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Hedging Illiquid Assets

- **Illiquidity distorts relative price relationships, playing havoc with hedging strategies that work smoothly in liquid markets.**
- **Hedging in liquid markets requires no hard choices: the hedge ratio is the same whether designed for a day or a quarter, and quarterly value at risk is simply a scaled-up version of daily. This equivalence enables financial institutions with annual time horizons to manage earnings at risk on a daily basis.**
- **In illiquid markets, in contrast, the long run is not a sequence of short runs, because prices change infrequently. Ignoring this and hedging as if the markets were liquid has adverse consequences for risk and capital.**
    - **When prices are stale, the hedge ratio that is optimal on a daily basis is not optimal over a year. In our examples, there is a specific long-run hedge ratio with about one-fifth the long-run risk of the short-run hedge.**
    - **The annual capital allocated to daily hedging by the liquid markets recipe is less than half that required to cover annual risks in an illiquid market.**
- **Just as the short-run hedge is risky over a long horizon, the long-run hedge ratio creates high daily risk.**
    - **So illiquid markets necessitate a hard choice between controlling long-run or short-run risk, but not both.**
    - **Given that risk management is built around a short-horizon, the best choice for hedging illiquid assets may be a high-level overlay.**
- **This paper represents the first step towards a hedging and risk management framework that works for illiquid assets. It draws on recent experience in the US leveraged loan market to illustrate the differences between liquid and illiquid markets. It also provides a recipe for calculating the long-run hedge ratio, without requiring long runs of historical data.**

Global Asset Allocation

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Hedging assets that trade in liquid markets is relatively straightforward. Prices in liquid markets speedily reflect information the market considers relevant, or "information fundamentals". This informational efficiency causes an asset's daily returns to be uncorrelated over time (prices are a random walk), which implies that the hedge ratio for a liquid asset is the same, whether it is to be maintained for a day or a quarter. Similarly, value-at-risk over the long horizon is simply a scaled-up version of value-at-risk over the shorter one. This happy state of affairs has made it possible to meet the business need of managing risk and allocating capital over a yearly horizon, while respecting the limits of scarce historical data by measuring risk daily and scaling up accordingly.

Hedging offers an additional benefit in illiquid markets, where controlling risk by selling positions is intrinsically difficult and often unattractive. However, as this paper shows, a new set of rules are required to hedge illiquid assets effectively. Serious adverse consequences follow from hedging illiquid assets as if they were liquid.

A defining characteristic of illiquid markets is that trades occur infrequently, meaning that reported prices on any day can be "stale". Day to day, stale prices lower the correlation between the illiquid asset and liquid potential hedges, forcing hedge ratios down. Any link between the information fundamentals of the two assets only emerges over long time horizons, when the effects of stale prices are diminished. The hedge ratio that best tracks daily price movements is thus different from the best long-run hedge.

The most detrimental consequences concern Value-at-Risk and, therefore, allocation of capital. If your hedge strategy ignores illiquidity, just about everything that can go wrong will go wrong, and not by trivial amounts. Say you use the daily hedge ratio (that is, you estimate it using daily returns), and maintain this hedge for a quarter. Then, for an illiquid asset like the leveraged loan portfolio analysed in this paper, your VaR will be more than double the prediction of the liquid markets framework, which means a high likelihood that allocated capital will be inadequate.

The problems are not over if you decide you are really trying to hedge information fundamentals, and so opt for the long-run hedge. The benefit is that your realized VaR over a quarter will be about one-fifth that delivered by the daily hedge ratio. But to reap this benefit, your VaR calculation must account for illiquidity: scaling up the daily VaR of the quarterly hedge (as if the asset were liquid) overestimates the capital you need by a factor of two.

Meanwhile, when viewed over a short horizon, the quarterly hedge ratio is inferior: its daily VaR is twice that of the daily hedge (and we have come full circle). Only over long horizons does the long-run hedge dominate. But it is not straightforward to lengthen the horizon used in risk management; operational and control reasons make a short horizon desirable. To avoid creating adverse incentives, the long-run hedge and its associated capital may necessitate a high-level overlay.

In short, illiquidity requires a rethinking of the goals of hedging, of the way hedges are calculated, and their risk managed:

- It is necessary to choose between controlling long-run and short-run volatility. You cannot do both.
- The convenient risk management practice of estimating relationships using plentiful daily data, and then scaling up the results into a long-horizon VaR number will lead you astray.
- Hedging illiquid assets as if they were liquid adversely affects the return on capital, while acknowledging their illiquidity and employing the long-run hedge creates headaches for the existing framework of risk management, with its short-term focus.

So there are some hard choices to be made and consequences to be managed, none of which arise when hedging in liquid markets.

This paper provides a first step towards a framework for hedging and risk management of illiquid assets. We start off with a contrast between hedging in liquid equity markets and hedging in illiquid markets for corporate credit, and show how techniques that work well in the liquid case come to grief in the illiquid case. We trace the problem to stale prices, and describe the resulting tradeoff between the VaR of long- and short-horizon hedging strategies. Probably most important from a practical perspective, we show how to calculate the long-run hedge ratio without requiring long historical data series.

In a complementary paper ("Loan Sensitivities and Hedging", JPMorgan, 29 Jul 2008) Daniel Lamy analyses hedging in the European leveraged loan market in detail.

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Liquid Markets: Hedging Equity Risk

To set the stage, we examine the relationship between highly liquid equity indices. Figure 1 shows daily levels of the NASDAQ100 and the S&P500 indices since January 2003. Although the NASDAQ100 has a steeper trend than the S&P500, the two seem to move roughly together.

