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Estimating Hedge Ratios

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I. Introduction

A company's financial performance often depends on the uncertain price of a commodity or financial instrument. For example, a lumber distributor might enter into a fixed-price contract for a particular variety of lumber; or a cable manufacturer might have a short position in copper; or a firm might have debt whose interest rate is linked to the prime rate.

Although modern theories of valuation lead some people to conclude that non-market risk (unsystematic risk) need not be hedged, elimination of all non-essential risk is indeed a desirable goal, so long as it can be achieved at reasonable cost. Companies have good reason to be concerned about the total risk that they face. Total risk causes concern among those whose relationships with the firm are not diversified, such as employees, customers, and suppliers. In addition, reducing operating risks permits a company to accept greater financial risk through leverage, which brings with it the tax advantages of debt. (For a fuller discussion, see Adler and Dumas [1], Shapiro and Titman [14], Doherty [4], and Dufey and Srinivasulu [5].)

Quite often, hedging is not just a simple matter of "locking in" a price or a rate, since the relevant com-

modity might not be traded in a futures market (for example, there are no futures in the prime interest rate); even when it is, there may still be differences between the nature of the firm's exposure and the futures contract (the firm may need to deliver in June, but there is no June contract). In circumstances like these, a question arises as to whether the futures contracts that *are* traded can help to minimize the overall risk faced. Note that we do not need to restrict the hedging possibilities to a futures position that exactly matches the unit size of the exposure. For example, it is clear that other things being equal, the more volatile the firm's exposure, the larger its futures position should be. The size of the risk-minimizing position in the traded commodity in relation to the position that would have been taken had the desired commodity been traded is known as the "hedge ratio," and the position is known as a "cross-hedge" (see Working [17] and Anderson and Danthine [2]).

The appropriate hedge ratio can be determined accurately if the joint probability distribution for all the relevant random variables is known, for then it is simply a problem of mathematics, but the usual practical

problem is to estimate hedge ratios from historical data and this is much more prone to difficulty. In recent years, numerous articles, both methodological and applied (*e.g.*, Kolb and Chiang [10]), have suggested increasingly sophisticated approaches to this statistical estimation problem. It appears that some authors have adopted a focus of trying to estimate a parametric model for the joint probability distribution between a firm's payoff and the futures price rather than directly estimating the hedge ratio. Perhaps this is a holdover from the mathematical formulation of the problem, but this perspective seems to be a source of confusion in the literature. Our goal is to show that there is a much more straightforward nonparametric approach, which not only is easier to understand and apply but also is more robust in that it makes fewer assumptions about the process underlying the data.

As a foundation for our approach, we state and prove a theorem that characterizes the hedge ratio as the solution to a certain least-squares problem. Although the theorem is simple to prove, and in retrospect almost self-evident, the orientation it provides should have great value to practitioners in constructing simple, and correct, models for the estimation of hedge ratios. To motivate these claims, we discuss some of the models in the current literature and derive implications for future analyses.

II. The Relevance of Regression

We will assume throughout that the current period is $t-1$ and that we wish to hedge for period t . Let Y_t be the quantity that is to be hedged; for example, quarterly profits from a business. Let F_{t-1} be the futures price at time $t-1$, for delivery in period t , of a commodity that is traded on a futures market; and let X_t be the futures price in period t for period- t delivery (rather than the cash-market price of that commodity). If k units of futures are sold, the net cash flow (ignoring the timing of margin calls) is $Y_t + k(F_{t-1} - X_t)$. Our objective is to find the value k that minimizes the riskiness of this quantity. As has been common since Markowitz [12], we will use variance as the measure of risk. Since F_{t-1} is known at the time of the hedge we have $\text{var}[Y_t + k(F_{t-1} - X_t)] = \text{var}(Y_t - kX_t) = \text{var} Y_t + k^2 \text{var} X_t - 2k \text{cov}(Y_t, X_t)$. This quantity is minimized when $k = \text{cov}(Y_t, X_t) / \text{var} X_t$. (In some problems it would be important to recognize that k must be a whole number since fractions of contracts are not traded.)

