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Abstract

This paper demonstrates that, under plausible ergodicity conditions, the "random objective function" justification for disturbances in complete demand systems is not relevant when aggregate data are employed. In fact, we show that if the sole source of disturbances in individual demand equations is individual-specific unobservables and aggregate data are employed, then the implied errors in demand and share equations are almost surely zero.

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1 Introduction

A nagging criticism of empirical analyses of complete demand systems is the *ad hoc* tacking on of disturbances.[1] Recent advances in economic theory (see Brown and Walker (1989); Chavas and Segerson (1987); and McElroy (1987)), provide a microeconomic rationale for the inclusion of random errors in *individual* demand equations. In essence, this line of research assumes that some components of the individual objective functions are known only by the individuals, and that the econometrician models these unobservables as varying across individuals according to some distribution function. In the context of consumer demand theory this is known as the *random utility model*; see Brown and Walker.

An important implication of the random objective function justification for disturbances is that additive disturbances and neoclassical restrictions together imply heteroskedasticity. Thus the random objective function explanation for disturbances is important not only because it provides a rationale for including errors in demand equations, but also because it suggests that heteroskedasticity may be at the root of the pervasive rejections of neoclassical consumer demand theory.

The purpose of this paper is to demonstrate that, under plausible ergodicity conditions, the random objective function justification for (and the resulting heteroskedasticity of) disturbances does not apply to models based on aggregate data. In essence, there is a potential *fallacy of composition*: the fact that individual demands are subject to heteroskedastic errors does not imply that demand models based on aggregate data possess heteroskedastic errors. In fact, we show that if the sole source of disturbances in individual demand equations is individual-specific unobservables, as is implied by the random objective function approach, then the implied errors in demand (or share) equations based on aggregate data are almost surely zero. Moreover, our results hold regardless of whether individual demands satisfy the conditions of exact linear or nonlinear aggregation.

[1] See, for instance, Barten (1977).

2 The Random Utility Model and Individual Demand

For expositional convenience, we shall present our results in the context of neoclassical consumer theory and Brown-Walker's random utility model. Consider an economy consisting of a H individuals, each of whom attempt to maximize utility subject to a competitive budget constraint:

$$\max_{x^h}\{U^h(x^h,\epsilon^h) : p \cdot x^h \leq y^h\}. \tag{1}$$

Here, $U^h : \Re^n_{++} \times \Re^m \rightarrow \Re$ is individual h's (ordinal) quasiconcave utility function that is assumed to be regular strictly quasiconcave in the $n-$vector of commodities, x^h; p is the vector of prices corresponding to x^h, and y^h denotes the income of individual h.[2] The distinguishing feature of the random utility model is that the utility of individual h depends on an $m-$ vector of "disturbances," ϵ^h, which are known by the individual but are not observable by the econometrician.

The vector-valued function that solves equation 1 (the Marshallian demand vector) is denoted by

$$x^h = g^h(p, y^h, \epsilon^h). \tag{2}$$

In order to empirically implement the above theory, one must first impose structure on g^h. Typically, the structure imposed involves an additive disturbance vector, so that the Marshallian demand vector of consumer h is given by

$$x^h = g^h(p, y^h, \epsilon^h) \equiv f^h(p, y^h) + v^h(p, y^h, \epsilon^h), \tag{3}$$

where v^h is an $n \times 1$ disturbance vector induced by the distribution of ϵ^h, and is assumed to satisfy $E[v^h \mid p, y^h] = 0$ and $var(v^h \mid p, y^h] = \Omega^h(p, y^h)$. The specification in equation 3 is termed the *additive RUM demand specification.* Thus, the random utility model provides a microeconomic basis for incorporating additive disturbances in complete demand systems.

