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The Error of Forecast for Multivariate Regression Models

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I. Introduction*

In this paper we present a generalized error of forecast for the set of dependent variables in a multivariate regression model. Since in many practical situations statisticians and econometricians are concerned with forecasting the future values of a group of dependent variables it seems desirable to be able to construct confidence regions and test hypotheses about the forecast of these variables.

The generalized error of forecast which we develop is a quite straightforward extension of the standard error of forecast used when making predictions with single equation regression models. We shall review this latter concept in Section II. In Section III we derive an expression for the generalized error of forecast and show how it can be used to construct forecast regions and test hypotheses; an application of this statistic to a two equation model is then made in Section IV. Finally, in Section V some further uses and limitations of the generalized error of forecast are discussed.

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* We wish to express our appreciation for the many constructive comments which Professors T. C. Koopmans, A. T. James and Mr. T. N. Srinivasan have made concerning both the substance and form of this paper. However, the final form and contents, including any errors which might remain, are the joint responsibility of the authors.

II. The Single Equation Error of Forecast*

* The error of forecast for a single equation regression model appears to have a rather long history. It seems to have been first discussed by H. Working and H. Hotelling in [9]. For other references to this problem the reader is referred to [2, 181]. An excellent presentation of the error of forecast in matrix notation can be found in [7, 280-284].

The single equation regression model may be written as

$$(2.1) \qquad y_n = \sum_{k=1}^{K} \beta_k X_{kn} + v_n \qquad (n = 1, 2, \ldots, N)$$

or in matrix notation as,

$$(2.2) \qquad y = \beta X + v$$

where y is a row vector of N observations on the dependent variable, X a KxN matrix of nonstochastic or fixed values taken by the K independent variables ($K \leq N$), β a row vector of K unknown regression coefficients, and v a random row vector consisting of N independently distributed terms, each with zero expected value and a common finite variance σ_v^2 . Upon estimating β by the method of least squares, we obtain

$$(2.3) \qquad y = bX + \bar{v}$$

where

$$(2.4) \qquad b = yX'(XX')^{-1} = \beta + vX'(XX')^{-1}$$

and $\bar{v}$ is the vector whose components are the N calculated residuals.

If we have a set of values available for the independent variables for the period in which the forecast is made, say X_F , (where X_F is a Kx1 vector) we can then predict a value of y , say y_F^* , by using the estimated regression relationship. We then obtain

$$y_F^* = bX_F \quad (2.5)$$

The true value of y, say y_F, in this prediction period is

$$y_F = \beta X_F + v_F \quad (2.6)$$

where v_F is the scalar value of the random term in the forecast period. When we subtract (2.6) from (2.5) we obtain as the error of forecast

$$y_F^* - y_F = (b - \beta)X_F - v_F \quad (2.7)$$

The expected error is (using E as the expected value operator)

$$E(y_F^* - y_F) = E[(b - \beta)X_F - v_F] = 0 \quad (2.8)$$

since b is an unbiased estimator of β, $Ev_F = 0$, and X_F is assumed to be nonstochastic.*

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* If X_F is stochastic, as would be the case if a forecast of the independent variables for the prediction period were used, it would be necessary to assume that X_F and $b - \beta$ are distributed independently for $E(y_F^* - y_F)$ to be equal to zero.

We notice that the forecast error in (2.7) may be divided into two parts. One source of error is due to the inaccuracies in estimating the regression coefficients and the other is due to the presence of the random term v_F. Thus the error of forecast is a function of two random variables, b and v_F, and these variables are independently distributed since by assumption v_F is independent from $v_n (n = 1, \ldots, N)$, and hence independent of b which is but a linear function of v_n. If we now make the further assumption that the random terms, the v_n's , are each normally distributed then the forecast error is also normally distributed since it is just a linear combination of these normally distributed variables.

The variance of the forecast error is given by*

$$\sigma_F^2 = E(y_F^* - y_F)^2 = Ev_F^2 + X_F' \,[E(b - \beta)'(b - \beta)]X_F \tag{2.9}$$

which can be written as

$$\sigma_F^2 = \sigma_v^2[1 + X_F'(XX')^{-1}X_F] \; . \tag{2.10}$$

* The variance of the forecast error as given by (2.9) is valid regardless of whether the random terms are normally distributed. The assumption of normality is needed in order to determine the distribution of the statistic defined in (2.13).