Houthakker [9, p. 156] noted that the hedge ratio might be estimated by the regression coefficient of Y

on X , since the least-squares estimator of the slope b_1 in the model $Y = b_0 + b_1 X + \varepsilon$ is precisely $\text{cov}(Y, X) / \text{var} X$. This association between hedge ratios and regression has led to confusion in subsequent research for two reasons, one terminological, the other substantive. In standard usage, the regression of Y on X refers to the way $E(Y|X)$, the conditional expectation of Y given X , varies with X . If $E(Y|X)$ is a linear function of X , then its slope equals $\text{cov}(Y, X) / \text{var} X$. It is therefore common to use the term "regression coefficient" to refer to the latter quantity. However, this quantity solves the preceding variance-minimization problem regardless of whether $E(Y|X)$ is linear. Better terminology for $\text{cov}(Y, X) / \text{var} X$ is the "projection" coefficient of Y on X , defined as the unique number k such that $\text{cov}(Y - kX, X) = 0$.

The substantive problem with Houthakker's suggestion is that it generally gives the wrong answer (Peck [13]). For example, suppose $Y_t = Z_{t-1} + \varepsilon_t$ and $X_t = Z_{t-1} + u_t$, where ε and u are uncorrelated, and where Z is some additional variable that is uncorrelated with ε and u . Then $\text{cov}(Y_t, X_t) / \text{var} X_t = \text{var} Z_{t-1} / (\text{var} Z_{t-1} + \text{var} u_t)$, but clearly the correct hedge ratio is zero, since the *uncertain* parts of Y_t and X_t at time $t-1$ are the uncorrelated variables ε_t and u_t .

The error arises because the projection coefficient $\text{cov}(Y, X) / \text{var} X$ should be not that of the "marginal" distribution for Y and X , but rather that of the conditional distribution, conditional on information available at time $t-1$. To emphasize the point, we will write $\text{cov}(Y_t, X_t | \phi_{t-1}) / \text{var}(X_t | \phi_{t-1})$, where ϕ_{t-1} represents the information set at $t-1$.

Ederington [6] used the first differences of the prices, $\Delta Y_t = Y_t - Y_{t-1}$ and $\Delta X_t = X_t - X_{t-1}$, rather than the prices themselves, to account for this problem, computing the hedge ratio as $\text{cov}(\Delta Y_t, \Delta X_t) / \text{var} \Delta X_t$. This will not give the correct hedge ratio in general — for example, $\text{cov}(\Delta Y_t, \Delta X_t) / \text{var} \Delta X_t$ is nonzero in the example described above. However, it will give the correct hedge ratio if the hedge ratio is the same for all values of ϕ_{t-1} , and if also $E(\Delta X_t | \phi_{t-1})$ is the same for all ϕ_{t-1} . This and other results follow easily from a well known and easily derived property, that for any random variables A , B , and C ,

$$\text{cov}(A, B) = \text{cov}(E(A|C), E(B|C)) + E \text{cov}(A, B|C). \quad (1)$$

Proposition 1: If both the variance-minimizing hedge ratio $k(\phi_{t-1}) = \text{cov}(Y_t, X_t | \phi_{t-1}) / \text{var}(X_t | \phi_{t-1})$ and $E(\Delta X_t | \phi_{t-1})$ are the same for all values of ϕ_{t-1} , then

the hedge ratio equals $\text{cov}(\Delta Y, \Delta X) / \text{var} \Delta X$.

