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ECONOMETRICS AND ECONOMIC POLICY

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Abstract: This is a survey paper on five important developments in econometrics, with illustrative applications to economic policy formulation in Taiwan, Mainland China and the United States. The developments are the endogeneity of explanatory variables in a stochastic equation, nonstationarity of dynamic models in the form of cointegrated variables, the determination of optimal policies, accounting for reactions of economic agents to changing policy rules, and the use of conditional expectations to capture forward looking behavior.

Key words and phrases: Cointegration, econometrics, economic policy, endogeneity, optimal control, nonstationarity, rational expectations, simultaneous equations.

1. Introduction

Statistics is a set of methods for making decisions under uncertainty. Economic policies are decisions made under uncertainty. Accordingly statistics is useful for the formulation of economic policy. It is the purpose of this paper to describe the nature of economic statistics, or econometrics, as it has evolved in the last half century, and how it has been applied in economic policy formulation. The elements of econometrics covered in this paper are selective and confined mainly to those useful for the formulation of macroeconomic policy. Thus important developments in microeconometrics are excluded. The applications included are also limited in scope and based on the experiences in Taiwan in the 1960's and 1970's, in the Chinese mainland in the 1980's and 1990's, and in the United States since the 1970's. Let it be pointed out at the outset that economic policies are often not based on economic considerations alone. Politicians and government officials have other objectives in mind, such as gaining political power and popularity. Nevertheless non-economic considerations can sometimes be incorporated into a statistical decision framework and subject to econometric analysis. In cases where economic considerations are taken into account, intuition and informal analysis outside the framework of econometrics are frequently applied. Thus the framework of econometrics, or statistics, is boarder than economic policy analysis in one sense, and narrower in another.

Five major developments in econometrics since the 1950's are surveyed in this paper. They are the endogeneity of explanatory variables in a system of simultaneous equations, nonlinearity as expressed by cointegration in the variables, the use of methods of optimal control for the analysis and formation of economic policies, possible change in model parameters due to change in government decision rules, and the use of mathematical expectations to capture forward looking behavior of economic agents. These five topics are discussed in the five subsections of Section 2 which deals with theoretical developments in econometrics. Space does not permit the illustrations of all of them in application to economic policy formulation, but their possible uses will be mentioned. More detailed discussions of the applications will be given in selected cases. The three subsections of Section 3 present, respectively, illustrative applications to economic policy analyses in Taiwan in the 1960's and 1970's, in Mainland China in the 1980's and 1990's, and in the United States since the 1970's. Section 4 includes some comments on the prospects of future research in the five areas and on economic policy analysis in practice applying these research ideas. Section 5 concludes.

2. Five Major Theoretical Developments in Macro-Econometrics

2.1. Endogeneity of explanatory variables

Regression analysis was applied to estimate economic relations in the 1930's. Outstanding examples are the study of business cycles by Tinbergen (1939), and the study of demand for agricultural products by Schultz (1938). For his contribution to econometrics, Tinbergen received one of the first two Nobel Prizes for Economic Science in 1969. However, it was the monumental 1943 work of Trygve Haavelmo (who received the Nobel Prize in 1989) which broke new ground in econometric method departing from traditional regression analysis in statistics. The idea of "structural equations" was proposed to indicate basic economic relations, such as a demand function and a supply function, both including as variables price and quantity of a commodity traded in the market. If one uses time series data on quantity and price to estimate a regression of quantity on price, one might get a negative or a positive regression coefficient. A negative coefficient would be obtained if the observations have been generated by shifting supply conditions which traced out the demand function; a positive coefficient if shifting demand conditions traced out points on a supply function. If there are variables shifting the demand and supply functions one has to identify these variables in each equation and specify the manner in which they affect the correponding equation in order to estimate the demand and supply functions consistently. The *identification problem* for consistently estimating structural parameters in a system of simultaneous equations from observed data is the problem of specifying correctly and adequately the shifting variables and the manner they affect each of the equations in the system. The problem was recognized as early as 1927 in non-mathematical terms by E. J. Working.

To put the above ideas in more formal terms, let y denote a vector of g endogenous variables which the econometric model, consisting of an equal number of simultaneous stochastic equations, is designed to explain. In our example of demand and supply equations, price and quantity are the two endogenous variables. Let z denote a vector of k predetermined variables assumed to be statistically independent of the vector e of g residuals. In our example, income may be a variable affecting demand and weather may be a variable affecting the supply of a farm product. If the system of structural equations is linear, we can write

$$By + \Gamma z = e, \tag{1}$$

where B is a g by g matrix of structural parameters, Γ, is a g by k matrix of structural parameters, and e is a vector of random residuals independent of z. To be able to identify the structural parameters, one may specify that certain structural parameters are zero, e.g., that certain variables affect demand but not supply and other variables affect supply and not demand. If all endogenous and predetermined variables appear in all equations, one cannot distinguish one structural equation from another. In the econometrics literature there is much discussion on the conditions required for identification. These conditions take the form of restrictions on the structural parameters, including the covariance matrix of e. In practice, they are specified a priori by the judgment of the econometrician based on economic theory. Without such assumptions, identification of structural parameters is impossible. Such a priori assumptions are used in economics as substitutes for controlled experiments which are often not available or are too costly to run.