Unfortunately, for the deterministic part of equation 3 $[f^h(p, y^h)]$ to satisfy the neoclassical Slutsky symmetry restrictions, it is known that the disturbance vector

[2]Note that this analysis assumes all individuals face the same *exogenous* price vector, p. This assumption is not innocous; see Anglin and Baye (1987).

v^h must be functionally dependent on p, y^h, or both.[3] Thus, given a time series of observations on the consumption behavior of *individual h*, the underlying vector of disturbances are almost everywhere heteroskedastic.[4]

As an alternative, one might consider writing the components of equation 2 in share form

$$w_i^h \equiv \frac{p_i x_i^h}{y^h} = \phi_i^h(p, y^h, \epsilon^h), (i = 1, 2, \ldots, n) \tag{4}$$

and assume the share equations involve an additive disturbance term. In this case individual h's share equation for good i is given by

$$w_i^h = \phi_i^h(p, y^h, \epsilon^h) \equiv \psi_i^h(p, y^h) + v_i^h(p, y^h, \epsilon^h), \tag{5}$$

where again, v_i^h is the disturbance term for the ith good induced by the distribution of ϵ^h. The vector of v_i^h's are assumed to satisfy $E[v^h \mid p, y^h] = 0$ and $var(v^h \mid p, y^h] = \Gamma^h(p, y^h)$. The specification in equation 5 is termed the *additive RUM share specification.*

As is the case for the additive rum demand specification, for the deterministic part of equation 5 $[\psi_i^h(p, y^h)]$ to satisfy the neoclassical Slutsky symmetry restriction, the disturbance vector v^h must be functionally dependent on p, y^h, or both.[5]

To summarize, the RUM model and additive errors implies heteroskedastic errors in individual demand and share equations.

3 The Random Utility Model and Aggregate Behavior

Many empirical studies of demand analysis are based on aggregate time series data, and it is thus important to examine implications of the random utility model for econometric models based on aggregate data. Our first proposition reveals that the random utility model is not generally an appropriate justification for the presence of disturbances in *per capita* demand equations. First, however, we introduce

[3]See Brown and Walker's Theorem 2.

[4]See, Brown and Walker's Theorem 5.

[5]See Brown and Walker's Theorem 3.

Definition 1 (Ergodic) *A discrete parameter process* $\{v_i^h\}$ *is said to be ergodic if* $\lim_{H\to\infty} var(\overline{v_i}(H)) = 0$, *where* $\overline{v_i}(H) = \frac{1}{H}\sum_{h=1}^{H} v_i^h$.

Proposition 1 *Suppose an economy consists of H individuals whose behavior implies an additive RUM* *<u>demand</u> specification, as in equation 3. If the individual disturbance vectors,* $v^h(p, y^h, \epsilon^h)$ $[h = 1, 2, 3, \ldots, H]$ *are ergodic,*[6] *then the error in aggregate per capita demand is almost surely zero for large H.*

Proof. Summing equation 3 over h yields

$$\sum_{h=1}^{H} x^h = \sum_{h=1}^{H} g^h(p, y^h, \epsilon^h) \equiv \sum_{h=1}^{H} f^h(p, y^h) + \sum_{h=1}^{H} v^h(p, y^h, \epsilon^h), \tag{6}$$

so that the vector of per capita demand functions for an economy with H individuals is given by

$$\overline{x}(H) \equiv \frac{1}{H}\sum_{h=1}^{H} x^h = \frac{1}{H}\sum_{h=1}^{H} f^h(p, y^h) + \frac{1}{H}\sum_{h=1}^{H} v^h(p, y^h, \epsilon^h) \tag{7}$$

$$= \phi(p, y^1, y^2, \ldots, y^H) + \frac{1}{H}\sum_{h=1}^{H} v^h(p, y^h, \epsilon^h). \tag{8}$$

But since $\{v_i^h\}$ forms an ergodic sequence with zero mean, it follows that (cf. Parzen, p. 72)

$$\lim_{H\to\infty} \overline{v_i}(H) \equiv \lim_{H\to\infty} \frac{1}{H}\sum_{h=1}^{H} v_i^h(p, y^h, \epsilon^h) = 0.$$

□

Remark 1 It is important to note that Proposition 1 holds whether or not individual demand vectors satisfy the conditions of exact linear aggregation. However, when individual preferences satisfy the (Gorman) conditions for exact linear aggregation, the individual demands are linear in income and thus

$$\overline{x}(H) \equiv \frac{1}{H}\sum_{h=1}^{H} f^h(p, y^h) \equiv f(p, \overline{y}(H)), \tag{9}$$

where $\overline{y}(H) = \sum_{h=1}^{H} y^h/H$ is per capita income. One example of a demand system that satisies these conditions is the linear expenditure system.