Proof: Dropping the subscripts for notational simplicity, we have $\text{cov}(\Delta Y, \Delta X) = \text{cov}[E(\Delta Y|\phi), E(\Delta X|\phi)] + E \text{cov}(\Delta Y, \Delta X|\phi) = E \text{cov}(\Delta Y, \Delta X|\phi)$, since $E(\Delta X|\phi)$ is constant. Moreover, $\text{cov}(Y, X|\phi) = \text{cov}(\Delta Y, \Delta X|\phi)$, since both Y_{t-1} and X_{t-1} are constants given ϕ_{t-1} . Similarly, $\text{var}(\Delta X) = E \text{var}(\Delta X|\phi)$ and $\text{var}(X|\phi) = \text{var}(\Delta X|\phi)$. Now, since $k = \text{cov}(Y, X|\phi) / \text{var}(X|\phi) = \text{cov}(\Delta Y, \Delta X|\phi) / \text{var}(\Delta X|\phi)$ is constant in ϕ , taking expectations through the equation $k \text{var}(\Delta X|\phi) = \text{cov}(\Delta Y, \Delta X|\phi)$ yields the desired result, $k \text{var}(\Delta X) = \text{cov}(\Delta Y, \Delta X)$.||

Hilliard [8] proposed correlating neither the levels of the variables nor their first differences, but their "unanticipated changes" $Y'_t = Y_t - E(Y_t|\phi_{t-1})$ and $X'_t = X_t - E(X_t|\phi_{t-1})$, taking for the hedge ratio $\text{cov}(Y'_t, X'_t) / \text{var} X'_t$. Notice that this formula does give the correct hedge ratio of zero in the example shown earlier, since $Y'_t = \varepsilon_t$ and $X'_t = u_t$. More generally, we have the following result:

Proposition 2: If the variance-minimizing hedge ratio is the same for all values of ϕ_{t-1} , then it equals $\text{cov}(Y'_t, X'_t) / \text{var} X'_t$.

Proof: Since $E(X'_t|\phi) = 0$ for all ϕ , we find as in the proof of proposition 1 that $\text{cov}(Y', X') = E \text{cov}(Y', X'|\phi)$ and $\text{var} X' = E \text{var}(X'|\phi)$. Also, $k = \text{cov}(Y, X|\phi) / \text{var}(X|\phi) = \text{cov}(Y', X'|\phi) / \text{var}(X'|\phi)$. Taking expectations through the equation $k \text{var}(X'|\phi) = \text{cov}(Y', X'|\phi)$ then yields $k \text{var} X' = \text{cov}(Y', X')$, as claimed.||

III. A General Formulation of the Hedge-Ratio Problem

Proposition 2 shows that the approach used by Hilliard will yield the correct hedge ratio whenever it is possible for a single number to be correct; *i.e.*, whenever the hedge ratio is the same irrespective of the information. Though this condition might reasonably be assumed in Hilliard's application, it is not difficult to imagine circumstances under which it would be violated. For example, if X and Z are prices of alternative raw-material inputs and Y represents profits from a derivative product, then Y' might be highly correlated with X' if $X < Z$, but not otherwise. In other words, the hedge ratio itself may vary with ϕ . It might appear that under these circumstances one would have to estimate the conditional moments, $\text{cov}(Y, X|\phi)$ and $\text{var}(X|\phi)$, as functions of ϕ . However, the following theorem greatly simplifies the determination of the

hedge-ratio function, by showing that it can be characterized as the solution to a least-squares problem.

Theorem: The functions $b_0(\phi)$ and $b_1(\phi)$ minimize $E[Y - b_0(\phi) - b_1(\phi)X]^2$ if and only if, for every ϕ , $b_1(\phi)$ minimizes $\text{var}(Y - b_1(\phi)X|\phi)$ and $E(Y - b_0(\phi) - b_1(\phi)X|\phi) = 0$.

Proof: Let $\varepsilon = Y - b_0(\phi) - b_1(\phi)X$; then $E(\varepsilon^2) = (E\varepsilon)^2 + \text{var} \varepsilon = (E\varepsilon)^2 + \text{var}(E(\varepsilon|\phi)) + E \text{var}(\varepsilon|\phi)$. The third term on the right is minimized by choosing $b_1(\phi)$ to minimize $\text{var}(\varepsilon|\phi)$ for each ϕ ; $b_0(\phi)$ is irrelevant since it is constant given ϕ . The second term is then minimized by choosing $b_0(\phi)$ so that $E(\varepsilon|\phi)$ is constant in ϕ . Choosing this constant to be zero gives $E\varepsilon = 0$ and so minimizes the first term as well. The theorem extends immediately to multiple hedging instruments by interpreting $b_1(\phi)$ and X as vectors.||

