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In this paper, the adoption of electric arc furnace steelmaking technology is examined within a growth model of technological diffusion. The results indicate that the trend rate of adoption of electric arc furnace technology is well represented by the S-shaped growth curve. Further results indicate that the trend rate of adoption is, for the most part, stable with respect to locally changing factors to production, such as input prices and activity levels. It appears that inertial aspects have an overwhelming influence on the diffusion process.

I. INTRODUCTION

World steel production has increased quite markedly over the last two decades. In 1970 world crude steel production totalled 595 Mt and by 1990 had reached 770 Mt. This increase in production came from two different types of steel making technologies - integrated steel works, using basic oxygen or open hearth steel making methods which use iron ore and coking coal as major inputs, and the electric arc furnace, which uses steel scrap and electricity as the major inputs. Of the increase in world steel production between 1970 and 1990, 75% was accounted for by electric arc furnaces.

The proportion of crude steel produced via the electric arc furnace has important implications for the demand for raw steelmaking materials-particularly iron ore and coking coal. The electric arc furnace substitutes scrap for these raw materials. The continued adoption of electric arc furnace technology in the world's major steel producing regions could have a significant impact on future iron ore and coking coal demand.

In this paper, we examine the adoption of electric arc furnace technology within a growth model of technological diffusion. The growth model has been successfully employed by researchers in analysing the diffusion process of a wide range of technologies (see, for example, Griliches, 1957; Chow, 1967; Dixon, 1980; Bewley. and Fiebig, 1988). In using the diffusion model, we were able to estimate the trend in the adoption of a technology. Given such a trend, we then examined whether observed deviations in this trend systematically alter with movement in variables which may be relevant to the adoption of the technology. We hope that the results of our research will allow for a better understanding of the impact of changing factors, such as input prices and activity levels, on the diffusion process.

In the next section of this paper, we describe the basic aspects of the technology. In Section III we present the application within the framework of a static model of diffusion. In Section IV, we employ a more flexible diffusion model to examine the effect of changes in key variables in terms of short run, or adaptive adjustment to temporary deviations in factors such as changing relative prices of inputs, and the level of output. In Section V we examine the long run effect of sustained changes in these factors. Some conclusions are drawn in Section VI.

II. ELECTRIC ARC FURNACE TECHNOLOGY

The process of producing steel via the electric arc furnace route is quite different from the process used in the more traditional integrated steel mills. The steelmaking process within an integrated steel mill requires extensive preparation of raw materials, particularly iron ore and coking coal. The production process in an electric arc furnace requires considerably fewer steps. Steel scrap is fed into the electric arc furnace which melts the scrap into molten steel and residual slag. The molten steel is then separated from the slag and transferred to a ladle furnace for further processing. In the ladle furnace alloys are added to produce the required quality of steel. The molten steel is then cast into semi-finished steel products which are then processed in the same way as steel from integrated mills.

The commercial production of steel via the electric arc furnace started as early as 1899. However, widespread production of steel by this route has occurred only recently. The increase in production from the electric arc furnace has come primarily from the development of the minimill-a combination of electric arc furnace and continuous casting technology. These minimills primarily produce long products which are mostly used in the construction industry.

Minimills appear to have an advantage over integrated mills in that they can produce long products at lower per unit costs than integrated plants. For example, Barnett and Crandall (1986) calculated that the cost of producing wire rods in 1985 was about 30% lower in minimills than in integrated mills in the United States.

Electric arc furnaces also have an advantage over integrated plants in that they tend to have less impact on the environment, and require less than half as much energy as blast furnace production of steel (International Iron and Steel Institute, 1983). The electric arc furnace consumes scrap steel which would be difficult and costly to dispose of otherwise and does not produce many of the undesirable by products which integrated steel plants produce. The coke ovens, blast furnace and basic oxygen furnace of an integrated plant produce significant amounts of carbon dioxide, carbon monoxide and other undesirable emissions. Apart from noise pollution, which can be controlled, the electric arc furnace process does not produce any more pollution than most manufacturing processes. As a result, electric arc furnace operations have been located in suburban areas with minimal impact. It should be noted, however, that the electricity used in the electric arc furnace process involves an environmental cost, and this cost will depend on the fuel used in the electricity-generation process. The upstream environmental costs of operating an electric arc furnace, however, would appear to be small relative to the direct environmental costs of operating an integrated steel plant.

