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Abstract

This paper estimates a translog cost function for the Australian coal industry from 1968 to 2001. We use a variable measuring the shift to open-pit mining to capture the impact of technical change, while using a time trend to capture the impact of resource exhaustion. The cost function is estimated with the Zellner's SUR procedure. Technical change is significant in lowering cost, but over time this cost reduction has been largely offset by the impact of resource exhaustion.

Keywords: Coal mining, Translog, Cost functions, Technical Change

JEL Classifications: D24, L71

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1. Introduction

Australia is currently the largest global exporter of black (hard) coal and has been since 1986 when its exports surpassed those of the United States. Black coal is also Australia's largest export industry and accounted for around 10% in value of exports in 2003 (ABS Cat 5368.0). The prominence of the industry is due to Australia's many natural advantages, including its abundant supplies of easily accessible good quality coal located relatively close to established rail and port facilities.

Despite Australia's natural advantages, resource exhaustion can still be expected to affect the costs of coal production over time. Hotelling's (1931) seminal contribution to the analysis of non-renewable resource production demonstrates an optimal movement from the exploitation of superior to inferior reserves over time. This implies that unit production costs can be expected to rise steadily over time unless there are new discoveries or improvements in the technology of coal mining. In this paper we examine the offsetting effects of resource exhaustion and technical progress on the cost of production in Australian coal mining over the period 1968 to 2001.

There have been a variety of methods used to model coal supply. Being a resource industry predominantly managed by engineers, attempts to understand cost relationships have typically been couched in terms of physical variables such as coal seam conditions and thickness (Zimmerman, 1977; Lev and Murphy, 1983; Gordon, 1983; Steenblik, 1992). Although they are often used to assess the impact of a variety of government policies, these engineering based models do not provide an understanding of the fundamental economic relationships. Similarly, logistic functions and surveys have been used to forecast capacity and future production based on current technology and practices, again without recognising the underlying production processes (Hotard, Liu and Ristroph, 1983; ABARE, 1997).

Production and cost functions provide greater clarity in understanding the relationships between inputs and their impact on output as well as providing a basis for assessing technical change. In seminal studies, Rhodes (1945) and Lomax (1950) model coal mining in Great Britain using a Cobb-Douglas production function. However, limitations in the data and implicit model constraints restrict the contribution to understanding of the technology of coal production. In light of the downturn of the Welsh coal industry (many inefficient underground mines were closed down), Chakravarty and Hojman (1982) use a non-homogenous production function, allowing variable elasticities and variable returns to scale, to assess productivity improvements. They find significant returns to scale and variable elasticities of substitution over the 16-year period examined.

Donnelly and Dragun (1984) model the Australia coal industry with a homogenous, constant returns to scale, translog cost function. Their interest is in assessing differences in elasticities of substitution between production processes. However, their findings are limited by a small data set and the failure of the estimates to satisfy the required regularity conditions of a proper cost function. We follow Donnelly and Dragon in using a translog cost function to model the Australian coal industry over the 34 years, 1968 through 2001. Unfortunately, changes in data collection make it impossible to separate coal-mining processes, so our estimates are for the aggregate coal industry.

Standard practice in production or cost function estimation is to use a time trend as a proxy for technical change. While this may provide a reasonable approximation in the case of manufacturing or renewable resource industries, there is a substantial difficulty in the case of a non-renewable resource, such as coal, due to the cost-increasing effects of resource exhaustion. Thus, the coefficient of a time trend conflates the two opposing influences of technical change and resource exhaustion.

We separate the effect of technical progress from the effect of resource exhaustion by including a variable measuring the relative importance of open-pit mines as a proxy for technical progress, which allows the time trend to capture the residual influence of resource exhaustion. The shift in Australian coal mining from a primarily underground mining industry to a predominantly open-cut mining industry over the sample period reflects technical advance, in that input requirements for open-pit mining are generally lower. The transition has occurred gradually due to the fixed capital that had been committed to underground mining prior to the development of modern open-pit mining methods. Thus, we expect the impact of technical progress to be associated with the rise in the ratio of open-pit mine output to underground mine output.[1]

The translog cost function model used for our estimates is described in Section 2. The variables and data sources used in estimation are described in Section 3. Empirical results are reviewed in Section 4, which also includes tests of various restrictions on the translog form to determine whether coal mining can be better described with a less flexible functional form. We conclude with our observations on the interplay of technical change and resource exhaustion in Australian coal mining.