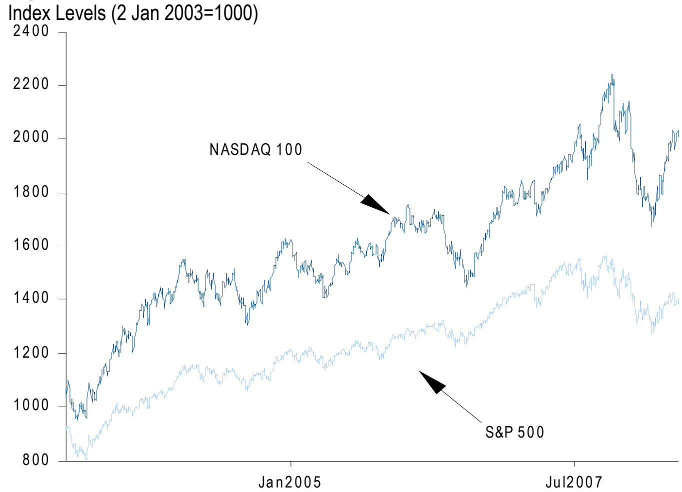
For the sake of illustration, rather than realism, imagine you wanted to hedge NASDAQ100 exposure with the S&P500. The standard way of calculating a hedge ratio is to run a regression of the returns of the asset you want to hedge (which we will call the "asset", for short) against the returns of the one you intend to use as the hedge (the "hedge", for short). The hedge ratio is the slope estimated by the regression. Its selling point is that it minimizes the volatility of hedge errors, although it provides no guarantee that the resulting position (long the asset, short the hedge in the amount of the hedge ratio) will have a zero expected return: it could make or lose money over time. Figure 2 shows the result of this regression on daily equity data since January 2003. It seems to fit very well, and produces a hedge ratio of 1.3, meaning that you sell $1.30 notional of the S&P500 for every $1 of the NASDAQ100 you own.

Of course, hedging takes place in real time, and so you would run your regression over some historical period, and hedge subsequently. Then, as time passes, you would rerun the regression, and change the hedge ratio as the regression slope moves over time. The results of this "rolling regression" procedure are not substantively different from the full sample results, as demonstrated by Figure 3, which shows hedge ratios daily, each calculated from the preceding 60 business days of returns.

Figure 4 introduces some terminology, in an effort to keep clear the several time intervals that will crop up in the following discussion. There is the *history* you use (Jan 2003 – June 2008 in Figure 2, preceding 60 days in Figure 3), the *sampling interval* between successive observations taken from the history (1 day in Figures 2 and 3), the *hedge horizon*, which is the period over which the hedge is held constant (1 day in Figures 2 and 3), and the *evaluation horizon*, which is the period over which the performance of the hedge is judged (implicitly, 1 day in Figure 2). The sampling interval and hedge and evaluation horizons do not all have to be the same.

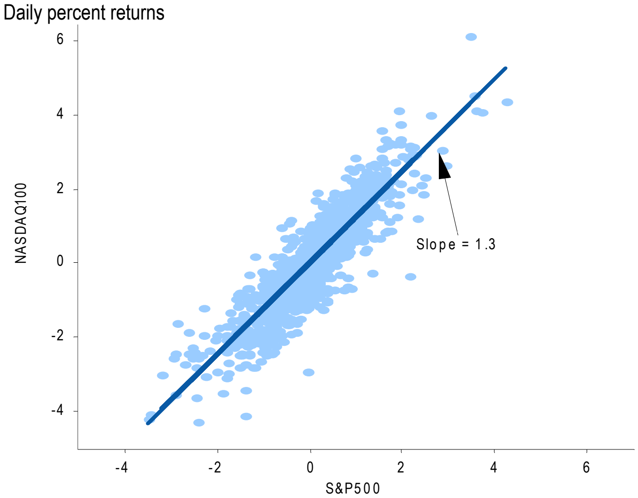
There is also no presumption that the sampling interval should be daily, and a general recommendation in

Figure 1: NASDAQ 100 and S&P 500
Index Levels (2 Jan 2003=1000)



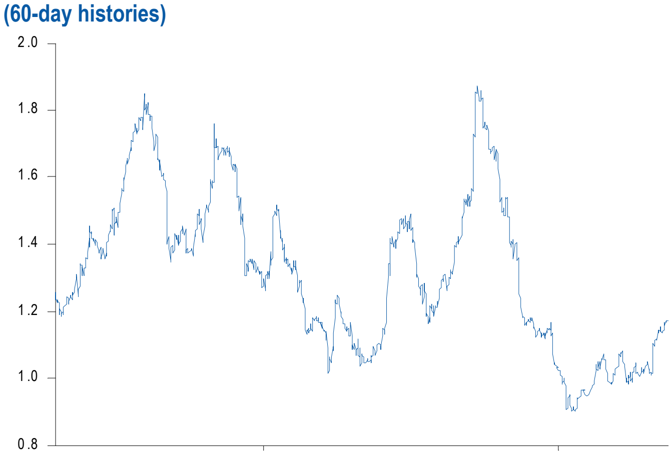
Source: JPMorgan

Figure 2: NASDAQ 100 and S&P 500 1/2003 – 5/2008
Daily percent returns



Source: JPMorgan

Figure 3: NASDAQ 100 and S&P 500, daily rolling regression hedge ratio (60-day histories)



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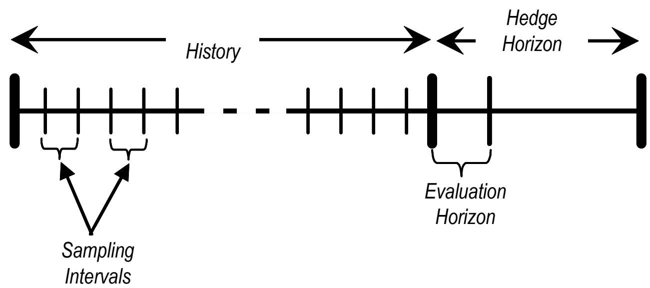
academic writing on hedging is that, all other things equal, it should equal the hedge horizon. So, hedges rebalanced monthly should be based on regressions using monthly returns, and so on. What is not equal here, of course, is the number of observations available to run the regressions, so the estimated hedge ratios will be less precise, the less frequent the data. This problem emerges clearly from the two equity indices. Figure 5 repeats the exercise of Figure 3 for sampling intervals of 5,10,15, and 20 business days, using the same underlying data. The history at each date is the preceding 60 days, so in the 20 day case each regression only has 3 observations. Longer sampling intervals are represented in Figure 5 by larger (and less frequent) dots. Hedge ratios vary more over time, the longer the sampling interval. However, the average for each sampling interval is much the same, as Figure 6 shows. It is likely that, irrespective of sampling interval, the estimated hedge ratios measure the same thing, in which case we should go with the most precise one, which corresponds to the shortest interval, or daily data.