Methods for estimating the parameters of (1) can be full-information or limited information. The former methods require the specification of the identification restrictions for all equations and enable one to estimate all parameters. The latter methods require the specification of the identification restrictions for a subset, in an important case only one, of the structural equations, and provide estimates of the parameters of the subset only. Classic treatment of estimation can be found in Koopmans (1950) and Hood and Koopmans (1953), and the subject is treated in econometrics texts, including Chow (1983). Let Y, Z and E denote, respectively, n by g, k and g matrices of endogenous variables, predetermined variables and residuals given a sample of n observations. If e is assumed to be normal, then the method of maximum likelihood can be interpreted as generalized least squares in the sense of minimizing the ratio of $\det(E'E)$ to $\det(BY'YB'')$ where a prime denotes transpose and $E' = BY' + \Gamma Z'$, as discussed in Chow (1964), with computational problems discussed in Chow (1968). The numerator of the above ratio is the generalized variance while the denominator is a normalization function.

If we are interested in the parameters of only a subset of equations we can choose a limited-informtion method of estimation. Limited information methods have the advantage of not requiring the specification of the other equations in the system, and errors in the specification can lead to poor sampling properties of all estimates. Consider the problem of estimating only one of the structural equations. If we choose one of the endogenous variables as the dependent variable, we find that there are other endogenous variables on the right-hand side of the equation which are correlated with the residual. This is so because all endogenous variables are correlated with all residuals, as seen by solving the above set of structural equations (1) for the endogenous variables y and recognizing that each of them is partly a linear combination of the elements of the residual vector e. One widely used method for estimating one structural equation is the method of instrumental variables. Let y_1 be a column vector of n observations of the endogenous variable chosen as the dependent varible, X be the matrix of n observations of all of its explanatory variables (some endogenous and some predetermined) and b be the vector of coefficients in the equation. The instrumental-variable IV estimator of b is the solution of

$$(W'X)b = W'y_1, \tag{2}$$

where W is a matrix of observations of instrumental variables which are assumed to be correlated with X but uncorrelated with e. Although the estimator given by (2) is simple, the choice of the instrumental variables W is a delicate matter. Different choices of instrumental variables lead to different estimators, as discussed for example in Chow (1983). If W is the matrix of estimated values of X obtained by regressing X on all predetermined variables in the system, (2) is the normal equations for the method of two-stage least squares.

One criticism of this method is that the estimates depend on which of the endogenous variables in the equation is chosen as the dependent variable. This criticism does not apply to the limited information maximum likelihood method suggested by Anderson and Rubin (1950). This method minimizes the ratio of the sum of squared residuals of a regression of the linear combination of the endogenous variables in the equation on the predetermined variables *included* in the equation to the sum of squared residuals of a regression of the same linear combination on *all* predetermined variables in the system. Note that a linear combination of the endogenous variables in the equation is treated as a dependent variable, and not just one of them is so treated as in (2). This is just like the definition of a canonical correlation coefficient which involves the correlation between two linear combinations of variables. If the specification is correct, that is, if only the specified predetermined variables appear in the equation of interest, one would expect the numerator of the above ratio to be not much larger than the denominator. Let $M = I - Z(Z'Z)^{-1}Z'$ and M_1 be the same matrix with Z replaced by the matrix of only the predetermined variables included in the equation to be estimated. Let Y_1 be the matrix of only those endogenous variables included in the equation, and β_1 be the column vector of its coefficients. To minimize the ratio according to the method of limited information maximum likelihood, we find the vector β which solves the equation $Y_1'M_1Y_1\beta = \mu Y_1'MY_1\beta$ with μ being the smallest root of the determinantal equation $\det[Y_1'M_1Y_1 - \mu Y_1'MY_1] = 0$. The two matrices in this equation are matrices of residuals of the regression of Y_1 on the predetermined variables appearing in the equation to be estimated and all pretermined variables in the simultaneous equations model, respectively. If, instead of solving an eigenvalue problem to find the coefficient vector β corresponding to the smallest root of the determinantal equation, we arbitrarity let the first element of β be -1, ignore the first equation and solve the remaining linear equations for the remaining coefficients of β, we obtain what is known as a k-class estimator, where k correponds to a choice of the value of μ in the equation. (See Chow (1964, p.537)). If μ is set equal to 1, we have the two-stage least squares estimator which is also an IV estimator given by equation (2). Estimation of nonlinear simultaneous equations, and those with serially correlated residuals, was investigated in the 1970's, as partially described in Chow (1983).