II The Model

Australian coal mining is modelled using a cost-function approach. We utilise a cost function rather than a production function, as it is more likely that the input prices faced by the industry, rather than input quantities, are exogenous under the assumption of perfectly competitive markets.[2] In comparison to other specifications, such as the Cobb-Douglas and CES functional forms, a feature of the translog functional form is that input substitution elasticities can change over the range of values of the independent variables. A generalised translog cost function as a function of three input prices (the rental price of capital, (R) labour, (L) and materials (M)) and characterised by non-homothetic, disembodied technical change (Christensen et al, 1973) is:[3]

$$
\begin{aligned}
\ln C = \alpha_0 &+ \sum_i \alpha_i \ln P_i + \alpha_t t + \alpha_{tp} \ln tp + \alpha_q \ln q + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln P_i \ln P_j \\
&+ \sum_i \alpha_{ti} t \bullet \ln P_i + \sum_i \alpha_{tpi} \ln tp \bullet \ln P_i + \sum_i \alpha_{qi} \ln q \ln P_i + \alpha_{qt} \ln q \bullet t \\
&+ \alpha_{qtp} \ln q \bullet \ln tp + \frac{1}{2}\alpha_{qq} (\ln q)^2 + \alpha_{tpt} \ln(tp) \bullet t + \frac{1}{2}\alpha_{tt} t^2 + \frac{1}{2}\alpha_{tptp} (\ln tp)^2
\end{aligned} \tag{1}
$$

where i, j = R, L and M; t = time; tp = technical proxy; q = output and $\alpha_{ij} = \alpha_{ji}$, $\alpha_{ti} = \alpha_{it}$, $\alpha_{tpi} = \alpha_{itp}$, $\alpha_{qi} = \alpha_{iq}$, $\alpha_{qt} = \alpha_{tq}$, $\alpha_{qtp} = \alpha_{tpq}$ and $\alpha_{tpt} = \alpha_{ttp}$. Note that this general specification includes the passage of time (t) and a technical change proxy (tp), which is defined as the ratio of open-cut mines to underground mines.

Estimation is simplified by assuming that returns to scale are constant implying:[4]

$$\alpha_q = 1,\ \alpha_{\mathrm{qi}} = 0,\ \alpha_{\mathrm{qt}} = 0,\ \alpha_{\mathrm{qtp}} = 0,\ \alpha_{\mathrm{qq}} = 0\ ,\ \forall \mathrm{i}$$

so that equation (1) can be rewritten as a unit cost function:

$$
\begin{aligned}
\ln UC = \alpha_0 &+ \sum_i \alpha_i \ln P_i + \alpha_t t + \alpha_{tp} \ln tp + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln P_i \ln P_j \\
&+ \sum_i \alpha_{ti} t \bullet \ln P_i + \sum_i \alpha_{tpi} \ln tp \bullet \ln P_i + \alpha_{tpt} \ln(tp) \bullet t + \frac{1}{2}\alpha_{tt} t^2 + \frac{1}{2}\alpha_{tptp} (\ln tp)^2
\end{aligned} \tag{2}
$$

where i, j = R, L and M; t = time; tp = technical proxy; q = output; and $\alpha_{\mathrm{ij}} = \alpha_{\mathrm{ji}}$, $\alpha_{ti} = \alpha_{it}$, $\alpha_{tpi} = \alpha_{itp}$ and $\alpha_{\mathrm{tp,t}} = \alpha_{\mathrm{t,tp}}$. As is typical in cost function analyses, the function is restricted to be homogeneous of degree one in prices, so that: [5]

$$\sum_i \alpha_i = 1\ ,\ \alpha_{\mathrm{ii}} = -\sum_j \alpha_{ij}\ ,\ \forall\, i,\ \ j \neq i\ ,\ \sum_i \alpha_{ti} = 0 \text{ and } \sum_i \alpha_{tpi} = 0$$

Using Shephard's Lemma (Shephard, 1953), we derive share equations for each input by taking the first derivative of equation (2) with respect to each of the input prices as follows:

$$S_i = \frac{\partial \ln C}{\partial \ln P_i} = \frac{\partial C}{C} \bullet \frac{P_i}{\partial P_i} = \frac{\partial C}{\partial P_i} \bullet \frac{P_i}{C} = \frac{P_i x_i}{C} = \alpha_i + \alpha_{ii} \ln p_i + \sum_j \alpha_{ij} \ln P_j + \alpha_{ti} t + \alpha_{tpi} \ln tp, \;\; \forall\, i \tag{3}$$

These input share equations, when estimated simultaneously with the cost function, increase the degrees of freedom and the efficiency of the estimates. By construction, the share equations sum up to one. Therefore, to prevent singularity in the covariance matrix when estimating the system, one of the share equations must be dropped. As discussed in Berndt (1991) the parameter estimates, log-likelihood values and estimated standard errors are invariant to which equation is dropped when the system is estimated by maximum likelihood methods.

