INCOME AND PRICE ELASTICITIES IN THE U.S. DEMAND FOR COMPUTERS

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ABSTRACT
In order to assess the impact of changing income and computer prices on the demand for minicomputers and mainframes, we have developed simple demand models. The model proposed relates the number of computer units sold with measures of computer prices and the industrial production index. The results applied to computers during the years 1965-1986 indicate that demand for minicomputers is more sensitive than the demand for mainframes to changes in economic conditions.

INTRODUCTION
The computer industry is one of the most rapidly-growing areas in the U.S. economy. In spite of dramatic price decreases, U.S. domestic computer sales reached 24.8 billion dollars in 1986, up from 1.8 billion dollars in 1965. Because of this rapidly-changing environment, computer manufacturers have had to make decisions under much more unpredictable conditions than other manufacturing sectors. It is our contention that, in order to properly evaluate alternative policies, computer vendors should be able to estimate the impact of economic conditions on the demand for computers.

Computer manufacturers face questions such as "What will be the demand for mainframes if their prices are decreased by 15%?", "How will the demand for minicomputers be affected if mainframe prices are reduced by 10% next year?", or "If industrial activity or the GNP is increased by 5% next year, how will this influence the demand for minicomputers or mainframes?". In spite of the practical usefulness and importance of finding answers to these questions, there are not many studies which can lead to their solutions.

In the past, Chow [1] has done the only study to analyze income and price effects on the demand for computers. Using mainframes available during the years 1955-1965, he found that the demand for computers was significantly affected by their prices, but not by income. There have been tremendous changes in the computer industry since Chow investigated the responsiveness of computer demand 20 years ago. For example, Chow could not investigate the effect of price changes in one type of computer on the demand for other types of computers, since the only computer type available at that time was a general purpose mainframe.

Since the time when Chow analyzed mainframes, there have been no studies examining the effect of economic conditions on the demand for computers. One of the major reasons for the dearth of research in this area is the difficulty in obtaining the required data. Even though this study is only preliminary in nature, we hope our approach and results will stimulate new interest in this important area of study.

In order to investigate the sensitivity of computer demand to changes in economic conditions, we have developed simple models for computer demand. From these models, we have estimated short-run and long-run price and income elasticities which correspond to theoretical expectations. We have limited our analysis to two computer categories: minicomputers and mainframes. We have not included microcomputers in our analysis because they have not been used in business long enough to provide us adequate time-series data. The demand equation consists of the price of a particular computer type, plus the price of another computer type functioning as a substitute, plus industrial output.

The estimation results applied to the computers available during the years 1965-1986 indicate that a 10% decrease in computer prices will increase the demand for computers, on the average, by 12% in...
the short-run, and by 16% in the long-run. On the other hand, the effects of the price changes in one computer category on the demand in the other category do not seem to be significant. A 10% increase in industrial activity increases the demand for minicomputers by 12% in the short-run, and by 15% in the long-run. However, industrial activity does not affect the demand for mainframes either in the short-run or in the long-run. Also, the estimation results indicate that the demand for minicomputers adjusts more quickly to the new equilibrium than does the demand for mainframes. In addition, the full impact of changes in economic conditions on the demand for both categories spreads over more than one year.

From the above results, we can conclude that the demand for minicomputers is more sensitive to changes in economic conditions than is the demand for mainframes. Therefore, a minicomputer manufacturer should be more concerned with changes in economic conditions than should mainframe manufacturers.

THEORETICAL FORMULATION

We assume that computer prices are determined by computer manufacturers. Users decide their demand for computers based on given computer prices and output levels generated by computer manufacturers. However, we would like to point out that the pre-determined price assumption clearly ignores the interdependence that describes actual computer markets, where computer price and quantity demanded are simultaneously determined by the demand and supply of computers. For example, computer prices are set by computer manufacturers, based on their expectations of computer demand as well as costs required in order to manufacture computers. On the other hand, the quantity demanded is affected by computer price as well as by industrial activity.

If we reject the assumption that computer prices are pre-determined for the users, then we have to use the simultaneous-equation method to obtain consistent estimates. However, estimation of the simultaneous-equation model would be quite difficult due to insufficient data on the supply model. In order to estimate computer supply, we need to have the cost data required for manufacturing computers, such as material prices for computer components, wage rates for workers in the computer industry, and the price of the capital paid for fixed investment. However, there are no public data sources for those variables. Furthermore, our models require the supply side data for both mainframes and minicomputers.

