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An implicit model of adjustment costs in differential input demand systems

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Abstract. *This study provides a theoretical framework for implicitly accounting for adjustment costs in differential systems of factor demand relationships. Differential factor demand relationships, as they are represented by parameters of the cost function, are generally assumed to be linear in the parameters in the existing empirical literature. I argue that this linearity might not always hold because firms may incur adjustment costs that are inherent in the act of adjusting the mix of inputs applied in the underlying production technologies. Implications of convex and non-convex adjustment costs for estimating differential systems as well as price and substitution elasticities are explored.*

Keywords: differential factor demand systems, adjustment costs, threshold nonlinearities, factor price elasticities, factor substitution elasticities.

JEL Classification: D24, E23.

1. Introduction

Applied economists have long used factor demand modeling to represent production conditions through estimates of input price elasticities and elasticities of substitution. In simplest terms, the price elasticity of demand for an input measures firms' response in the quantity demanded of this input to a factor price change of one percent. This relationship, represented by the parameters of the cost function, is generally assumed to be linear in the parameters in the existing empirical literature (Hamermesh and Pfann, 1996). In other words, the parameters reflecting the response to input price changes are assumed constant, such that *any* increase in input price is associated with a corresponding decrease in the quantity demanded of that input.

I argue that this implied linearity in input demand relationships may not always hold due to the adjustment costs embedded in the act of adjusting the input mix underlying the production technologies. Depending on the type and the size of adjustment costs, firms may respond to input price shocks in a nonlinear fashion, where periods of little to no response to such shocks are followed by periods of large changes to input mix. These adjustment costs may have significant implications for empirical modeling as they result in nonlinearities in parameters of factor demand equations and the resulting elasticity estimates that are not captured by conventional linear models (Onel, 2018).

Adaptation to input price shocks by re-adjusting the input mix used in production may be costly. Adjustment costs are most apparent in changing the capital utilization levels; however, other inputs, including labor, energy, and materials, may be just as costly to adjust in the case of an external input price shock. Adjusting the levels of capital services often disrupt workers' routines because tasks are often reassigned and restructured according to new levels of capital services. Equipment installation also involves implicit adjustment costs due to delivery lags and significant time required for installation. Labor adjustment costs include hiring costs (advertising, screening, and processing new employees), firing costs (e.g., mandated or non-mandated severance pay), costs of training, and costs arising from changes in contracts and bargaining with labor unions. Even when the net change in employment is close to zero, these labor adjustment costs can be significant for hiring and training new workers to replace those who leave.

While energy and intermediate materials inputs are often considered to be variable factors of production, their use is typically tied to the amounts of capital equipment and structures or labor. In addition, the purchase of intermediate materials also involves significant transport costs, which are a specific type of adjustment costs. Therefore, adjusting levels of energy and intermediate materials used in production can similarly be costly. Most adjustment costs are mainly implicit costs with only a few directly observable components, making it difficult to quantify them. The approach taken in this study allows modelling adjustment costs in the context of differential input demand systems without directly measuring them. In addition, this flexible approach has the potential to capture the sector-specific nature of adjustment costs, making it suitable for cross-sector applications where the nature and magnitude of adjustment costs vary depending on the production technology and the input mix used within a particular sector.

There are two main ways that adjustment costs can affect the implied input price elasticities within a factor demand system. Input adjustments that are too large in size may be more costly than small adjustments. This type of costs is often represented with convex adjustment cost functions reflecting that adjustment becomes increasingly costlier as larger adjustments are needed (Hamermesh and Pfann, 1996; Hall, 2004). Alternatively, very small price changes may not be large enough to make input adjustments profitable given the costs of adjustments. In such a case, very small input price changes may not trigger significant adjustments. This type of adjustment is represented by a non-convex (i.e., fixed or kinked) adjustment cost function, which implies little or no action during periods of small price changes (Caballero and Engel, 1999; King and Thomas, 2006). The failure to account for either type of adjustment costs and the corresponding threshold sensitivity to input price changes may cause the estimates of input price elasticities to be biased. The modeling approach in this paper allows for both convex and non-convex types of adjustment costs in the input demand systems.