Minimills are, however, somewhat limited in the proportion of the market they can capture because of the limited variety of products they produce. Flat products, which include steel sheets used in automobiles and other consumer durables, are not generally produced by minimills owing to quality considerations which arise from the residual impurity of the scrap base. As such, it is unlikely that the electric arc furnace will completely replace the blast furnace in the production of steel.

III. MODELLING THE DIFFUSION OF THE ELECTRIC ARC FURNACE IN STEELMAKING

The adoption of a new technology, whether in the form of a process or product, is rarely instantaneous; it is rather gradual, given adjustment costs, physical constraints, lack of information or other such factors. Researchers (see, for example, Griliches, 1957; Chow, 1967; Dixon, 1980; and Bewley and Fiebig, 1988) have noticed that the diffusion of new technologies often proceeds in a fairly systematic manner, which has been successfully modelled within the framework of S-shaped growth curves.

The intuitive appeal of the growth model is that it incorporates the notion that, at the early stage of diffusion, growth often develops at a relatively slow pace. As the diffusion process continues, so does the rate of growth, possibly due to the increase in information as the use of the technology expands (see, for example, Mansfield, 1961; and Stoneman, 198 I). Finally, as the level of diffusion converges to its long-run equilibrium level, the rate of growth decreases until the diffusion process is complete. Differences in the age and profitability of existing capital equipment (Stoneman, 1983); and differences in attitudes towards risk (Oren and Schwartz, 1988) are other factors which may lead to S-shaped growth curves. We might thus expect the general class of S-shaped curves to be helpful in modelling a large range of diffusion processes.

Operationally, the growth model has proved to be a powerful summary of the many underlying economic relations which determine the adoption of a technology. Many of these relations are often neither well understood, nor directly observable. The growth model offers a method by which to describe certain characteristics of this complex economic system.

Table 1. *Proportion of crude steel output produced in electric arc furnaces*

	Western Europe	United States	Japan
1970	0.172	0.153	0.167
1971	0.172	0.174	0.176
1972	0.176	0.178	0.186
1973	0.179	0.184	0.179
1974	0.190	0.197	0.178
1975	0.217	0.194	0.164
1976	0.229	0.192	0.186
1977	0.238	0.222	0.191
1978	0.253	0.235	0.219
1979	0.254	0.249	0.236
1980	0.270	0.279	0.245
1981	0.271	0.283	0.248
1982	0.298	0.311	0.266
1983	0.301	0.315	0.284
1984	0.302	0.339	0.277
1985	0.299	0.339	0.290
1986	0.301	0.372	0.297
1987	0.305	0.381	0.298
1988	0.308	0.369	0.297
1989	0.318	0.359	0.306
1990	0.323	0.368	0.314

Source: *IISI* (various issues).

This form of trend analysis seems particularly well suited for examining some of the major characteristics of the adoption of electric arc furnace technology. An evaluation of the data (Table 1) reveals a slow, but constant, upward trend in electric arc furnace production share over the past 20 years. Intuitively, it seems reasonable to expect the adoption of electric arc furnace technology to take quite a while given the huge amounts of capital sunk in existing integrated plants. As these plants are decommissioned, electric arc furnace shares have tended to increase. This is particularly evident in the United States, where around 40 Mt of obsolete open hearth furnace technology was decommissioned during the period 1970 to 1990.

Although total steel production fell by around 30 Mt over the 1970s and 1980s, production from electric arc furnaces increased by over 14 Mt. In contrast, total Japanese steel production increased by 17 Mt between 1970 and 1990. Over this period there was a 19 Mt increase in steel production from the electric arc furnace sector, while producers using basic oxygen furnace technology increased production by only 2 Mt, and 4 Mt of obsolete open hearth furnace based plants were decommissioned. The 1970s and early 1980s appear to have been the high growth period in electric arc furnace adoption worldwide. More recently, the growth in electric arc furnace production share has tapered off. Barnett and Crandall (1986) have suggested that a continued increase in electric arc furnace production will be constrained by demand for production by electric furnace technology, and the availability of scrap.

