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METHODS OF ESTIMATION FOR MARKETS IN DISEQUILIBRIUM: A FURTHER STUDY

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This paper is concerned with the problem of estimating demand and supply schedules in disequilibrium markets. The results of Fair and Jaffee are expanded in three ways. (1) Their directional method I is modified to yield consistent estimates. (2) A maximum likelihood alternative to their quantitative method is proposed. (3) The price equation is generalized to be a multivariate, stochastic function, and a method is proposed for estimating demand and supply schedules in this case.

1. INTRODUCTION

IN A RECENT paper Fair and Jaffee [4] considered the problem of estimating demand and supply schedules in disequilibrium markets. They suggested four possible methods of estimation: a general maximum likelihood method for finding the optimal separation of the sample period into demand and supply regimes; two "directional" methods, which relied on price-setting information to separate the sample period; and a "quantitative" method, which relied on price-setting information to adjust the observed quantity for the effects of rationing. The Fair-Jaffee study is subject to several limitations. First, Fair and Jaffee found that the general maximum likelihood method was not computationally feasible. Second, their directional method I, although yielding a correct sample separation under the assumptions of the model, does not yield consistent estimates. Finally, their quantitative method is based on a rather strict assumption about price-setting behavior, namely that price changes are *strictly proportional* to excess demand.

The purpose of this paper is to expand upon the results of Fair and Jaffee in three ways. First, their directional method I will be modified to yield consistent estimates, and then this modified technique will be used to estimate a particular model so that these estimates can be compared to the directional method I estimates. Second, a maximum likelihood alternative to the quantitative method will be proposed under the same strict assumption that price changes are proportional to excess demand. Third, and most important, the strict assumption about price-setting behavior will be relaxed and a method will be proposed for estimating supply and demand schedules under the much weaker assumption that the price equation is a multivariate and stochastic relationship.

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2. DIRECTIONAL METHODS OF ESTIMATION

The Model

The model under consideration in this section is[2]

(1a) $$D_t = X_{1t}\beta_1 + P_{t-1}\beta_2 + u_{1t},$$

(1b) $$S_t = X_{2t}\beta_3 + P_{t-1}\beta_4 + u_{2t},$$

(1c) $$\Delta P_t = P_t - P_{t-1} = f(D_t - S_t),$$

and

(1d) $$Q_t = \min\{D_t, S_t\} \qquad (t = 1, 2, \ldots, T),$$

where, at time t, D_t and S_t are the quantities demanded and supplied respectively, Q_t is the actual quantity observed, P_t is the price, X_{1t} and X_{2t} are vectors of predetermined variables, and u_{1t} and u_{2t} are the disturbance terms. The vectors β_1 and β_3 are vectors of parameters, conformably defined. The stochastic assumptions are

(2) $$E[u_{1t}|X_t] = E[u_{2t}|X_t] = 0,$$
$$E[u_{1t}^2|X_t] = \sigma_1^2, \qquad E[u_{2t}^2|X_t] = \sigma_2^2,$$

where $X_t = (X_{1t}, X_{2t}, P_{t-1})$; u_{1t} and u_{2t} are assumed to be continuous.

The problem of estimation concerning the parameters of (1a) and (1b) is that the price equation, (1c), implies that prices do not adjust in every period in such a manner as to equate D_t and S_t. Therefore, unless some adjustments are made, all of the observations on Q_t cannot be used in the estimation of equations (1a) and (1b).

Directional Method I

Fair and Jaffee's directional method I is based on the assumption that $f(D_t - S_t) \gtreqless 0$ when $D_t - S_t \gtreqless 0$. Under this assumption, if $\Delta P_t > 0$, then $Q_t = S_t$; if $\Delta P_t < 0$, then $Q_t = D_t$; and if $\Delta P_t = 0$, then $Q_t = D_t = S_t$. Directional method I takes those sample points for which $\Delta P_t \geqslant 0$ and estimates the supply equation, and takes those sample points for which $\Delta P_t \leqslant 0$ and estimates the demand equation.

Although directional method I yields a correct sample separation under the above assumptions, the coefficient estimates are not consistent. For instance, according to the method

(3) $$Q_t = D_t = X_{1t}\beta_1 + P_{t-1}\beta_2 + u_{1t}, \quad \text{when } \Delta P_t \leqslant 0,$$

and

(4) $$Q_t = S_t = X_{2t}\beta_3 + P_{t-1}\beta_4 + u_{2t}, \quad \text{when } \Delta P_t \geqslant 0.$$

[2] In this section the price terms are assumed to enter the demand and supply equations with a lag rather than contemporaneously. In Sections 3 and 4 the price terms are allowed to enter the demand and supply equations contemporaneously.