The objective of this paper is to develop a conceptual framework where the possibility of nonlinearities in the underlying input demand relationships in a differential system due to significant adjustment costs is acknowledged and incorporated in the model. Estimation strategy and tests of nonlinearities that would correspond to threshold effects in the differential system of factor demands are presented. The remainder of the paper is organized as follows. In Section 2, the standard linear differential demand system with no adjustment costs and its extensions with alternative parametrizations are presented. Section 3 introduces the conceptual model of adjustment costs in differential input demand systems and discusses the implications of such costs for input demand elasticities. Section 4 presents the approach to testing and estimation of the differential input demand model with adjustment costs. Section 5 presents conclusions.

2. Linear differential input demand system with no adjustment costs

The differential input demand model with adjustment costs presented in the next section builds upon the neoclassical dual approach to the cost minimization problem of producers. The differential systems of input demand can be theoretically derived from the firm's optimization process and can be extended to decisions involving production of multiple goods. The differential approach amounts to the differentiation of the optimizing conditions for the cost-minimizing inputs and profit-maximizing outputs of the multiproduct firm (Laitinen and Theil, 1978; Laitinen, 1980; Theil, 1980; Rossi, 1984; Davies, 1997; Suh and Moss, 2017). Therefore, it has the advantage of allowing for simultaneous consideration of the differential input demand and output supply systems. Another attractive feature of differential input demand systems is that input demand elasticities can easily be computed from the coefficients of the system. This section presents the derivation and properties of the linear differential demand system that do not account for adjustment costs or other frictions in the economy.

Consider a competitive firm with the following production function

$$y = F(q), \tag{1}$$

where q is an $(n \times 1)$ vector of variable inputs and F denotes a twice-differentiable function. The cost-minimizing firm chooses the level of inputs that minimizes the cost of producing output level y. Firm's problem can be written as

$$C(p, y) = \min_{q} \, [p'q; F(q) = y], \tag{2}$$

where C is the cost function and p is the $(n \times 1)$ vector of input prices. Following Theil (1980), the general differential input demand system corresponding to the cost minimization problem given in Equation (2) is derived as

$$w_i d(In\, q_i) = \gamma \theta_i d\left(\ln y\right) + \sum_j \pi_{ij} d\left(\ln p_j\right), \quad i, j = 1, 2, ..., n., \tag{3}$$

where w_i is the cost share of input i and ln(.) is the natural logarithm operator. The coefficient γ in Equation (2) is the elasticity of cost with respect to output given by $\gamma = d(\ln Q) / d(\ln \mathrm{y})$, where $d\left(\ln Q\right) = \sum_j w_i d\left(\ln q_i\right)$ is the Divisia input volume index representing the log change of real input expenditure, and the π_{ij} are the input price parameters. Substituting the expression for γ in Equation (3) yields the differential demand system representing the firm's input allocation decision:

$$w_i d(In\, q_i) = \theta_i d\left(\ln Q\right) + \sum_j \pi_{ij} d\left(\ln p_j\right), \quad i, j = 1, 2, ..., n. \tag{4}$$

The right-hand side of Equation (4) sums the impacts of changes in the total input volume and changes in input prices on the firm's input allocation decisions. The marginal share of input i (i.e., the change in the cost share of input i with respect to a change in y) is denoted by the coefficients θ_i and it is given by $\theta_i = (\partial p_i / \partial q_i) / (\partial C / \partial y)$.