This conclusion is supported by a plausible model for the link between the S&P and the NASDAQ, namely that each component stock responds daily to a common market shock, to which is added its own idiosyncratic shock. The S&P tracks the NASDAQ well because both track the market shock. Add a dose of market efficiency, which means that new information is fully reflected in prices, and returns become independent over time. This implies that anything you can learn from running regressions on monthly data you can learn more precisely by running regressions on daily data, and rescaling accordingly. For example, the P&L volatility for a one-month hedge horizon (20 business days) will be $\sqrt{20}$ times the daily hedge error volatility[1]. The monthly hedge ratio will be the same as the daily, and you will not be subject to Figure 5's fluctuations of hedge ratios whose hedge horizon and sampling interval are aligned. This is the "liquid markets model" referred to in the Introduction.

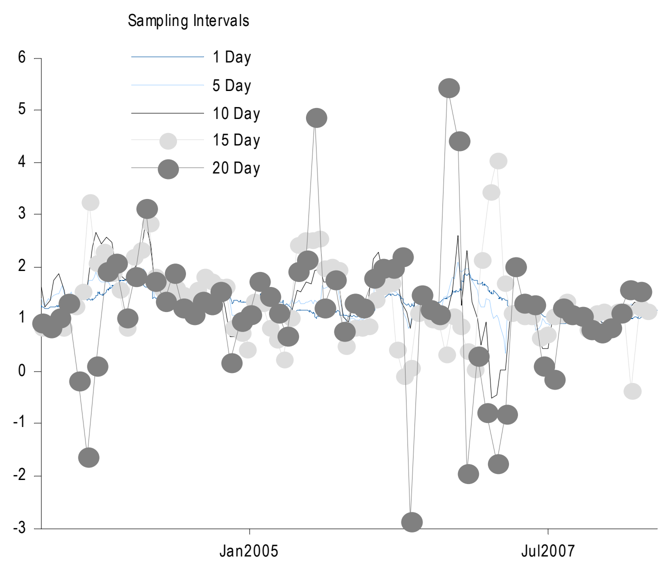
By way of full disclosure, it should be mentioned that these same clean conclusions do not emerge from the few years prior to 2003, which encompass the dot-com boom and collapse. However, the above is just intended as an example, there is never any guarantee against structural change, and 5½ years is a long time in finance.

Figure 4: Hedging terminology



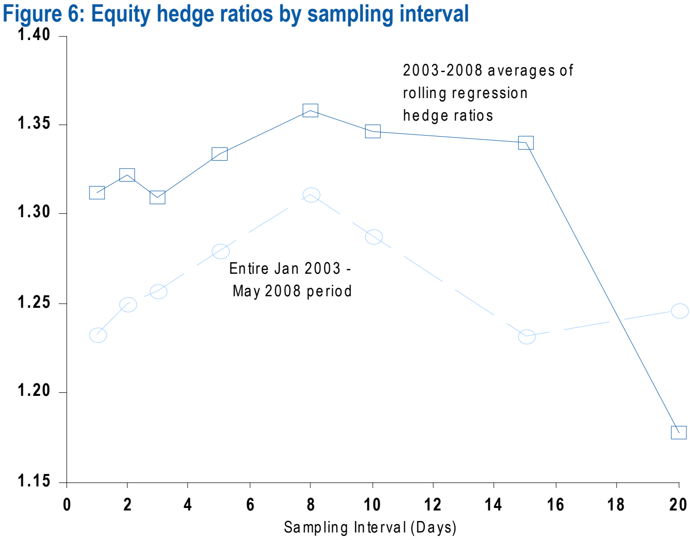
Source: JPMorgan

Figure 5: NASDAQ 100 and S&P 500, daily rolling regression hedge ratios (60-day histories)



Source: JPMorgan

Figure 6: Equity hedge ratios by sampling interval



Source: JPMorgan

[1] Hedge errors are the difference between the return of the asset and the return of the hedge multiplied by the hedge ratio, and so equal the Profit & Loss of the hedging strategy.

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Less-Liquid Markets: Corporate Loans

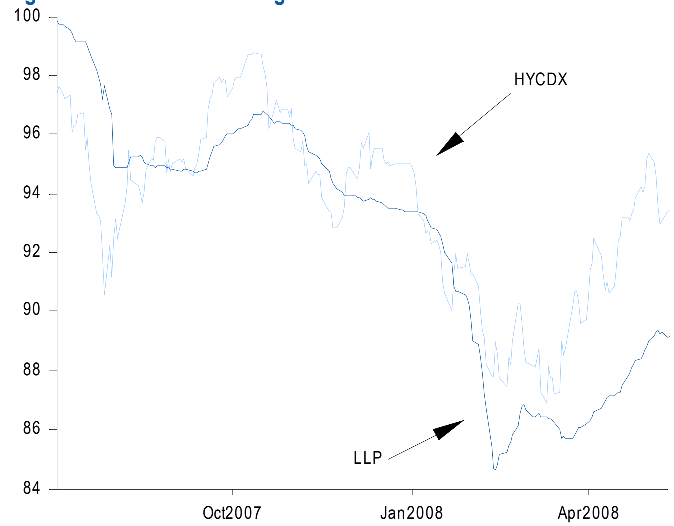
Figure 7 shows a daily price index of a portfolio of 700 leveraged loans, based on information provided by the Loan Pricing Corporation. The other line tracks the price of an index based on default swaps on high yield bonds, the CDX Series 8. We shall refer to these two price series as LLP (for "Leveraged Loan Portfolio") and HYCDX, respectively. The two seem to move together, and one might guess the hedge ratio to be somewhere around 1. On the same reasoning as above, we estimate the hedge ratio using the daily returns of the two indices, and find it to be very close to zero (Figure 8), with very little variation over time. Figure 9 gives a flavour of how this can happen (over the entire history): there is indeed zero correlation between daily loan and high-yield returns. But a hedge ratio of zero means that over the long term, you are exposed to the full potential variation in the loan index, which looks more risky than the gap between loans and HYCDX (your exposure with a hedge ratio of 1).