Now, the ordinary least squares parameter estimates of (3) and (4) are inconsistent because the means of the disturbance terms are no longer independent of X_{1t}, X_{2t}, and P_{t-1} over the relevant sample points. To see this, consider $E[u_{1t}|X_t, \Delta P_t \leqslant 0]$. In light of (1c), (1d), and the assumption that $f(D_t - S_t) \gtreqless 0$ when $D_t - S_t \gtreqless 0$:

$$(5) \qquad E[u_{1t}|X_t, \Delta P_t \leqslant 0] = E[u_{1t}|X_t, D_t \leqslant S_t].$$

Let $D_t^* = X_{1t}\beta_1 + P_{t-1}\beta_2$, and $S_t^* = X_{2t}\beta_3 + P_{t-1}\beta_4$. Then from (1a), (5) may be written as

$$(6) \qquad E[u_{1t}|u_{1t} - u_{2t} \leqslant S_t^* - D_t^*, X_t].$$

Now, if the joint density of u_{1t} and u_{2t}, conditional on X_t, is specified, the conditional density of $\phi_t = u_{1t} - u_{2t}$, say $g_1(\phi_t|X_t)$, may be derived, and the joint conditional density of u_{1t} and ϕ_t, say $g_2(u_{1t}, \phi_t|X_t)$, may be derived. Therefore, (6) can be evaluated as[3]

$$(7) \qquad E[u_{1t}|\phi_t \leqslant S_t^* - D_t^*, X_t] = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{S_t^*-D_t^*} u_{1t} g_2(u_{1t}, \phi_t|X_t)\, d\phi_t\, du_{1t}}{\int_{-\infty}^{S_t^*-D_t^*} g_1(\phi_t|X_t)\, d\phi_t}.$$

Clearly, the expectation in (7) will not, in general, be independent of X_t unless u_{1t} and ϕ_t are independent, in which case g_2 factors.

A Consistent Method of Estimation

The demand and supply equations, (3) and (4), can be consistently estimated by a maximum likelihood technique that is conditional on the segmentation of the sample. Let $g_3(u_{1t}|\Delta P_t \leqslant 0, X_t)$ be the conditional density of u_{1t} given X_t and $\Delta P_t \leqslant 0$, and let $g_4(u_{2t}|\Delta P_t \geqslant 0, X_t)$ be the conditional density of u_{2t} given X_t and $\Delta P_t \geqslant 0$. In view of the above assumptions, these conditional densities can be written as $g_3(u_{1t}|\phi_t \leqslant S_t^* - D_t^*, X_t)$ and $g_4(u_{2t}|\phi_t \geqslant S_t^* - D_t^*, X_t)$ respectively. Now, the maximum likelihood estimators of the parameters $\beta_1, \beta_2, \beta_3, \beta_4, \sigma_1^2$, σ_2^2, and σ_{12}, can be obtained by maximizing the likelihood function

$$(8) \qquad \mathscr{L} = \prod_{\Delta P_t < 0} g_3(u_{1t}|\phi_t \leqslant S_t^* - D_t^*, X_t) \prod_{\Delta P_t > 0} g_4(u_{2t}|\phi_t \geqslant S_t^* - D_t^*, X_t),$$

where $u_{1t} = Q_t - D_t^*$, $u_{2t} = Q_t - S_t^*$, and the products are taken, respectively, over the periods for which $\Delta P_t < 0$ and $\Delta P_t > 0$. Equation (8) is defined in terms of strict inequalities because the disturbance terms are assumed to be continuous and thus the probability that $\Delta P_t = 0$ is zero.

Empirical Results

The likelihood technique can be implemented as follows: First, note that

$$(9) \qquad g_3(u_{1t}|\phi_t \leqslant S_t^* - D_t^*, X_t) = \frac{\int_{-\infty}^{S_t^*-D_t^*} g_2(u_{1t}, \phi_t|X_t)\, d\phi_t}{\int_{-\infty}^{S_t^*-D_t^*} g_1(\phi_t|X_t)\, d\phi_t},$$

[3] See Mood and Graybill [**12**, Chs. 1–5] for a discussion of the concepts in the development up through (7).

where, as above, $g_2(u_{1t}, \phi_t|X_t)$ is the joint density of u_{1t} and ϕ_t, given X_t. Likewise,

$$(10) \qquad g_4(u_{2t}|\phi_t \geqslant S_t^* - D_t^*, X_t) = \frac{\int_{S_t^*-D_t^*}^{\infty} g_5(u_{2t}, \phi_t|X_t)\, d\phi_t}{\int_{S_t^*-D_t^*}^{\infty} g_1(\phi_t|X_t)\, d\phi_t},$$

where $g_5(u_{2t}, \phi_t|X_t)$ is the joint density of u_{2t} and ϕ_t, given X_t. If the joint density of u_{1t} and u_{2t}, conditional on X_t, is specified to be normal, then $g_1(\phi_t|X_t)$ will be normal and $g_2(u_{1t}, \phi_t|X_t)$ and $g_5(u_{2t}, \phi_t|X_t)$ will each be jointly normal. Therefore, since it is quite easy numerically to evaluate normal integrals, an attempt can be made to maximize the likelihood function in (8) using a nonlinear maximization program. Note that the parameters β_1, β_2, β_3, and β_4 enter both the limits of the integral and the integrand. The parameters σ_1^2, σ_2^2, and σ_{12} enter only into the integrand.