A model of diffusion

A growth model common to the literature is represented in differential form as,

$$dy_t/dt = \beta y_t(y^* - y_t) \qquad (1)$$

The adjustment, or rate of growth, as represented by the time derivative dy,/dt, is proportional to the level of y,, which in this case is the level of steel produced by the electric arc furnace over a given period, and the difference between this level and the long run equilibrium level y*. The coefficient β is a measure of the speed of adjustment and determines the slope of the curve implicit in Equation

1. An important feature of this model is that the rate of growth is greatest when the diffusion process is at 50% of its long run equilibrium value which occurs when y, = y*, with the rate of growth symmetric about this inflection point. Following Chow, we use a discrete approximation of Equation 1 for estimation by replacing the time derivative of y, with its difference y,- y,-,. The approximation is represented as:

$$y_t - y_{t-1} = \beta\, y_{t-1}\,(y^* - y_{t-1}) + v_t \qquad (2)$$

The curve implicit to Equation 2 is defined by the two parameters, β and y*. Equation 2 can be rearranged in order to allow for standard estimation procedures:

$$y_t - y_{t-1} = \theta y_{t-1} - \beta y_{t-1}^2 + v_t \qquad (3)$$

where θ is defined as by βγ*. θ and β can be estimated directly, and y* can be recovered given the definition of θ. The quadratic represented in Equation 3 retains the essential properties of Equation 1. The diffusion follows an S-shape, with the rate of growth relatively small in both the early (y, close to 0) and late stage of adoption (y, close to y*), and converges to a stable equilibrium value as determined by the parameter y*.

The basic growth model as represented in Equation 1 can be modified and estimated in numerous ways. The most common is the logistic,[1] which is symmetric about an inflection point of 50% of its long-run equilibrium. An often used alternative to the logistic is the Gompertz curve, which is asymmetric, with an inflection point at 37% of its long run equilibrium. Bewley and Fiebig (1988) present a modified logistic, which allows for a time varying speed of adjustment coefficient, which implicitly determines the point of inflection. We compared the relative merits of these alternative models (or approximations, where necessary) under various stochastic representations, and determined the form presented in equation 3 to be the most appropriate for our data set.

Some further points should be made regarding the application of the diffusion model to steelmaking technology. Electric arc furnace production is actually a process imbued within fixed capital, which might be measured in terms of production capacity per annum, for example. However, electric arc furnace capacity figures are not generally available. As such we have used figures on actual production of steel produced via the electric arc furnace per annum.

The second point to be made is that annual electric arc furnace production (y,), and the long run level of electric arc furnace production (y*), are partly determined by changing aggregate demand for steel. If we examine the relative proportion of electric arc furnace production to total steel production, we can filter out these aggregate demand disturbances, and focus on the diffusion of technology. This point is similar to that made by Knudson (1991), who has argued that the relative measure is more relevant than the absolute level of production since it reflects the displacement of other technologies. As such, for the rest of this paper, we will define y, as the proportion of electric arc furnace steel production to the total production of steel, and the long run value y* analogously, with both falling within the interval from 0 to 1.

We have estimated the electric arc furnace diffusion process following Equation 3 for three major steelmaking regions in which the data are readily available-the United States, Western Europe and Japan. The sample period is from 1970-90. As explained above, the observations are in terms of production share, which is simply the ratio of steel produced via the electric arc furnace to total steel

[1] Chow (1967) remarks that the solution to Equation 1 is the logistic; however, Stoneman (1983) has commented that this is not exactly true. The solution to dy/dt=by(l -y/y) is the logistic, which does vary slightly from Equation 1. In this study, the proper specification is treated as an empirical matter*

production (by weight) for a given region. A description of the data is in Appendix A. The estimated coefficients, and t-statistics are:

United States

$$y_t - y_{t-1} = \underset{(2.892)}{0.141 y_{t-1}} - \underset{(2.231)}{0.346 y_{t-1}^2} \qquad (4)$$