On the other hand, it has been found that the ordinary least squares method applied to single-equation models is more robust against specification errors than many of the simultaneous-equation models [8, p. 231]. Because of the limited data availability, we are especially concerned with specification errors, so that we may minimize possible bias in income and price elasticities. Therefore, the use of single-equation demand models and the related estimation techniques seems to be appropriate.

The demand models utilized in this study have the following variables: the current year's quantity sold for a particular type of computer, its price, the price of its substitute, a measure of the U.S. industrial production, year of observation, and the previous year's computer quantity sold. Two types of models are investigated. The first one is a static model which relates the current quantity demanded to current industrial production, year of observation, and the current prices of the two computer categories. The second one is a dynamic model which relates all variables of the static model and the computer quantity demanded in the previous year.

The static model, which has been widely used in demand studies [4] has the following form:

\[ X_t = \alpha_0 + \alpha_1 Y_t + \alpha_2 P_t + \alpha_3 Q_t + \alpha_4 T_t + u_t, \]  

(1)

where \( X_t \) is the number of units sold for a particular type of computer, \( Y_t \) is the industrial production in the U.S., \( P_t \) is the unit price of a computer being analyzed, and \( Q_t \) is the price of a substitute. Mainframes and minicomputers are considered to be substitutes of each other. Other possible complementary or substitution effects have been disregarded. \( T_t \) is the year of observation, which is included in the model in order to control the quality change of computers over the years. \( u_t \) is the random error. All variables, except \( T_t \), are expressed in natural logarithms so that the coefficients \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) are the income, own-price, and cross-price elasticities, respectively. According to microeconomic theory, we would expect the income elasticity to be positive, the own-price elasticity to be negative, the cross-price elasticity to be positive, and quality change to be positive.

The dynamic model was developed by Nerlove and Addison [9] and applied to the demand for mainframes by Chow [1] using time-series data. Later, Houthakker et al. [5] and Johnson and Oksanen [7] applied the dynamic approach to time-series and cross-section data. The dynamic model has the following form:

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where $X_t$ is the long-run equilibrium of a particular computer type demanded. Since all variables, except $T_t$, are expressed in natural logarithms, $\beta_1$, $\beta_2$, and $\beta_3$ are long-run income, own-price, and cross-price elasticities, respectively.

The long-run equilibrium level of a computer can be observed if $Y_t$, $P_t$, and $Q_t$ remain at a fixed level for a sufficiently long period. However, $Y_t$, $P_t$, and $Q_t$ change continuously. Therefore, $X_t$ can never be observed. We assume that, during one year, computer demand may not adjust totally to the long-run equilibrium level, $X_t$, but only to the observed level $X_t$ such that:

$$X_t = X_t^* = \beta_1 Y_t + \beta_2 P_t + \beta_3 Q_t + \beta_4 T_t + \epsilon_t,$$  

(2)

where $\epsilon_t$ is a fraction measuring the speed of adjustment.

The static model (1) is a special case of the dynamic model described by (2) and (3). The speed of adjustment is one for the static model so that the adjustment of demand is assumed to be completed within one year. Using Eq. (3), we can express Eq. (2) in terms of observable quantities as:

$$X_t = \delta_0 + \delta_1 Y_t + \delta_2 P_t + \delta_3 Q_t + \delta_4 T_t + (1-\delta) X_{t-1} + \epsilon_t,$$  

(4)

Eq. (4) can be estimated as:

$$X_t = \delta_0 + \delta_1 Y_t + \delta_2 P_t + \delta_3 Q_t + \delta_4 T_t + \delta_1 X_{t-1} + \epsilon_t,$$  