In order to see whether it is feasible to maximize (8), the housing starts model that Fair and Jaffee used as an example in their study was also used as an example in this study. The model consists of one demand equation and one supply equation:

$$(11) \qquad HS_t^D = \alpha_0 + \alpha_1 t + \alpha_2 \sum_{i=1}^{t-1} HS_i + \alpha_3 RM_{t-2} + u_{1t},$$

and

$$(12) \qquad HS_t^S = \psi_0 + \psi_1 t + \psi_2 DF6_{t-1} + \psi_3 DHF3_{t-2} + \psi_4 RM_{t-1} + u_{2t},$$

where HS_t^D and HS_t^S denote the demand for and supply of housing starts respectively, RM_{t-1} and RM_{t-2} denote the mortgage rate lagged one and two months respectively, $DF6_{t-1}$ denotes the six-month moving average of the flow of deposits into savings and loan associations (SLAs) and mutual savings banks lagged one month, and $DHF3_{t-2}$ denotes the three-month moving average of the flow of borrowings by SLAs from the Federal Home Loan Bank lagged two months.[4] Fair and Jaffee assumed that the error terms, u_{1t} and u_{2t}, were first-order serially correlated, but for present purposes serial correlation problems will be ignored. Serial correlation questions will be considered at the end of this section. Fair and Jaffee also used seasonally unadjusted data and seasonal dummy variables, but for purposes here seasonally adjusted data were used.

The results of estimating equations (11) and (12) by directional method I and by the consistent likelihood technique are presented in Table I. The price variable in the model is the mortgage rate. Two nonlinear maximization techniques were tried in the maximization of the likelihood function: the quadratic hill-climbing technique of Goldfed, Quandt, and Trotter [9] and the technique of Powell [13]. The quadratic hill-climbing technique requires first and second derivatives, and for this purpose numerical first and second derivatives were used. The normal integrals were evaluated using the ERF function in the FORTRAN library. It turned out that the likelihood function was not very well behaved. The function

[4] See Fair [3, Ch. 8] for a more complete description of this model.

was very flat with respect to the parameter σ_{12}, for example, and the function appeared to have many local maxima. The quadratic hill-climbing technique and Powell's technique worked about equally well in their ability to find local maxima. The maximum likelihood estimates presented in Table I correspond to the largest value of the likelihood function found after considerable experimentation, but there is no guarantee that this is the global maximum.

TABLE I

ESTIMATES OF THE HOUSING STARTS MODEL

Coefficient	Directional Method I	Maximum Likelihood Method
α_0	223.7	223.4
α_1	2.428	2.429
α_2	−.0188	−.0119
α_3	−.2032	−.2013
ψ_0	15.53	15.49
ψ_1	−.195	−.209
ψ_2	.0515	.0521
ψ_3	.0469	.0519
ψ_4	.1017	.1019
σ_1^2	151.04	222.90
σ_2^2	76.39	69.06
σ_{12}	—	59.92

The maximum likelihood estimates in Table I are quite close to the directional method I estimates, which suggests that for this particular example the bias using directional method I does not appear to be very great. Whether this is true in general is, of course, not clear.

Serial Correlation Questions

If the error terms in equations (1a) and (1b) are serially correlated, then it turns out that the coefficients of (1a) and (1b) are not identified if it is assumed that u_{1t} and u_{2t} are continuous random variables. Assume, for example, that the error terms are first-order serially correlated:

(13) $$u_{1t} = u_{1t-1}\rho_1 + \varepsilon_{1t},$$

and

(14) $$u_{2t} = u_{2t-1}\rho_2 + \varepsilon_{2t},$$

where the assumptions in (2) now pertain to ε_{1t} and ε_{2t} rather than to u_{1t} and u_{2t}. Using (13) and (14), equations (1a) and (1b) can be written:

(15) $$D_t = D_{t-1}\rho_1 + X_{1t}\beta_1 - X_{1t-1}\beta_1\rho_1 + P_{t-1}\beta_2 - P_{t-2}\beta_2\rho_1 + \varepsilon_{1t},$$

and

(16) $$S_t = S_{t-1}\rho_2 + X_{2t}\beta_3 - X_{2t-1}\beta_3\rho_2 + P_{t-1}\beta_4 - P_{t-2}\beta_4\rho_2 + \varepsilon_{2t}.$$

The problem with estimating equations (15) and (16) is that the explanatory variables D_{t-1} and S_{t-1} will generally not be observed at the same time. For instance, given the above assumptions, only if $\Delta P_{t-1} = 0$ are both S_{t-1} and D_{t-1} observed; otherwise only one of them is observed. However, if u_{1t} and u_{2t} are continuous random variables, the probability that $\Delta P_t = 0$, for any t, is zero. Consequently, as the sample size approaches infinity, that portion of it corresponding to time periods for which $\Delta P_t = 0$ will remain finite. Now, if it is recalled, from either (7) or (9) and (10), that a consistent estimation technique, for either or both equations, necessarily involves observations on all of the predetermined variables, the result concerning lack of identification follows.[5] The same situation also holds if D_{t-1} and S_{t-1} enter directly as explanatory variables in equations (1a) and (1b) rather than entering indirectly by way of the serial correlation assumption.

