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ECONOMETRICS

by Fumio Hayashi

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1. OVERVIEW

There are six factors that can enhance or weaken an econometrics text: coverage, lucidity, speed, independence, examples, and exercises. With clear explanations and a smooth pace, Fumio Hayashi's *Econometrics* succeeds as a solid first-year graduate text. The ample empirical applications examples reflect the author's research interest—applied econometrics—and make the work best suited for students sharing that interest.

Hayashi covers both classical and modern developments of econometrics in plain language. However, the coverage of some topics (limited dependent-variables models and nonstationary times series regressions) is limited by space constraints. Additionally, there are several important specification tests missing from the discussion (the Lagrange multiplier test for heteroskedasticity, tests for structural change, etc.). Finally, there are several areas in the book that lack proper references. For example, Hansen (1982) is not mentioned when the generalized method of moments (GMM) is introduced in Chapter 3, and Huber (1967) is not referred to in the chapter discussing *M*-estimation.

Lucidity is a distinctive success of this book. Hayashi successfully explains many different estimators using the unified framework of GMM. In addition, the expositions are clear and helpful. The only downfall of this approach is that estimators that do not belong to the GMM class (GLS, IV-GLS, frequency domain estimators, etc.) are poorly covered or left out entirely.

The pace of exposition is appropriate in most of *Econometrics*, but introducing conditional heteroskedasticity in the first chapter on asymptotics may make students confused. I admit that one may consider this an advantage.

Independence is the weakest point for this book. There should be more discussion on conditional expectation in the beginning chapters, and more matrix algebra (perhaps in the Appendix) seems to be needed. Fortunately, a well-prepared instructor can remediate this lack with additional readings from other texts.

With a plethora of theoretical and empirical examples and a solid set of analytical and empirical exercises for each chapter (many with hints) *Economet-*

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rics covers the last two factors very well. The empirical examples in almost every chapter make it quite instructive, and the real-world exercises make it most useful for both instructors and students. With all of its strengths, this text will be well received by many graduate courses throughout the world.

2. CHAPTER-BY-CHAPTER COMMENTS

Chapter 1 introduces the classical linear regression model and its ordinary least squares (OLS) estimation. In addition to OLS, Chapter 1 deals with maximum likelihood estimation (MLE) under a normality assumption, generalized least squares (GLS) estimation, and *t*- and *F*-tests. Properties of the OLS, MLE, and GLS estimators in finite samples are discussed, and the distributions of the *t*- and *F*-tests are derived under a normality assumption. Whereas most econometrics texts assume nonstochastic regressors in introductory chapters, the estimators and tests of this chapter are based on strictly exogenous, stochastic regressors, and their properties are developed using conditional expectation and conditional likelihood. This is a more realistic approach because most economic variables are considered random in real-world applications. However, it requires a good understanding of conditional expectation, detailed discussions on which are missing from the text. Thus, an instructor using this book needs to cover conditional expectation before teaching the materials in this chapter. Chapter 1 contains an entire section devoted to an empirical study of returns to scale in electricity supply, but the methods and discussions for the application are equally useful for other applications.

Chapter 2 presents elementary limit theorems, basic concepts of time series analysis, and large-sample properties of the OLS estimator and related tests. Specification tests for conditional heteroskedasticity and serial correlation are also introduced. The elementary limit theorems in this chapter are standard, so often used in the literature that their proofs do not have to be reproduced in the chapter. However, examples of these theorems need to be provided for econometrics beginners. This chapter assumes predetermined regressors and emphasizes that the more restrictive assumption of strictly exogenous regressors in Chapter 1 is not required for the large-sample approach of Chapter 2. Moreover, conditional heteroskedasticity is assumed in this chapter, which prompts the author to introduce heteroskedasticity-robust *t*- and Wald tests and also White's (1980) test for conditional heteroskedasticity.

Assuming conditional heteroskedasticity in this introductory chapter has both advantages and disadvantages. The main advantage is that it is a more general approach and reflects often observed empirical evidence for the presence of conditional heteroskedasticity in daily economic data. On the other hand, it entails a loss of simplicity in introducing asymptotic theory to beginners in econometrics. Perhaps, if a more step-by-step approach is allowed, asymptotic theory could be introduced assuming conditional homoskedasticity in the first place. Then its extension to conditional heteroskedasticity can be considered at a later

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stage. Although conditional heteroskedasticity is allowed for in the linear model of this chapter, the model is still specialized in the sense that serial dependence of the error terms is not allowed. One way to generalize the model is to assume linear processes for the error terms and regressors and assume a vector martingale difference sequence for the innovation process of the error terms and regressors.