Investigating productivity and technological progress within a cost function framework is based on duality theory.[6] Duality theory (Shephard, 1953 and then Uzawa, 1962) says that a well-behaved cost function satisfying the following conditions: non-negative; linearly homogeneous in input prices; non-decreasing in output and input prices; concave in input prices and; continuous in output and input prices can be used to derive the technology exhibited by a well-behaved production function. In other words, it is possible to use a cost function to identify the economically meaningful features of the underlying production technology.[7] A further condition, that the cost function is differentiable, allows the application of Shephard's Lemma and the derivation of share equations.

As discussed earlier, to ensure compliance with the regularity conditions for well-behaved cost functions, linear homogeneity in input prices is imposed prior to estimation. A further regularity condition is that the cost function is concave in input prices. A necessary condition for concavity in input prices is that the n x n matrix of second-order derivatives $\left(\partial^2 \ln C / \partial \ln p_i \, \partial \ln p_j\right)$ is negative semi-definite at each observation. The flexibility of the translog form means that concavity is not arbitrarily imposed but must be explicitly tested.

Substitution elasticities describe the shape of the production isoquants, so that shallow curve isoquants have large substitution effects and sharply curved isoquants have small substitution effects. In the two-variable case, Hicks (1963) defines the direct elasticity of substitution between two inputs i and j, σ_{ij}^{D}, as the percentage change in the input ratio following a percentage change in the marginal rate of technical substitution, where two inputs are substitutes in production if $\sigma_{ij}^{D} > 0$ and complements in production if $\sigma_{ij}^{D} < 0$. Allen (1938) uses a measure for the n-input case by allowing for cross affects between inputs, σ_{ij}^{A}, which is interpreted in the same way as the Hicks elasticity and is equal to the Hicks elasticity when there are only two inputs. When a firm is cost minimising, the Allen partial elasticity of substitution shows how input demands change in response to a change in input prices. It can also be shown that the Allen partial elasticity of substitution can be rewritten as $\sigma_{ij}^{D} = \varepsilon_{ij}/S_j$ where ε_{ij} is the elasticity of derived demand and S_j is the cost share of input j.

Uzawa (1962) shows that the Allen partial elasticities of substitution for a general dual cost function can be calculated as:

$$\sigma_{ij} = \frac{C \bullet C_{ij}}{C_i \bullet C_j} \tag{4}$$

where $C_{i,}$, C_j and C_{ij} are the first and second partial derivatives respectively of the cost function (C) with respect to input prices P_i and P_j. For the translog cost function, the Allen partial elasticities of substitution are (see Berndt 1991):

$$\sigma_{ij} = \frac{\alpha_{ij} + S_i S_j}{S_i S_j} \quad \text{for } i \neq j \qquad \text{and} \qquad \sigma_{ii} = \frac{\alpha_{ii} + S_i^2 - S_i}{S_i^2} \quad \text{for } i = j \tag{5}$$

where S_i and S_j are the cost shares of inputs i and j, respectively. Berndt (1991) suggests that in deriving the elasticities fitted shares should be used and that these should be evaluated at the midpoint of the dataset.

Within a cost framework, the rate of technical progress is described by a decrease in costs holding all input prices and output constant (also known as cost diminution). This concept of technical change includes the effect of improved mining techniques. In this study we use a general non-homothetic model of technical progress using a technical proxy based on the ratio of coal production in open-cut mines to coal production in underground mines. It is generally accepted that open-cut mining is more efficient and therefore less expensive on a per unit basis than underground mining.

It would be preferable to model open-cut and underground cost functions separately. However, data limitations prevent this being done. Instead, we attribute cost savings due to mining technique through the technical proxy term. Specifically, the rate of technical change or rate of cost diminution is found by taking the first derivative of the cost function with respect to the natural log of technical proxy (tp):

$$\theta_{tp} = \frac{\partial \ln C}{\partial tp} = \alpha_{tp} + \alpha_{tptp} \ln tp + \alpha_{tpt} t + \sum_i \alpha_{itp} \ln P_i \tag{6b}$$

A cost function characterised by $\theta_{tp} < 0$ indicates technical progress, $\theta_{tp} = 0$ characterises no technical change and technical regress is captured when $\theta_{tp} > 0$. Hicks-neutral technical change occurs when $\alpha_{itp} = 0$ for all i reflecting technical change that causes a parallel shift of the isoquants, irrespective of the inputs used. We then calculate a residual rate of cost change, which we attribute to resources exhaustion, by taking the first derivative of the cost function with respect to time:

$$\theta_t = \frac{\partial \ln C}{\partial t} = \alpha_t + \alpha_{tt} t + \alpha_{tpt} tp + \sum_i \alpha_{it} \ln P_i \tag{6a}$$