The Divisia elasticity that reflects the demand elasticity of input i with respect to the total input volume (Q) holding input prices constant (i.e., $d \ln(q_i) / dIn(Q)$) is written as

$$e_i^D = \frac{\theta_i}{w_i}. \tag{5}$$

The demand elasticity of input i with respect to the j th input's price holding the total input volume (Q) constant is computed as

$$e_{ij}^{p} = \frac{\pi_{ij}}{w_i} . \tag{6}$$

Equation (6) yields a matrix of input price elasticities, where off-diagonal elements provide a measure of substitutability between factor i and factor j and the diagonal elements provide own price elasticities of demand for input i.

The differential demand system given in Equation (4) satisfies the following characteristics of a demand system:

a) Adding up conditions: $\sum_i \theta_i = 1$ and $\sum_i \pi_{ij} = 0, \quad j = 1,...,n.$

b) Homegeneity: $\sum_i \pi_{ij} = 0, \quad i = 1,...,n.$

c) Symmetry: $\pi_{ij} = \pi_{ji}, \quad i \neq j.$

d) Concavity: The matrix of price parameters, $[\pi_{ij}]$, is negative semi-definite.

Note that the coefficients θ_i and π_{ij} in the theoretical differential demand given in Equation (4) need not be constant over time. In empirical time series applications, however, one can treat θ_i and π_{ij} as parameters to be estimated. By treating θ_i and π_{ij} in Equation (4) as constant parameters to be estimated, Theil (1980) derived an empirically plausible differential model of input demands that is analogous to the Rotterdam model in consumer demand literature (Fousekis and Pantzios, 1999; Moss et al., 2010). This linear input demand model in finite-change form instead of the infinitesimal change form used in Equation (4) is

$$\bar{w}_{it} Dq_{it} = \theta_i DQ_t + \sum_j \pi_{ij} Dp_{jt} + \varepsilon_{it} , \tag{7}$$

where $\bar{w}_{it} = \frac{1}{2}\left(w_{i,t} + w_{i,t-1}\right)$,

$Dq_{it} = \ln q_{i,t} - \ln q_{i,t-1}$, $Dp_{jt} = \ln p_{j,t} - \ln p_{j,t-1}$,

$DQ_t = \sum_j \bar{w}_{jt} Dq_{jt}$ is the Divisia volume index representing total input volume for all inputs, t is the time index, and ε_{it} is a random error term. The Divisia and input price elasticities are computed using Equations (5) and (6) – typically at sample means of input shares. Equation (7) is the linear differential input demand system that constitutes the basis for the modified input demand model with adjustment costs that is presented in the following section.

3. A nonlinear differential input demand system under adjustment costs

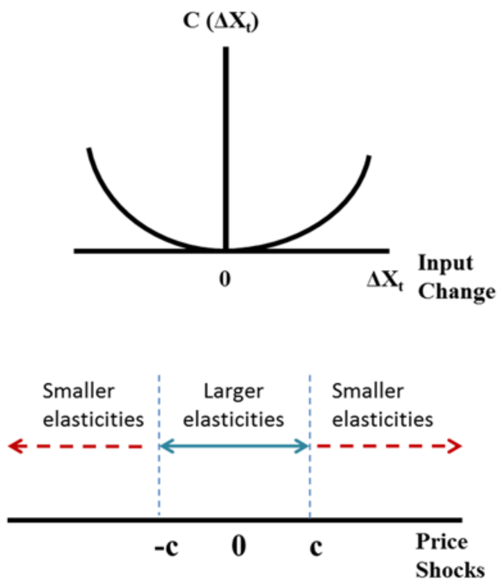
The factor demand model presented above assumes that there are no adjustment costs involved in a producer's decision-making process. However, anytime firms change their quantities of inputs they face a cost for that adjustment. These costs, if significant, cause producers to change their demand for inputs more slowly than the shocks to input demand warrant. In other words, the slow adjustment is the result of adjustment costs that are inherent in the act of changing the amount of the input used, causing a delay in the response to a price shock. This delay may not necessarily result from imperfect expectations or short-run supply inelasticity in factor markets. Even without such problems, the producer might still have difficulty altering its use of inputs in response to shocks because of either direct costs incurred in making such an adjustment (such as costs involved in installation of new equipment, or training new workers) or profit foregone incurred by producing at less-than-optimal scale. These adjustment costs are likely to vary among different inputs, capital typically being the most costly to adjust.