DW = 2.13 MAE = 0.015

Western Europe

$$y_t - y_{t-1} = \underset{(2.731)}{0.121 y_{t-1}} - \underset{(2.147)}{0.347 y_{t-1}^2} \qquad (5)$$

DW = 2.07 MAE = 0.008

Japan

$$y_t - y_{t-1} = \underset{(1.561)}{0.086 y_{t-1}} - \underset{(1.047)}{0.223 y_{t-1}^2} \qquad (6)$$

DW = 2.06 MAE = 0.011

Standard diagnostic tests suggest that the growth model represents the adoption process reasonably well. For the most part, the coefficients are significant at the 95% critical level. The point estimates of the speed of adjustment coefficient, p, are slightly different, although not significantly different as judged by the F test of equality of coefficients. While the adjustment coefficients are not different within a sampling context, the fact that the point estimates vary across regions does imply that, for this particular sample period, the speed of adoption relative to the equilibrium ceiling was greater in the United States and Western Europe than in Japan. This may be at least in part due to the fact that Japan had built much of its steelmaking capacity in the 1960s, and may have been less likely to decommission relatively efficient steelmaking plants. On the other hand, the United States and Western Europe may have had more reason to shut down existing facilities which were to a large degree, already obsolete.[2]

Tests for serial correlation can be a particularly useful diagnostic in trend analysis. Nelson and Kang (1984) have demonstrated that it is not difficult to fit a low order trend to sample data even when no trend exists. The Durbin Watson (DW) test statistic may suggest that the regression results are spurious. More generally, systematic behaviour on the part of the residuals may be evidence of misspecification, particularly with respect to the nature of the restrictive shape of the curve which we have imposed on the data. For example, it is possible to imagine fitting a linear trend to data actually generated from the S-shaped process which we are studying. The predicted values would overestimate the true values during the first half of the adoption process then underestimate the true values over the latter half. Systematic behaviour in the residuals is rejected in terms of serial correlation as judged by the DW statistic.

As a performance indicator, the predicted electric arc furnace production shares were compared to the actual shares and the mean absolute error (MAE) was calculated. The predicted production shares were computed using only the initial value observed in 1970, the estimated parameters, and the predicted values of the predetermined variables. This performance indicator is unlike the regression diagnostics since we are evaluating imputed values of the production shares, rather than the regression residuals which are in terms of first differences. The in-sample fit appears to be very good, with a mean absolute error of 0.015 for the United States, 0.011 for Japan and 0.008 for Western Europe. Since the data are already in terms of proportions, the magnitude of the mean errors can be

[2] The proportion of steel produced by the open hearth furnace (which has been obsolete for several decades) is one measure which is often used to compare the relative efficiency of a region's steelmaking capacity. As of 1970, the proportion of steel production by the open hearth furnace was 36.5OI0 in the United States, 25.7% in Western Europe, but only 4.1% in Japan.

interpreted straightforwardly. In the case of the United States, for example, the mean absolute error of 0.015 can be compared to the observed 1990 electric arc furnace production share of 0.368.

The results reported above indicate that the adoption of the electric arc furnace is well approximated by the S-shaped growth trend. However, it seems reasonable to consider whether deviations in observable market factors have an additional effect on the diffusion process. The next two sections extend the static model in order to examine the influence of some potentially relevant market factors on the diffusion process.

IV. ADAPTIVE ADJUSTMENT

The static growth model, as presented above, is based on the presumption that the structure underlying the process of diffusion is stable, even though the diffusion process itself is dynamic. Williams (1972), and Bewley and Fiebig (1988), among others, have relaxed this constraint to allow for the coefficient of the speed of adjustment P, to vary over time. In this section, we examine the basic idea of adaptive adjustment to consider the impact of exogenous factors on the diffusion process. Within the context of steelmaking technology, it seems reasonable to consider to what extent, if any, temporary market disturbances affect the short-run adjustment to the long-run equilibrium. To illustrate this more clearly, consider the following extension of the growth model as represented by equation 1:

$$\mathrm{d}y_t/\mathrm{d}t = \beta_t y_t (y^* - y_t), \qquad (7)$$

where the coefficient of adjustment is now subscripted by time. Defining β_t, as a linear function of observable exogenous market factors (Z_{it})

$$\beta_t = b_0 + \Sigma\, b_i\, Z_{it} \qquad (8)$$

and on substituting 8 into 7:

$$\mathrm{d}y_t/\mathrm{d}t = b_0 y_t (y^* - y_t) + \Sigma\, b_i Z_{it} y_t (y^* - y_t) \qquad (9)$$