Figure 10 shows one significant difference between this and the equity case. As the sampling interval increases, the average of the rolling regression hedge ratios goes up, rather than staying constant. Figure 11 (which repeats Figure 5) shows the contrast with the equities case. And although the long-data-interval hedge ratios are again more volatile than the high-frequency ones, this does not obscure the rise in hedge ratios. So we have a more complicated message here: to arrive at a hedge ratio, you first have to determine the right data frequency. Worse still, limited historical data give us only 10 monthly observations, for which the average hedge ratio is around 0.4. What if our hedge horizon is longer? Should the hedge ratio be correspondingly higher?

Infrequent Trading

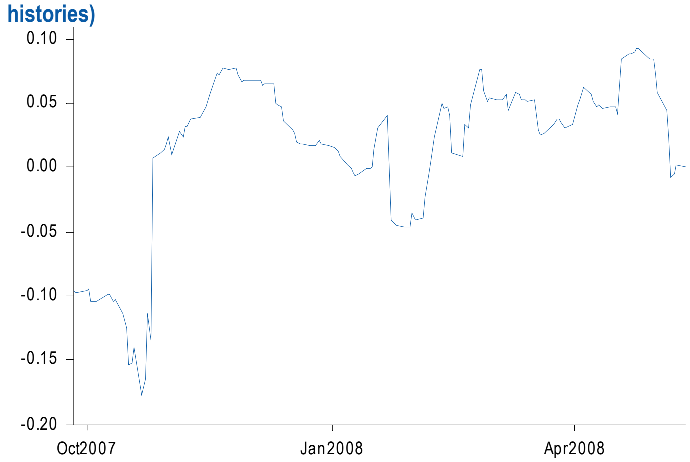
In the equity case, the argument for the choice of a hedge ratio (there, the one based on the shortest sampling interval available) was bolstered by appeal to a plausible model of how prices are generated. The behavior of corporate credit prices suggests this model needs some refinement. For one thing, loan returns are correlated over time, which would seem to violate market efficiency (as we shall see later, it doesn't necessarily). More important in the hedging context, it takes away the right to make inferences about long horizons by scaling up results about short horizons. To get the same kind of grip on corporate credit hedging as we (seem to) have on

Figure 7: HYCDX and Leveraged Loan Portfolio Price Levels



Source: JPMorgan

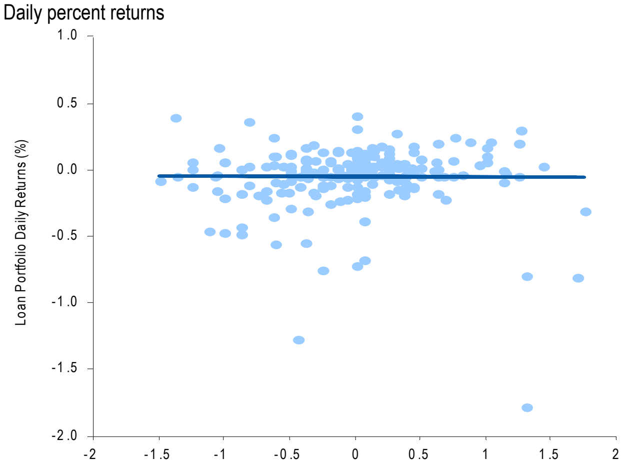
Figure 8: HYCDX and LLP, daily rolling regression hedge ratio (60-day histories)



Source: JPMorgan

Figure 9: HYCDX and LLP 7/2007 – 5/2008

Daily percent returns



Source: JPMorgan

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equity, we again need to understand the source of this correlation.

The place to look seems to be the frequency of price moves, one of the markers of liquidity. From daily prices of the individual loans comprising the LLP portfolio, we can measure the length of spells of time during which a loan's price does not change. Figure 12 charts the profile of these spells, revealing that 31% of them represented price changes on successive days (i.e., a spell of zero length), while 17% of them followed a spell of 20 days or more without a price move. The average no-price-move spell lasted 2.2 days.

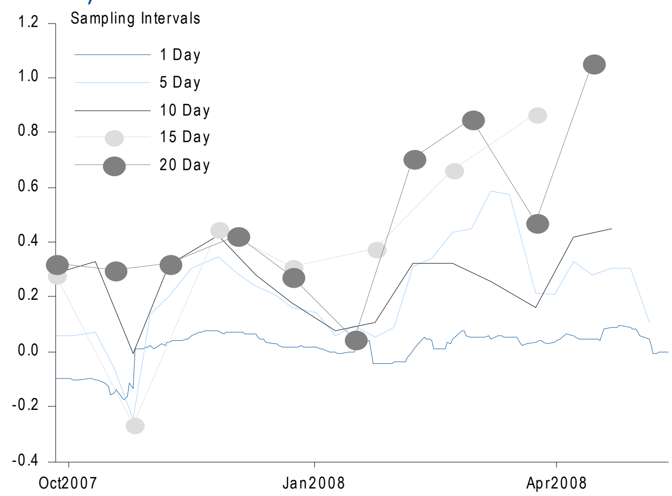
To benchmark these numbers against the equity example, we looked at the last two years of daily volumes transacted (as a proportion of shares outstanding) by each of the 600 companies. For each company, we recorded the first percentile of these figures (i.e., on 99% of days, more was transacted). The lowest of these first percentile daily volume rates was 0.01% of shares outstanding, or 208 round lots, which would seem to provide reasonable scope for price discovery.