It is the "only if" part of the theorem that is important, for it says that in order to minimize $\text{var}(Y_t - k(\phi_{t-1})X_t|\phi_{t-1})$ over $k(\phi_{t-1})$, one need only find functions $b_0(\phi_{t-1})$ and $b_1(\phi_{t-1})$ that minimize $E(Y_t - b_0(\phi_{t-1}) - b_1(\phi_{t-1})X_t)^2$. Of course, from data one would estimate these functions by minimizing

$$\sum_{t=1}^T (Y_t - b_0(\phi_{t-1}) - b_1(\phi_{t-1})X_t)^2,$$

that is, one would minimize the sum of squared residuals in a model of the form

$$Y_t = b_0(\phi_{t-1}) + b_1(\phi_{t-1})X_t + \varepsilon_t \quad (t = 1, \dots, T). \quad (2)$$

It is thus natural to think of the problem as one of estimating the coefficients of the projection of Y on X , but where the "coefficients" are not numbers, but functions of ϕ . On the other hand, one should not think of Equation (2) as representing the regression equation $E(Y|X, \phi)$. While $b_0(\phi)$ and $b_1(\phi)$ may involve nonlinear transformations of the variables comprising the information, Equation (2) must be *linear* in X , even if $E(Y|X, \phi)$ is not. Many of the pitfalls that face practitioners stem from a belief that hedge ratios can be derived from the regression function $E(Y|X, \phi)$ (or worse still, $E(Y|X)$) rather than a projection of the form of Equation (2).

For example Toevs and Jacobs [16], discussing a situation in which $E(Y|X)$ is a concave function of X , suggest running the regression

$$Y_t = b_0 + b_1X_t + b_2X_t^2 + \varepsilon_t \quad (3)$$

and using $b_1 + 2b_2X_t$ as an estimate of the hedge ratio. This suggestion presumably derives from analogy to the case in which the regression of Y on X is linear, say $E(Y|X) = a_0 + a_1X$, so that the projection coefficient $\text{cov}(Y,X)/\text{var } X$ equals a_1 , the derivative with respect to X . However, since X_t is not known at time $t - 1$, one cannot base the hedge ratio on it. It is nevertheless instructive to see how b_0 , b_1 , and b_2 would enter into the correct formula for the hedge ratio if Equation (3) were the generating process for Y . Taking the covariance with X of both sides of Equation (3), conditional on ϕ , gives $\text{cov}(Y,X|\phi) = b_1 \text{var}(X|\phi) + b_2 \text{cov}(X^2,X|\phi)$, so that the hedge ratio, $\text{cov}(Y,X|\phi)/\text{var}(X|\phi)$, equals $b_1 + b_2 \text{cov}(X^2,X|\phi)/\text{var}(X|\phi)$. Therefore, the b 's are not sufficient to determine the hedge ratio; one still needs the coefficient of the projection of X^2 on X , conditional on ϕ . If this coefficient is independent of ϕ , an argument similar to that in the proofs of the propositions shows that it equals $b_1 + b_2 \text{cov}(X^2,X')/\text{var } X'$. In this case, then, one would compute the hedge ratio in two steps, first estimating the b 's from Equation (3), and then estimating the coefficient of the projection of X^2 on X' . Notice, however, that it would be simpler to use proposition 2 and compute the projection coefficient $\text{cov}(Y',X')/\text{var } X'$ directly.