3. QUANTITATIVE METHODS OF ESTIMATION

The Model

The model under consideration in this section is

(17a) $$D_t = X_{1t}\beta_1 + P_t\beta_2 + u_{1t},$$

(17b) $$S_t = X_{2t}\beta_3 + P_t\beta_4 + u_{2t},$$

(17c) $$\Delta P_t = \gamma(D_t - S_t),$$

and

(17d) $$Q_t = \min\{D_t, S_t\} \qquad (t = 1, 2, \ldots, T).$$

The model in this section differs from the model in Section 2 in that the price term is allowed to enter contemporaneously in the demand and supply equations and the change in price is assumed to be directly proportional to the level of excess demand. The model is assumed to be identified. Fair and Jaffee demonstrated that the above model can be estimated by relating Q_t to D_t and S_t by means of equations (17c) and (17d).[6]

[5] For directional method I this problem of identification does not arise since one ignores the problems that arise because of sample segmentation and one chooses as sample points for, say, the demand equation only those points for which both D_t and D_{t-1} are observed. This sample segmentation requires throwing away one observation for every switching point. For their empirical work using directional method I, Fair and Jaffee did not actually throw away the requisite number of observations, but assumed that at a switching point both D_t and D_{t-1} or S_t and S_{t-1} were observed.

[6] For example, if $\Delta P_t \geqslant 0$, then $S_t = Q_t$ and $D_t = Q_t + (1/\gamma)\Delta P_t$.

The model in (17a)–(17d) can also be estimated by the maximum likelihood technique in a manner similar to that done for the model in Section 2. First, the sample can be partitioned as follows:

$$(18)\qquad Q_t = X_{2t}\beta_3 + P_t\beta_4 + u_{2t},$$

$$Q_t = X_{1t}\beta_1 + P_t\left(\beta_2 - \frac{1}{\gamma}\right) - P_{t-1}\frac{1}{\gamma} + u_{1t}, \quad \text{when } \Delta P_t \geqslant 0,$$

and

$$(19)\qquad Q_t = X_{1t}\beta_1 + P_t\beta_2 + u_{1t},$$

$$Q_t = X_{2t}\beta_2 + P_t\left(\beta_4 - \frac{1}{\gamma}\right) - P_{t-1}\frac{1}{\gamma} + u_{2t}, \quad \text{when } \Delta P_t \leqslant 0.$$

Consider the equations in (18) corresponding to the sample segmentation, $\Delta P_t \geqslant 0$. These equations can be considered as a two equation system in the variables Q_t and P_t. Therefore, the likelihood function for the equations of (18), given the sample segmentation, is based on the joint conditional density of u_{1t} and u_{2t} given X_t and $\Delta P_t \geqslant 0$, where, as in Section 2, $X_t = (X_{1t}, X_{2t}, P_{t-1})$. Let this density be $g_6(u_{1t}, u_{2t}|\Delta P_t \geqslant 0, X_t)$. Then, in a manner not dissimilar from that of Section 2,

$$(20)\qquad \begin{aligned} g_6(u_{1t}, u_{2t}|\Delta P_t \geqslant 0, X_t) &= g_6(u_{1t}, u_{2t}|D_t \geqslant S_t, X_t) \\ &= g_6(u_{1t}, u_{2t}|X_{1t}\beta_1 + P_t\beta_2 + u_{1t} \geqslant X_{2t}\beta_3 \\ &\quad + P_t\beta_4 + u_{2t}, X_t) \\ &= g_6(u_{1t}, u_{2t}|\alpha_1 u_{1t} + \alpha_2 u_{2t} \geqslant G(X_t), X_t), \end{aligned}$$

where the last step of (20) is obtained by replacing P_t by its reduced form expression in u_{1t}, u_{2t}, and the predetermined variables, putting all terms *not* involving u_{1t} or u_{2t} on the right hand side, and denoting the resulting expression as $G(X_t)$. The parameters α_1 and α_2 are functions of the parameters in equations (17a)–(17c).

The likelihood function for the equations of (19), given the sample separation, is based on the joint conditional density of u_{1t} and u_{2t} given X_t and $\Delta P_t \geqslant 0$. Let this density be $g_7(u_{1t}, u_{2t}|\Delta P_t \geqslant 0, X_t)$. The derivation of $g_7(u_{1t}, u_{2t}|\Delta P_t \leqslant 0, X_t)$ is almost identical to that for $g_6(u_{1t}, u_{2t}|\Delta P_t \geqslant 0, X_t)$. Now, the maximum likelihood estimators of the parameters of equations (17a)–(17c) are obtained by maximizing the likelihood function

$$(21)\qquad \mathscr{L} = \prod_{\Delta P_t > 0} g_6(u_{1t}, u_{2t}|\Delta P_t \geqslant 0, X_t)J_1 \times \prod_{\Delta P_t < 0} g_7(u_{1t}, u_{2t}|\Delta P_t \leqslant 0, X_t)J_2,$$

where u_{1t} and u_{2t} are replaced in both products of (21) by their corresponding expressions in (18) and (19), and J_1 and J_2 are the corresponding Jacobians of transformation from u_{1t} and u_{2t} to Q_t and P_t.