Suitable cost data covering the total cost of all inputs, especially capital input, used in the coal industry are not available. However, under long-run equilibrium price is equal to cost. To this end, we specify that the natural log of the long-run equilibrium price of coal, $\ln P^*_{coal,t}$, is equal to the natural log of unit cost,

$$\ln P^*_{coal,t} = \ln U\mathrm{C}_{\mathrm{t}} \tag{7}$$

and that the natural log of the short-term price of coal, $\ln P_{coal,t}$, partially adjusts to differences in this equality. Thus,

$$\ln P_{coal,t} - \ln P_{coal,t\text{-}1} = \lambda(\ln P^*_{coal,t} - \ln \mathrm{P}_{coal,t\text{-}1}) + \varepsilon_t \tag{8}$$

It is further expected, given the nature of coal and its relationship with oil, that the natural log of the price of oil will impact on the natural log of the price of coal such that:

$$\varepsilon_t = \beta(\ln P_{oil,t} - \ln P^{*}_{oil}) + \upsilon_t \qquad (9)$$

where υ_t is a well-behaved error term. Combining equations (7), (8) and (9) defines the estimating equation as:

$$\ln P_{coal,t} = \lambda(\ln UC_t) + (1-\lambda)\ln P_{coal,t-1} + \beta(\ln P_{oil,t} - \ln P^{*}_{oil}) + \varepsilon_t \qquad (10)$$

In equation (10) the rate of adjustment of the natural log of coal prices to the natural log of unit cost is measured by λ, whilst the sensitivity of the natural log of coal prices to changes in the natural log of oil prices is captured by β. This equation is estimated along with the system of equations defined at (3). The parameter estimates are then used to calculate the rate of cost change with respect to time and the rate of cost diminution that with respect to the ratio of open cut to underground mining as defined by equations (6a) and (6b), respectively.

III Data

This study uses Australian annual coal data on all coal types (black and brown) for the 34 year period, 1968-69 to 2001-02. Data limitations mean that it is not possible to model the coal type or the mining method separately. Either of these approaches would be preferable as the two methods of mining and coal types use different technology and input combinations.[8] While Donnelly and Dragun (1984) take this approach, changes in the form of the data published since their study prevents their approach being used here.[9]

Price indices for labour and materials (P_L, P_M) are taken from various issues of ABS catalogue 8415.0: *Mining Operations*. The rental price of capital, P_R, is defined as, $P_R = (1/m + i)P_k$. Where m is the average age of the gross capital stock, i is the 10-year bond rate (opportunity cost) and P_k is the price of new capital. These data are taken from ABS Cat 5204, *Capital Stock by Industry* and various *RBA Bulletins*. Coal prices are derived from revenue data, which is found in ABS catalogue 8415.0: *Mining Operations*. Labour and materials shares are calculated from data given in various issues of ABS catalogue 8415.0: *Mining Operations*, 8221.0 *Manufacturing Industry*, Australia and tables from the Electricity Suppliers Association (www.esaa.com.au). The capital share is given as the residual of revenue minus labour and materials costs.

The technology index is defined as the ratio of output from open-cut mines to output from underground mines. There is an observable trend in the industry with an increasing amount of coal mining carried out using open-cut methods. With firms being cost minimising, this suggests that the open-cut method is more productive. Data to construct the technology index are taken from Coal Services Pty Ltd, *Australian Black Coal Statistics*, 2002. Finally, the index for crude oil prices in Australian dollars is derived from crude oil prices reported by the Department of Energy, http://www.eia.doe.gov and the OECD, *Main Economic Indicators*.

IV Results

To estimate our rates of cost diminution we estimate 3 different models:

A. The simplest model assumes that prices are in perfectly competitive long-run equilibrium, so that there is no distinction between unit cost and prices. We estimate equation (2) along with the set of equations specified at (3).

B. The second model allows for oil price shocks to create a divergence between the unit cost of coal and the price of coal,

$$\ln P_{coal,t} = \ln UC_t + \varepsilon_t$$

where $\varepsilon_t = \beta(\ln P_{oil,t} - \ln P^*_{oil}) + \upsilon_t$, υ_t is a well-behaved error term and $\ln P^*_{oil}$ is the long-run average oil price over the sample period. This yields

$$\ln P_{coal,t} = \ln UC_t + \beta(\ln P_{oil,t} - \ln P^*_{oil}) + \upsilon \quad (11)$$

We then estimate equation (11) along with the set of equations specified at (3), assuming that the share equations are not altered by oil price shocks.

C. The final model we estimate incorporates oil price shocks as in (11), while allowing coal prices to only partially adjust to deviations from the long-run coal price. We then estimate equation (10) along with the set of share equations described in (3).