This model still retains the basic time invariant trend, as represented by the first term of the right hand side of Equation 9, but also contains an adaptive component which depends on the exogenous factors Zit. Furthermore, the impact of the exogenous factors is proportional to the growth rate. As such, any given change in the exogenous factor will have a greater influence when the system is in its rapid adjustment phase than it would at either the beginning or end of the diffusion process. Following the discussion of steelmaking technology presented in the first section, the adaptive model is used to determine whether the relative price of inputs, and the product type of steel production affect the path of adoption of the electric arc furnace. The relative price of scrap to iron ore (Z,) is used as a proxy for the cost of the raw feedstock. The price of electricity relative to the price of coking coal (Z_2) captures the cost of energy inputs, and the ratio of long products to total steel deliveries (Z_3) captures the product composition of steel production most relevant to the electric arc furnace.[3]

The model used for estimation is again based on the approximation to the differential equation in difference form:

$$y_t - y_{t-1} = b_0 y_{t-1} (y^* - y_{t-1}) + \Sigma\, b_i Z_{it} y_{t-1} (y^* - y_{t-1}) + \varepsilon_t \qquad (10)$$

[3] It does appear that the system is 'approximately identified', though. While the proportion of steel produced by the electric arc furnace has had a pronounced upwards trend over the sample period, the relative price of scrap has actually fallen. As such, it seems as if the relative price of scrap is largely determined, in an empirical sense, by deviations in supply, not demand, and that the price of scrap is largely independent of deviations in the proportion of steel produced by the electric arc furnace.

To simplify the estimation procedure, we substitute the estimated values for the y* that were determined in the preceding section. As such, Equation 10 can be represented as:

$$y_t - y_{t-1} = b_0 Q_{t-1} + \Sigma\, b_i Z_{it} Q_{t-1} + \varepsilon_t \qquad (11)$$

where Q_{t-1} is the quadratic y_{t-1} (y^* - y_{t-1}).

To determine which variables have an obvious impact on the short run adjustment process, we employed the model selection criterion described by Schwarz (1978). The Schwarz criterion (SC) is based on maximizing the posterior odds of choosing the true model. Schwarz has shown that under certain conditions, the posterior odds of selecting the true model are highest when the following loss function is minimized with respect to the k variables under consideration:

$$L_t = -\log\ (\text{maximized likelihood function}) + k/2 \log n \qquad (12)$$

Intuitively, Equation 12 can be seen as a loss function which balances goodness of fit, as measured by the value of the likelihood, with the concept of parsimony, by assigning a penalty for additional regressors which is proportional to log n, where n is the number of observations.[4] For thoroughness, the SC is supplemented by the likelihood ratio test for parametric restriction.[5] The results of the variable selection tests and the log-likelihood (log-L) are shown in Table 2.

Table 2. *Variable addition tests for factors influencing the rate of adoption*

	United States		Western Europe		Japan	
Variables	SC	Log-*L*	SC	Log-*L*	SC	Log-*L*
$Z_1\ Z_2\ Z_3$	0.232	61.30	0.097	70.06	0.143	65.89
$Z_1\ Z_3$	0.200	61.29	0.091	69.14	0.131	65.52
$Z_2\ Z_3$	0.217	60.46	0.086	69.71	0.146	64.41
$Z_1\ Z_2$	0.204	61.11	0.085	69.89	0.130	65.63
Z_3	0.192	60.21	0.080	68.91	0.130	64.07
Z_2	0.187	60.45	0.074	69.68	0.138	63.50
Z_1	0.179	60.90	0.078	69.14	0.113*	65.49
Nil	0.177*	59.53	0.069*	68.86	0.119	63.50

Notes: *denotes variables to be included based on the Schwarz criterion (SC). Z_1 is the relative price of scrap to iron ore; Z_2 is the relative price of electricity to coking coal; Z_3 is the proportion of long products to total steel deliveries.