R. A. Fisher's advocacy of parametric models and the associated method of maximum likelihood dominated the statistics profession for three decades up to the early 1960's. Since then we have seen the partial return to nonparametric and semiparametric methods (the latter specifying the form of the regression function but not of the distribution of the residual) as exemplified by the method of instrumental variables (least squares being a special case with $W = X$). An important example of IV and the return to the method of moments, not dependent on specification of the distribution of the residuals, is the work of Hansen (1982) and Hansen and Singleton (1982). Although the method of instrumental variables was first used in macroeconometrics, it is now widely used in microeconometrics as well. The latter application occurs because many micro explanatory variables are also correlated with the regression residuals. Research on nonparametric and semiparametric methods for the estimation of econometric equations with endogenous explanatory variables continues to be active today.

In applications to the formulation of macroeconomic policy, the system of equations is a set of equations describing the macroeconomy. In Keynesian models there are equations explaining consumption, investment, government expenditures, exports, imports, and the demand for money or the rate of interest. These equations are projected forward under alternative assumptions concerning monetary and fiscal policies which are specified by the time paths of the policy or control variables (a subset of predetermined variables). The policies which yield more desirable paths of the important economic variables, such as the unemployment rate and the inflation rate, can be selected.

2.2. Cointegrated models

Nearly all simultaneous equations models used in macroeconomics are dynamic in the sense that some of the predetermined variables are lagged endogenous variables, while the remaining are exogenous variables. A simple example is a first-order autogression. Dynamic properties of such models have been intensively studied in the literature, e.g., as summarized in Chow (1975). Up to the early 1980's, such dynamic models were generally assumed to be covariance stationary; in a system of equations explaining a vector endogenous variable the matrix of coefficients of the lagged dependent variables (after a higher order system is converted into first order) is assumed to have all eigenvalues smaller than unity in absolute value. Beginning with the influential paper of Engle and Granger (1987), models with unit roots have become more popular. It is recognized that taking the first difference of a variable amounts to introducing a unit root in the system of the original variables and that taking the first differences of all endogenous variables amounts to assuming the existence of as many unit roots as the number of endogenous variables in the system. In economic applications taking differences of all variables and assuming the existence of as many unit roots will frequently give rise to overdifferencing, i.e., assuming more unit roots than the data warrant.

If we write the reduced form of a linear simultaneous model as

$$y_t = Ay_{t-1} + A_1\Delta y_{t-1} + \cdots + A_p\Delta y_{t-p} + b_t + \varepsilon_t, \tag{3}$$

the model will be nonstationary if some roots of the matrix A equal one. Let there be d unit roots and $g-d$ stationary roots. By subtracting y_{t-1} from both sides of equation (3), we have Δy_t as the dependent variable and $\Pi = A - I$ as the coefficient matrix of y_{t-1}:

$$\Delta y_t = \Pi y_{t-1} + A_1\Delta y_{t-1} + \cdots + A_p\Delta y_{t-p} + b_t + \varepsilon_t. \tag{4}$$

The d unit roots of A correspond to d zero roots of Π. If d equals the number g of endogenous variables the matrix Π is a zero matrix and the model can be written in the first differences of all the variables. When $g-d$ roots of Π are not zero we can write Π as the product $\alpha\beta$, where α is g by $g-d$ and β is $g-d$ by g. A variable is said to be integrated of order 1 if it becomes stationary after differencing once. A variable following a first-order autogression with a unit root is such a variable, its first difference being stationary. Two variables, each being integrated of order 1, are said to be cointegrated if a linear combination of them is stationary. One can imagine national income and aggregate consumption being nonstationary in the sense of being integrated of order 1, and yet income minus 0.9 times consumption being stationary. Defining βy_{t-1} as x_{t-1}, we find these $g-d$ linear combinations of the variables to be stationary. These stationary relationships are the cointegration vectors. The model (4) explaining Δy_t can be interpreted as an error-correction model since y is changed or corrected by the values of the cointegration vectors $\beta y_{t-1} = x_{t-1}$ in the previous period. For example, if income minus .9 times consumption in the last period was different from zero, a fraction (given by the corresponding element of α) of the difference will be adjusted in the current y_t. The cointegration vectors or the rows of β can be consistently estimated by least squares as suggested by Engle and Granger (1987). Given β we can estimate model (4) by least squares using x_{t-1} as an explanatory variable. Methods of estimating (4) and testing for the number of unit roots have been extensively discussed in the literature, including Johansen (1988, 1989).