A stochastic framework is specified where additive error terms are appended to each of the factor share equations to reflect unexplained factors that impact on cost shares (such as measurement error by the data collectors and/or the possibility that firms make random errors in choosing their cost-minimizing input bundles). Ordinary least Squares (OLS) could be used to estimate each factor share equation separately. However, this ignores the additional information available from imposing cross-equation restrictions. The cross-equation restrictions result from the application of Young's Theorem to equation (1). We also impose the restrictions implied by assuming the cost function is homogenous of degree one in input prices and exhibiting constant returns to scale. Equation by equation estimation by OLS also ignores the additional information available when error terms are correlated across observations. This is likely to be the case when share equations are dependent on the same industry conditions. To take into account these factors, Seemingly Unrelated Regression (SUR) estimation is used to jointly estimate the systems of equations described by models (A), (B) and (C). (Zellner, 1962).

By construction, the share equations add up to one and therefore one of the share equations is a linear function of the others. To prevent singularity in the residuals, one of the factor share equations is dropped. Joint estimation is then based on two of the factor share equations and the coal price equation, so that all parameters are included. We assume that the error terms are normally distributed with a zero mean, that they have a constant variance over time, and that there is contemporaneous correlation between equations (but impose zero covariance over time). We estimate the parameters of the SUR system using an iterative maximum likelihood procedure. As discussed in Barten (1969) the parameter estimates are invariant to which share equation is dropped, as long as the estimates are indeed maximum likelihood estimates (or, equivalently, iterative generalised feasible least squares estimation is used).

Fundamental requirements of a well-behaved cost function include monotonicity (so that an increase in input prices does not decrease cost) and concavity in input prices. For a cost function to be monotonic, the fitted shares (the first derivative of cost with respect to input prices) must be positive, this is checked and found to be the case over the sample period. As discussed in Berndt (1991), concavity requires that the matrix of substitution elasticities be negative semi-definite. Eigenvalues for these matrices are calculated at the mid-point of the sample and found to be consistent with a negative semi-definite matrix.[10]

Using the Durbin-Watson statistic, the hypothesis of autocorrelation could not be rejected on the share equations or the price function in any of the models. The system is therefore re-estimated, taking into account 1st order auto-correlation. This leads to the results for the three models given in Table 1. The values for the rates of cost change due to our technical proxy and due to time, fitted shares and elasticities for models A and B are midpoint values, whilst the values for model C are taken from the corresponding observation (given that the sample size decreases by one data point when the price of coal is lagged).

TABLE 1 NEAR HERE

Lambda is the coefficient on the coal price partial adjustment term. Theory suggests that lambda is positive and less than one. For example, when an unexpected shock increases the short-term price of coal relative to the long-run equilibrium price, the subsequent short-run price of coal should decrease. The estimated lambda in Table 1 is within these bounds and suggests that movements in the short-term coal price are bounded by some long-term coal price. It is also expected that beta is positive, so that a positive shock to oil prices increases the current price of coal relative to unit production cost. This term is found to be significant only in the partial adjustment model.

We also test the significance of the cost change coefficients for both time and the technical progress proxy. We find that theta tp, the derivative of cost to our technical progress proxy is negative and that theta t, the derivative of cost to time is positive in all three models, with each coefficient statistically significant. This fits the expectation that the technical proxy measures cost-reducing technical change in the coal industry associated with the shift from underground to open-cut mining. The time coefficient captures residual cost changes associated with the passage of time, which includes the cost-increasing impact of resources exhaustion. Thus, there is clear evidence of offsetting cost changes over time associated with the technical progress, as captured by the trend towards open-cut mining, and resource exhaustion, as captured by the residual time trend.

The impact of technical progress and resources exhaustion of coal mining is further examined by calculating their impact at the sample midpoint, incorporating interaction with other variables. The estimated technical progress impact is negative and the time impact is positive in Models A and B, with highly significant p-values ranging from .00008 through to .00881. The signs of the impacts are reversed at the equivalent point in the estimates for Model C, but neither estimate is statistically significant.

Mid point values for the Allen partial elasticities of substitution (σ_{ij}) and own price elasticities of demand (ε_{ii}) are shown in Table 2. Own price elasticities of demand and Allen partial elasticities of substitution evaluated at the midpoint of the sample are all negative, which is consistent with economic theory. The estimates of demand elasticities show each input demand is price inelastic. Capital exhibits very low and generally not statistically significant own-price elasticity, indicating that its price has minimal effects on quantity of these inputs demanded in coal mining.[11] These low elasticities lend support to the idea that engineering requirements are such that capital and labour requirements of Australian coalmines are not responsive to input prices. This is further supported by the relatively low partial cross-price elasticities between capital and labour. Capital equipment such as conveyors, draglines, dumpers, dozers or hydraulic props do not allow easy substitution with labour alternatives, leading to low elasticity values. However, all inputs are shown to be substitutes to each other, supporting Kadekodi's (1990) findings.

