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Structural estimation of continuous choice models: Evaluating the EGM and MPEC

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HIGHLIGHTS

- I evaluate the performance of two recently proposed methods to structural estimation.
- These are the Endogenous Grid Method (EGM) and Mathematical Programming with Equilibrium Constraints (MPEC).
- A canonical model of consumption choice is estimated using these approaches.
- Both the EGM and MPEC estimate the structural parameter in fractions of the time conventional methods require.
- In particular, the EGM proved fast, robust and straightforward to implement.

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ABSTRACT

In this paper, I evaluate the performance of two recently proposed approaches to solving and estimating structural models: The Endogenous Grid Method (EGM) and Mathematical Programming with Equilibrium Constraints (MPEC). Monte Carlo simulations confirm that both the EGM and MPEC have advantages relative to standard methods. The EGM proved particularly robust, fast and straightforward to implement. Approaches trying to avoid solving the model numerically, therefore, seem to be dominated by these approaches.

1. Introduction

One of the novelties of structural models is the ability to perform counter-factual policy analysis. This requires – besides a realistic model – that researchers uncover the underlying structural parameters. Most existing approaches are notoriously slow, and it is therefore tempting to calibrate the parameters.

The Endogenous Grid Method (EGM) proposed by Carroll (2006) and Mathematical Programming with Equilibrium Constraints (MPEC) proposed by Su and Judd (2012) apply fundamentally different approaches aimed at overcoming the time-consuming task of estimating structural models by, for example, time iterations (TI). The EGM does this by a small but efficient modification of TI, while MPEC abandons the "nested fixed-point" estimation structure, NFXP, which most other approaches follow.

The aim of this paper is to discuss a concrete implementation of these two recently proposed methods and supply new Monte Carlo evidence on performance in terms of speed, accuracy, and practical implementation when estimating structural continuous choice models.[1] Hopefully, this will inspire estimation of more realistic models in terms of heterogeneity and uncertainty.

The paper proceeds as follows. Section 2 presents the model used in the analysis. Section 3 briefly discusses the estimation procedures, TI, the EGM, and MPEC. Section 4 discusses data generation and presents Monte Carlo results. Finally, Section 5 discusses and concludes the analysis.

2. The model and Data-generating Process

I use the canonical model of Deaton (1991) in which agents solve the infinite-horizon problem

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[1] Su and Judd (2012) illustrate the applicability of MPEC to discrete choice models, using the bus-replacement model of Rust (1987), but do not consider explicitly continuous choice models.

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$$\max_{\{c\}_{t=0}^{\infty}} \mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta^t u(c_t)\right],$$
$$\text{s.t. } a_{t+1} = R(a_t + y_t - c_t),$$
$$a_t \geq 0 \quad \forall t,$$

where $0 < \beta < 1$ is the discount factor, R is the real gross interest rate, c_t is the consumption in period t, a_t is the assets at the beginning of period t, and $y_t \sim \mathcal{N}(\mu_y, \sigma_y^2)$ is the stochastic income at the beginning of period t. More complicated models could be formulated without changing the results. Preferences are assumed to be Constant Relative Risk Aversion (CRRA):

$$u(c_t) = \frac{c_t^{1-\rho}}{1-\rho}.$$

It is convenient to formulate the state in this model as the total cash-on-hand available at the beginning of period t being $m_t = a_t + y_t$, such that the state in the model evolves as

$$m_{t+1} = R(m_t - c_t) + y_{t+1}. \tag{1}$$

3. Estimation approaches considered

In this section, I provide a brief introduction to the implemented approaches. The first two, TI and the EGM, are based on the nested fixed point (NFXP) approach, in which the model is solved in an inner algorithm for a given set of trial values of parameters. An outer optimization algorithm estimates the structural parameters by varying these, leading to successively solving the structural model. The third approach, MPEC, abandons NFXP and formulates the solution of the model as equilibrium constraints when estimating the structural parameters.