Anderson (2000) provides the following interpretation to the problem of estimating the cointegrating vectors and its relation to the problem of limited information maximum likelihood estimation of one equation in a linear simultaneous system. Consider equation (4) as a regression of Δy on y_{t-1} with coefficient matrix Π. When the rank of Π is $g-d$, we have the reduced rank regression problem of finding as many linear combinations $\phi'\Delta y$ of the dependent variable which have the highest signal to noise ratios. The signal to noise ratio of $\phi'\Delta Y'$ in the regression is the ratio of the signal sum of squares $\phi'\Pi Y_{-1}'Y_{-1}\Pi'\phi$ to the noise sum of squares $\phi'E'E\phi$. In estimation, the coefficient matrix Π and the matrix E of residuals of (4) are replaced by the least squares estimates, and the problem amounts to finding a vector ϕ which solves the equation $\Pi Y_{-1}'Y_{-1}\Pi'\phi = \lambda E'E\phi$ with λ corresponding to one of the largest $g-d$ roots of the determinantal equation $\det[\Pi Y_{-1}'Y_{-1}\Pi' - \lambda E'E] = 0$. This problem is mathematically identical with the one of estimating one equation in a simultaneous system by the method of limited information maximum likelihood. Let Φ' denote the $g-d$ by g matrix consisting of the row vectors ϕ' which correspond to the $g-d$ largest roots of the above determinantal equation. We can write $\Phi'\Pi = \Phi'\alpha\beta = \Phi'\Phi\beta$ if we let $\alpha = \Phi$. Solving this equation, we have $\beta = (\Phi'\Phi)^{-1}\Phi'\Pi$, and the reduced rank coefficient matrix is estimated by $\alpha\beta = \Phi(\Phi'\Phi)^{-1}\Phi'\Pi$, where Π is the least squares estimate of the coefficient matrix. Besides estimating the cointegration vector β and the error correction coefficients α, we need to estimate the rank of the coefficient matrix. The above discussion starts with a dynamic model (3). If we start with a simultaneous equations model, with a coefficient matrix multiplying the vector of endogenous variables on the left-hand side of (3) we may be interested in estimating the parameters of such simultaneous structural equations from which the reduced form equations (3), are derived. This problem is addressed in Chow (1993), which also cites some relevant literature on cointegration. An application of cointegration models for economic policy will be discussed in Section 3.2.

2.3. The determination of optimal policies

Once econometric models in the form of a system of simultaneous equations were used to study likely consequences of alternative policies, it was a natural step to make such studies more systematic. Besides the econometric model one would specify an objective function involving both endogenous and exogenous variables. Some of the exogenous variables are subject to the control of the decision maker. The basic ideas of optimum economic policy were set out by Tinbergen in his books (1952, 1956) and by Theil (1961). Further developments were presented in Chow (1975). A standard formulation of optimum economic policy is to maximize

$$E\sum_t \left\{\beta^t r(y_t, x_t) - \beta^{t+1}\lambda'_{t+1}\left[y_{t+1} - f(y_t, x_t, e_t)\right]\right\} \tag{5}$$

were r is the objective function. The expression in square brackets, when set equal to zero, is the dynamic econometric model; β is the discount factor used by the policy maker. I have skipped one step in writing out this optimal control problem which consists of the multiperiod objective function to be maximized subject to the constraint given by the dynamic econometric model. I have assumed that this problem is to be solved by the method of Lagrange multipliers and written the Lagrange expression (5) to be maximized. E denotes mathematical expectation, λ is a column vector of Lagrange multipliers.

The common method to solve such dynamic optimization problems is dynamic programming, which involves solving a partial differential equation for the value function. The value function is a mapping from the expected value of the multiperiod objective function under the optimal policy to the vector of state variables x in the initial period. It is argued in Chow (1997) that the method of Lagrange multipliers is more efficient that the method of dynamic programming in solving such dynamic optimization problems, in discrete time and in continuous time. By the Lagrange method, one obtains two sets of first-order conditions by setting the vector derivatives of (5), with respect to the control and state variables respectively, to zero. These conditions can be solved to obtain the optimal control function and the Lagrange function, both of the state variables. In the special case when the stochastic element e_t in (5) is absent, the problem is a deterministic optimal control problem. The Lagrange method is reduced to the well-known maximum principle, as shown in Chow (1975, p.162) for dicrete time stochastic models and Chow (1997, p.145) for continuous time stochastic models. Since the early 1970's dynamic optimization using econometric models has been used to study economic policies in many parts of the world.

2.4. Reactions of the public to changing policy rules

As economists were doing active research on optimum economic policy using the framework just described, Robert Lucas in a well-known 1976 paper suggested that when government policy makers use a given econometric model to formulate economic policies, the model parameters will be changed as the government policies change, thus making the method for policy evalution based on an invariant model invalid. Many economists were persuaded by this criticism. Others, especially the practitioners, have continued their work of using and improving econometric models and optimization methods. From the theoretical point of view, Sims (1980), points out that the users of such optimization methods are not advising the government to change to a new policy rule, but are only helping the decision makers to compute efficiently in carrying out a given policy rule. The solution to the above optimum control problem takes the form of a feedback control equation mapping the optimal vector policy or control variable to the vector state variable, and can be viewed as a policy rule. Such rule are seldom changed. If the rule were changed materially, then perhaps the Lucas critique might apply. Sims suggests that the use of optimal control in practice is to assist the decision makers to carry out a given policy rule. The fact that rule are seldom changed, or that the Lucas critique is seldom relevant, is illustrated by numerous attempts to estimate a time-invariant Federal Reserve monetary policy rule in practice in econometric studies.