TABLE 2 NEAR HERE

The combined impacts of input prices, technical proxy and time on the unit cost of coal mining are depicted in Figure 1 for Models A and B. Cost is shown as rising over time, largely due to rising input costs[12]. The residual influence of time, which we attribute to resource exhaustion, also tends to increase cost. However, these cost-increasing influences are partially offset by the impact of technical progress in the form of a shift from underground to open-cut mining.

FIGURE 1 NEAR HERE

V Conclusions

The Australian coal mining industry over the last 30 years has seen major developments, particularly with growth in large-scale, open-cut mines and improved technology embodied in plant and equipment. Further, the response to higher competition levels in the mid-1980's has been towards greater output levels and reducing labour inputs. In this study, a flexible, non-homogenous translog cost function is shown to provide a satisfactory econometric model of the changing conditions in the industry.

The empirical results show that own-price and cross-price elasticities of demand for capital and labour are low, indicating that input combinations are not very flexible with respect to input prices. However, the estimates of the own-price elasticity for labour are all statistically significant, showing that rising wages explain at least part of the decline in the industry's labour force, in spite of rising output levels, in the 1980s and 1990s.

Technology improvement occurring as a result of the shift from underground to open-cut mining is estimated to have significantly reduced mining cost. This influence has been more than offset by rising input costs and the influence of resource exhaustion (as captured by the residual impact of time on mining costs). Thus, unit costs have risen in the industry over the period of study, 1968-9 to 2001-2, but at a lower rate than would have been experienced in the absence of progressive changes in mining method.

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Figure 1: Decomposition of Cost Changes – Model A