Evidently LLP prices change only intermittently. To understand the effect on hedging, it is easiest to think in terms of the probability of a price move for a name on any given day. The simplest possible assumption is that price moves occur randomly each day, irrespective of what has gone before. Based on the LLP data, we estimate a probability of 31% that any loan name experiences a price change on any day. This is also the probability that a spell is zero days long. This model also implies a probability for a spell of any length, which is charted by the line in Figure 12. Apparently, we are assuming that long intervals between price changes are rarer than actually occur. However, since this will play down the effects of intermittent price moves in the results that follow, our assumption is conservative, and we will stick with it because of its simplicity.

Hedging Infrequent Price Moves: The One-Asset Case

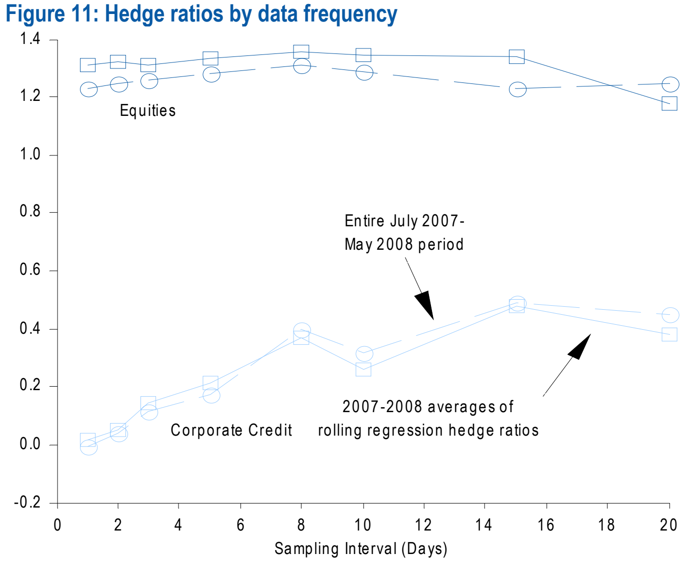
To trace the effect on hedge ratios, consider just a single name, on which two versions of the same security are available: a liquid one, whose price moves every day, and an illiquid one, which has a probability of trading 30% of the time. When the illiquid security trades, it does so at the same price as the liquid security. A real-life example might be an illiquid subordinated bond and its associated CDS (presumably more liquid). Figure 13

Figure 10: HYCDX and LLP, daily rolling regression hedge ratios (60-day histories)



Source: JPMorgan

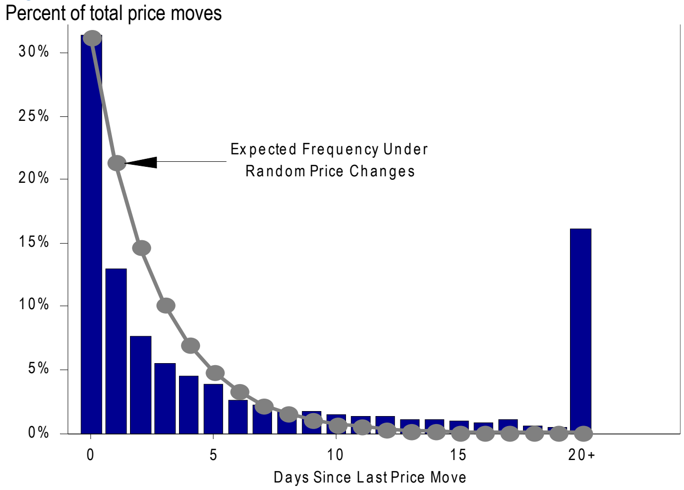
Figure 11: Hedge ratios by data frequency



Source: JPMorgan

Figure 12: Price movements of individual LLP loans

Percent of total price moves



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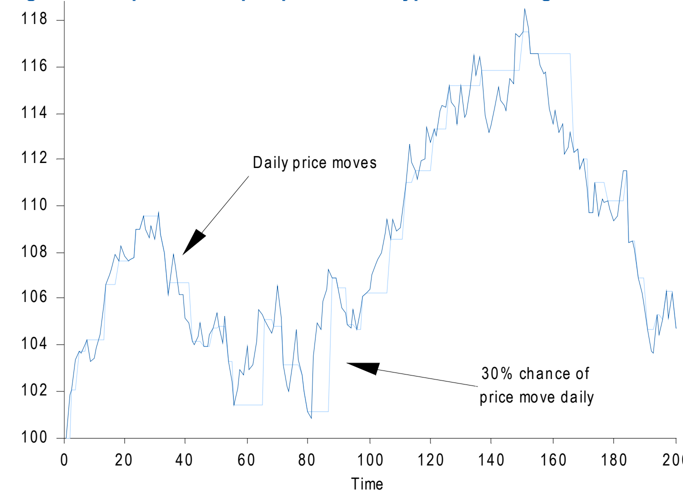
shows simulated paths for the two securities, illustrating how the price of the illiquid one is constant for periods of time, and then jumps (when it trades) to the price of the liquid security. Figure 14 graphs the resulting daily price changes of the illiquid against the liquid. A couple of "natural" lines are traced out by subsets of the dots. One has a slope of 1, corresponding to price changes in the illiquid security on two successive days. If the probability of price adjustment were 1, all points would lie on this line. The other is the horizontal axis, populated by days on which the illiquid asset did not experience a price move. The remaining dots correspond to days that mark the end of a no-price-move spell of 1 day or more.