(5)

so that the estimates of $\delta_1$, $\delta_2$, $\delta_3$, $\delta_4$, $\delta_5$ and $\delta_6$ can be computed from the coefficient estimates of $\delta_0$, $\delta_1$, $\delta_2$, $\delta_3$, $\delta_4$, $\delta_5$ and the following relationships:

$$\delta_1 = \frac{(1-\delta)}{\delta_0},$$

$$\delta_2 = \frac{(\delta_1 - \delta)}{(1-\delta)},$$

$$\delta_3 = \frac{(1-\delta)}{\delta_2},$$

$$\delta_4 = \frac{(\delta_3 - \delta)}{(1-\delta)},$$

$$\delta_5 = \frac{(1-\delta)}{\delta_4},$$

$$\delta_6 = \frac{(\delta_5 - \delta)}{(1-\delta)}.$$

The short-run income, own-price, and cross-price elasticities $\delta_1$, $\delta_2$, $\delta_3$ should be positive, negative, and positive, respectively. A measure of quality change, $\delta_4$, should be positive. Since it would take time to adjust to the long-run equilibrium level, we would expect the adjustment coefficient $\delta_5$ to be positive, but less than or equal to one. Therefore, the long-run elasticities $\beta_1$, $\beta_2$, and $\beta_3$ are greater than or equal to the short-run elasticities in absolute values.

The DATA

We have analyzed two types of computers: minicomputers and mainframes. We have not included microcomputers in our analysis. Microcomputers play an important role in business, and may affect the demand for the other computer categories. However, microcomputers have not been used long enough in business to provide useful time-series data. We need to have the following data for each type of computer: computer quantity demanded, computer price, and a measure of production activity for each year.

For the computer quantity demanded, we have used the number of units sold for minicomputers and mainframes for each year. These values are obtained from Industry Marketing Statistics [6]. The number of computer units sold is plotted as a function of year in Figure I.

For computer prices, we have assumed the unit value of computers to be an average price for each type of computer. The unit value for each type of computer is obtained by dividing each year's computer sales revenue by the number of computers sold. In order to remove inflationary effects on computer price over the years, the unit values of computers are discounted with the implicit price deflator, which is obtained from the Economic Report of the President [10]. The unit value of computers, for 1981 constant dollars, is plotted as a function of year in Figure II.

We would like to point out that the number of units sold and the unit value of a computer are values which are not adjusted for changes in computer quality. In order to calculate quality-adjusted computer quantity, we need to have data on computer characteristics and computing power for each category of computer in each year. On the other hand, for quality-adjusted computer prices, we need to calculate what a computer would have cost if it had been introduced in some reference year. For this calculation, we need to have data on the computer price and its basic characteristics for each category in each year.

Despite the increasing statistical activity for the computer industry, there are still few consistent data available for computer characteristics and prices over the years. Therefore, we cannot use the quality-adjusted quantities and prices for the demand models developed. Instead, we have limited this study by ignoring computer quality changes for the years 1965 to 1986 in the present analysis. In the APPENDIX: ON QUALITY VARIATION section, we further discuss issues and potential problems if the models are estimated without quality adjustment.

For the measure of U.S. production activity, we can use either the real GNP or
### Table I: Estimation Results of the Static Model

<table>
<thead>
<tr>
<th>MINICOMPUTERS</th>
<th>MAINFRAMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULTIPLE CORRELATION</td>
<td>0.992</td>
</tr>
<tr>
<td>DURBIN-WATSON</td>
<td>0.915</td>
</tr>
<tr>
<td>DEGREES OF FREEDOM</td>
<td>17</td>
</tr>
<tr>
<td>SUM OF SQUARED ERRORS</td>
<td>0.513</td>
</tr>
<tr>
<td>CONSTANT</td>
<td>-9.424** (3.596)</td>
</tr>
<tr>
<td>ln(MINI-PRICE)</td>
<td>-1.926** (0.282)</td>
</tr>
<tr>
<td>ln(MAIN-PRICE)</td>
<td>0.552** (0.218)</td>
</tr>
<tr>
<td>ln(OUTPUT)</td>
<td>2.223** (0.835)</td>
</tr>
<tr>
<td>TIME</td>
<td>0.036 (0.036)</td>
</tr>
</tbody>
</table>

Notes: ln(MINI-PRICE) and ln(MAIN-PRICE) are the prices of minicomputers and mainframes, respectively, transformed by natural logarithms. ln(OUTPUT) is the industrial production index transformed by natural logarithm. TIME is the year of observation. The values in parentheses are standard errors. ** and * indicate coefficient estimates statistically different from 0 at the 5% and 10% significance levels, respectively, using a one-tailed test.