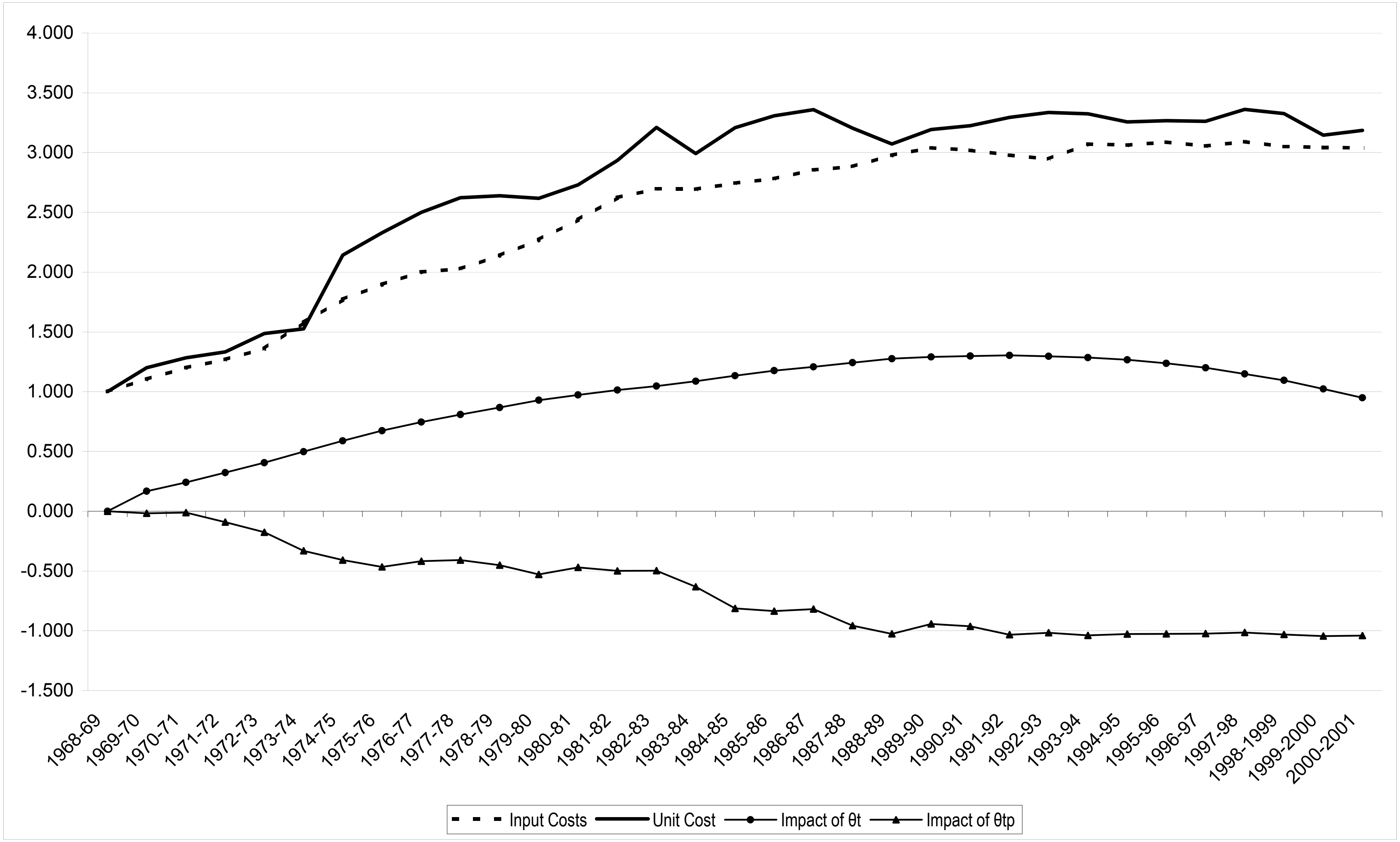

Figure 1: Decomposition of Cost Changes – Model B

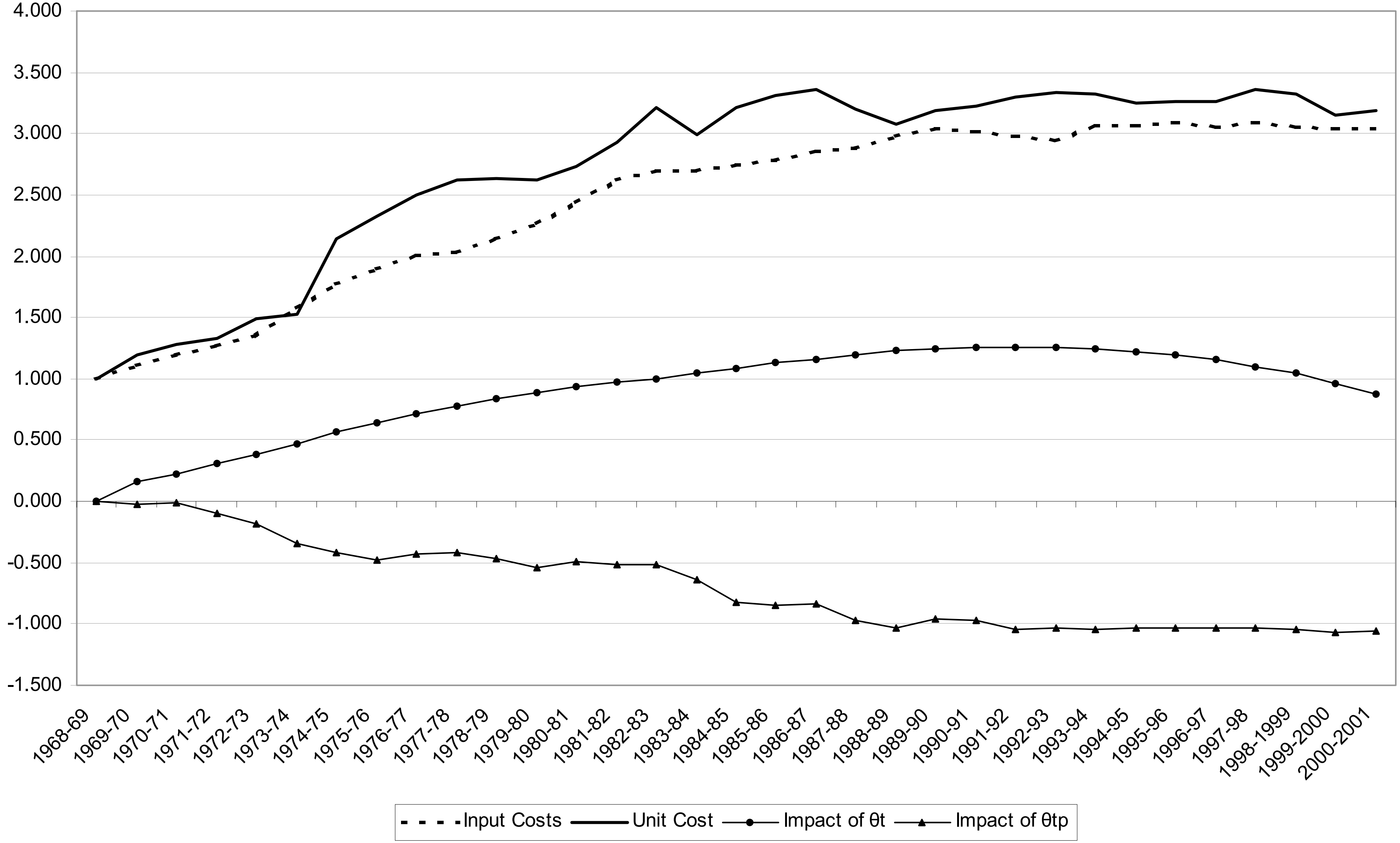

Table 1 Results for Models A, B and C [a]