Now consider hedging the illiquid asset with the liquid one. The (daily) hedge ratio is the slope of the straight line that best fits the dots in Figure 14, and so is going to be somewhere between the +1 of the successive price move days and the 0 of the no-price-move days. For this example, it is 0.24. Its theoretical value is 0.3: precisely the daily chance of a price adjustment. Evidently, the shape of the relationship between the two securities' returns, and the resulting hedge ratio, are driven by illiquidity.

The correspondence of this example and the LLP/HYCDX situation emerges when we look at longer hedge horizons and less frequent observations. Figure 15 shows 3-day returns from exactly the same history. These are less concentrated on the horizontal axis, a consequence of there being a greater chance of some price move over three days than over a single day. This pushes the resulting hedge ratio up to 0.47. Its theoretical value is 0.65. So we have the result that illiquidity causes hedge ratios to rise as the hedge and estimation horizon lengthens.

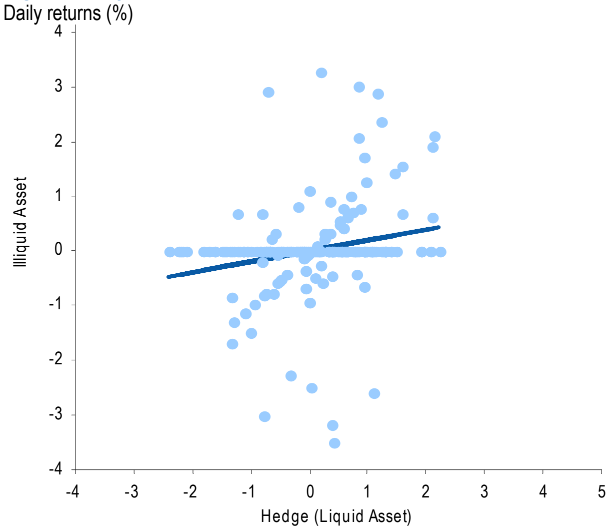
Rather than run simulations, we can calculate exactly how the expected hedge ratio changes with the sampling interval, which Figure 16 illustrates, again for the case where the daily probability of a price move is 30%. As the interval increases the hedge ratio tends to 1, which we shall refer to as the *long-run hedge*. This reflects the fundamental relationship between the asset and the hedge. An intuitive explanation would run something like this: The average time since the last price move is independent of the sampling interval, and here equal to (1-0.3)/0.3, or 2 1/3 days. The longer the interval the smaller the expected proportion of the interval since the last adjustment, causing price moves of both assets to look more like they are simultaneous.

Figure 13: Liquid and illiquid prices on a hypothetical single name



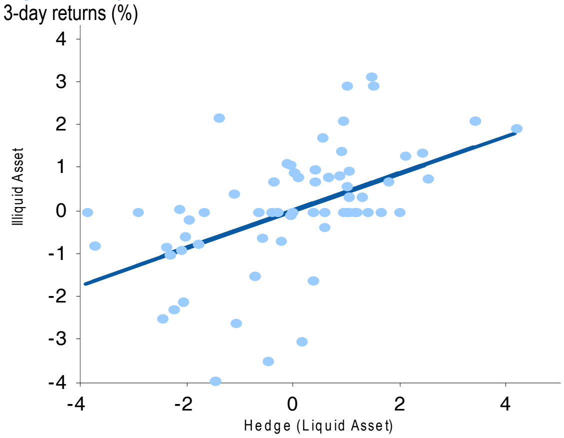
Source: JPMorgan

Figure 14: Hypothetical liquid and illiquid asset
Daily returns (%)



Source: JPMorgan

Figure 15: Hypothetical liquid and illiquid asset
3-day returns (%)



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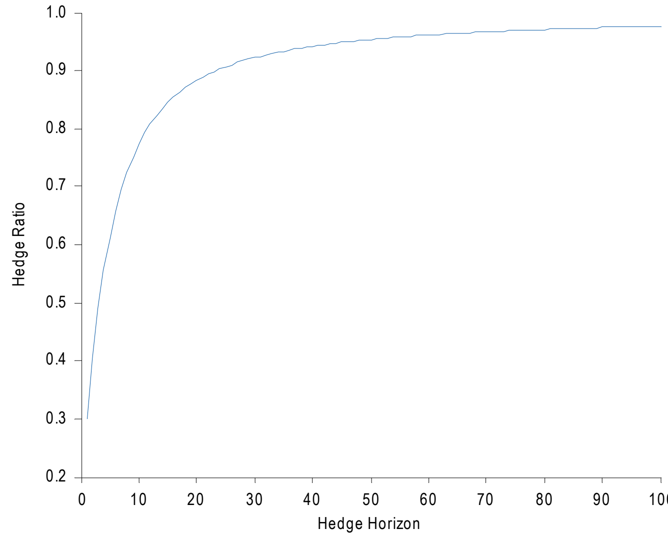
The long run hedge effectively ignores stale prices, which causes it to track badly over short horizons, when this phenomenon dominates asset price movements. Figure 17 displays the volatility of P&L or hedge errors for the daily and long run hedge strategies (hedge ratio equal to 30% and 1, respectively) over the range of hedge horizons. For comparability, the volatility numbers have been divided by the square root of the horizon, so what is reported is akin to average daily volatility over the hedge horizon. At a daily horizon, the long-term hedge's volatility is about 1½ times that of the daily hedge (point A versus point B). But over a long horizon the average daily volatility of the short term hedge tends to 0.7, while that of the long-term hedge goes to zero, overtaking at about a 7-day horizon. Under the independent returns framework, we would simply scale daily volatility with the square root of time, and so both would be represented by the horizontal dashed lines at their one-day levels, leading to the conclusion that long term hedge error volatility would be higher at every horizon.