The positive square root of (2.10) is the population standard error of forecast. As an estimator of σ_F^2 we use the unbiased estimator

$$\hat{\sigma}_F^2 = \hat{\sigma}_v^2[\; 1 + X_F'(XX')^{-1}X_F] \tag{2.11}$$

where

$$\hat{\sigma}_v^2 = \frac{yy' - b(XX')b'}{N - K} \tag{2.12}$$

We can now consider the statistic

$$t = \left(\frac{y_F^* - y_F}{\sigma_F}\right) \Bigg/ \left(\frac{\hat{\sigma}_F}{\sigma_F}\right) \quad . \tag{2.13}$$

This is the familiar t statistic with $N - K$ degrees of freedom since, under the assumption that the random terms are normally distributed, $y_F^* - y_F$ is normally distributed with expected value zero and variance σ_F^2 ,

$(N - K)\,\hat{\sigma}_F^{\,2}/\sigma_F^{\,2}$ is distributed as a χ^2 variable with $N - K$ degrees of freedom, and $\hat{\sigma}_F$ and $y_F^* - y_F$ are independently distributed.* We can then

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* Cf. [7, 206, 298]

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make probability statements about t in the form

(2.14) $$\Pr.\,(\,|\,t\,|\, > t_\alpha) = \alpha$$

when testing hypotheses about y_F, where t_α is the value of the t statistic at the α level of significance, or in the form

(2.15) $$\Pr.\,(y_F^* - \hat{\sigma}_F t_\alpha < y_F < y_F^* + \hat{\sigma}_F t_\alpha = 1 - \alpha$$

for the purpose of determining a confidence interval** for y_F .

** See Section V for a discussion of the interpretation of this forecast interval.

III. The Generalized Error of Forecast

We now consider the following multivariate regression model:

(3.1) $$y_{in} = \sum_{k=1}^{K} \pi_{ik} X_{kn} + v_{in} \qquad \begin{matrix}(i = 1, 2, \ldots, G;\\ n = 1, 2, \ldots, N)\end{matrix}$$

which can be written in matrix notation as

(3.2) $$Y = \Pi X + V .$$

Y represents a GxN matrix of the N sets of sample values taken by the

G jointly dependent variables, Π a $G\times K$ matrix of unknown regression coefficients, X a $K\times N$ nonstochastic matrix* of values taken by the independent

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* We also make the usual assumption that the rank of X is K which ensures that none of the X's can be expressed as a linear combination of the others and that $K \leq N$.

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variables, and V a $G\times N$ matrix of random terms. It is also assumed that the N column vectors of V are independent random drawings from a G-dimensional normal population such that each column has a zero expected value and the columns have a common variance-covariance matrix,** Σ_{vv}. These

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** It should be noticed that this model is completely analogous to what is referred to as the reduced form equations in econometrics. Under this interpretation the y's are the set of endogenous variables, the π's the reduced-form regression coefficients, the x's the exogenous variables, and the v's the reduced-form disturbances. The reader is referred to [5, 113-121] for precise definitions of these terms. It should be noticed that we are here excluding reduced form equations in which some of the x's are lagged endogenous variables.

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conditions on V may be summarized as

$$(3.3) \qquad E\, v_{in} = 0 \qquad (i = 1, \ldots, G\ ;\ n = 1, \ldots, N)$$

and

$$(3.4) \qquad E\, v_{in} v_{jn'} = \begin{cases} 0 & n \neq n' \\ \sigma_{ij} & n = n' \end{cases} \qquad \text{for all } i \text{ and } j .$$

Thus interdependence between the random terms in different equations in the same time period is allowed but not between random terms of different time periods.

By applying the method of least squares to (3.2) we obtain

$$(3.5) \qquad Y = PX + \bar{V}$$

where P , the matrix of estimated regression coefficients is*

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* The expression for P in (3.6) also shows that P is an unbiased estimator of Π , since when taking expected values of both sides we have that $E[\bar{V}X'(XX')^{-1}] = 0$ so $EP = \Pi$.

$$P = YX'(XX')^{-1} = \Pi + VX'(XX')^{-1} \tag{3.6}$$

and $\bar{V}$ is the matrix of calculated residuals.