The likelihood technique can be implemented in a manner similar to that described in Section 2, although the situation is somewhat more complicated in the present case. The joint conditional density g_6, for example, can be obtained as

$$(22)\qquad g_6(u_{1t}, u_{2t}|\alpha_1 u_{1t} + \alpha_2 u_{2t} \geqslant G(X_t), X_t) = \frac{g_8(u_{1t}, u_{2t}|X_t)}{\iint_{(\alpha_1 u_{1t} + \alpha_2 u_{2t} \geqslant G(X_t))} g_8(u_{1t}, u_{2t}|X_t)\, du_{1t}\, du_{2t}},$$

where $g_8(u_{1t}, u_{2t}|X_t)$ is the joint density of u_{1t} and u_{2t} conditional on X_t and where the double integral in the denominator represents the probability that $\alpha_1 u_{1t} + \alpha_2 u_{2t} \geqslant G(X_t)$. A similar expression can be derived for the joint conditional density g_7. If the joint density of u_{1t} and u_{2t}, conditional on X_t, is specified to be normal, then it is possible to evaluate numerically the double integral in (22). It is thus possible to attempt to maximize the likelihood function in (21) using a nonlinear maximization program.

4. A METHOD OF ESTIMATION FOR THE GENERALIZED MODEL

The Generalized Model

The models described in Sections 2 and 3 contain price equations which are *nonstochastic* functions of only one variable, namely excess demand. In this section the price equation is generalized to be a multivariate, stochastic function. The model is taken to consist of equations (17a), (17b), (17d), and

$$(17c')\qquad \Delta P_t = \beta_5(D_t - S_t) + X_{3t}\beta_6 + u_{3t},$$

where X_{3t} is a vector of predetermined variables and β_6 is a vector of parameters.

A Method of Estimation

Because the price equation is multivariate and stochastic, the observed quantity, Q_t, cannot be strictly identified with either D_t or S_t on the basis of observed price changes. Hence, Q_t must be related to D_t and S_t probabilistically on the basis of observed price changes. Define a selector variable r_t, where

$$(23)\qquad r_t = 1 \quad \text{if } D_t > S_t, \qquad r_t = 0 \quad \text{if } D_t < S_t.$$ [7]

Using this variable, equations (17a), (17b), and (17d) can be written as

$$(24)\qquad Q_t = r_t S_t + (1 - r_t) D_t.$$

Now, from (17c') $r_t = 1$ if $\Delta P_t > X_{3t}\beta_6 + u_{3t}$ and $r_t = 0$ if $\Delta P_t < X_{3t}\beta_6 + u_{3t}$. In light of these relations, the conditional density of r_t given ΔP_t and X_t, where X_t

[7] Since the disturbance terms of the model are assumed to be continuous variables, the probability is zero that D_t will equal S_t. Thus, the problem of defining r_t when $D_t = S_t$ can be ignored.

now includes X_{3t} as well as X_{1t}, X_{2t}, and P_{t-1}, can be expressed as

$$\text{(25)} \qquad \text{prob}\,(r_t = 1|\Delta P_t, X_t) = H(\Delta P_t, X_t),$$

$$\text{prob}\,(r_t = 0|\Delta P_t, X_t) = 1 - H(\Delta P_t, X_t),$$

where $H(\Delta P_t, X_t) = \text{prob}\,(u_{3t} \leqslant \Delta P_t - X_{3t}\beta_6|\Delta P_t, X_t)$.

The probability statement, $\text{prob}\,(u_{3t} \leqslant \Delta P_t - X_{3t}\beta_6|\Delta P_t, X_t)$, can be obtained from the conditional density of u_{3t} given ΔP_t and X_t. This density in turn depends upon the joint density of ΔP_t and u_{3t} and the marginal density of ΔP_t, both conditional on X_t. Finally, these densities can be derived if the joint density of the disturbance terms is specified.[8] Thus, if the joint density of the disturbance terms is specified, the functional form of $H(\Delta P_t, X_t)$ is determined.[9]

Assuming that the joint density of the disturbance terms is specified, the estimation of the model can now be considered. The model under consideration is

$$\text{(26a)} \qquad Q_t = r_t S_t + (1 - r_t)D_t,$$

$$\text{(26b)} \qquad D_t = X_{1t}\beta_1 + P_t\beta_2 + u_{1t},$$

$$\text{(26c)} \qquad S_t = X_{2t}\beta_3 + P_t\beta_4 + u_{2t},$$

$$\text{(26d)} \qquad \Delta P_t = \beta_5(D_t - S_t) + X_{3t}\beta_6 + u_{3t},$$

and

$$\text{(26e)} \qquad r_t = H(\Delta P_t, X_t) + u_{4t},$$

where, in light of (25), u_{4t} is a random variable such that $E[u_{4t}|\Delta P_t, X_t] = 0$. Since observations on D_t, S_t, and r_t are not available, these variables will first be eliminated from the model. For the sake of having a compact notation, let $D_t^* = X_{1t}\beta_1 + P_t\beta_2$, $S_t^* = X_{2t}\beta_3 + P_t\beta_4$, and $H_t = H(\Delta P_t, X_t)$. Now, D_t, S_t, and r_t can be eliminated from (26a)–(26e) to get

$$\text{(27a)} \qquad Q_t = H_t S_t^* + D_t^* - H_t D_t^* + \Omega_t + e_{1t}$$

and

$$\text{(27b)} \qquad \Delta P_t = \beta_5(D_t^* - S_t^*) + X_{3t}\beta_6 + e_{2t},$$

where $\Omega_t = H_t(u_{2t} - u_{1t})$, $e_{1t} = u_{1t} + u_{4t}(S_t - D_t)$, and $e_{2t} = u_{3t} + (u_{1t} - u_{2t})$. It is clear that $E[e_{2t}|X_t] = 0$. Also, since $E[u_{4t}|\Delta P_t, X_t] = 0$ for any values of X_{3t} and