The estimation framework adopted here is maximum likelihood. Without changing the results, a General Method of Moments (GMM) framework could be adopted in which moments from the data are matched moments predicted from the model. It is assumed that panel data on consumption are observed with measurement error, such that

$$c_{it}^{data} = c(m_{it}^{data}|\rho) + \varepsilon_{it},$$

where $c(\cdot|\rho)$ is the consumption function predicted by the model and the measurement error, ε is assumed to be *iid* Gaussian with mean zero and variance σ.[2] The (mean) log likelihood function can be written as

$$\mathcal{L}(\rho; c, c^{data}, m^{data}) = -\log(\sigma) - \sum_i^N \frac{1}{NT_i}\sum_t^{T_i}\frac{1}{2\sigma^2}\left(c_{it}^{data} - c(m_{it}^{data}|\rho)\right)^2. \tag{2}$$

Since the consumption function in the present model has no closed-form solution, $c(m|\rho)$ is found numerically. TI and the EGM find $c(m|\rho)$ for a given ρ and use that solution to evaluate the likelihood function. MPEC estimates $c(m|\rho)$ and ρ jointly. The solutions from each of the methods are indistinguishable, as shown in Fig. 1.

I use $Q = 8$ Gauss–Hermite nodes (y^q) and weights (w^q) to approximate expectations with regard to labor market income, y. Consumption is approximated by 200 unequally spaced grid points over m_t, with more mass at the bottom of the distribution. In the EGM, the grid for m_t is determined endogenously, as discussed below. Linear interpolation is applied between grid points.

All approaches are implemented in MATLAB 2012b using the KNITRO solver for optimization (see Byrd et al., 2006) on a laptop with Intel® Core™i5-2520M CPU @ 2.50 GHz and 4 GB RAM. The code is available from http://www.tjeconomics.com/code.

[2] Alternatively, the estimation could be framed as measurement error in the difference in log consumption or assets without changing the results.

3.1. Time iterations (TI)

The Euler residual, $\mathcal{E}$, from the present model is a nonlinear equation in consumption, c_t:

$$\mathcal{E}(c_t|m_t) \equiv R\beta\mathbb{E}[u_c(c_{t+1})|m_t] - u_c(c_t),$$
$$\doteq R\beta\sum_{q=1}^{Q} w^q \check{c}_{t+1}(\underbrace{R(m_t - c_t) + y^q}_{m_{t+1}})^{-\rho} - c_t^{-\rho}, \tag{3}$$

where $\check{c}_{t+1}(m_{t+1})$ represents a linear interpolation function. A numerical procedure, such as bisection or Newton iterations, is used to find optimal consumption that puts the residual in (3) to zero:

$$c_t^*(m_t) : \mathcal{E}(c_t^*|m_t) = 0,$$
$$\text{s.t. } c_t \leq m_t.$$

In order to find the stationary solution to the infinite-horizon model, iterate over time until $\max_m\{|c_t^*(m) - c_{t+1}^*(m)|\} < 1.0\text{E}^{-7}$.

3.2. The endogenous grid method (EGM)

The EGM proposed by Carroll (2006) modifies time iteration by defining the interpolation grid over the end-of-period assets, a_t, instead of the beginning-of-period cash-on-hand, m_t. This trick facilitates an analytical solution to optimal consumption today by inverting the Euler equation,

$$c_t^*(m_t) = u_c^{-1}\left(R\beta\mathbb{E}[u_c(c_{t+1})|m_t]\right),$$
$$\doteq \left(R\beta\sum_{q=1}^{Q} w^q \check{c}_{t+1}(Ra_t + y^q)^{-\rho}\right)^{-\frac{1}{\rho}}, \tag{4}$$

where the right-hand side now is independent of c_t. Since no numerical methods are needed to find the optimal consumption (contrary to time iteration), the method dramatically increases the speed. Finding the stationary solution is done as for time iterations above.

The cash-on-hand today, m_t, consistent with the end-of-period assets a_t and consumption c_t^*, is determined endogenously as

$$m_t = c_t^*(m_t) + a_t.$$

The EGM perfectly tracks the credit constraint. This is because the lowest point in the grid over a_t, $\underline{a} = 1.0\text{E}^{-6}$, is (very close to) the point where agents are on the cusp of being credit constrained. This is illustrated in the right panel of Fig. 1. Including the interpolation point $(m, c) = (0, 0)$ ensures that the credit-constrained level of cash-on-hand is handled correctly.