If we now desire to predict simultaneously** the values of the G

** We are here concerned with finding a statistic that will enable us to make probability statements about the set of dependent variables and not each variable considered separately. The latter has been done under the assumption that the coefficients of the structural equations were estimated by the method of full maximum likelihood and also for the resulting reduced form equations. Cf. [2].

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dependent variables using the estimated regression coefficients and a set of values for the independent variables, X_F , the forecast would be

$$Y_F^* = PX_F \tag{3.7}$$

where Y_F^* is a column vector of forecast values and X_F is a column vector of nonstochastic known values for the independent variables. The observed value of Y in the prediction period, say Y_F , is given by

$$Y_F = \Pi X_F + V_F \tag{3.8}$$

where V_F is the column vector of values assumed by the random terms in the forecast period. The error of forecast is

$$Y_F^* - Y_F = (P - \Pi)X_F - V_F \; . \tag{3.9}$$

The expected error is

$$(3.10) \qquad E(Y_F^* - Y_F) = E[(P - \Pi)X_F - V_F] = 0$$

since P is an unbiased estimator of Π , $EV_F = 0$, and X_F is nonstochastic and thus independent of P . The variance-covariance matrix of the forecast error is given by

$$(3.11) \qquad \begin{aligned} \Sigma_{FF} &= E[(Y_F^* - Y_F)(Y_F^* - Y_F)'] = \\ &= E[(P - \Pi)X_F X_F'(P - \Pi)'] - E(P - \Pi)X_F V_F' - EV_F X_F'(P - \Pi)' + EV_F V_F' . \end{aligned}$$

The two middle terms in (3.11) are equal to zero since V_F and P are independent and $EV_F = 0$.

To evaluate the first term in (3.11) we let $(P - \Pi)$ be a GxK matrix A with a typical element $[a_{ij}]$ and $X_F X_F'$ be a KxK matrix M_F with typical element $[m_{kk'}]$. We find that

$$(3.12) \qquad E[(P - \Pi)X_F X_F'(P - \Pi'] = E\, AM_F A' = \begin{bmatrix} \sum_{k'=1}^{K} \sum_{k=1}^{K} \sigma_{k'k}^{(1)(1)} m_{kk'} \cdots \sum_{k'=1}^{K} \sum_{k=1}^{K} \sigma_{k'k}^{(1)(G)} m_{kk'} \\ \vdots \\ \sum_{k'=1}^{K} \sum_{k=1}^{K} \sigma_{k'k}^{(G)(1)} m_{kk'} \cdots \sum_{k'=1}^{K} \sum_{k=1}^{K} \sigma_{k'k}^{(G)(G)} m_{kk'} \end{bmatrix}$$

where $\sigma_{k'k}^{(i)(j)}$ is the element in the k'th row and kth column of the variance-covariance matrix of the ith and jth rows of P . The covariance matrix between P_i and P_j , two rows of P , is

$$(3.13) \qquad \begin{aligned} E(P_i - \Pi_i)'(P_j - \Pi_j) &= (XX')^{-1}X(E\, V_i'V_j)X'(XX')^{-1} = \\ &= (X'X)^{-1}X\sigma_{ij}I_N X'(XX')^{-1} = \sigma_{ij}(XX')^{-1} \end{aligned}$$

where V_i is the ith row of V as defined in (3.2) and V_j the jth row. This means that the row vector of GK components, $(P_1, P_2, \ldots, P_G)$ is normally distributed (since the columns of V are normally distributed) with an expected value $(\Pi_1, \Pi_2, \ldots, \Pi_G)$, and with a variance-covariance matrix, Σ_{pp}, where*, **

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* Cf. [1, 182] for an alternative derivation of these results.

** Σ_{pp} is recognized as the Kronecker product of the matrices Σ_{vv} and $(XX')^{-1}$, i.e., $\Sigma_{pp} = \Sigma_{vv} \otimes (XX')^{-1}$.

$$(3.14) \qquad \Sigma_{pp} = \begin{bmatrix} \sigma_{11}(XX')^{-1} & \ldots & \sigma_{1G}(XX')^{-1} \\ \vdots & & \vdots \\ \sigma_{G1}(XX')^{-1} & \ldots & \sigma_{GG}(XX')^{-1} \end{bmatrix}$$

and Σ_{pp} is of order $GK \times GK$.