[8] As an example, the reduced form equation for ΔP_t is linear in the elements of X_t and u_{1t}, u_{2t}, and u_{3t}. If the disturbance terms are assumed to be normally distributed and independent of X_t, then the conditional density of ΔP_t and u_{3t} is also normal and, therefore, is completely specified by two conditional means and variances and by the covariance of ΔP_t and u_{3t}. The mean and variance of u_{3t} are given by the specifications of the model; the mean and variance of ΔP_t, as well as the covariance of ΔP_t with u_{3t}, are easily derived from the reduced form equation for ΔP_t.

[9] Note that for certain specifications of the disturbance terms (e.g., normality) this function will involve integrals. More will be said concerning this function below.

u_{3t}, it follows from the price equation that $E[u_{4t}|(D_t - S_t), X_t] = 0$. Therefore, $E[e_{1t}|X_t] = 0$. Thus, e_{1t} and e_{2t} can be considered as disturbance terms.

Unlike the remaining terms of (27a) and (27b), Ω_t depends directly upon the disturbance terms u_{1t} and u_{2t}. Therefore Ω_t cannot be considered as part of the regression function; Ω_t also cannot be considered as a disturbance term because it involves the product of H_t and $(u_{2t} - u_{1t})$ and so will not in general have a mean of zero. The procedure here, therefore, will be to abstract the mean of Ω_t, conditional on ΔP_t and X_t, and incorporate it within the regression function so as to end up with a two-equation system based on the two endogenous variables, Q_t and ΔP_t, or, since $\Delta P_t = P_t - P_{t-1}$, on Q_t and P_t.

Since the expectation of one variable conditional upon a set of others is, in general, a function of the conditioning variables, it follows that

$$E[\Omega_t|\Delta P_t, X_t] = H_t E[u_{2t} - u_{1t}|P_t, X_t] = H_t L(P_t, X_t), \quad (28)$$

where $L(P_t, X_t)$ is a function of the elements of X_t and P_t. It is interesting to note that if u_{1t}, u_{2t}, and u_{3t} are assumed to be jointly normal, the joint distribution of $(u_{2t} - u_{1t})$ and P_t will be normal and, therefore, the conditional distribution of $u_{2t} - u_{1t}$ given P_t will be normal; hence, the function L in (28) will be linear in P_t and X_t. In any event, the parameters of L will be functions of the parameters of the demand, supply, and price equations, as well as of the variances and convariances of u_{1t}, u_{2t}, and u_{3t}.

In light of equation (28), it follows that Ω_t can be expressed as

$$\Omega_t = H_t L(P_t, X_t) + \theta_t, \quad (29)$$

where $E[\theta|P_t, X_t] = 0$, and so $E[\theta_t|X_t] = 0$. Therefore, equations (27a) and (27b) can be expressed as

$$Q_t = H_t S_t^* + D_t^* - H_t D_t^* + H_t L(P_t, X_t) + \psi_t \quad (30a)$$

and

$$\begin{aligned} \Delta P_t &= \beta_5(D_t^* - S_t^*) + X_{3t}\beta_6 + e_{2t} \\ &= X_{1t}(\beta_5\beta_1) + P_t(\beta_5\beta_2) - X_{2t}(\beta_5\beta_3) - P_t(\beta_5\beta_4) + X_{3t}\beta_6 + e_{2t}, \end{aligned} \quad (30b)$$

where $\psi_t = e_{1t} + \theta_t$, and so $E[\psi_t|X_t] = 0$.

Equations (30a) and (30b) form a simultaneous two-equation system for Q_t and P_t, which is nonlinear in the parameters and also in one of the endogenous variables, P_t.[10] Aside from the maximum likelihood technique, general results concerning the estimation of such systems are not available. The difficulty in applying the maximum likelihood technique to the system (30a)–(30b) is that the joint distribution of ψ_t and e_{2t} will be, for just about any specification of u_{1t}, u_{2t}, and u_{3t}, quite complicated. However, a consistent estimation technique can be

[10] Note that although P_t does not depend directly on Q_t in (30b), the system is fully simultaneous because ψ_t and e_{2t} are correlated, e.g., they both contain u_{1t}.

developed, subject to certain approximations, using the method of moments because $E[\psi_t|X_t] = E[e_{2t}|X_t] = 0$.