This example is something of an allegory for the pressures on risk management and hedging experienced by many asset holders. To maintain a strategy that performs best over a quarter, you need to hedge according to the long run ratio. But over the short term, say the earnings-at-risk horizon used in risk management, this is more volatile than the short-horizon hedge. Moreover, the short-horizon hedge is the one mandated by the independent returns model, under which it provides the most precise estimate of the common value of the hedge ratio. So in the short run, the illiquidity story faces an uphill struggle on two counts: it requires you to endure higher interim volatility, and to argue for a model different from the independent returns framework that is the backbone of risk-management, and justifies the short-term hedge.

To summarize the argument to this point: with a simple intermittent price change model, we have succeeded in replicating a key feature of the LLP/HYCDX case: the tendency of the hedge ratio to rise as the sampling interval increases. In this simple model, the long-run hedge clearly reflects the fundamental relationship between asset and hedge. Short data-interval hedge ratios derive from the more cosmetic effects of stale prices, which nevertheless may be very real if performance is evaluated over a short horizon.

Figure 16: Hedge ratios when probability of a daily price move is 30%

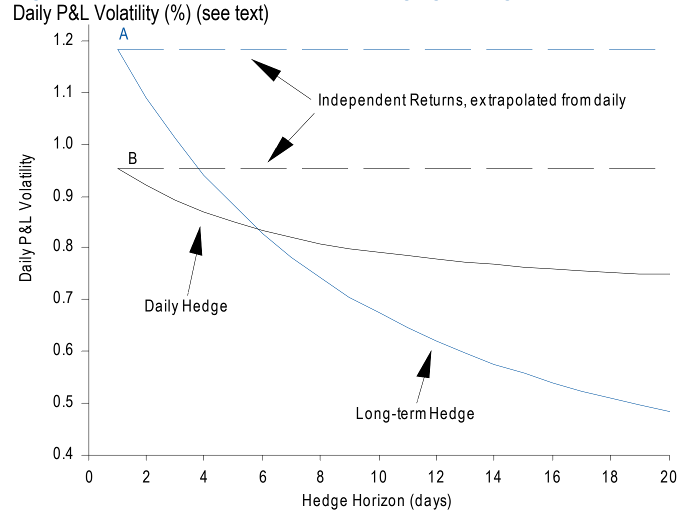
Hedge ratio



Source: JPMorgan

Figure 17: Performance of alternative hedging strategies

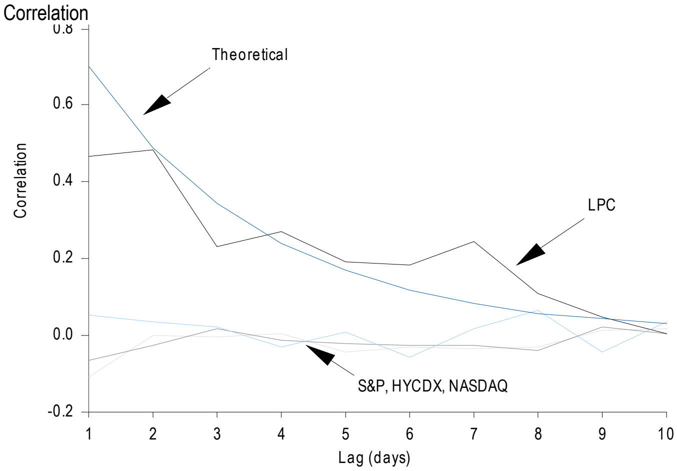
Daily P&L Volatility (%) (see text)



Source: JPMorgan

Figure 18: Serial correlation of daily returns

Correlation



Source: JPMorgan

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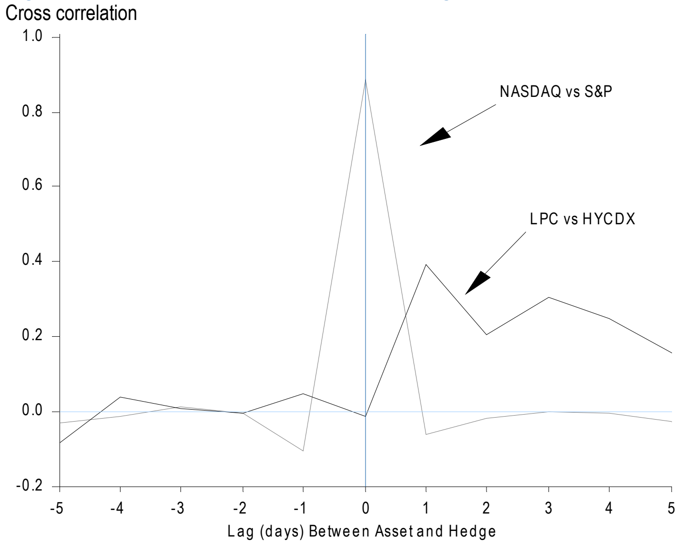
Hedging Infrequent Price Moves: The Many-Asset Case

To make the example more representative of hedging the LLP with the HYCDX, we need to broaden it to the case where the asset and hedge names are different, and number more than one. We use the same format as discussed for equities: the return of each name is composed of a common market shock and an idiosyncratic shock. However, this time, the return on the asset aggregates the intermittent price changes of its component names. The hedge, being liquid, is assumed to refresh prices daily.

In this more elaborate setup, the returns of the illiquid index are correlated over time, as in the case of the LLP. This is again the joint consequence of the common market shock and intermittent price movement. Take a name whose price moves today and last moved two days earlier. Today's return will contain the market shocks of today and yesterday. It will share yesterday's shock with the return of any name whose price changed yesterday. So today's and yesterday's illiquid index returns will be positively correlated. The size of this correlation over time will be greater, the less frequent are price movements, and the higher is the correlation of each name with the common market shock. Figure 18 charts serial correlations (the correlation of today's returns with returns a certain number of days earlier) of the four asset returns we have been looking at. The S&P, NASDAQ, and HYCDX all exhibit numbers around zero at all lags, which is to be expected from a random walk, and liquid, informationally efficient markets. In contrast, the LLP's serial correlations start at about 0.5, and tail off as the lag becomes more distant. This is closely matched by what one would expect from our intermittent price move model, with the probability of a daily price move for each name set at 30%. (This form of correlation in returns is not a sign of market inefficiency: there is no trading strategy that can exploit it. It is in fact, a consequence of the absence of trades, and trading would make it go away.)