Some economists mistakenly attribute to Robert Lucas the idea that reduced-form parameters will change when government policy changes. This idea was a basic idea of the researchers at the Cowles Commission in the late 1940's and early 1950's when they proposed the use of simultaneous structural equations, pointing out that the corresponding parameters will change when government policy changes (see Marschak (1953)). One simple example is a structural consumption equation in a Keynesian model with consumption specified as a linear function of disposable income, i.e., $(1-\theta)$ times income, θ being the tax rate. Let national income be the sum of consumption and investment, and investment be an exogenous variable. Given the parameters including θ in the consumption function, one can solve for the reduced-form equation explaining national income by investment. If θ changes to a new value, it can be used to calculate disposable income in the new model. The new model has the same structural parameters but different parameters in the reduced-form equation explaining income by investment. One application of this idea can be found in Chow (1967) on a simple macro-econometric model of the United States which was subject to a change in the tax rate. Lucas (1976) applies this idea to the framework of optimal control where the policy takes the form of decision rules or feedback control equations rather than the value of a parameter such as the tax rate. In order to account for the public's reaction to a change in such a policy rule, the econometrician has to solve its dynamic optimization problem given the new rule, using a method set forth in Chow (1981, Chapter 17).

2.5. Forward looking behavior-use of conditional expectations

Closely related to the previous point of the need to account for the reactions of the public to changes in government decision rules is the assumption that the public is forward looking in making its decisions. Since economic decisions are often based on the expectations of the economic agents regarding future events, variables representing expected future values of economic variables must enter an econometric model. How to measure these expectations is an important problem in econometrics. One useful idea applied successfully by Cagan (1956) is adaptive expectations. In Cagan's study, the demand for money depends on the expected rate of inflation, and the latter is assumed to be formed adaptively:

$$\pi_t^* - \pi_{t-1}^* = \theta(\pi_{t-1} - \pi_{t-1}^*), \tag{6}$$

where π denotes the rate of inflation, π^* denotes the expected rate of inflation, and θ is the fraction of the error in expectation in the previous period which will be incorporated in forming the current period's expectation. In contrast to the above adaptive expectations hypothesis, an alternative hypothesis of rational expectations was introduced by Muth (1961). When expectations variables enter any econometric equations, according to this hypothesis, they are assumed to be the conditional mathematical expectations generated by the econometric model. The term rational is used to convey the idea that economic behavior as described by the econometric model takes into account the knowledge of the model in the formation of expectations. This hypothesis assumes that economic agents who form expectations for their decisions, and the econometrician who studies their behavior, share the same model in explaining the economic data. This is a very strong assumption as econometricians often do not agree on the same model. An example of an equation containing an expectations variable based on rational expectations is equation (8) below, where expected inflation is the conditional expectation generated by the model. To solve this equation we can use the same equation for π_{t+1} to form the expectation $E_t\pi_{t+1}$ and continue to substitute forward. This is in contrast with adaptive expectations as defined in equation (6).

In practice the rational expectations hypothesis has been adopted by many economists in their research, and the econometric models so constructed have more often than not been rejected by statistical testing. The rejection could be due to the rational expectations hypothesis or to some other incorrect specifications of the model. In testing the present value model of stock price, Chow (1989) found that this model combined with the adaptive expectation hypothesis was accepted, but when compined with the rational expectations hypothesis was strongly rejected by US data. Using Hong Kong data, Chow and Kwan (1997) found strong support for the present value model of stock prices combined with adaptive expectations and strong rejection when combined with rational expectations. The present value model was combined with the adaptive expectations hypothesis also in Lin (1998), and in Chow, Fan and Hu (1999) both giving excellent results.

One interesting application of the hypothesis of rational expectations is contained in the model used by Woodford (1999) to study optimal monetary policy inertia. The model consists of two structural equations, an IS equation and an aggregate supply equation written respectively as

$$x_t - E_t x_{t+1} + \sigma^{-1}(r_t - r_t^n - E_t \pi_{t+1}) = 0, \tag{7}$$

$$\pi_t - \kappa x_t - \beta E_t \pi_{t+1} = 0, \tag{8}$$

where x is the output gap, or deviation of log real output from trend minus an exogenous "natural rate" of output, r is the deviation of the short-term nominal interest rate (the central bank's control variable) from its steady value in the case of zero inflation and steady output growth, r^n is the natural rate of interest, and π is the inflation rate. The objective of monetary policy is assumed to maximize, with respect to the interest rate, the expectation of a sum of discounted

$$L_t = \pi_t^2 + w_x(x_t - x^*)^2 + w_r(r_t - r^*)^2, \tag{9}$$

where a star denotes a given target value of the corresponding variable. Such an optimization problem can be solved by forming a Lagrangean

$$L = \sum_{t=0}^{\infty} E_t \beta^t \{L_t - \lambda_{1,t+1}(7) - \lambda_{2,t+1}(8)\}, \tag{10}$$

where (7) and (8) stand for the constraints specified by equations (7) and (8), respectively. Note that the expectations in these equations are automatically accounted for by the conditional expectation operator in front of the expression in curly brackets. First-order conditions for an optimum can be derived by differentiating (10) with respect to the control variable r and the state variables x and π. Dynamic programming cannot be applied to solve this problem because the dynamic model given by equations (7) and (8) includes conditional expectations of future variables.