[6]A vector is ergodic if each component is ergodic.

Our next proposition deals with aggregate budget share equations, since many empirical studies that employ aggregate data are based on budget share specifications.[7] We first present the following lemma, which is used to prove our Proposition 2.

Lemma 1 *Suppose the sequence of individual disturbances for good i, v_i^h, has a bounded covariance kernel, $cov(v_i^h, v_i^j)$ $[h, j = 1, 2, \ldots, H]$. Then a necessary and sufficient condition for the individual disturbances to be ergodic is*

$$\lim_{H\to\infty} cov(v_i^H, \overline{v_i}(H)) = \lim_{H\to\infty} \frac{1}{H}\sum_{j=1}^{H} cov(v_i^H, v_i^j) = 0.$$

Proof. See Parzen, pp. 74-75.

The Lemma states that a stochastic process is ergodic if and only if the covariance between the sample mean of the individual disturbances and the last sampled individual's disturbance approaches zero as the number of individuals in the sample approaches infinity. We use this result to prove that the random utility model is not generally a justification for errors in aggregate share equation models.

Proposition 2 *Suppose an economy consists of H individuals, whose behavior implies additive RUM share specification, as in equation 5. Further suppose that the ratio of the maximum individual income to the average income is uniformly bounded, in the sense that there exists a fixed number, G, such that $Y_U/\overline{y}(H) \leq G < \infty$ for all H, where $Y_U = \max_h\{y^h\}$. Then if the individual disturbance vectors, $v^h(p, y^h, \epsilon^h)$, $h = 1 \cdots H$, are ergodic, the error term in a budget share model based on aggregate data is almost surely zero for large H.*

Proof: Note that the budget share for good i appearing in models based on aggregate data can be written as

$$\overline{w}_i \equiv \frac{\sum_{h=1}^{H} p_i x_i^h}{\sum_{h=1}^{H} y^h} = \sum_{h=1}^{H} \theta^h w_i^h, \tag{10}$$

where

$$\theta^h = \frac{y^h}{\sum_{h=1}^{H} y^h}$$

[7] Examples include Deaton and Muellbauer (1980) and Christensen Jorgenson and Lau (1975).

is individual h's fraction of total income in the economy. Applying equation 10 to equation 5, the budget share based on aggregate data is given by

$$\overline{w}_i = \sum_{h=1}^{H} \theta^h \psi_i^h(p, y^h) + \sum_{h=1}^{H} \theta^h v_i^h(p, y^h, \epsilon^h). \tag{11}$$

We will show that the last term in equation 11, namely

$$\overline{z_i}(H) = \sum_{h=1}^{H} \theta^h v_i^h(p, y^h, \epsilon^h),$$

tends to zero under the conditions of the theorem. By Lemma 1, it is sufficient to show that $Cov(z_i^H, \overline{z_i}(H))$ tends to zero as H tends to infinity, where

$$z_i^h \equiv H\theta^h v_i^h \equiv \frac{y^h}{\overline{y}(H)} v_i^h.$$

Now[8]

$$\begin{aligned} Cov(z_i^H \overline{z_i}(H)) &= \frac{1}{H}\sum_{h=1}^{H} cov(z_i^H, z_i^h) \\ &= \frac{1}{H}\left(\frac{1}{\overline{y}(H)}\right)^2 \sum_{h=1}^{H} cov(y^H v_i^H, v_i^h y^h) \\ &\leq \left(\frac{Y_U}{\overline{y}(H)}\right)^2 \frac{1}{H}\sum_{h=1}^{H} Cov(v_i^H, v_i^h). \end{aligned}$$

But by the ergodicity of v_i^h, $\lim_{H\to\infty} \frac{1}{H}\sum_{h=1}^{H} Cov(v_i^H, v_i^h) = 0$. Since

$$\left(\frac{Y_U}{\overline{y}(H)}\right)^2 \leq G < \infty,$$

it follows that $Cov(z_i^H \overline{z_i}(H)) \to 0$ as $H \to \infty$. By the corrolary, this implies

$$\lim_{H\to\infty} \overline{z_i}(H) = 0$$

as required. □

Remark 2 Note that Proposition 2 holds whether or not individual demand vectors satisfy the conditions of exact aggregation. However, when individual preferences satisfy the (Muellbauer, 1975) conditions for exact nonlinear aggregation, then