	Lambda (λ)	Beta (β)	Cost Change Time	Cost Change Ln TP	Cost Change Time (Ave.)	Cost Change Ln TP (Ave.)	Fitted Share of Capital	Fitted Share of Labour	Fitted Share of Materials	Concavity condition met[b]
Model A: Basic Model			0.047	-0.982	0.029	-0.596	0.692	0.206	0.102	yes
p-value			0.00008	0.00084	0.00216	0.00963				
Model B Oil Price Shocks in the current period only		0.017	0.047	-0.979	0.027	-0.579	0.692	0.206	0.102	yes
t-stat		0.316								
p-value			0.00017	0.00128	0.008847	0.01493				
Model C Shock through Oil Prices and partial adjustment of coal prices	0.443	0.120	0.052	-1.463	-0.019	0.037	0.701	0.196	0.100	yes
t-stat	4.144	2.436								
p-value			0.0081	0.00241	0.47626	0.92883				

Notes:

a. The data given in the table for cost diminution (average) and fitted shares are for midpoint values.
b. Concavity relates to whether the cost function satisfies the condition that for strict quasi-concavity the matrix of substitution elasticities must be negative semidefinite.

Table 2: Elasticity estimates from results for Models A, B and C [a]

	Own AES (L)	Own AES (K)	Own AES (M)	AES (LM)	AES (LK)	AES(KM)	Own PED (L)	Own PED (K)	Own PED (M)
Model A: Basic Model	-1.412	-0.126	-3.087	0.75724	0.30912	0.22853	-0.291	-0.087	-0.314
p-value	*0.01874*	*0.25579*	*0.37610*	*0.44505*	*0.106062*	*0.68104*	*0.01874*	*0.25579*	*0.37610*
Model B Oil Price Shocks in the current period only	-1.357	-0.124	-2.970	0.68756	0.3024	0.23263	-0.279	-0.086	-0.303
p-value	*0.02669*	*0.23784*	*0.40302*	*0.50344*	*0.11208*	*0.66235*	*0.02669*	*0.23784*	*0.40302*
Model C Shock through Oil Prices and partial adjustment of coal prices	-1.7586	-0.283	-2.0574	-1.2235	0.67137	0.63614	-0.347	-0.198	-0.212
p-value	0.00642	0.00365	0.57950	0.30266	0.0030	0.22400	0.00642	0.00365	0.57950

Note: All values are calculated at the midpoint

Endnotes

[1] Any technical progress in underground mining or ongoing operations at open-pit mines may be still reflected in the coefficient of the time trend, which would lead to an upward bias in our estimate of the impact of resource exhaustion.
[2] Note that input quantities may be endogenous within the production function as cost function minimisation is a necessary condition for profit maximisation and therefore input quantities are determined simultaneously with output quantities. Failure to take account of this results in simultaneous equation bias.
[3] The technical change is disembodied in the sense that it can be applied equally over the existing capital stock or labour force regardless of vintage or skill, respectively.
[4] In a competitive industry individual firms maximise profits in long-run equilibrium by operating at a point of local constant returns to scale. However, there may be external effects of firm expansion on other firms, leading to non-constant returns to scale at the industry level. Also, the cost function is estimated with a disturbance term, implying disequilibrium at some level. Experimentation with allowing for non-constant returns by including output variables does show some evidence of non-constant returns, but multicolinearity with time and the technical progress variables makes interpretation of the coefficients problematic. Results including quantity variables are available from the authors.
[5] This implies that if all prices double, total cost will also double.
[6] A comprehensive description of the theory can be found in Chambers (1988).
[7] Note that there may be some issues in relation to reproducing non-convex areas in the isoquants but as these are ignored by rational entities it doesn't matter that these cannot be reproduced.
[8] An alternative way to capture differences in mining method is to analyse NSW and Queensland coal industries individually (NSW is predominantly underground and Queensland open cut).
[9] The Australian Bureau of Statistics (ABS) reports black coal statistics prior to 1982-83, brown coal statistics for the period 1982-83 to 1987-88 and an all-coal category after 1987-88. The two types of coal prior to 1987-88 are combined to produce a dataset based on total coal regardless of type.
[10] Details of the tests are available from the authors.
[11] This compares to the results reported by Donnelly and Dragun (1984) and Kadekodi (1990), who find capital and labour demand for underground mines to be price elastic, while the corresponding demands are price inelastic for open-cut mines.
[12] No corresponding chart is shown for Model C. The point estimates of the impact of technical change and time for individual years vary substantially and distort the scale of the chart. This variability is also reflected in the low probability values for the average impact estimates for time and technical change reported in Table 1.