3.3. Mathematical programming with equilibrium constraints (MPEC)

Su and Judd (2012) propose formulating the solution and estimation problem as a joint constrained maximization problem. The intuition is that NFXP spent most of the time solving models with high accuracy for "wrong" parameters. The behavior only needs to be optimal at the true parameters. Formalized as a nonlinear constrained optimization problem,

$$\max_{c,\rho} \mathcal{L}(\rho; c, c^{data}, m^{data})$$
s.t.
$$1 < \rho, \tag{5}$$
$$0 \leq c \leq m - c, \tag{6}$$
$$0 \geq \beta R\mathbb{E}\left[u'\left(c(R(m-c)+y)\right)\right] - u'(c), \tag{7}$$
$$0 = (m-c)\left(\beta R\mathbb{E}\left[u'\left(c(\cdot)\right)\right] - u'(c)\right), \tag{8}$$

where $\mathcal{L}(\cdot)$ is the likelihood function in (2), (5) is a lower bound on the risk aversion parameter, (6) gives the lower and upper bounds on the consumption parameters, (7) is the Euler residual

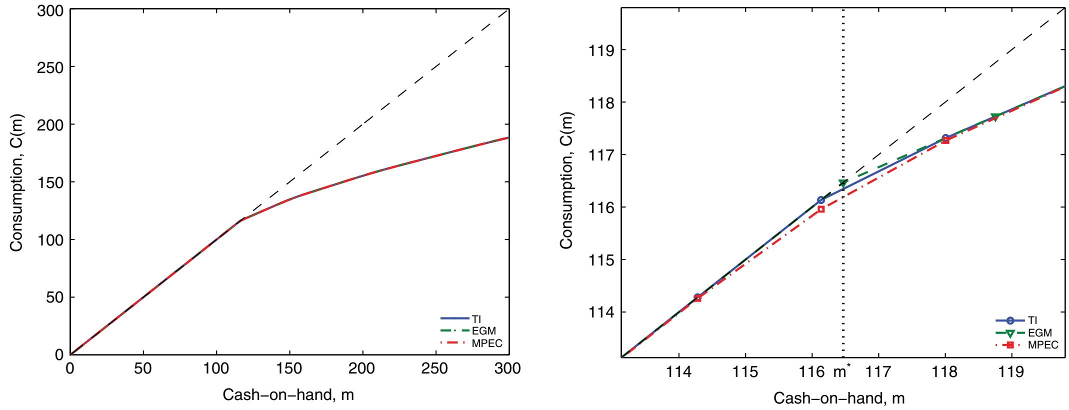

Fig. 1. The consumption function, $c(m|\rho)$, from TI, the EGM and MPEC.

Table 1
Monte Carlo comparison.

β		RMSE	MCSTD	Time (secs)	Standard deviation of time	Number of iterations		
						Level 1	Level 2	Level 3
	TI	0.002	0.002	26.0	0.48	5	142	147,900
0.70	EGM	0.002	0.002	0.1	0.03	5	174	
	MPEC	0.049	0.046	112.4	269.97	123		
	TI	0.009	0.006	650.7	6.80	5	3473	3,621,124
0.95	EGM	0.006	0.006	1.9	0.05	5	3636	
	MPEC	0.009	0.006	93.7	37.00	94		
	TI	0.000	0.000	1682.6	15.74	6	9215	8,475,336
0.99	EGM	0.000	0.000	5.0	0.08	6	9247	
	MPEC	0.000	0.000	30.9	6.26	23		

Notes: Based on 50 MC runs with $N \cdot T = 5000 \cdot 10$ simulated observations each run. Columns 3, 5, 6, and 7 are Monte Carlo averages. Only ρ is estimated. $R = 1.05$, $\mu_y = 10$, $\sigma_y^2 = 100$ and 200 grid points are used to approximate consumption.

formulated as a nonlinear inequality constraint, and (8) is a complementarity constraint, stating that, if the credit constraint is not binding, the Euler equation must hold.