Consider the following linear regression model from chapter 2:

$$y_i = x_i'\beta + \varepsilon_i \qquad (i = 1, \ldots, n). \tag{1}$$

Chapter 2 assumes ergodic stationarity of $\{(y_i, x_i')'\}$ and a martingale difference sequence for $\{x_i\varepsilon_i\}$. The former assumption is used to find the probability limit of the sample moment matrix and the latter to apply the central limit theorem to the sum of the sequence $\{x_i\varepsilon_i\}$. Although these assumptions appear innocuous, a question emerges: What kind of ergodic, stationary process $\{x_i\}$ satisfies the martingale difference assumption for the sequence $\{x_i\varepsilon_i\}$? An easy answer is $\{x_i\}$ being an $\mathfrak{F}_{i-1}$-measurable, ergodic, stationary process where $\mathfrak{F}_i$ is the smallest σ-field generated by $\{x_k, \varepsilon_k\}_{k=-\infty}^{i}$. But the measurability assumption may be too restrictive. Besides this simple answer, it seems difficult to obtain a useful answer to the question. In a nutshell, the assumptions on x_i and ε_i do not clarify the properties of the regressor.

Alternatively, one may assume a linear process for x_i (i.e., $x_i = \sum_{k=0}^{\infty}\rho_k\xi_{i-k}$) and a vector martingale difference sequence for $\{(\xi_i', \varepsilon_i)', \mathfrak{F}_i\}$ with $\mathfrak{F}_i$ being the smallest σ-field generated by $\{(\xi_k', \varepsilon_k)'\}_{k=-\infty}^{i}$. Under some additional conditions, it can be shown that the central limit theorem holds for the sum of the sequence $\{x_i\varepsilon_i\}$ and that the sample moment matrix has a proper probability limit upon standardization. Under this setup, $\{x_i\varepsilon_i\}$ is a martingale difference sequence, and the ergodic stationarity of $\{(y_i, x_i')'\}$ need not be assumed.

This chapter also introduces the Box–Pierce and Ljung–Box tests for serial correlation. Although these tests are widely used in practice, an obvious drawback is the need to choose cutoff points for these tests. Compared to these tests, Andrews and Ploberger's (1996) tests are completely data dependent and have better finite-sample properties according to their simulation results. Moreover, Durlauf's (1991) spectral-measure tests are also completely data dependent and have good finite-sample properties. In ignoring these tests, this book may appear out of date. The empirical example about the U.S. Treasury Bill market is interesting and illustrates how testable null hypotheses can be formulated and how empirical results should be presented.

Chapter 3 introduces the GMM method for a single equation, useful when the orthogonality condition between the error term and regressors is violated. This chapter starts with a number of examples from the literature of simultaneous equations. Interestingly, there are no separate chapters on simultaneous equations, and the issues surrounding simultaneous equations are discussed only briefly in chapters about GMM. Of course, this reflects a recent lack of interest in simultaneous equations, but important issues like identifiability of simulta-

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neous equations should be discussed in detail. Moreover, the simultaneous equations system was a starting point of econometrics (cf. Morgan, 1990), and its importance should not be neglected. This chapter states a few conditions for the GMM methods and derives large-sample properties of the GMM estimator and related tests. The exposition is easy to follow, and the results are useful for understanding the properties of various estimators that are special cases of the GMM estimator—2SLS, IV, etc. In addition, this chapter introduces the GMM overidentifiability test and shows that it is the general case of Sargan's (1958) test. It is also emphasized that the overidentifiability test is a specification test that tests not only the orthogonality condition but also other assumptions. The empirical example of this chapter is about the wage equation, for which endogeneity of regressors has been a concern of researchers. The estimation methods of this chapter are applied to the wage equation, and the parameter estimates are shown to depend on the correction of endogeneity.

Chapter 4 is concerned with estimating several equations by GMM. Given discussions on single-equation GMM in Chapter 3, it is straightforward to follow asymptotic theory for the multiple-equation GMM of this chapter though the relevant notation is more complicated. This chapter shows that well-known estimators such as full information IV, 3SLS, and seemingly unrelated regression (SUR) estimators are special cases of the GMM estimator and, therefore, their asymptotic properties can be deduced from those of the multiple-equation GMM estimator. The approach of presenting the general theory and investigating special cases later is quite economical and simple. On the other hand, a drawback of this approach is that the reader is not motivated by examples of the well-known estimators. In addition, this chapter shows that the multiple-equation system can be written as an equation system with its coefficients constrained to be the same across equations. A special case of this estimator is the random-effects estimator. Its asymptotic properties are easily analyzed within the framework of GMM estimation. Notation for multiple-equation GMM is bound to be complicated, but the tables and figures in this chapter make it relatively easy to follow. As an illustrating example, the SUR estimator is applied to a system of factor demand functions.

Chapter 5 introduces the one-way error component model for panel data and studies the fixed-effects (or within) and random-effects estimators. Their asymptotic properties are derived using the framework of GMM. In addition, the Hausman test and estimation of unbalanced panels are discussed. The empirical section of this chapter takes up growth empirics and uses a dynamic panel data model. Panel data analysis is becoming more and more important these days as a result of the availability of country and firm data sets. Considering this importance, this chapter seems too brief and misses many important topics. Examples are estimation methods for dynamic panels, the two-way error component model, specification tests for panel data, heterogeneous panels and nonstationary panels. Of course, there are other monographs (cf. Hsiao, 1986; Baltagi, 1995) that can be consulted for further studies, but a few more topics would make this book more self-contained as a text.