### Table II: Estimation Results of the Static Model after Correcting Serial Correlation

<table>
<thead>
<tr>
<th>MINICOMPUTERS</th>
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</tr>
</thead>
<tbody>
<tr>
<td>MULTIPLE CORRELATION</td>
<td>0.972</td>
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<tr>
<td>DURBIN-WATSON</td>
<td>1.873</td>
</tr>
<tr>
<td>DEGREES OF FREEDOM</td>
<td>16</td>
</tr>
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<td>SUM OF SQUARED ERRORS</td>
<td>0.178</td>
</tr>
<tr>
<td>CONSTANT</td>
<td>-3.427* (2.325)</td>
</tr>
<tr>
<td>ln(MINI-PRICE)</td>
<td>-1.394** (0.255)</td>
</tr>
<tr>
<td>ln(MAIN-PRICE)</td>
<td>0.239* (0.140)</td>
</tr>
<tr>
<td>ln(OUTPUT)</td>
<td>0.966** (0.530)</td>
</tr>
<tr>
<td>TIME</td>
<td>0.055** (0.017)</td>
</tr>
</tbody>
</table>

Notes: See Table I.

### Table III: Estimation Results of the Dynamic Model after Correcting Serial Correlation

<table>
<thead>
<tr>
<th>MINICOMPUTERS</th>
<th>MAINFRAMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULTIPLE CORRELATION</td>
<td>0.978</td>
</tr>
<tr>
<td>DURBIN-WATSON</td>
<td>2.268</td>
</tr>
<tr>
<td>DEGREES OF FREEDOM</td>
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<tr>
<td>SUM OF SQUARED ERRORS</td>
<td>0.106</td>
</tr>
<tr>
<td>CONSTANT</td>
<td>-4.214** (1.813)</td>
</tr>
<tr>
<td>ln(MINI-PRICE)</td>
<td>-1.192** (0.221)</td>
</tr>
<tr>
<td>ln(MAIN-PRICE)</td>
<td>0.173** (0.117)</td>
</tr>
<tr>
<td>ln(OUTPUT)</td>
<td>1.193** (0.394)</td>
</tr>
<tr>
<td>TIME</td>
<td>0.029 (0.023)</td>
</tr>
<tr>
<td>ln(LAST-DEMAND)</td>
<td>0.184* (0.134)</td>
</tr>
</tbody>
</table>

Notes: See Table I. ln(LAST-DEMAND) is the previous year's demand for each type of computer transformed with natural logarithms.
the industrial production index. The real GNP is obtained by dividing the inflation rate from the nominal GNP. We have found that these two measures of output yield very similar results, but we have nevertheless decided to use the industrial production index since it performs slightly better than the real GNP. The industrial production index is obtained from the Economic Report of the President [10].

ESTIMATION

We have estimated the static demand equation, Eq. (1), using the ordinary least squares method. The results are summarized in Table I. All coefficients, except the year of observation, have the expected signs. Many standard errors are small in relation to the coefficient estimates. However, the Durbin-Watson statistics indicate statistically significant positive serial correlations in the error terms. For an equation with 5 explanatory variables and 22 observations, the upper limit of the Durbin-Watson statistic is 1.80 at the 5% significance level. Therefore, we cannot accept the null hypothesis of no positive serial correlations for both minicomputers and mainframes. Serial correlation causes ordinary least squares to underestimate the variances of the coefficients.

We use the Durbin procedure [3] in order to remove serial correlations. Serial correlations are estimated to be 0.628 for minicomputers and 0.504 for mainframes. The estimation results of the static model after correcting the serial correlation is reported in Table II. The Durbin-Watson statistics for both minicomputers and mainframes show no positive serial correlation.

Based on Eq. (5), we have estimated the dynamic model and report the results in Table III. Since the dynamic models have lagged dependent variables, ln(LAST-DEMAND), the conventional Durbin-Watson statistics cannot be used in order to check serial correlation. Therefore, we have used Durbin's [2] h-test for the presence of serial correlation. We have accepted the null hypothesis of no positive serial correlations for the minicomputer and mainframe equations.

All coefficient estimates of the dynamic models, except those of TIME for mainframes, have the theoretically expected signs. On the other hand, the coefficient estimates of TIME are not statistically significant at the 10% significant levels. It appears that a more explicit admissable method than that of using the TIME variable is needed in order to control computer quality changes over the years. Later, we will discuss possible directions of this resulting from not controlling quality change. The coefficient estimates of the lagged computer demand are positive and less than one, as expected. A comparison of the estimates of the dynamic model in Table III with those of the static model in Table II shows that the coefficient estimates are reasonably stable, except the constant term of the mainframe demand equation. With respect to goodness of fit, the dynamic models perform slightly better than their static counterparts.