From the viewpoint of econometrics, solving for the optimum decision rules in dynamic optimization models corresponds to solving for the reduced form equations in simultaneous equations models. The structural parameters in dynamic optimization models are the parameters in the objective function and in the dynamic model. If one applies the method of maximum likelihood to estimate the structural parameters, one begins with some initial values for the parameters, uses the model to derive the reduced form equations by solving a dynamic optimization problem, evaluates the likelihood function by the reduced form equations, and finally maximizes the likelihood function with respect to the structural parameters by some numerical method. Examples of econometric estimation of such dynamic optimization models are Chow and Kwan (1996, 1998) and Kwan and Chow (1996). This is an area of active current research.

3. Applications to Economic Policy

3.1. Economic policy in Taiwan in the 1960s and 1970s

The formulation of Taiwan's economic policies in the 1960s and 1970s, and similarly the economic reform strategies of mainland China in the 1980s and 1990s, was influenced by professional economists to a larger extent than in most other countries, with the possible exception of the Netherlands while Jan Tinbergen was active. For Taiwan the important influence of Ta-chung Liu and Sho-chieh Tsiang beginning in the 1950's should be noted. While Tsiang provided advice on monetary policy and ways to promote the free-market system, Liu helped reform the entire tax system and promote the use of econometrics for economic policy deliberations. Liu was a pioneer in econometric model building in the United States (See Liu (1960, 1963, 1969) and Liu and Hwa (1974)) and in Taiwan where he directed the building of an econometric model for the use of policy analysis in the Bureau of Accounting and Statistics of the Executive Yuan. This model is in the form of a simultaneous equations model as described in Section 2.1. It was used to trace out the consequences of alternative economic policies when the government budget was being decided. The government was especially concerned with possible inflation, and the inflationary effects of a high level of government expenditures can be explored by using such a model.

From the latter part of the 1960s to the end of 1970s, Liu (until his untimely death in 1975), Tsiang, Anthony Koo, Mohuan Hsing, John Fei and I regularly visited Taiwan in the summer for one and half to two months to provide economic policy advice to the government, as guests of the Central Bank or the Council for Economic Planning and Development. Although much of the advice was not quantitative in nature, all of us were trained in theoretical and quantitative analysis of economic problems. Quantitative and statistical tools were applied often, as partly illustrated in our reports Liu, et. al. (1974) and Tsiang, et. al. (1978). My contribution to the second report includes the use of optimal control techniques as discussed in Section 2.3.

The particular application in this report is to estimate the total amount of resources available for investment. To obtain an estimate of total investable resources I, one may begin with the following definition for potential GDP^*.

$$\begin{aligned} I &= GDP^* - C_p - C_g + IM - EX \\ &= (GDP_{t-1} - C_p - C_g) + (IM - EX) + (GDP^* - GDP_{t-1}), \end{aligned} \tag{11}$$

where the other symbols denote private consumption, government consumption, imports and exports. The three terms in parentheses on the second line of (11) measure, respectively, total private and government savings from last period's output, import surplus and potential growth of GDP. These are the three sources of the total investable resources for private and government investments. One might attempt to estimate the three terms in order to estimate I. To do so one needs an econometric model. The model may include government consumption and perhaps money supply as policy variables and some exogenous variables. The model can be solved for the required endogenous variables given by the three terms above. If the policy variables are chosen arbitrarily the resulting GDP, by solving the model, may not equal the potential GDP^*, leading to an incorrect estimate of total investable resources. One may try to set one policy variable such as money supply to achieve the potential GDP^*, but the resulting solution of the model may entail a high inflation rate. Therefore the solution has to take into account the values of other relevant variables than GDP. By specifying an objective function of all relevant variables in an optimal control framework, we can solve the problem of estimating the amount of investable resources while insuring that the variables in the macroeconomy will behave in ways desired by the policy maker.

Our work was only a small part of the economic policy analysis carried out in Taiwan in several government agencies. The important agencies included the Central Bank, the Council for Economic Planning and Development, the Bureau of Accounting and Statistics, the Ministry of Economic Affairs, the Ministry of Finance, the Commission for Rural Development, among others, as well as Academia Sinica, universities, and other research institutions. For example, Shann-yan Li, the Director in charge of open-market operations at the Central Bank in 1999, wrote and applied an optimal control program in the Council for

Economic Planning and Development in the late 1970s for the purpose of policy analysis. Many other statistical and econometric analyses were carried out. These activities have continued and flourished up to the present time, including a joint project of the Academia Sinica and the University of Chicago to build an econometric model which can be used for policy analysis. See Tiao, et. al. (1998).

