent with expectations. Only models (3) and (4) have positive elasticities of cost with respect to customer numbers. Model (2) has a negative elasticity of cost with respect to gas throughput, which is inconsistent with expectations. In all of the other models the elasticity of cost to gas throughput is insignificantly different from zero. All models have a positive elasticity of cost with respect to network length. In summary, the signs of the elasticities of cost with respect to the outputs are consistent with expectations only for models (3) and (4).

The sum of the elasticies of cost to the outputs is greater than one for models (1) and (5). The other three models satisfy the expectation that they should sum to less than one. The elasticity of cost to fixed capital is negative for models (1) and (5), while the other three models satisfy the expectation that they should be positive. The elasticity of cost to load factor has the expected negative sign only for models (2), (3) and (4). Hence models (1) and (5) are inconsistent with sign expectations with respect to several other variables in the model.

These observations suggest that only models (3) and (4) meet the expectations regarding the signs or significance of the elasticities. Among these two models, model (3) has a slightly better, fit. However, it comes at the cost of an extreme degree of multicollinearity. Model (4), which is the simplest of the models with no second-order effects, is therefore preferred.

A.2 Fixed effects models

Table 3.3 shows the estimation of the fixed-effects (FE) model with three outputs and Table 3.4 shows associated joint parameter significance tests and elasticity estimates relating to each primary variable. The models shown in columns (1) to (4) were estimated using Stata's *xtreg* routine (*fe* option). Model (5) was derived using the *genspec* routine, and then re-estimated using *xtreg* to obtain comparable goodness-of-fit statistics.

Table 3.3: **Fixed effects models with 3 outputs - Estimates**

Var	(1)	(2)	(3)	(4)	(5)
t	0.0034	-0.0008	0.0013	0.0013	
	(1.47)	(0.37)	(0.60)	(0.85)	
x1	1.3055	1.4797	8.6888	-0.2027	
	(0.21)	(0.35)	(2.92)**	(0.87)	
x2	6.4885	-1.5657	-0.2237	-0.0044	
	(1.92)	(0.63)	(0.12)	(0.03)	
x3	-11.8640	-3.6413	-2.2945	0.2130	
	(1.73)	(0.86)	(0.63)	(0.73)	
x4	1.5500	-3.0521	-4.6225	0.6012	
	(0.33)	(0.84)	(1.20)	(3.78)**	
x5	5.0443	-5.8659	-0.0233	-0.3123	17.1150
	(0.61)	(1.93)	(0.08)	(1.08)	(9.92)**
x6	10.5177	-6.5363	-0.7532	-0.5538	
	(0.64)	(1.19)	(2.37)*	(2.02)*	
x7	3.5388	7.2799	0.0994	0.0070	
	(1.33)	(3.38)**	(1.86)	(0.13)	
x8	1.7493	1.0271	-0.2227	-0.3614	
	(0.34)	(0.47)	(1.63)	(2.66)**	
x11	1.2154	0.8165	0.6874		
	(0.91)	(0.77)	(0.79)		
x12	-1.5455	-0.9449	-2.2167		-0.3955
	(1.95)	(1.74)	(5.79)**		(8.64)**
x13	-1.5525	-1.8427	-0.7358		
	(1.27)	(1.50)	(0.68)		
x14	2.0573	2.8651	1.7276		0.6495
	(2.38)*	(3.87)**	(2.41)*		(10.49)**
x22	0.9792	1.0863	1.7245		0.5172
	(1.54)	(2.92)**	(5.49)**		(8.50)**
x23	1.0380	1.5687	1.9889		
	(1.38)	(2.42)*	(3.80)**		
x24	-0.5457	-1.6774	-0.9816		
	(1.07)	(3.65)**	(2.53)*		
x33	4.0804	2.3355	-0.5034		
	(2.45)*	(1.57)	(0.38)		
x34	-2.8457	-2.1819	-0.6489		-0.5042
	(2.66)**	(2.55)*	(0.78)		(8.72)**
x44	0.6939	0.6553	-0.0840		
	(0.83)	(0.90)	(0.11)		
x15	0.2788	0.9153			
	(0.15)	(0.87)			
x16	7.7508	14.0877			5.2801
	(2.37)*	(5.68)**			(4.29)**
x17	-0.4713	-1.1050			-0.0911
	(1.37)	(3.67)**			(5.99)**
x18	-0.8184	0.4832			
	(0.97)	(0.92)			
x25	2.4430	0.8624			
	(2.30)*	(1.02)			
x26	-0.6662	-0.3861			
	(0.52)	(0.53)			
x27	0.0672	0.2256			
	(0.33)	(1.19)			
x28	2.0123	0.5697			0.2336
	(2.78)**	(1.43)			(10.03)**
x35	-5.5893	-1.5412			-4.6128
	(2.52)*	(1.24)			(8.28)**
x36	-15.6691	-19.3814			-7.7707
	(3.90)**	(6.21)**			(4.35)**
x37	-0.3357	0.5459			
	(0.71)	(1.41)			
x38	-1.2339	-1.4586			
	(1.03)	(2.21)*			