First, it will be assumed that u_{1t}, u_{2t}, and u_{3t} are jointly normal so that $L(P_t, X_t)$ is linear in P_t and X_t. Second, it will be assumed that the error of approximation in the expansion of H_t (as a function of P_t and X_t) in a Taylor series is negligible after a *finite* number of terms.[11] Now, substituting the expression for $L(P_t, X_t)$ and the polynomial expansion of H_t into (30a) yields an equation of the form

$$\text{(30a')} \qquad Q_t = Z_{1t}\gamma_1 + Z_{2t}\gamma_2 + \psi_t,$$

where Z_{1t} is a row vector of observations on known polynomial functions of the predetermined variables, X_t, and Z_{2t} is a row vector of observations on known polynomial functions of the endogenous variable P_t and predetermined variables X_t.[12] The vectors γ_1 and γ_2 are vectors of parameters, the elements of which are nonlinear functions of β_1 through β_6 and of the variances and covariances of u_{1t}, u_{2t}, and u_{3t}. The order of these vectors depends on the degree of the polynomial expansion.

Equations (30a') and (30b) form a two-equation system that contains nonlinear, but known, endogenous functions and nonlinear restrictions on the parameters—a system, in other words, that is nonlinear in both variables and parameters. The system may be consistently estimated by a nonlinear two-stage least squares procedure. Specifically, since Z_{2t} is the vector of endogenous functions in (30a'), each element of Z_{2t}, one of which is P_t, can be regressed on the elements of Z_{1t} and on the predetermined variables in (30b) as well as on powers of these variables.[13] Let $\hat{Z}_{2t}$ and $\hat{P}_t$ denote the predicted values of the elements of Z_{2t} and P_t. Now, as will be shown below, the basic parameters of the system β_1 through β_6 and the variances and covariances of u_{1t}, u_{2t}, and u_{3t}, can be estimated by minimizing

$$\text{(31)} \qquad \begin{aligned} S = {} & (Q - Z_1\gamma_1 - \hat{Z}_2\gamma_2)'(Q - Z_1\gamma_1 - \hat{Z}_2\gamma_2) + \alpha(\Delta P - X_1\beta_5\beta_1 \\ & - \hat{P}\beta_5\beta_2 + X_2\beta_5\beta_3 + \hat{P}\beta_5\beta_4 - X_3\beta_6)'(\Delta P - X_1\beta_5\beta_1 \\ & - \hat{P}\beta_5\beta_2 + X_2\beta_5\beta_3 + \hat{P}\beta_5\beta_4 - X_3\beta_6), \end{aligned}$$

where $Q, Z_1, \hat{Z}_2, \Delta P, X_1, X_2, X_3$, and $\hat{P}$ are the vectors and matrices of observations on the corresponding elements, and α is any nonnegative number. If α is taken to be zero, then only information regarding equation (30a') is used to obtain the estimates, whereas if α is taken to be positive, then information regarding equation (30b) is also used in obtaining the estimates.

[11] Note, if u_{1t}, u_{2t}, and u_{3t} are jointly normal, H_t will be of the form

$$H_t = \int_{-\infty}^{L_1(P_t, X_t)} f(Z)\,dZ,$$

where $f(Z)$ is the density for a standard normal variable and $L_1(P_t, X_t)$ is linear in X_t and P_t; see (25) and Footnote 7. Therefore, the expansion of H_t is straightforward. In a sense, most econometric systems may be considered as depending upon such polynomial approximations; see, for example, Fisher [**6**, pp. 127–29].

[12] For example, one such function might be $P_t^2X_{1t}$, where X_{1t} is a predetermined variable.

[13] See Kelejian [**10**].

For a given value of α, the minimization of S in (31) with respect to the parameters β_1 through β_6 and the variances and covariances of u_{1t}, u_{2t}, and u_{3t} is quite straightforward and should be able to be handled by nonlinear optimization programs like those used in Section 2. If first and second derivatives of S are required, these can be computed numerically or else one can go to the bother of actually differentiating S twice with respect to β_1 through β_6. Indeed, the problem of minimizing S in (31) does not appear to be as difficult as was the problem of maximizing $\mathscr{L}$ in (8) since the maximization of $\mathscr{L}$ required the evaluation of normal integrals, where the limits of the integrals were themselves functions of some of the parameter values. The steps involved in computing the estimates of the parameters of equations (30a) and (30b) are tedious because of the need to expand H_t in a Taylor series and the need to express $L(P_t, X_t)$ as an explicit function of P_t, X_t, and the parameter values, but aside from the tediousness the computation of the estimates does not appear infeasible or impractical.

The choice of the value of α in (31) is somewhat arbitrary. A choice of a value of one means that both equations are weighted equally, and this may be as good a choice as any. One might also want to consider a two-step procedure in which initial estimates of the parameter values are obtained by, say, using $\alpha = 1$, then estimating the variances of ψ_1 and e_{2t}, and then reestimating the parameters taking α to be the ratio of the estimated variance of ψ_t to the estimated variance of e_{2t}.[14]

It remains to be shown that the minimization of (31) yields consistent parameter estimates. To see this, let $\hat{V}_{1t} = Z_{2t} - \hat{Z}_{2t}$ and $\hat{V}_{2t} = P_t - \hat{P}_t$. Also, rewrite equation (30b) as

$$(32) \qquad \Delta P_t = Z_{3t}\gamma_3 + P_t\gamma_4 + e_{2t},$$

where $Z_{3t} = (X_{1t}, X_{2t}, X_{3t})$ and γ_3 and γ_4 are the corresponding vectors of parameters, the elements of which are nonlinear functions of β_1 through β_6. Equations (30a′) and (32) can be written:

$$(33) \qquad Q_t = Z_{1t}\gamma_1 + \hat{Z}_{2t}\gamma_2 + \psi_t + \hat{V}_{1t}\gamma_2$$

and

$$(34) \qquad \Delta P_t = Z_{3t}\gamma_3 + \hat{P}_t\gamma_4 + e_{2t} + \hat{V}_{2t}\gamma_4.$$