IV. Implications for Model Building

Though the functions $b_0(\phi)$ and $b_1(\phi)$ that enter Equation (2) are in principle arbitrary, in practice one has to restrict attention to relatively simple functions. For example, if Z_{t-1} is thought to be the only variable that gives information about the hedge ratio (and Z_{t-1} might be Y_{t-1} or X_{t-1} or both), one might try fitting by least squares the model

$$Y_t = (\alpha + \beta Z_{t-1}) + (\gamma + \delta Z_{t-1})X_t + \varepsilon_t, \quad (4)$$

taking $\gamma + \delta Z_{t-1}$ as the hedge ratio. However, one might obtain a substantial reduction in the sum of squared residuals with a model like

$$Y_t = [\alpha + \beta \exp(\rho Z_{t-1})] + (\gamma + \delta Z_{t-1} + \eta Z_{t-1}^2)X_t + \varepsilon_t, \quad (5)$$

or one incorporating still more complicated functions of Z_{t-1} . Of course, overfitting is a concern with limited data, and so it is often helpful to let the form of $b_0(\phi)$ and $b_1(\phi)$ derive from some thought about the underlying process. For example, if Y_t and X_t are security prices it is sometimes reasonable to suppose that the

joint distribution for the "returns" $\tilde{Y}_t = (Y_t - Y_{t-1})/Y_{t-1}$ and $\tilde{X}_t = (X_t - X_{t-1})/X_{t-1}$ is independent of information at time $t - 1$. In this case one can show that the variance-minimizing hedge ratio equals $(Y_{t-1}/X_{t-1}) \text{cov}(\tilde{Y}_t, \tilde{X}_t)/\text{var } \tilde{X}_t$, which suggests that Y_{t-1}/X_{t-1} will often be a useful part of the function $b_1(\phi_{t-1})$. Alternatively, recall that we have defined the hedge ratio k to be the number of *units* of the hedge commodity that should be sold, per *unit* of the fixed position. One can instead work with the number of *dollars* of the hedge commodity to sell per *dollar* of the fixed position, denoted by β . Since $k = \beta Y_{t-1}/X_{t-1}$, the result stated before can be reexpressed as saying that if the joint distribution for $(\tilde{Y}_t, \tilde{X}_t)$ is independent of ϕ_{t-1} , then the hedge ratio in "dollar terms" is simply $\text{cov}(\tilde{Y}_t, \tilde{X}_t)/\text{var } \tilde{X}_t$, the coefficient of the projection of \tilde{Y} on \tilde{X} . More generally we have the following result, whose proof is similar to that of propositions 1 and 2.

Proposition 3: If both the hedge ratio in dollar terms and $E(\tilde{X}_t|\phi_{t-1})$ are the same for all ϕ_{t-1} , then the hedge ratio in dollar terms equals $\text{cov}(\tilde{Y}_t, \tilde{X}_t)/\text{var } \tilde{X}_t$.

The requirement that $E(\tilde{X}_t|\phi_{t-1})$ be independent of ϕ_{t-1} might be plausible when X_t is the price of a non-disappearing commodity such as gold or a security (Lintner [11]). However, it seems less appropriate for agricultural products, such as wheat, that have cyclical harvests, since $E(\tilde{X}_t|\phi_{t-1})$ could be expected to be lower before a harvest (Brown [3]).

Often the model from which the hedge ratio is determined, say (4), will exhibit heteroskedastic residuals, and so it is important to know when it is desirable to "correct for" the heteroskedasticity by reweighting the observations prior to estimating. Provided the appropriate weights depend only on ϕ_{t-1} , then the reweighting has no effect on the hedge ratio. To see why, let $w(\phi_{t-1})$ denote the weight applied to the t^{th} observation. The correct hedge ratio is $\text{cov}(Y_t, X_t|\phi_{t-1})/\text{var}(X_t|\phi_{t-1})$, but because $w(\phi_{t-1})$ is a constant given ϕ_{t-1} , this ratio is exactly equal to $\text{cov}(w(\phi_{t-1})Y_t, w(\phi_{t-1})X_t|\phi_{t-1})/\text{var}(w(\phi_{t-1})X_t|\phi_{t-1})$, since the $w(\phi_{t-1})$ cancel. Thus, working with reweighted variables whose weights depend only on ϕ_{t-1} does not cause bias, and may improve the estimation efficiency.