Var	(1)	(2)	(3)	(4)	(5)
x45	3.4946				4.5889
	(3.81)**				(9.45)**
x46	4.8916				
	(1.95)				
x47	0.5421				
	(1.85)				
x48	0.2573				
	(0.32)				
x55	1.5518				3.5311
	(0.57)				(3.38)**
x56	-5.6757				
	(1.02)				
x57	-1.6435				-1.4052
	(2.78)**				(5.38)**
x58	-0.3860				-0.9211
	(0.32)				(10.87)**
x66	3.5977				
	(0.82)				
x67	0.1100				
	(0.18)				
x68	1.7465				
	(0.75)				
x77	-0.1799				
	(1.03)				
x78	-0.6628				
	(1.55)				
x88	0.8666				
	(0.63)				
_cons	8.2976	12.5961	-28.2332	-0.4276	6.7213
	(0.42)	(0.78)	(2.15)*	(0.15)	(6.23)**
N	234	234	234	234	234
BIC	-268.8697	-274.1473	-229. 9546	-193.4901	-370.4648
DH (p)	0.0457	0.8285	0.4812	0.7790	0.1594
VIF	996,319	685,362	403,387	27	7,509

Note: T-statistics in parentheses. * $p<0.05$; ** $p<0.01$

Table 3.4: **Fixed effects models with 3 outputs – joint parameter significance tests and elasticity estimates**

Var	(1)	(2)	(3)	(4)	(5)
Joint test (p)					
x1 - all	0.0002	0.0000	0.0000	.	0.0000
- 2nd order	0.0236	0.0000	0.0000	.	0.0000
x2 - all	0.1535	0.0017	0.0000	.	0.0000
- 2nd order	0.1064	0.0010	0.0000	.	0.0000
x3 - all	0.0011	0.0000	0.0022	.	0.0000
- 2nd order	0.0011	0.0000	0.0011	.	0.0000
x4 - all	0.0000	0.0000	0.0000	.	0.0000
- 2nd order	0.0000	0.0001	0.0142	.	0.0000
x5 - all	0.0000	0.2939	.	.	0.0000
- 2nd order	0.0000	0.1832	.	.	0.0000
x6 - all	0.0000	0.0003	.	.	0.0000
- 2nd order	0.0003	0.0000	.	.	0.0000
x7 - all	0.0012	0.0000	.	.	0.0000
- 2nd order	0.0010	0.0001	.	.	0.0000
x8 - all	0.0346	0.0173	.	.	0.0000
- 2nd order	0.0216	0.0199	.	.	0.0000
Elasticities					
x1 - est	-0.9586	-0.8582	-0.1336	-0.2027	-0.6470
- se	(0.3665)	(0.3699)	(0.3419)	(0.2320)	(0.1740)
x2 - est	0.0009	0.1903	0.4012	-0.0044	0.0402

Var	(1)	(2)	(3)	(4)	(5)
- se	(0.1944)	(0.1739)	(0.1732)	(0.1594)	(0.1286)
x3 - est	1.2264	0.7778	-0.0450	0.2130	0.4829
- se	(0.4518)	(0.3688)	(0.3653)	(0.2899)	(0.1934)
x4 - est	0.0745	0.9715	0.7422	0.6012	0.8632
- se	(0.2932)	(0.1821)	(0.1835)	(0.1589)	(0.1138)
x5 - est	2.3502	0.5616	-0.0233	-0.3123	0.8795
- se	(0.5863)	(0.4483)	(0.2977)	(0.2891)	(0.2046)
x6 - est	-1.5591	-1.6749	-0.7532	-0.5538	-0.9445
- se	(1.0622)	(0.4238)	(0.3175)	(0.2748)	(0.1761)
x7 - est	0.0659	0.7906	0.0994	0.0070	0.4539
- se	(0.3676)	(0.2561)	(0.0534)	(0.0550)	(0.0532)
x8 - est	0.4538	0.2354	-0.2227	-0.3614	0.1166
- se	(0.2329)	(0.1990)	(0.1363)	(2.9242)	(0.0954)

The FE models shown in Table 3.3 has better goodness-of-fit statistics compared to the corresponding random effects models in Table 3.1. This is perhaps to be expected since they have 12 additional parameters compared to the RE models.[4] However, the coefficients of the exogenous variables (and the resulting elasticities) are generally less well identified. For example, model (4) in Table 3.3 has two significant (at $\alpha = 0.05$) elasticities with respect to the exogenous variables, compared to model (4) in Table 3.1, which has five significant elasticities.

All of the models in Table 3.3 except model (1) satisfy the test for normality of the residuals. The multicollinearity test results are unaffected by the change in specification because it is a test of the relationships between the regressors. All of the models except model (4) have severe multicollinearity.