Now, let

$$(35) \qquad Y = \begin{vmatrix} Q \\ \sqrt{\alpha}\,\Delta P \end{vmatrix}, \qquad Z = \begin{vmatrix} Z_1 & \hat{Z}_2 & 0 & 0 \\ 0 & 0 & \sqrt{\alpha}\,Z_3 & \sqrt{\alpha}\,\hat{P} \end{vmatrix}, \qquad \gamma = \begin{vmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \end{vmatrix},$$

$$\varepsilon = \begin{vmatrix} \psi \\ \sqrt{\alpha}\,e_2 \end{vmatrix}, \qquad \hat{V} = \begin{vmatrix} \hat{V}_1 & 0 \\ 0 & \sqrt{\alpha}\,\hat{V}_2 \end{vmatrix}, \qquad \gamma^* = \begin{vmatrix} \gamma_2 \\ \gamma_4 \end{vmatrix},$$

[14] It should be noted, of course, that the variance of ψ_t is not constant over the sample period, and so what one is obtaining using this procedure is an estimate of the average variance of ψ_t over the sample period.

where the dropping of the t subscripts means that the symbols refer to vectors or matrices of observations. Equations (33) and (34) can now be written, after (34) is multiplied across by $\sqrt{\alpha}$, as

$$(36) \qquad Y = Z\gamma + \varepsilon + \hat{V}\gamma^*.$$

Using this notation, S in (31) is

$$(37) \qquad \begin{aligned} S &= (Y - Z\gamma)'(Y - Z\gamma) \\ &= Y'Y - 2\gamma'Z'Y + \gamma'Z'Z\gamma. \end{aligned}$$

Let β be the vector of parameters consisting of β_1 through β_6 and of the variances and covariances of u_{1t}, u_{2t}, and u_{3t}.[15] Minimizing S with respect to β yields

$$(38) \qquad \frac{\partial S}{\partial \beta} = -2\hat{\gamma}_\beta' Z'Y + 2\hat{\gamma}_\beta' Z'Z\hat{\gamma} = 0,$$

where $\hat{\gamma}$ is γ evaluated at $\hat{\beta}$ and $\hat{\gamma}_\beta$ is the matrix of partial derivatives $\partial\gamma/\partial\beta$ evaluated at $\hat{\beta}$. Linearizing (38) about β yields

$$(39) \qquad \gamma_\beta' Z'[Z\gamma + Z\gamma_\beta(\hat{\beta} - \beta) - Y] = 0,$$

or, using (36),

$$(40) \qquad \hat{\beta} - \beta = (\gamma_\beta' Z'Z\gamma_\beta)^{-1}\gamma_\beta' Z'(\varepsilon + \hat{V}\gamma^*).$$

Since $\text{plim}_{T\to\infty} T^{-1}Z'\varepsilon = 0$, $\text{plim}_{T\to\infty} (\hat{\beta} - \beta)$ will be zero if $\text{plim}_{T\to\infty} T^{-1}(\gamma_\beta' Z'\hat{V}\gamma^*)$ is zero. Now,

$$(41) \qquad Z'\hat{V} = \begin{vmatrix} Z_1'\hat{V}_1 & 0 \\ \hat{Z}_2'\hat{V}_1 & 0 \\ 0 & \alpha Z_3'\hat{V}_2 \\ 0 & \alpha\hat{P}'\hat{V}_2 \end{vmatrix}.$$

Since it was assumed that all of the predetermined variables were used in constructing the calculated values, it follows by the least squares property that $Z'\hat{V} = 0$; therefore, $\hat{\beta}$ is consistent.

5. CONCLUSION

The study of the estimation of disequilibrium models has become quite popular recently.[16] In this paper three methods of estimating disequilibrium models have been proposed. The first two methods—maximum likelihood methods—are concerned with the estimation of models in which the price equation is a non-

[15] The following derivation is similar, although in a different context, to a derivation given by Aigner and Goldberger [**1**, p. 715, n. 1].

[16] In addition to the study of Fair and Jaffee [**4**], the following studies are concerned in one way or another with the question of estimating disequilibrium models: Goldfeld and Quandt [**8**], Quandt [**14**], Goldfeld, Kelejian, and Quandt [**7**], Brown and Durbin [**2**], Farley and Hinich [**5**], and McGee and Carleton [**11**]. See Quandt [**14**] for a brief review of these studies.

stochastic function of excess demand. The third method is concerned with the estimation of a more general model in which the price equation is allowed to be a multivariate, stochastic function. The problems involved in estimating disequilibrium models turn out to be fairly complicated, and for this reason one may in practice want to begin with the estimation of simply-specified models before considering more general models. Nevertheless, it is encouraging that the quite general model considered in Section 4 of this paper appears capable of estimation.

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