3.2. Economic policy in mainland China in the 1980s and 1990s

The importance of econometrics was well recognized in mainland China ever since the establishment of diplomatic relation with the United States in 1979. In the summer of 1980 a group of seven econometricians led by Lawrence Klein, including T. W. Anderson, Albert Ando, Gregory Chow, Chen Hsiao, Lawrence Lau and Vincent So, was invited by Xu Dixin, then Vice President of the Chinese Academy of Social Science, to lecture on econometrics in Beijing to about one hundred researchers selected from the whole country. Econometric model building has since taken root and econometric analysis has been applied for economic policy analysis. As one example, I was organizing and teaching a workshop in macroeconomics in Beijing in 1985 for the State Education Commission. Before the workshop began, two staff members from Premier Zhao Ziyang's office informed me that the Premier was concerned about the possible inflationary effect of the 50 percent increase in money supply in 1984. The increase was a result of giving the specialized banks more freedom to extend credits. I was asked to make a forecast of inflation for 1985 and 1986. Given such a request, I estimated an econometric equation to explain inflation and presented it to the macroeconomic workshop before reporting to the Premier. The forecast was that inflation was not likely to exceed 9 percent in 1985, in spite of the large increase in money supply in 1984, because of lagged and moderate error-correction effects. This study uses an elementary unit root and cointegration model, and was later published in Chow (1987).

Letting P, M, and y denote, respectively, the general retail price index, money supply (currency in circulation) and real national output, the estimated model is a cointegration or error-correction model of the form

$$\Delta \ln P_t = \underset{(.00376)}{0.00422} - \underset{(.1209)}{0.3771} x_{t-1} + \underset{(.0201)}{0.1430} \Delta \ln(M/Y)_t + \underset{(.1098)}{0.2176} \Delta \ln P_{t-1}$$

$$R^2 = .717, s = .019, DW = 2.068, \qquad (12)$$

where x_{t-1} is a linear combination of $\ln P_{t-1}$ and $\ln(M/y)_{t-1}$, i.e., the stationary cointegration vector. The cointegration vector was estimated by regressing the first variable on the second and taking the residual as x_{t-1}, as the residual equals the estimated linear combination of the cointegrated variables. This is the method suggested by Engle and Granger (1987). One could also formulate the model in the form (4) with a vector of two dependent variables on the left-hand side, the second being $\Delta \ln(M/y)$. The cointegration vector in this case could be estimated by the method of maximum likelihood as described above.

Although this model provided a useful and fairly accurate forecast of inflation in 1985, the result might have given a mistaken notion to some top economic policy makers that serious inflation would not occur even if money supply were allowed to increase rapidly. Such an inference is certainly incorrect, as a one-time increase in money supply in 1984 had a smaller effect on inflation than the continued rapid increases of over 20 percent per year from 1984 to 1988. The rate of increase in money supply reached 47 percent in 1988 and, together with past increases, led to an annual inflation of 18 percent during 1988 but to a 30 percent annual rate during the fall of 1998. Observers have attributed social discontent in 1989 mainly to inflation in the economy and corruption in the government. I invited Sho-chieh Tsiang, Anthony Koo, John Fei, Lawrence Lau and Tsong-shien Yu to meet with An Ziwen and Liu Hongru (repectively Chairman and Vice Chairman of the Commission for Restructuring the Economic System) in Hong Kong in March 1989 to discuss economic reform issues, but the most important subject was how to slow inflation. Tsiang had had much experience in giving advice in this area, including the increase in interest rate in bank deposits, which the government adopted. After the meeting I was fully confident that the government would adopt our policy recommendation and that inflation would be stopped.

Soon after the Tienanmen incident of June 4 1989, Milton Friedman published an article in the *SanFrancisco Chronicle* forecasting economic chaos and high inflation in China. This pessimistic forecast turned out to be incorrect although Friedman is a very distinguished economist, my respected teacher, and very knowledgable about the American economy. I mention this economic forecasting error to make a statement about economic forecast and policy that specific knowledge about the economic situation is an important determinant in producing good forecasts. If economic knowledge is inadequate, the econometric model specified will also be inadequate in the sense of selecting the wrong relationships and the irrelevant variables, leading to mistakes in forecasts and policy analysis.

In the 1990's, economics education and research in China advanced rapidly although, like other areas in China's modernization, it is still much below the standard achieved in more developed economies. At the same time the level of competence of economists working in the government and elsewhere who have influence on economic policy also increased. Statistical and econometric methods are being applied in the Council for Social and Economic Development and the

Center for Rural Development in the State Council, in the Research Division of the People's Bank and in the State Planning Commission, and in many other government supported research organizations at the national and provincial levels. More sophisticated applications can be foreseen in the future.