From (3.12) and (3.14), letting $(XX')^{-1}_{kk'}$ be a typical element of $(XX')^{-1}$, we have for a typical element $[\sum_{k,k'} \sigma_{gg'}(XX')^{-1}_{kk'} m_{kk'}]$ of $E(AM_F A')$ that

$$(3.15) \qquad [\sum_{k,k'} \sigma_{gg'}(XX')^{-1}_{kk'} m_{kk'}] = \sigma_{gg'} \sum_{k,k'} (XX')^{-1}_{k,k'} m_{kk'} = \sigma_{gg'} q$$

where

$$(3.16) \qquad q = X_F'(XX')^{-1} X_F$$

is a scalar. So we find that

$$(3.17) \qquad E(AM_F A') = q\, \Sigma_{vv}$$

From (3.11) and (3.17), we obtain for the variance-covariance matrix of

$Y_F^* - Y_F$, Σ_{FF} , that

(3.18) $$\Sigma_{FF} = q\Sigma_{VV} + \Sigma_{V_F V_F} = (1 + q)\ \Sigma_{VV}$$

since $\Sigma_{V_F V_F} = \Sigma_{VV}$.

We will not in general know Σ_{VV} so we estimate it by the unbiased estimator* S_{VV} , where

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* Cf. [1, 183] for a proof that this is the unbiased estimator of Σ_{VV} .

(3.19) $$S_{VV} = (YY' - PXX'P')\ /_{N - K}\ .$$

Thus from (3.18) and (3.19) we find that the estimated variance-covariance matrix of the error of forecast, S_{FF} , is

(3.20) $$S_{FF} = (1 + q)\ S_{VV}\ .$$

For the purpose of making probability statements about the forecast we can use Hotelling's T^2 statistic,** where

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** Cf. [6]. Notice that we could also use the statistic

$$(1 + q)T^2 = (Y_F^* - Y_F)\ S_{VV}^{-1}\ (Y_F^* - Y_F\ )$$

which has the same distribution as T^2 except for the multiplicative constant, $1 + q$. In computing a forecast region this expression is easier to use as it eliminates the necessity of dividing the elements of S_{VV}^{-1} by $1 + q$.

(3.21) $$T^2 = (Y_F^* - Y_F)'\ S_{FF}^{-1}\ (Y_F^* - Y_F)\ .$$

Now it has been shown* that the distribution of

* Cf. [1, 105-106] . That this theorem applies in our case may be seen by considering the following: (i) $Y_F^* - Y_F$ is normally distributed with zero expected value and variance-covariance matrix Σ_{FF} , and (ii) $(N - K)\ S_{FF}$ is distributed independently of $Y_F^* - Y_F$ as the sum of N-K vector products, i.e., as $\sum_{n=1}^{N-K} s_n s_n'$ (where s_n is a G element random column vector), where these vectors are independent of each other and each has a multinormal distribution with zero expected value and variance-covariance matrix, Σ_{FF} .

$$(3.22) \qquad \frac{(N - K - G + 1)T^2}{(N - K)G}$$

is the F distribution with G and $N - K - G + 1$ degrees of freedom.

We can now with the use of (3.22) construct forecast regions or test hypotheses about the forecast. The procedure is to choose a level of significance, say α , and then find the corresponding value of F , say F_α , in the tables of the F distribution. Then we have that the set of points for which the inequality

$$(3.23) \qquad \left(\frac{N - K - G + 1}{(N - K)G}\right)T^2 \leq F_\alpha$$

holds forms the area of the forecast region.** This region may be interpreted

** It should be noticed that this is a direct generalization of the forecast region for a single equation model with K independent variables. In this case $G=1$ so we obtain, substituting t^2 for T^2 , the t^2 distribution, which is, as is well known, the F distribution with 1 and $N - K$ degrees of freedom.

in the same way as the forecast interval for a single equation, viz.; if repeated samples are taken, holding X and X_F fixed, then $1 - \alpha$ per cent of the time a region as in (3.23) will cover the true values of the forecasted variables, i.e., Y_F .