[8] We assume, without loss of generality, that the covariances are positive.

$$\overline{w_i} \equiv \sum_{h=1}^{H} \theta^h \psi^h(p, y^h) \equiv \psi(p, y^*(y^1, \ldots, y^H, p)),$$

where y^* is usually interpreted as the "representative" consumer's budget level. One demand system that satisfies these conditions is Deaton and Muellbauer's (1980) almost ideal demand system.

Thus if income is bounded, in the sense that the ratio of the highest individual income to average income is finite as the population grows to infinity, then the ergodicity of errors in individual budget share equations implies that the errors in the aggregate budget share equation converges to zero in large populations.

The conditions of the theorem would be violated, for example, if one individual had all the income, because then $Y_U/\overline{y}(H) = H$, which is unbounded. On the other hand, the condition clearly holds if income is evenly distributed, since in this case $Y_U/\overline{y}(H) = 1$. Further, if a subset of the population containing K members receives all of the income, and if income is equally divided among the K members, then

$$\frac{y_U}{\overline{y}(H)} = \frac{y/K}{y/H} = \frac{H}{K}.$$

If K/H is a fixed proportion (e.g. 1%) then H/K is finite, and the conditions of the theorem are satisfied.

4 Examples

A (trivial) example of a situation where the individual disturbance vectors satisfy the conditions of Propositions 1 and 2 is the case where the individual disturbances, v_i^h, are independently and identically distributed *across individuals.*[9] The following three nontrivial examples show how the use of aggregate data can lead to RUM errors that are almost surely zero.

Example 1 Consider an economy where, at each point in time, the individual disturbance vectors in equations 3 or 5 are correlated within families. Formally,

[9]In this case, Proposition 1 is not very revealing because the per capita errors tend to zero by the law of large numbers.

let M_k denote the number of individuals in family k, and let F_k denote the set of individuals belonging to family k.

Then

$$cov(v_i^h, v_i^j) = \begin{cases} \sigma_{ii}^k & \text{if } h, j \in F_k \\ 0 & \text{otherwise} \end{cases} .$$

Now let $M = \max_k\{M_k\}$, and $\sigma_{ii} = \max_k\{\sigma_{ii}^k\} < \infty$. Hence

$$var(\overline{v_i}(H)) = \frac{1}{H^2} E\left[\sum_{h=1}^{H} v_i^h\right]^2 \leq \frac{1}{H^2}\left[\frac{H}{M} M^2 \sigma_{ii}\right] = \frac{M}{H}\sigma_{ii},$$

which tends to zero as $\frac{M}{H}$ tends to zero.

Thus, if the maximal family size relative to the total size of the population tends to zero for large populations, and disturbances are only correlated among individuals in the same family, the random utility model cannot explain the presence of disturbances in demand models based on aggregate data.

Example 2 Suppose that, an a given point in time, disturbances are correlated across individuals according to

$$v_i^h = \rho_i v_i^{h-1} + \eta_i^h,$$

where η_i^h is $iid(0, \sigma_{\eta_i}^2)$ and $\rho_i \in [0, 1)$. Further assume that $var(v_i^1) = \sigma_{\eta_i}^2 / \tau_i$, where τ_i is an arbitrary positive number. Then one can show that

$$\max_h\{var\ v_i^h\} = \max\{\frac{\sigma_{\eta_i}^2}{1 - \rho_i^2}, \frac{\sigma_{\eta_i}^2}{\tau_i}\} = \sigma_{ii}.$$

If the agents are indexed according to their geographic location, this specification may be interpreted as a situation where each individual's disturbance for a good is related to that of his "neighbor," and these disturbances follow an $AR(1)$-type specification. In other words, individual disturbances are geographically correlated.[10]

In this instance, it is immediate that, for $j = 0, 1, 2, \ldots,$

$$cov(v_i^h, v_i^{h+j}) = \rho_i^j var(v_i^h) \leq \rho_i^j \sigma_{ii},$$

[10]See Bronars and Jansen (1988) for an empirical application of time series methods to data ordered on a two dimensional lattice (i.e. geographically).

which tends to zero as j tends to infinity. Using Lemma 1, one can show that this implies v_i^h is ergodic. Hence, under the conditions of this example, the errors in models based on aggregate data are almost surely zero for large H.