We have performed a standard F-test in order to check the equivalence of the static models and the dynamic models. The F-statistics are 9.597 for the minicomputer equation and 17.769 for the mainframe equation, rejecting the null hypothesis that the static model is equivalent to the dynamic one for both categories. Since the tests indicate that dynamic models cannot be simplified into static models for minicomputers and mainframes, and dynamic models are more general than static models, we will analyze the implications of our results based on the estimation results of the dynamic models.

DISCUSSION AND IMPLICATION OF THE RESULTS

As discussed earlier, the theoretical specification of the dynamic demand model suggests that the income and price coefficients in Table III measure short-run elasticities. If Y, P, and Q remain fixed for a sufficient time, then X, progressively approaches X, which, given (5), leads to:

\[
X_t = (\delta_3/(1-\delta_3) + \delta_5/(1-\delta_5))Y_t + (\delta_4/(1-\delta_4))P_t + (\delta_5/(1-\delta_5) + \delta_6/(1-\delta_6))Q_t + \epsilon_t, \tag{7}
\]

where the coefficients of Y, P, and Q are the long-run income, own-price, and cross-price elasticities, respectively. We have

| OWN-PRICE ELASTICITY | -1.461** (0.261) | -1.800** (0.171) |
| CROSS-PRICE ELASTICITY | 0.212 (0.160) | 0.094 (0.271) |
| INCOME ELASTICITY | 1.462** (0.417) | 0.247 (0.609) |
| ADJUSTMENT VELOCITY | 0.816** (0.134) | 0.635** (0.088) |

Notes: See Table I.
computed long-run elasticities for minicomputers and mainframes, and report them in Table IV. Since the elasticities are non-linear functions of coefficients of Eq. (5), we have reported only approximate values for standard errors.

Computer demands are sensitive to the changes in own-prices for both minicomputers and mainframes, but are not sensitive to the changes in prices of other computer types. According to Tables III and IV, a 10% decrease in minicomputer price would, other things being equal, lead to an increase in demand for minicomputers by 12% in the short-run and, by 15% in the long-run. However, changes in minicomputer price do not seem to have a significant effect on the demand for mainframes.

A 10% decrease in mainframe price would lead to an increase in the demand for mainframes by 11% in the short-run, and by 18% in the long-run. On the other hand, a 10% decrease in mainframe price would decrease the demand for minicomputers by 2% in the short-run because minicomputers become relatively more expensive than mainframes. The estimate of the own-price elasticity for mainframes is comparable to the previous results found by Chow [1]. Chow reported that the own-price elasticity for mainframes was -1.44 during the years 1955-1965.

Income (industrial production activity) significantly affects the demand for minicomputers, but does not affect the demand for mainframes. A 10% increase in industrial activity affects the demand for minicomputers by 12% in the short-run, and by 15% in the long-run. However, income does not affect the demand for mainframes either in the short-run or in the long-run. The particular result concerning mainframes is also compatible with Chow's results, who reported no significant income effect on the demand for mainframes. This implies that, even though computer technology has changed tremendously over the years, the economic behavior of mainframes which was demonstrated during the years 1955-1965, has not changed significantly.

Given relatively high own-price elasticities, the low or zero cross-price elasticities should provide useful information in assessing price policies for computer manufacturers. Because of the high income elasticity of minicomputers, minicomputer vendors should therefore be more concerned about U.S. industrial activity than should mainframe vendors.

Table IV gives the estimate of $v$, the velocity of adjustment. These values measure the speed of demand adjustment to changes in income and prices. The estimates for both minicomputers and mainframes are less than one, indicating adjustment lags of more than one year. Since the purchase decision for minicomputers would involve fewer factors to take into consideration than that for mainframes, we may expect that the demand for minicomputers to respond more quickly to changes in economic conditions than the demand for mainframes, resulting in a higher adjustment velocity for minicomputers than for mainframes. Our results agree with this observation showing that the speed of minicomputer demand adjustment to the changing economic conditions is somewhat higher than that of mainframes.