It is interesting to determine those values of the independent variables used for the forecast, i.e., X_F , which would minimize the value of $q = X_F'(XX')^{-1}X_F$. As can be seen from (3.18), minimizing q will minimize the generalized variance*

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* The generalized variance of a multivariate distribution is defined as the determinant of the variance-covariance matrix. So we have that the generalized variance of the error of forecast is $|\Sigma_{FF}| = |(1+q)\Sigma_{vv}| = (1 + q)^K|\Sigma_{vv}|$. This is a minimum when q is a minimum since $|\Sigma_{vv}| > 0$ because Σ_{vv} is a positive definite matrix and the determinant of a positive matrix is always positive.

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of the error of forecast. This is the multivariate analogue to the minimization of the variance of the error of forecast in single equation models.

To take account of the constant term in each equation, we let X_{1t} be a dummy variable, i.e., $X_{1t} \equiv 1$ for all t . Then we can partition X_F and (XX') as follows:

$$X_F = \begin{bmatrix} 1 \\ \cdots \\ X_{2F} \\ \vdots \\ X_{KF} \end{bmatrix} = \begin{bmatrix} 1 \\ \cdots \\ \tilde{X}_F \end{bmatrix}$$

(3.24)

$$(XX') = \begin{bmatrix} N & \sum_{n=1}^{N} X_{kn} \\ \sum_{n=1}^{N} X_{k'n} & \sum_{n=1}^{N} X_{k'n} X_{kn} \end{bmatrix} = \begin{bmatrix} N & X_{12} \\ X_{21} & X_{22} \end{bmatrix}, \quad (k, k' = 2, \ldots, K).$$

Designating $(XX')^{-1}$ as $\begin{bmatrix} A & B \\ B' & D \end{bmatrix}$ we obtain

$$(3.25)\quad (XX')^{-1} = \begin{vmatrix} \bar{A} & \bar{B} \\ \underline{B}' & \underline{D} \end{vmatrix} = \begin{bmatrix} (N - X_{12}DX_{21})/_{N^2} & -X_{12}\ D'/_{N} \\ -DX_{21}/_{N} & N(NX_{22} - X_{21}X_{12})^{-1} \end{bmatrix}$$

where $D = N(NX_{22} - X_{21}X_{12})^{-1}$. Making use of (3.24) and (3.25) we find that

$$(3.26)\qquad q = (N + X_{12}DX_{21})/_{N^2} - (2\tilde{X}_F'\ DX_{21})/_{N} + \tilde{X}_F'\ D\tilde{X}_F\ .$$

Differentiating with respect to the elements of $\tilde{X}_F$ and setting the results equal to zero we obtain

$$(3.27)\qquad -(DX_{21})/_{N} + D\tilde{X}_F = 0\ .$$

Thus we have for the minimizing value of $\tilde{X}_F$, say $\tilde{X}_F^*$,

$$(3.28)\qquad \tilde{X}_F^* = X_{21}/_{N} = \frac{1}{N}\ [\ \sum_{n=1}^{N} X_{k'n}]\ ,\quad (k' = 2,\ \ldots,\ K)\qquad *$$

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* That the second-order conditions for a minimum are met is seen by differentiating (3.27) with respect to the elements of $\tilde{X}_F$. We are left with the matrix D which is positive definite.

This shows that q is minimized when the values of the independent variables used in the forecast are equal to the mean sample values of the independent variables. The minimum value of q , obtained by substituting (3.28) in (3.26) is

$$(3.30)\qquad q_{min} = \frac{1}{N} + X_{12}DX_{21}/_{N^2} - (2X_{12}DX_{21})/_{N^2} + (X_{12}DX_{21}/_{N^2} = 1/_{N}\ .$$

The minimum value of the generalized variance of the error of forecast is then

$$(3.31) \qquad | \Sigma_{FF} |_{min} = (1 + \frac{1}{N})^K | \Sigma_{vv} | .$$

IV. Construction of Forecast Regions: An Example.

For the purpose of illustrating the construction of a forecast region for a set of equations we shall use the familiar model of Haavelmo.* This

* Cf. [4, 83-91] for a complete description of this model.