3.3. Monetary policy in the United States

The Research Division of the Board of Governors of the Federal Research System (the Fed) was well-known for its cooperation with Franco Modigliani and Albert Ando of MIT in the 1960's in the construction of a Fed-MIT model of the US economy which can be used for policy analysis. This model placed more emphasis on the financial sector than most other models at the time. It originally took the form of a system of simultaneous equations as described in Section 2.1, and has gone through a number of revisions including the incorporation of rational expectations as described in Section 2.5. Together with the results of other econometric analysis, the simulations using the current version of the model are presented before the important FOMC meetings of the Fed in the setting of its interest rate policy. These results are used to supplement other less quantitative information and judgment in the formation of monetary policy. Such procedures are also used in the executive branch of the United States government. For example, the Council of Economic Advisers uses the forecasts of several econometric models as an aid to policy analysis as well.

The idea, that when the government changes its policy regime (as distinguished from setting its policy under the same regime) it ought to consider the possible effects on the behavior pattern of the economic agents, has affected the thinking of economists and policy makers. However, formal analysis incorporating this idea and using models as described in Section 2.5 is still fairly limited in policy applications. One reason is that the models which can be analyzed under such a framework, as illustrated by Woodford (1999), are rather small and do not include many economic factors which the policy makers wish to examine. Such limitations might change in the future. On the other hand, models that can be used under the optimal control framework described in Section 2.3 can have more details and have been more widely applied for economic policy analysis. Since the 1970's such applications can be found in the United Kingdom, as seen in the Report of Committee on Policy Optimization, chaired by Robert J. Hall, presented to Parliament by the Financial Secretary to the Treasury by Command of Her Majesty (London: Her Majesty's Stationary Office, March 1978).

4. Future Prospects

In all five areas of development of econometrics surveyed in this paper, active research continues. Endogeneity of explanatory variables is still a problem in many situations. Examples are models with discrete endogenous variables, the estimation using non-parametric or semi-parametric methods, and serial correlations in the residuals. Nonstationary economic time series, including the case of unit roots, is an important area of research, including studies in the time domain and the frequency domain. Dynamic optimization has become an intrinsic part of the economist's tool kit for the study of both macro- and microeconomics. It is used to model behavior of economic agents assumed, as economists are accustomed to assume, to maximize some objective function over time. To account for the change in behavior resulting from the policy itself is an important consideration when the government sets its policy. This consideration is more often addressed in theory than in the practice when econometric models with some details are applied. Both the quality of the models and the computional techniques to allow for the public's reactions are expected to improve with continued research. Dealing with expectations is still an unresolved problem in economics. Even the choice between adaptive and rational expectations as two competing hypotheses is subject to much disagreement. It is recognized that even if eventually both economists and the public can discover the same truth concerning the functioning of the economy, the economic agents may need time to learn in the formation of expectations. The learning process towards forming rational expectations remains to be further studied. As economists and econometricians devote time and effort to these research topics one can expect continued progress to take place. The relevance of research in these topics to economic policy analysis will continue to be a subject of profession discussion, e.g., Ericsson, Hendry and Mizon (1998).

On the formulation of economic policies in various countries in the world one can expect an increase in the use of econometric models and optimization techniques, with or without explicit considertion of possible changes in equation parameters and of the effect of future expectations as formed by rational expectations. The reasons are the expected improvement in the quality of the models and the availability of researchers capable of performing the analyses. Econometric analysis will be an important supplement to qualitative analysis and judgment. Political considerations will remain important in economic policy deliberations.

5. Concluding Comments

In this paper I have selected five important theoretical developments in econometrics and illustrated their applications to economic policy. In both the selection of major developments and the illustrative applications the scope is limited. Important ideas in micro-econometrics and applications to microeconomic policies have not been discussed. However there are certain general observations about the subject of this paper which apply as well to areas not discussed here. First, many important ideas in econometrics have originated from the inability (or expense) in generating experimental observations. Econometricians have to model the data-generating process and rely on the assumptions made concerning the process to identify structural parameters. For example, this is true for models in micro-econometrics based on specifying the sample selection mechanism. Second, methods of econometrics have become more specialized as a branch of statistics and an independent discipline of its own. Continued communications between professional statisticians and econometricians would be beneficial to both professions. The former will get stimulation by being exposed to actual problems, and the latter may receive help in solving some of the technical problems. Third, in terms of applications, as pointed out in the beginning of this paper, economic policies for macro- or micro-economic problems are determined by factors other than quantitative-economic analysis. There are important noneconomic considerations, and economic analysis itself depends on intuition and non-statistical information. Some of the non-statistical information has been included in statistics by Bayesian analysis, but writing down the decision problem in the Baysian framework, including a list of all possible states of the world, etc., has its limitation for the purpose of including all relevant information. Once we recognize the limitations of econometric analysis, we can appreciate the important contributions that it can make for economic policy formulation.

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