None of the FE models have positive elasticities of cost to customer numbers, although only in models (1), (2) and (5) are they significantly different from zero. None of the models have a significant negative elasticity of cost with respect to gas throughput or with respect to network length. In summary, the signs of the elasticities of cost with respect to the outputs are consistent with expectations for models (3) and (4).

The sum of the elasticities of cost to the outputs is negative for model (5), but positive and less than one for all of the other models. However, the sums of the elasticities are smaller than would be expected. For example, in models (3) and (4) they sum to 0.22 and 0.01 respectively. In model (3), the only positive and statistically significant elasticity of cost to output is with respect to gas throughput. In model (4) none of the cost elasticities with respect to outputs are significantly different from zero.

The elasticity of variable cost with respect to the capital stock (x4) should be positive and usually less than equal to one. All the models in Table 3.3 satisfy this requirement, although for model (1) it is very low (0.07) and for model (2) it is very high (0.97). This elasticity is statistically significant for models (2) thru (5).

The elasticity with respect to the load factor (x5) should be negative, but only models (3) and (4) satisfy this expectation, and both elasticities are insignificantly different from zero. The

[4] ie, 13 more intercepts in the FE model compared to the RE model, but the latter includes the standard error of the random effect.

elasticity with respect to the proportion mains not made of cast iron or unprotected steel (x6) should be negative and all of the models satisfy this expectation. The elasticity with respect to the number of city gates (x7) should be positive and all of the models satisfy this expectation.

In summary, most attention is given to model (4) because of the severe multicollinearity problems with the other models. However, this model is not satisfactory because none of the elasticities of cost with respect to the outputs are statistically significant. This reflects the general observation that, in this dataset, it is much more difficult to identify the effects of interest with the FE specification compared to the RE model.

A.3 Testing fixed versus random effects

This section presents formal statistical tests of the fixed and random effects models to establish whether the fixed effects model is statistically superior to the random effects model and whether neither of these models should be preferred to the ordinary least squares (OLS) that has no such fixed or random effects. Several hypothesis test statistics are used for this purpose and are presented in Table 3.5. The specifications used for preparing Table 3.5 are equivalent to those shown in Table 3.1.[5]

Table 3.5: **Tests statistics, fixed & random effects**

	(1)	(2)	(3)	(4)	(5)
F-test (significance of fixed effects)[(1)] – test stat	3.88	5.83	7.82	7.39	2.84
– F(df)	(13, 175)	(13, 189)	(13, 201)	(13, 211)	(13, 197)
– P-value	0.0000	0.0000	0.0000	0.0000	0.0009
Hausman test (random v fixed effects)[(2)] – test stat	42.03	57.79	71.90	11.58	33.11
– χ^2(df)	(13)	(13)	(13)	(8)	(13)
– P-value	0.0001	0.0000	0.0000	0.1710	0.0016
Breusch-Pagan (significance of random effects)[(3)] – test stat	0.00	0.00	0.00	81.83	0.00
– $\bar{\chi}^2$(df)	(1)	(1)	(1)	(1)	(1)
– P-value	1.0000	1.0000	1.0000	0.0000	1.0000

(1) Ho: u_i are all equal to zero; (2) Ho: difference in coefficients not systematic; (3) Ho: u_i are all equal to zero.

The null hypothesis that all of the fixed effects (u_i) are equal to zero is tested using an F-test. The test statistic has an F distribution and degrees of freedom of the critical F statistics are shown in Table (3.5). P-values < 0.05 indicate there is less that 5 per cent probability that the null hypothesis is correct. The F-test for the significance of fixed effects versus OLS regression rejects the null hypothesis that all fixed effects are equal to zero in every model. This indicates an unobserved GDB-specific effect may be present.

5 That is, the fixed effects model used for column (5) differs from that shown in column (5) of Table 3.3.

The Hausman test provides a test of the hypothesis that the GDB-specific effects are adequately modelled as random effects because they are sufficiently close to being normally distributed. This statistic tests the hypothesis that the difference in coefficients between random effects and fixed effects models is not systematic. The test statistic has a χ^2 distribution with degrees of freedom shown in the table. P-values < 0.05 indicate there is less that 5 per cent probability that the null hypothesis is correct. The random effects specification is rejected in all of the models except model (4). For model (4), which as previously indicated is the preferred model, the random effects specification cannot be rejected in favour of the fixed effects model. This suggests that the random effects model is preferred to the fixed effects model because it cannot be rejected and it is more parsimonious.

The hypothesis that all of the random effects (u_i) are equal to zero is tested using the Breusch Pagan LM test for random effects. In this case the test statistic has a chibar^2 distribution. P-values < 0.05 indicate there is less that 5 per cent probability that the null hypothesis is correct. The P-values for this statistic indicate that the significance of random effects is rejected for all models except model (4). For model (4) the null hypothesis that all random effects are zero is strongly rejected. This suggests that the random effects model is preferred to OLS because the random effects are jointly significant in the preferred model (4).

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