model may be written as a set of two regression or reduced form equations. We have

$$(4.1) \qquad \begin{aligned} c_t &= \pi_{11}X_{1t} + \pi_{12}X_{2t} + V_{1t} \\ y_t &= \pi_{21}X_{1t} + \pi_{22}X_{2t} + V_{2t} \end{aligned} \qquad (t = 1, \ldots, N)$$

where the jointly dependent variables are consumers' expenditures (c_t) and disposable income (y_t). The independent variables are $X_{1t} \equiv 1$ and gross investment X_{2t}. The random terms are v_{1t} and v_{2t}. The regression coefficients as estimated by least squares are

$$(4.2) \qquad \begin{aligned} p_{11} &= 298.554 \qquad & p_{12} &= 1.499 \\ p_{21} &= 285.787 \qquad & p_{22} &= 2.105 \end{aligned}$$

and the inverse of the estimated variance-covariance matrix of the random terms is

$$(4.3) \qquad S_{vv}^{-1} = \begin{bmatrix} .02507 & -.02570 \\ -.02570 & .03125 \end{bmatrix}$$

The inverse of the moment matrix of the independent variables is

$$(4.4) \qquad (XX')^{-1} = \begin{bmatrix} .7329396 & -.00701333 \\ -.00701333 & .00007498 \end{bmatrix}$$

For the values of the independent variables in the forecast period we shall choose* $X_{1F} = 1$ and $X_{2F} = 100$. We then obtain that

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* The value of X_{2F} is close to the mean of this variable in the sample period, i.e., $\bar{X} = 93.5385$.

$$(4.5) \qquad 1 + q = 1.08007$$

Now from (3.22) we have that $\frac{(N - K - G + 1)T^2}{(N - K)G}$ has the F distribution, $F_{G,N-K-G+1}$. In our example $N = 13$, $K = 2$ and $G = 2$. So we have that $F = 4.10$ at the 5 per cent level of significance. The corresponding value of $(1 + q)T^2$ is

$$(4.6) \qquad (1 + q)T^2_{5\%} = \frac{(4.10)(1.08007)(11)(2)}{10} = 9.742$$

For the forecast values of the dependent variables we have

$$(4.7) \qquad \begin{aligned} c_F^* &= 448.454 \\ y_F^* &= 496.287 \end{aligned}$$

Using this and (4.3), (4.4), and (4.6) we obtain

$$(4.8) \qquad 9.742 = .02507(c_F^* - c_F)^2 - .05139(c_F^* - c_F)(y_F^* - y_F) + + .03125(y_F^* - y_F)^2 .$$