In this section, the linear differential factor demand model presented above is modified to implicitly account for such adjustment costs. The model with adjustment costs allows for switching between two regimes based on an unknown threshold parameter, yielding two sets of parameters that are determined based on size of input price shocks that warrant adjustment. The motivation underlying a threshold differential demand system specification is its ability to capture phenomena such as regime-specific parameters and elasticities within a simple and intuitive framework. The approach in this paper avoids the need for explicit calculation of adjustment costs while still allowing us to account for the impact of adjustment costs on input price elasticities from a differential demand system. In particular, the approach involves conceptually attributing the evidence of threshold sensitivity in parameter estimates to the existence of significant adjustment costs. This is an attractive feature of the model since it is difficult to explicitly calculate adjustment costs in empirical applications. The underlying hypothesis is that because adjustment costs makes responding to external input price shocks difficult, parameters of a differential system and resulting elasticity estimates may vary across regimes, depending on the magnitude of changes in (or shocks to) input prices in a previous period.

Two distinct types of adjustment cost functions often used in the literature and how they may lead to different producer behavior are illustrated in Figures 1 and 2. Upper portions of both figures show the adjustment cost functions, and the lower portions of the figures illustrate the anticipated response in own price input demand elasticities with respect to an input price shock. For simplicity, the lower and upper thresholds that trigger negative and positive response to input price shocks are assumed to be symmetric – in practice, this assumption can easily be relaxed. The threshold level of input price shock is denoted as c (or, $-c$ in case of negative shocks). Beyond this threshold, producers' behavior, as represented by the parameters of the factor demand system, is predicted to change.

The first case in Figure 1 illustrates the impact of convex adjustment costs on producers' behavior in terms of the shift such costs create in input demand elasticities. The convex adjustment costs in Figure 1 imply that small changes to the input mix cost less than larger adjustments. These costs are widely studies in the literature. Hamermesh (1989) and Hamermesh and Pfann (1996) discuss the role of convex adjustment costs in partial adjustment models of employment demand. Chirinko (1993) and Caballero (1999) survey their use in empirical investment models. Hall (2004) estimates an industry-level model of production with quadratic adjustment costs assumed for both capital and labor. Abel (1990) provides a synthesis of the neoclassical investment model with convex adjustment costs. Under convex adjustment costs, too large of a price shock that surpasses the threshold level, c, may not lead to as large of a response as a linear factor demand model would predict. Put differently, changes in factor prices might be too large to induce a significant response in the quantity demanded of factors as compared to the more modest adjustments that occur when price changes are smaller. As a result, under convex adjustment costs, one might expect to see smaller elasticities during periods of very large price changes than those that correspond to smaller price changes.

Figure 1. *The effect of convex adjustment costs on input demand elasticities*

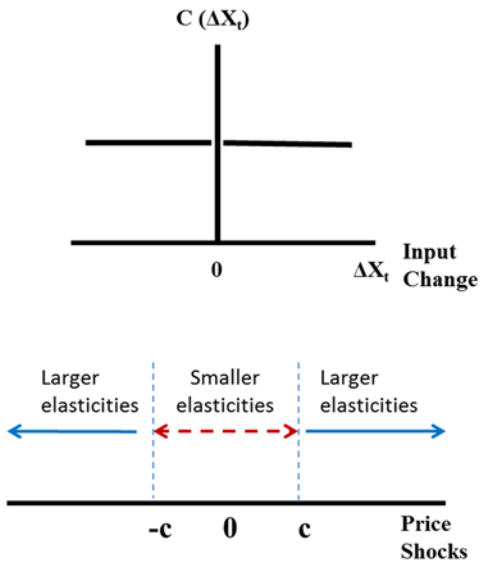


Source: Onel, 2018.