In general, the factors studied seem to have no obvious influence on the short-run adjustment process. The only variable found to influence the adjustment in electric arc furnace share was the price of scrap relative to iron ore, and only in the case of Japan. Otherwise, under the SC, the static growth curve seems to best represent the adoption of electric arc furnace technology in the short run. This result is supported by the likelihood ratio test at the 5% confidence level.

Apparently, short-run adjustment seems to be largely unaffected by factors which we had thought might be of importance. Still, it may be that we chose unreasonable proxies for the factors we thought

[4] See Amemiya (1980) for a survey of various model selection criteria.

[5] The likelihood ratio test procedure is a method used to test whether parametric restrictions are appropriate. The test statistic is defined as $2(\lambda_\mu - \lambda_t)$ where λ_μ is the log-likelihood for the unrestricted model, and λ_t is the log-likelihood for the restricted model. The test statistic is Y distributed as χ^2 with k degrees of freedom, where k is the number of restrictions placed on the model. The critical value of the chi-squared distribution with one degree of freedom is 2.71 at the 10% level, and 3.84 at the 5% level. For a discussion of the likelihood ratio test, see Engle (1984).

relevant, or simply looked at the wrong factor.[6] To judge the robustness of these results better, we further examined the problem in terms of systematic behaviour in the regression residuals.

Under the truth of the adaptive adjustment model, unobserved factors in Equation 8 will lead to a heteroscedastic error structure in regression Equation 11. This basic error structure is well understood within the random coefficients literature, and is described in Judge et al. (1985). The particular form of Equation 11 further suggests that unobserved factors will lead to regression residuals which tend to increase with the value of the quadratic term Q_{t-1} defined above as $y_{t-1}(y^*-y_{t-1})$. The test for heteroscedasticity described by Breusch and Pagan (1979) offers a reasonable framework for examining this sort of systematic behaviour in residuals. To perform this test, we obtained the residuals from the preferred models defined in Table 2. The squared residuals were then regressed on the quadratic term and a constant:

$$\varepsilon_t^2 = \alpha_0 + \alpha_1 Q_{t-1} + v_t \qquad (13)$$

The test for systematic behaviour in the residuals is reduced to a Lagrange multiplier (LM) test for the parametric restriction a, = 0.

Table 3. *Test for adaptive adjustment heteroscedasticity*

Region	United States	Western Europe	Japan
LM test statistic	0.098	1.232	3.140

Note: The LM test statistic is distributed as a χ_k^2 where k is equal to the number of parametric restrictions. The 5% critical value for the χ_1^2 is 3.84.

We found no evidence to indicate the presence of systematic behaviour in the regression residual based on the adaptive adjustment model. The results shown in Table 3 support the results of the more restrictive model selection tests and indicate that (except in the case of relative scrap prices in Japan) the speed of adjustment coefficient is well represented as a fixed parameter. In other words, the electric arc furnace adjustment process is not systematically influenced by short-run factors.

V. FACTORS AFFECTING THE ADOPTION CEILING

Given the long lead times involved in adjusting plant and equipment within the steelmaking industry, it may be more reasonable to consider whether sustained changes in market factors have an affect on the adoption of the electric arc furnace, even though temporary changes appear to have little impact. Investment in steelmaking technologies requires a view to the long-run market environment, rather than strictly short-run influences. Such a long-run view is incorporated into the growth curve in terms of the adoption ceiling. For example, it may be that sustained changes in relevant factors may influence expectations inherent to the investment decision, thereby having an effect on the long run adoption ceiling.