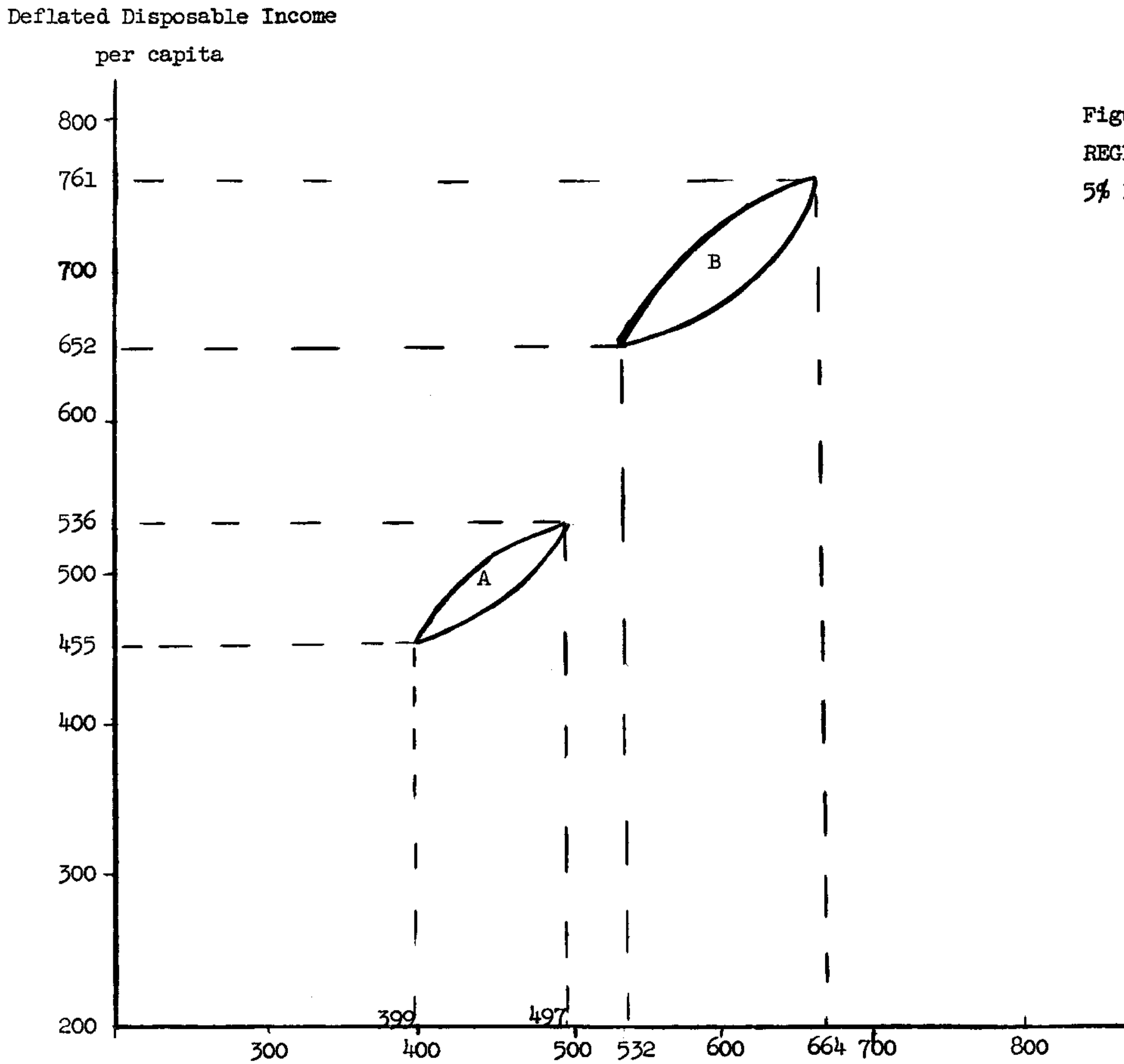

Figure 1: JOINT FORECAST REGIONS FOR C_F AND Y_F ; 5% LEVEL OF SIGNIFICANCE.

This represents an ellipse in the parameter space of c_F and y_F, where the center of the ellipse is (c_F^*, y_F^*). The area covered by the ellipse is the forecast region for c_F and y_F, the true values of the dependent variables in the forecast period. This is ellipse A in Figure 1. Ellipse B is the larger forecast region that results from using $X_{1F} = 1$, $X_{2F} = 200$ as the values of the independent variables in the forecast period at the same level of significance.

V. Conclusions

Our analysis has yielded an expression for the error of forecast for interdependent regression equations and the distribution of the resulting statistic has been given. In an illustrative calculation this result has been employed to construct forecast regions. Calculation of such regions is extremely important in appraising the forecasts provided by systems of equations. Since point forecasts, unaccompanied by a forecast region, may on occasion be seriously misleading, we recommend that those who forecast take the additional trouble needed to construct forecast regions.

Further, our work provides what is necessary to test hypotheses about forecasts. Thus, for example, it is possible to test the hypothesis that a forecast from a reduced form system is not significantly different from a "judgment forecast."

Finally we wish to point out several limitations associated with our result. Probability statements made about forecast regions constructed as we indicated above are valid providing the vector of exogenous variables employed in making the forecast is fixed, that is non-stochastic. Given this condition, one can state, as is usually done, that the constructed region will cover the true values of the endogenous variables in the forecast period a certain proportion of the time in repeated trials. However, in an actual set of repeated forecasts it may be impossible to hold fixed all the exogenous variables and in this situation the interpretation given above for the forecast region does not apply.* A similar situation prevails when some

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* R. A. Fisher discusses this problem in a different context. Cf. [3, 83-85].

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of the exogenous variables have to be forecasted; that is, the vector X_F can no longer be regarded as non-stochastic. Further it would be highly desirable to extend the present analysis to interdependent reduced form equations which have lagged endogenous variables in the set of predetermined variables.

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