Figure 2 presents another plausible alternative for a functional form of adjustment costs: the non-convex adjustment costs where even small changes in input mix have considerable costs. Non-convex adjustment costs have been considered within the investment literature. Caballero and Engel (1999) examine generalized (S, s) investment policies rationalized by stochastic fixed adjustment costs. Khan and Thomas

(2003) consider non-convex adjustment costs in business cycle models. King and Thomas (2006) show that non-convex adjustment costs stagger the adjustments undertaken by firms in response to shocks. Abel and Eberly (1994, 1996), Caballero et al. (1995), and Cooper et al. (1999) argue that non-convex adjustment costs play a central role in the investment process. Under the non-convex adjustment costs structure, the changes in input prices may be too small to trigger a change in input usage in the regime in which a threshold level of price shock is yet to be reached. Put differently, non-convex adjustment costs imply that the changes in factor prices will affect input shares only if that price change is sufficiently large (i.e., larger in absolute value than the threshold parameter that is defined by an upper bound c and a lower bound $-c$).

Figure 2. *The effect of non-convex (or, fixed) adjustment costs on input demand elasticities*



Source: Onel, 2018.

The threshold version of the differential input system is written as

$$\bar{w}_{it} Dq_{it} = \begin{cases} \theta_i^{(1)} DQ_t + \sum_j \pi_{ij}^{(1)} Dp_{jt} & if\ |z_{t-1}| > c \\ \theta_i^{(2)} DQ_t + \sum_j \pi_{ij}^{(2)} Dp_{jt} & if\ |z_{t-1}| \le c \end{cases} + \varepsilon_{it} \ . \quad (8)$$

The superscripts (1) and (2) denote the parameters of regime 1 and regime 2, respectively. c is an unknown threshold parameter and z_{t-1} is the threshold variable. In Equation (8), the threshold variable is hypothesized to be common to the entire differential input demand system of n equations (i.e., n inputs), and it represents changes in input prices in the previous period. The choice of common threshold variables, symmetric thresholds, and two regimes is particularly beneficial in empirical cases where data are short and degrees of freedom are expensive, although not necessary. The theoretical regularity conditions discussed in the previous section for the linear differential demand system also apply to each of the two regimes of threshold differential input demand system given in Equation 8.

Only a few studies consider threshold nonlinearities in demand systems. Mancuso (2000) uses a regime-switching Rotterdam model to estimate a system of consumer demand for meats in the United States. His argument is that there are costs associated with altering consumption bundles that would cause a nonlinear response in the quantity demanded for those goods when a price change occurs. He finds significant threshold effects in the system of demand for meats.

Huang and Yang (2006) set up a similar hypothesis to examine why estimates of income elasticity of cigarette demand are close to zero. They apply Tong's (1990) threshold regression model to a panel data of 47 U.S. states from 1963 to 1997. Specifying a single equation demand model and using a fixed-effects model for panel data, they find significant differences in elasticity estimates between linear and threshold demand models. Both studies address the issue from the consumers' perspective.

Although there are several studies that consider nonlinearities resulting from structural breaks in input demand systems (Goodwin and Brester, 1995), only the studies by Onel (2015, 2018) account for the potential for threshold nonlinearities in demand for inputs. Onel (2015, 2018) considers the case of threshold nonlinearities in translog input demand systems. A shortcoming of using translog input demand model with long time series data is that the variables of the translog demand model (which are measured at logarithmic levels) may contain unit roots. By construction, differential input demand systems are measured in logarithmic changes/differences and are unlikely to suffer from potential unit roots. This is the first study to provide a conceptual model that illustrates how different types of adjustment costs may affect regime-specific price elasticities of input demands characterized within a differential input demand system.