In order to examine the response to sustained changes in factors affecting the adoption of the electric arc furnace, we extend the static model of diffusion following Chow (1967), and Knudson (1991), to consider a flexible adoption ceiling. The static model of adoption is extended by allowing the adoption ceiling to vary in response to sustained movement in the factors considered in Section IV - the relative

[6] It is unlikely that a lack of variance in the regressors is causing a measurement problem, since the coefficients of variation range (by region) from 17% to 30% for the relative scrap price, 23% to 35% for the relative electricity price, and from 6% to 8% for the product mix of steel production.

price of scrap, electricity, and the product composition of steel production. Defining y: as a linear function of long run market factors (Z), in such a way that

$$y_t^* = c_0 + \Sigma c_i \bar{Z}_{it}. \qquad (14)$$

and substituting the time varying ceiling, y^*_t for fixed y* in Equation 2, then rearranging terms leaves,

$$y_t - y_{t-1} = C_0 y_{t-1} + \Sigma\, C_i y_{t-1}\, \bar{Z}_{it} - \beta y_{t-1}^2 + u_t \qquad (15)$$

where $C_0 = c_0\beta$, and the $C_i = 2c_i\beta$.

For estimation, the long run values of the Z_{it} are approximated by a five-year moving average of the variables considered. β is treated as a fixed parameter (just as y* was treated as a fixed parameter in the previous section). The sequential examination of adaptive adjustment, then flexible ceiling, is conceptually consistent with the growth model, however, the properties of our model selection tests may be affected by this procedure. Frankly, we feel that estimation of a combined model of adaptive adjustment and a flexible ceiling places too much of a burden on the limited data set. Allowing p and y* to vary within the same regression equation would substantially increase the number of regressors and severely restrict the remaining degrees of freedom. Intuitively speaking, deviations in trend are decomposed into short-run and long-run effects, without accounting for possible interaction between the two. The variables selected as having an obvious impact on the adoption ceiling were again chosen based on the SC and likelihood ratio test. The results of these tests are reported in Table 4.

Table 4. *Variable addition tests for factors influencing the adoption ceiling*

	United States		Western Europe		Japan	
Variables	SC	Log-*L*	SC	Log-*L*	SC	Log-*L*
$\bar{Z}_1\ \bar{Z}_2\ \bar{Z}_3$	0.267	48.66	0.093	57.06	0.200	50.74
$\bar{Z}_1\ \bar{Z}_3$	0.235	48.30	0.090	55.98	0.173	50.74
$\bar{Z}_2\ \bar{Z}_3$	0.257	47.59	0.079	57.03	0.172	50.80
$\bar{Z}_1\ \bar{Z}_2$	0.227	48.17	0.088	56.14	0.170	50.88
$\bar{Z}_3$	0.244	46.62	0.080	55.57	0.146	50.70
$\bar{Z}_2$	0.247	46.52	0.085	55.05	0.145	50.80
$\bar{Z}_1$	0.210	47.81	0.076	55.97	0.146	50.70
Nil	0.209*	46.46	0.072*	55.01	0.127*	50.48

Notes: *denotes variables to be included based on the Schwarz criterion (SC). $\bar{Z}_1$ is the five-year moving average of the relative price of scrap to iron ore. $\bar{Z}_2$ is the five-year moving average of the relative price of electricity to coking coal . $\bar{Z}_3$ is the five-year moving average of the proportion of long products to total steel deliveries.

The model selection tests suggest that sustained movement in the market factors studied here have no influence on the long-run adoption ceiling of electric arc furnace production share. An obvious weakness in this test is the arbitrary nature of the five-year moving average representation of long run changes in the market factors. To get a better idea of whether our results are robust to this problem, we have again framed the problem in terms of systematic behaviour in the regression residuals. From Equation 15 we can see that if the long-run factors are treated as unobservable, the variance of the regression residuals will be proportional to the level of electric arc furnace market share (y_{t-1}). To test for this particular form of heteroscedasticity, the same basic procedure outlined in Section I11 was followed, but the squared residuals from the preferred models were regressed on y_{t-1} rather than Q_{t-1}.

The test results shown in Table 5 offer no evidence in support of systematic behaviour in the residuals in the form implied by Equation 15. This indicates that our previous results regarding the stability of the long-run ceiling are robust to alternative definitions of the relevant market factors.