The consumption function is estimated along with the structural parameters. Hence, the number of parameters is the number of grid points used to approximate consumption in addition to the structural parameters. Here, that amounts to 201 parameters.

Convergence problems due to loose inner-loop stopping criteria are avoided completely. Inner-loop iterations are simply not performed in MPEC. In practice, however, supplying good starting values for the consumption parameters was necessary to obtain convergence to the right optimum.

4. Monte Carlo comparison

To assess the performance of the approaches described in Section 3, synthetic data (5000 individuals in 10 time periods) are generated for $\beta \in \{0.70, 0.95, 0.99\}$. To mitigate the influence of stochastic draws, I perform 50 Monte Carlo runs for each β.

Table 1 reports the root mean squared error (RMSE) and Monte Carlo standard error (MCSTD) along with the average time used, the standard deviation of time used across MC runs, and the number of iterations used by each method. Level 1 refers to the outermost optimization, level 2 refers to iterations until convergence to the infinite-horizon stationary solution, and level 3 refers to the innermost numerical procedure, finding the optimal consumption. The three methods differ in the levels of iteration. The EGM circumvents the innermost procedure while MPEC only operates on the outer level. All approaches are initialized using the same starting value for ρ.

As expected, TI is slowest overall and both TI and the EGM (which both rely on NFXP) are slowed by higher values of β. The EGM does, however, seem to be less sensitive to β relative to TI. MPEC should be roughly invariant to the level of the discount rate, and the variation across β-values reflects the difficulties in supplying good starting values for the consumption parameters rather than the effect of changing β. This instability is also reflected in the relatively large dispersion in time to convergence across MC runs (column 4) for MPEC. The large RMSE of 0.049 when $\beta = 0.7$ stems from MPEC not converging to the right optimum in five of the MC runs.

The EGM and TI use the same number of level 1 and level 2 iterations. The great speed gain from the EGM is clearly stemming from the elimination of the innermost searches for optimal consumption (level 3), which TI suffers from. MPEC uses significantly more level 1 iterations due to the fact that 201 parameters are estimated in MPEC. Since MPEC only operates on the outer level, the approach is considerably faster than TI.

The EGM outperforms MPEC in terms of both speed and RMSE. The EGM is able to uncover the structural parameter in on average five seconds while MPEC uses around 30 s and TI uses 30 min to complete the same task. Due to the EGM's relatively straightforward reformulation of time iterations, this result is very encouraging.

5. Discussion

Through this analysis, two recent proposed approaches to structural estimation, the EGM and MPEC, have been evaluated. The theoretically appealing constraint optimization approach, MPEC, proved to be somewhat disappointing. Even if researchers apply state of the art solvers to problems supplied with the (correct) gradients, Hessian, and sparsity pattern, the size limitation on solvable problems is a significant constraint. Problems that are not sparse with large state–space dimensions would require an intimidating amount of memory. This limitation is also recognized by Su and Judd (2012, p. 2215).

The size limitations of MPEC effectively rules out (realistic) finite-horizon models since the number of parameters and constraints is the number of time periods multiplied by the number of grid points in addition to the structural parameters, $T \cdot n + k$. Furthermore, using simulation-based estimation methods, such as indirect inference or simulated method of moments are generally not feasible in the MPEC framework. A small perturbation in a consumption parameter requires resimulation of synthetic data.

The EGM proved to be very robust and fast. The small change to time iterations is very straightforward to implement. Furthermore, the EGM includes the exact point where agents are on the curb of being liquidity constrained, increasing accuracy. The EGM (as well as TI and MPEC) can also handle continuous–discrete choice models; see, for example, Fella (2011) and Iskhakov et al. (2012), who generalize the EGM to handle discrete choices.

The fact that structural parameters can be estimated in a fraction of the time conventional methods require has widespread implications. Heterogeneous parameters and correlated uncertainty could be some of many "new" improvements in structural models. These features have often not been feasible to implement in structural estimation. This also means that several approaches trying to avoid solving the model numerically, such as nonlinear GMM estimation (Alan et al., 2009) or synthetic residual estimation (Alan and Browning, 2010), are dominated by the EGM and MPEC.

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