Example 3 As a final example, suppose the total population, H, can be decomposed into a N groups, with M_k individuals in group k, and let F_k denote the set of individuals belonging to group k $[k = 1, 2, \ldots, N]$. For concreteness, one can think of the groups as individuals living within a given square mile of real estate. Thus, $H = M_1 + M_2 + \cdots + M_N$. Suppose that individuals within a group have disturbances that are perfectly correlated, and the disturbances between groups are correlated as an $AR(1)$-type process. This example is relevant, for example, when *rainfall* is the unobservable variable (the ϵ^h) from the econometrician's point of view, and where there is a correlation across geographic space in the amount of rainfall.

More formally, suppose that for $h \in F_k$ and $j \in F_l$ with $k \geq l$

$$cov(v_i^h, v_i^j) = \rho_i^{k-l}\sigma_{ii}^l,$$

where again $\rho_i \in [0, 1)$. As before, let $M = \max_k\{M_k\}$, and $\sigma_{ii} = \max_k\{\sigma_{ii}^k\} < \infty$. Hence

$$\begin{aligned}
var(\overline{v_i}(H)) &= \frac{1}{H^2}E\left[\sum_{h=1}^{H} v_i^h\right]^2 \\
&\leq \frac{1}{H^2}\{(M_1^2 + M_2^2 + \cdots + M_N^2)\sigma_{ii} \\
&\quad + M_1(M_2\rho_i + M_3\rho_i^2 \cdots + M_N\rho_i^{N-1})\sigma_{ii} \\
&\quad + M_2(M_3\rho_i + M_4\rho_i^2 + \cdots + M_N\rho_i^{N-2})\sigma_{ii} \\
&\quad + \cdots \\
&\quad + M_{N-1}M_N\rho_i\sigma_{ii}\} \\
&\leq \frac{1}{H^2}\{(M_1 + M_2 + \cdots + M_N)M\sigma_{ii} \\
&\quad + M_1M(\rho_i + \rho_i^2 + \cdots + \rho_i^{N-1})\sigma_{ii} \\
&\quad + M_2M(\rho_i + \rho_i^2 + \cdots + \rho_i^{N-2})\sigma_{ii} \\
&\quad + \cdots
\end{aligned}$$

$$
\begin{aligned}
& + M_{N-1} M \rho_i \sigma_{ii} \} \\
< \ & \frac{1}{H^2} M \sigma_{ii} \left\{ H + (M_1 + \cdots + M_{N-1}) \left(\frac{1}{1-\rho_i} \right) \right\} \\
< \ & \frac{M}{H^2} \sigma_{ii} H \left(1 + \frac{1}{1-\rho_i} \right) \\
< \ & \frac{M}{H} \left(\frac{2\sigma_{ii}}{1-\rho_i} \right),
\end{aligned}
$$

which tends to zero if M/H tends to zero as H tends to infinity. Thus, if the number of individuals within each group are much less than the total population, the individual disturbances are ergodic and the errors in models based on aggregate data are almost surely zero.

Remark 3 *When $M_k = 1$ for all k, Example 3 reduces to Example 2. When $\rho_i = 0$, Example 3 reduces to Example 1.*

5 Conclusion

The RUM model is useful for modeling errors in individual demand and share equations when one has access to cross-section data. However, the results in this paper reveal that RUM specification does not always imply errors in demand or average share equations when *aggregate* data are employed. Roughly speaking, the act of aggregating these disturbances across a large population of individuals results in an aggregate specification with errors that converge to zero.

Two important papers cited in the literature on the random objective justification for errors are Deaton and Muellbauer (1980) and Christensen, Jorgenson and Lau (1975). Since both of these papers utilize aggregate time series data, our results suggest it is not obvious that their rejections of neoclassical theory were due to failure to account for RUM-generated heteroskedacity.

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