Clearly, the direction of future research is to investigate the demand for computers after adjusting changes in computer quality, which are themselves the results of improved computer technology. Furthermore, a simultaneous supply and demand model could be formulated by releasing the exogenous computer price assumption. However, as we have previously discussed, these refinements depend on considerable improvements regarding the quantity and quality of computer industry data. Another possible improvement would allow elasticities to vary. The elasticities we obtained must be regarded as averages during the years 1965-1986. This method can be expanded to different elasticities by classifying the covered periods into several categories based on certain criteria, such as breakthroughs in computer technology or significant changes in economic structures. We may also apply the developed models to various countries in order to find any systematic patterns for demand elasticities and adjustment velocities based on criteria such as the GNP per capita or the growth rate of the GNP.

APPENDIX: ON QUALITY VARIATION

In this section, we would like to examine issues related to quality changes and to the potential direction of bias for the estimates calculated without considering quality changes.

As earlier discussed, the dramatic improvement in computer technology necessitates adjustments for price and quantity for computer demand analysis. Computer prices observed each year are not reasonable measures for true prices since the prices observed over the years are those for products with different qualities. In order to obtain quality-adjusted prices, we need to (1) establish a relationship between the computer price and its basic characteristics, such as computing speed and storage capacity for each year for each type of computer, and (2) apply this relationship to estimate what each computer would have cost if it
had been introduced in some reference year. The ratio between adjusted and unadjusted price will be the adjustment factor.

Similarly, the computer quantity demanded each year should not be a simple sum of the total number of units sold each year because computers used in 1986 have much more capacity and power than computers used 20 years ago. The adjustment should be made by multiplying the number of units sold by a measure of quality improvement each year, where the measure of improvement is a growth rate of computer characteristics and power for a computer each year. Consequently, we need to have data on computer characteristics and power for each year in order to calculate adjustment factors for price and quantity demanded.

We write quality-adjusted prices and quantity demanded as $P_t = P_t + A_t$, $Q_t = Q_t + A_t$, and $X_t = X_t + A_t$, where all variables are transformed with natural logarithms, $A_t$ is the quality adjustment factor for own-price in the year $t$, $A_{st}$ is that for the price of its substitute and $A_{nt}$ is that for the quantity demanded. $P_t$, $Q_t$, and $X_t$ are the same as previously defined. After quality adjustment factors are incorporated, we can express Eq. (1) as,

$$X_t = X_t + A_{st} + A_{nt}$$

Based on Eq. (1-1), we can examine the direction of biases for the coefficient estimates when they are estimated without quality adjustment. In order to simplify expressions, we will assume that there are no correlations among independent variables, which is not a reasonable assumption in reality. In the population, the quantity-adjusted income elasticity can be expressed as the following:

$$\eta_I = \frac{C(X_t, Y_t)\cdot V(Y_t)}{V(Y_t)} = \frac{C(X_t, Y_t)}{V(Y_t)} + \frac{C(A_{nt}, Y_t)}{V(Y_t)},$$

where $C(\cdot)$ and $V(\cdot)$ stand for covariance and variance, and $a_1$ is the coefficient of $Y_t$ in Eq. (1).

$V(Y_t)$ is positive. $C(A_{nt}, Y_t)$ is also likely to be positive because both industrial activity and the computer quantity adjustment factor have grown over the years. Therefore, the estimate of $a_1$, unadjusted income elasticity, is probably an under-estimate of $\eta_I$, quality-adjusted income elasticity.

Similarly, the quality-adjusted own-price elasticity, $\eta_p$, can be expressed as $C(X_t, P_t)\cdot V(P_t)$.

We can suppose that, over the years, (1) the unadjusted computer quantity demanded has increased, (2) the unadjusted computer price has become cheaper, (3) the adjustment factor for computer quantity demanded has increased, and (4) the adjustment factor for computer price has become larger but in a negative value. As a result of those historical patterns, we can expect the following signs for the covariances: $C(X_t, P_t) < 0$, $C(a_{nt}, P_t) < 0$, $C(a_{nt}, A_{nt}) < 0$, and $C(P_t, A_{nt}) > 0$. Since the coefficient of $P_t$ in Eq. (4), $a_2$, can be expressed as $C(X_t, P_t)/V(P_t)$, the estimate of $a_2$ may either under- or over-estimate $\eta_p$. Similarly, the direction of bias of the unadjusted cross-product elasticity, $a_3$, cannot be predicted.

From the above analysis, it is clear that the estimates will be biased if the model is developed and estimated without considering quality adjustment factors. Therefore, the important issue that should be addressed by future research is how to solve the quality-adjustment problem with the limited data available.

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REFERENCES