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Chapter 6 introduces some basic time series processes and a central limit theorem for time series and extends the GMM to incorporate serial correlation in the error terms. Linear processes and ARMA processes are introduced, and estimation methods for the univariate and multivariate ARMA models are discussed. The latter part of this chapter shows how serially correlated errors can be handled within the framework of GMM by using the heteroskedasticity and autocorrelation consistent estimation of the variance-covariance matrix. The empirical example of this chapter is a test of the efficient market hypothesis for the foreign exchange market. The linear processes are important building blocks in time series analysis, and it is appropriate to introduce them in introductory texts. But limit theorems for linear processes are not discussed. The interested reader may wish to consult Phillips and Solo (1992) to study standard limit theorems for linear processes (e.g., law of large numbers, central limit, law of the iterated logarithm, etc.).

In the last section of Chapter 6, it is claimed that GLS requires more restrictive assumptions than GMM to achieve estimator consistency. This is not necessarily true. Suppose that the error terms of model (1) follow an AR(1) process represented by

$$\varepsilon_t = \phi\varepsilon_{t-1} + \eta_t, \qquad -1 < \phi < 1, \qquad \eta_t \sim iid(0, \sigma^2), \qquad \varepsilon_0 = 0.$$

It is shown in this book that GLS requires

$$E(z_t\eta_t) = E(z_t\eta_{t-1}) = 0 \tag{2}$$

for estimator consistency. However, GMM requires $E(z_t\varepsilon_t) = 0$. For this to hold with $-1 < \phi < 1$, we need

$$E(z_t\eta_t) = \cdots = E(z_t\eta_1) = 0. \tag{3}$$

Obviously, condition (3) is more restrictive than (2). On the other hand, if the error terms follow an invertible MA(1) process

$$\varepsilon_t = \eta_t + \phi\eta_{t-1}, \qquad -1 < \phi < 1, \qquad \eta_t \sim iid(0, \sigma^2), \qquad \eta_0 = 0,$$

it can be shown that GLS requires

$$E(z_t\eta_t) = \cdots = E(z_1\eta_t) = 0,$$

whereas GMM requires condition (2). In this case, requirements for GMM can be regarded as less restrictive than those for GLS. These examples show that no definitive statement can be made about the relative restrictiveness of the GMM and GLS requirements for estimator consistency.

Moreover, I found some experimental evidence in one of my research projects on panel data that the feasible IV-GLS estimator is more efficient than the GMM estimator in finite samples. Though I do not claim that the evidence is of general nature, the evidence and the discussions in the last paragraph indicate that there is no reason to castigate GLS in favor of GMM.

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Chapter 7 introduces extremum estimators in nonlinear models and studies their asymptotic properties. Wald, Lagrange multiplier, and likelihood ratio tests are also introduced. The extremum estimators of this chapter are GMM and *M*-estimators. The *M*-estimator includes the maximum likelihood estimator as a special case. Most students of econometrics find the techniques for asymptotic properties of the extremum estimators quite difficult to understand. This chapter, however, derives the asymptotic properties of the extremum estimators in an intuitive manner and should be accessible to the general readership. For those who have found nonlinear econometrics difficult to understand, this chapter is highly recommended.

Chapter 8 considers applications of the maximum likelihood estimation methods to some well-known econometric models. The models include qualitative response models, limited dependent variable models, multivariate regression models and AR models. Full information maximum likelihood (FIML) and limited information maximum likelihood (LIML) are also studied in the framework of multivariate regression. Once Chapter 7 is understood, materials in this chapter are straightforward to follow. This chapter provides techniques for understanding the asymptotics of qualitative response and limited dependent models, but a more detailed introduction and examples of these models are needed. Most econometrics texts deal with these models in separate chapters, and the discussions on these models in this text seem to be insufficient.

Chapter 9 is a brief introduction to unit-root econometrics. This chapter discusses trend-stationary and unit-root processes and introduces the Dickey–Fuller and augmented Dickey–Fuller tests for a unit root. As an empirical example, testing the purchasing power parity hypothesis is considered. Unit-root econometrics is still a growing area, and no doubt this short chapter is insufficient to include all new methods and concepts. However, reading this chapter, students of econometrics can learn most of the elementary and important developments in the research area without much difficulty. This chapter introduces old unit-root tests such as the augmented Dickey–Fuller tests, but there are tests with better finite-sample properties (e.g., Elliott, Rothenberg, and Stock, 1996), and these tests deserve more space in the text.

Chapter 10 introduces cointegration and discusses tests and estimation methods for a cointegrated linear regression model. As tests for cointegration, only residual-based tests are discussed. This does not reflect current empirical practice because Johansen's (1988) tests are very often used in the literature. Dynamic OLS (or leads-and-lags) estimator is discussed as a way to estimate the cointegrating regression. The U.S. money demand function is estimated as an empirical example.

3. CONCLUSION

The author notes in the preface of this book that he spent more than five years' free time on this book. The effort shows clearly in the result. This book will serve as a standard text in econometrics in coming years, and students will en-

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hance their analytical abilities in econometrics and also their skills in empirical applications by reading this book.

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