On the other hand, it will not be true in general that $\text{cov}(w(\phi_t)Y_t, w(\phi_t)X_t|\phi_{t-1})/\text{var}(w(\phi_t)X_t|\phi_{t-1})$ equals $\text{cov}(Y_t, X_t|\phi_{t-1})/\text{var}(X_t|\phi_{t-1})$. Therefore, if one reweights (Y_t, X_t) by a weight that depends on variables not observed at time $t - 1$, the hedge-ratio estimate will not be correct in general. For example, suppose for

simplicity that the observations (Y_t, X_t) are independently and identically distributed, so that the hedge ratio equals the slope coefficient, $\text{cov}(Y, X)/\text{var} X$ in the linear model

$$Y_t = \alpha_0 + \alpha_1 X_t + \varepsilon_t, \quad (6)$$

fit by least squares. Suppose that the residuals from this model are heteroskedastic, with standard deviation proportional to X_t . One might be tempted to apply least squares to the model

$$Y_t/X_t = \alpha_1 + \alpha_0(1/X_t) + \varepsilon_t/X_t. \quad (7)$$

However, the resulting estimate of α_1 is $E(Y/X) - E(1/X) \text{cov}(Y/X, 1/X)/\text{var}(1/X)$, which will not coincide with $\text{cov}(Y, X)/\text{var} X$ in general unless $E(Y/X)$ is linear in X . Otherwise, any gains in efficiency from the reweighting will be achieved only at the cost of introducing bias. Only in small samples might such a tradeoff be worthwhile.

Consider for example the model of Hill and Schneeweis [7],

$$\Delta Y_t = \alpha + \text{HR}_t^* \Delta X_t + \varepsilon_t, \quad (8)$$

where HR_t^* varies over time. In the first case, HR_t^* is assumed to deviate from a long-run average value HR_0^* by a random term u_t . Their concern is that the heteroskedasticity of the implied model

$$\Delta Y_t = \alpha + \text{HR}_0^* \Delta X_t + u_t \Delta X_t + \varepsilon_t \quad (9)$$

“results in a hedge ratio estimate that is inefficient in the statistical sense and is a biased measure of hedging effectiveness.” The suggested correction for this random-coefficients model (Theil [15, p. 622]) is a ΔX_t -weighted transformation of the data. However, as noted before, the resulting estimator will be biased unless $E(\Delta Y | \Delta X)$ is truly linear as assumed in Equation (8). On the other hand, the simple projection coefficient $\text{cov}(\Delta Y, \Delta X)/\text{var}(\Delta X)$ will be consistent under the weaker conditions stated in proposition 1.

In their second case HR_t^* is assumed related to variables we have called Z_t so that

$$\Delta Y_t = \alpha + (C_0 + C_1 Z_t) \Delta X_t + u_t \Delta X_t + \varepsilon_t \quad (10)$$

is to be estimated. Once again Hill and Schneeweis are concerned about heteroskedasticity, as part of their general orientation of estimating the parameters of a model for the variables. We noted at the outset that if the joint distribution for all the relevant variables were

known, the hedge ratio could be calculated from it. However, Equation (10) by itself is not a full model, because it does not specify the time-series characteristics of the variables. At a minimum, since Z_t is not known at time $t-1$, Equation (10) must be augmented by the process generating the Z 's. Of course, unless the parametric model is correct, this approach will give the wrong answer. By contrast, our approach has been to estimate the hedge ratio in a nonparametric framework. This will be less efficient if the model assumed under the parametric approach is correct, but will be consistent under much weaker assumptions.

As an illustration of this point, suppose you want to estimate the median of an unknown distribution, using a random sample S_1, S_2, \dots, S_n . The nonparametric estimator is the median of the sample. A parametric approach would be first to assume that the underlying distribution belongs to a particular parametric family of distributions, say the normal family, and then to find the most efficient estimator of those parameters. For example, the efficient estimator for the median of a normal distribution is the sample mean. While we do agree that *if* the underlying distribution is normal then the sample mean has better properties than the sample median, our view is that such a presumption is rarely, if ever, well-founded. The sample median, which is consistent irrespective of the shape of the distribution, is far more robust.

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