4. Estimation and testing strategy

The first step of testing for the significance of threshold effects is to estimate the linear differential input demand system given in Equation (7). Each equation of the system in (7) can be written in compact form as

$$\bar{w}_i Dq_i = \mathrm{X}_i \Gamma_i + u_i \,, i = 1, \ldots, n \,, \tag{9}$$

where $\bar{w}_i Dq_i$ represents a $T \times 1$ vector of annual observations for the contribution of input i to the Divisia volume index. There are n inputs in the model. X_i is a $T \times k$ matrix of observations of Divisia input volume index and logarithmic differential input prices. Therefore, k is equal to n (for log differential input prices) + 1 (for Divisia volume index)

+1 (for intercept) = $n+2$. Γ_i is a $k \times 1$ vector of unknown input demand parameters and u_i is a $T \times 1$ vector of random disturbances for the i th equation of the system.

The adding up restriction requires that the left-hand side of the system sum to one. This implies a singular contemporaneous disturbance covariance matrix for the system, and thus poses a problem for the estimation. The common solution is to delete one of the four input demand equations at the estimation stage and recover its parameters through the cross-equation restrictions given in Section 3. The remaining $n-1$ equations can be estimated applying the Iterated Seemingly Unrelated Regressions (ITSUR) or Maximum Likelihood (ML) method.

The next step is to estimate the nonlinear differential input demand system with threshold effects, corresponding to a switch in the parameters of the model between two regimes due to the size of the reaction to external input price shocks. Threshold models capture a rich set of dynamics despite its mathematical simplicity and they can easily be estimated using Maximum Likelihood (ML) based approaches. Threshold models can be viewed as a realistic approximation to a wider family of nonlinear functional forms, which are often more difficult to estimate. The threshold differential input demand model can be written in matrix form as

$$\bar{w}_i Dq_i = \delta_1 X_i \Gamma_i^{(1)} + (1-\delta_1) X_i \Gamma_i^{(2)} + e_i , \qquad (10)$$

where $\Gamma_i^{(1)}$ and $\Gamma_i^{(2)}$ are $k \times 1$ vectors of the parameters in regime 1 and regime 2, respectively. δ_1 and $(1-\delta_1)$ are dummy variables defined as follows: $\delta_1 = I(|z_{t-1}| > c)$ and $1-\delta_1 = I(-c \le z_{t-1} \le c)$. $I(.)$ denotes the indicator function. c is the unknown threshold parameter and z_{t-1} is the threshold variable. In practice, the threshold parameter can be defined as the largest absolute percentage change among all factor prices in the preceding period, or as the absolute value of changes in the Theil-Törnqvist input price index.

To estimate the threshold differential input demand system given in Equation (10), one can use a modified version of Hansen's (1996, 1997, 2000) threshold estimation procedures, such that his approach is generalized from estimation of a single regression to estimating a system of equations. Estimation of the system in Equation (10) is essentially a maximum likelihood problem with the assumption that errors are normally distributed, $e \sim N(0, \Sigma \otimes I_T)$. The parameters of interest are the vectors $\Gamma_i^{(1)}$ and $\Gamma_i^{(2)}$, the matrix Σ, and the threshold parameter c. The Gaussian likelihood is

$$\log L(\Gamma^{(1)}, \Gamma^{(2)}, \Sigma, c) = -\frac{T}{2}\log|\Sigma| - \frac{1}{2}\sum_{t=1}^{T} e_t'(\Gamma^{(1)}, \Gamma^{(2)}, c)\Sigma^{-1} e_t(\Gamma^{(1)}, \Gamma^{(2)}, c) . \qquad (11)$$

For computational convenience, the likelihood function can be concentrated by holding c fixed and computing the ML estimator for $(\dot{\Gamma}^{(1)}, \dot{\Gamma}^{(2)}, \Sigma)$. This concentrated likelihood function is

$$\log L(c) = -\frac{T}{2}\log\left|\Sigma(c)\right| - \frac{Tk}{2} \tag{12}$$

The threshold parameter, c, is estimated by searching over all possible values of c. The ML estimator, $\hat{c}$, minimizes $\log\left|\Sigma(c)\right|$ (or, maximizes $\log L(c)$) subject to the constraint $\pi \leq \Pr(|z_{t-1}| > c) \leq (1-\pi)$. π is a trimming parameter, typically set between 0.05 and 0.25. The constraint on π ensures that each regime has at least $\pi \times 100$ percent of the T total observations.