Table 5. Test for flexible ceiling heteroscedasticity

Region	United States	Western Europe	Japan
LM test statistic	0.466	0.848	3.276

Note: The LM test statistic is distributed as a X: where k is equal to the number of parametric restrictions. The 5% critical value of the χ^2 is 3.84

As one final check for systematic behaviour in the residuals, we tested for correlation in the regression residuals across regions. This cross-region analysis allows for a rather more flexible approach in examining the residuals. The test is formed as a likelihood ratio test for a diagonal covariance matrix. This test is a commonly used diagnostic within the seemingly unrelated regression framework. In our case, it should alert us to the presence of unobserved factors which affect the adoption of electric arc furnace technology across the three regions examined. The system examined is of the form:

$$y_{it} - y_{it-1} = c_{i0} y_{it-1} - \beta_i y_{it-1}^2 + u_{it} \qquad (16)$$

The likelihood ratio statistic for cross-regional correlation in the residuals is 0.183 which is to be compared to a 5% critical value of 7.81. Thus, the null of no cross-correlation in the residuals is not rejected. In other words, we have found no evidence to suggest that unobserved factors systematically alter the adoption of the electric arc furnace in a similar manner across the regions examined.

VI. CONCLUSIONS

The adoption of a technology over time is likely based on a complex set of decisions. Researchers have had a great deal of success in modelling important aspects of the adoption process within the framework of S-shaped growth curves. We have used the growth curve to determine whether deviations in the basic growth trend systematically alter with deviations in potentially important market factors, such as input costs and the product composition of steel production.

Under commonly used model selection criterion, we found little evidence to suggest that the adoption of electric arc furnace technology in terms of short-run adjustment, or the long-run equilibrium, systematically alters with observable market factors.[7] We conducted further tests to evaluate the robustness of our results to unobservable factors within a more flexible framework. These tests fully supported the more restrictive model selection tests on the basis of the presumption that the relevant factors are observable.

The finding that deviations in the factors examined have no systematic influence on the adoption of electric arc furnace technology does not imply that these factors are totally irrelevant to the adoption of the technology. Certainly, input costs and production levels must enter into the long-run investment decision implicit to the adoption of a technology. Rather, deviations in these factors of the order of magnitude observed over our sample period do not appear to be sufficiently large to alter the path of adoption. A great deal of inertia apparently exists in the system which overwhelms the potential influence of changing market factors, such as input prices and the level of production. Understanding the cause of this inertia is an obvious topic for further research. In the meantime, it appears that a fairly simple model of adoption can be used to forecast future electric arc furnace production shares. Furthermore, these forecasts are likely to be robust to a changing market environment.

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[7] Apparently, even the energy price shocks of the 1970s had little influence on the adoption decision. This is most likely due to the fact that while electricity prices increased substantially over that period, so did coking coal prices, which presumably limited the impact on the electric arc furnace adoption decision.

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APPENDIX A: DESCRIPTION OF THE DATA

Electric arc furnace production shares

Ratio of steel produced via the electric arc furnace to total crude steel production, by region. International Iron and Steel Institute (1991).

Scrap steel prices

Japan: non-alloy scrap series, derived from Japan Tariff Association (1 991).

Western Europe (Belgium): Machinery cast iron (prime broken) price series. Metal Bulletin (1992). United States: no. 2 bundles price series (Metal Bulletin, 1992).

Iron ore prices

Japan: contract price (fob)-Australian fines. (ABARE, 1992).

Western Europe: iron ore import unit values (United Nations, 1991),

United States: import unit values (US Department of Commerce, 199 1).

Coal prices

Japan: Japanese coking coal contract base prices, Coal Cliff LV (Australia) contracts with Japanese steel mills. (Energy Information Administration, 1991).

Western Europe: West German coking coal prices. (International Energy Agency, 1992).

United States: United States bituminous coal price, fob mines (Energy Information Administration, 1991).

Electricity

Japan: index (1985 = 100) derived from an electric power and gas wholesale price index (Statistics Bureau, 1991), and from an industrial electricity price series (International Energy Agency, 1992). The later series was used for post 1978 observations. The price index for 1970 to 1978 was adjusted to account for the inclusion of gas.

Western Europe: West German industrial price of electricity (International Energy Agency, 1992).

United States: Nominal industrial price of electricity sold by electric utilities. (Energy Information Administration, 1992).

Product mix

Ratio of deliveries to home and export markets of long products to deliveries of all steel products. (International Iron and Steel Institute.)