The third step after estimating the systems given in Equations (9) and (10) is to determine which model is preferred, in other words, whether the threshold effects in (10) are significant. The null hypothesis of the linearity test is given by $H_0 : \Gamma_1^{(1)} = \Gamma_2^{(2)}$. This testing problem is complicated by the fact that the threshold parameter c is not identified under H_0, which is known as the 'Davies problem' (Davies, 1987).

The implication is that the test statistic for the linearity test does not follow a standard asymptotic distribution because of the nuisance parameters problem. Hansen (1996, 1997, 2000) suggests bootstrap methods to simulate the distribution of the test statistic under the null hypothesis. Specifically, the supremum likelihood ratio (LR) test (*SupLR*) statistic for testing the hypothesis $H_0 : \Gamma_1^{(1)} = \Gamma_2^{(2)}$ is

$$SupLR = \sup_{c_L \leq c \leq c_U} LR(c) = T\left[\log\left|\hat{\Sigma}_R\right| - \log\left|\hat{\Sigma}_{UR}(c)\right|\right], \tag{13}$$

where $\log\left|\hat{\Sigma}_R\right|$ is obtained under the null hypothesis, $H_0 : \Gamma_1^{(1)} = \Gamma_2^{(2)}$, and $\log\left|\hat{\Sigma}_{UR}(c)\right|$ is obtained under the alternative hypothesis (Gallant, 1987). Under the null hypothesis, there is no threshold. Therefore, the model reduces to the conventional linear differential input demand system with no adjustment costs. The search region $[c_L, c_U]$ is set such that c_L is the π th percentile of the transition variable and c_U is the $1-\pi$ th percentile. The *SupLR* statistic is obtained through an evaluation of Equation (12) over $[c_L, c_U]$. If the null of $H_0 : \Gamma_1^{(1)} = \Gamma_2^{(2)}$ is rejected the threshold differential input demand system in Equation (10) is preferred to the linear differential input demand function given in Equation (9), providing empirical evidence for significant adjustment costs in differential input demand relationships.

5. Concluding remarks

The objective of this paper is to provide practitioners with a conceptual model of nonlinearities in the underlying differential input demand relationships. The underlying hypothesis is that adjustment costs may arise when firms change their quantities of inputs, and the response to a price shock may not be instantaneous due to such adjustment costs. In this case, nonlinearities in the parameters of differential factor demand system may arise. Consistent with this argument, this study modifies the standard linear differential input demand system to account implicitly for adjustment costs. The resulting model allows for switching between two regimes based on an unknown threshold parameter, depending on the magnitude of a forcing variable such as changes in (or shocks to) input prices in a previous period. Resulting regime-specific parameters and price elasticities depend upon the nature of the adjustment cost function (i.e., whether the adjustment costs are convex or non-convex). The model presented in the paper is flexible in that it does not restrict the functional form of the underlying adjustment costs.

After laying out the theoretical considerations, the study presents the empirical strategy to estimate and test for the significance of nonlinear differential input demand system over its linear counterpart. Accurate modeling of adjustment costs is vital for the evaluation of policies influencing aggregate investment. Because the sources and nature of adjustment costs may alter demand for inputs and investment activities, the threshold sensitivity in input demand relationships presented in this study is important in designing policies that would influence factor demands, including mandated severance for workers and tax policies altering depreciation on equipment, among other policies.

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