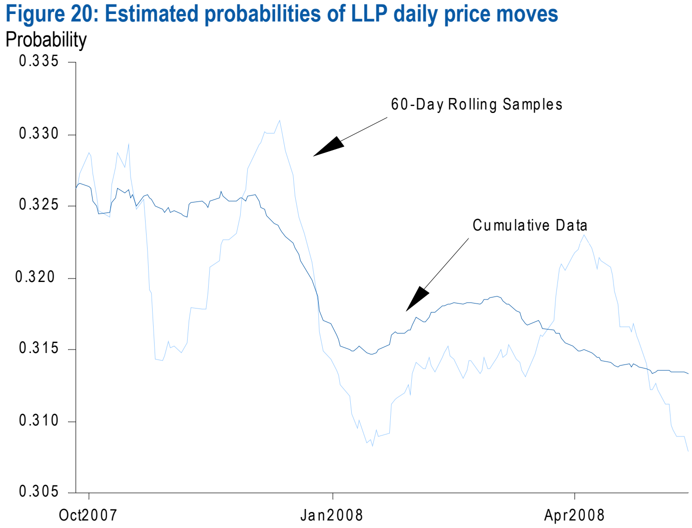
Another implication of intermittent price moves is that the asset's returns will be correlated with past returns of the hedge, but hedge returns will not be correlated with past asset returns. This state of affairs, illustrated in Figure 19, derives from the same cause as the serial correlation of the asset's returns: today's asset returns represent several days' worth of price changes. Consequently, they embody the market shocks of past days, which they share with the returns of the hedge on

Figure 19: Cross-correlation of assets and hedges



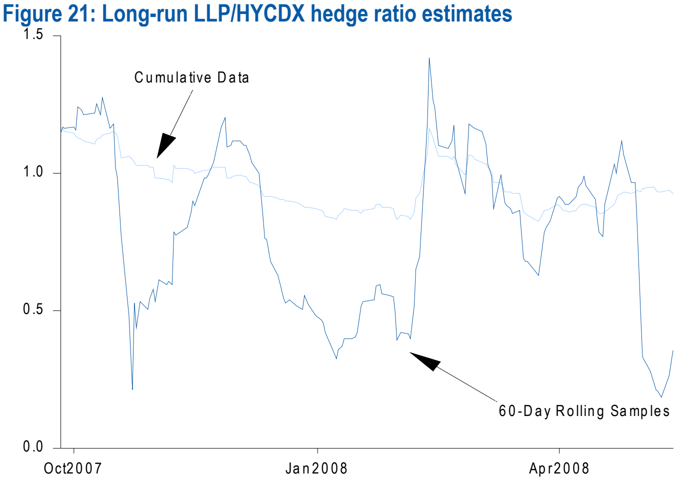
Source: JPMorgan

Figure 20: Estimated probabilities of LLP daily price moves



Source: JPMorgan

Figure 21: Long-run LLP/HYCDX hedge ratio estimates



Source: JPMorgan

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the corresponding days[2]. Once again, this correlation is absent from equity returns, another manifestation of informational efficiency.

The many-asset case also implies a value for the long-run hedge. Its interpretation is the same as before: the hedge ratio you would arrive at if prices of the illiquid asset moved daily. This time, it is not equal to one, but instead reflects the extent to which each index, the asset and the hedge, is correlated with the unobserved market shock.

Estimating the Long-Run Hedge Ratio

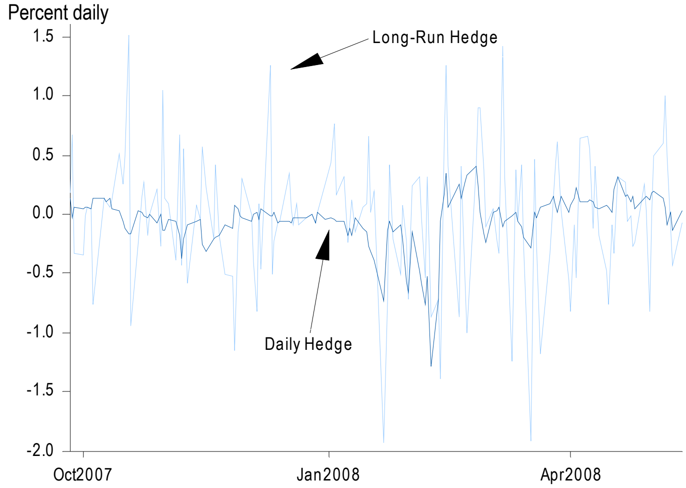
At this point, it is worth pausing to take stock. Equity markets experience frequent price movements, conform to the assumptions of liquid markets model, and so make it possible to infer long-run hedge ratios and performance from high-frequency data, which is accordingly plentiful. Our loan hedging example, in contrast, is consistent with intermittent price moves, meaning that we cannot arrive at the long run hedge by scaling up the high frequency case. Estimating hedge ratios using a long sampling interval seems to push us in the right direction, but data limitations make them very unreliable (Figure 10), and they underestimate the long-run ratio by an unknown amount in any case. What we need is a way of translating from high-frequency data (i.e., daily data), to the long-run hedge ratio, so that we do not have to wait forever for a reliable figure. It so happens that it is possible to extract such an estimate from the information we have already presented.

The idea is this: the cross-correlations in Figure 19 depend in a known way on the long-run hedge ratio, the probability of a price move, and the volatility of the asset. So, using estimates of the last two of these, and the cross-correlations, we can extract estimates of the long-run hedge ratio, one for the cross correlation at each lag. These estimates are based on daily data, so we can construct them using relatively short data histories, for example, 60 days. We look at the average of the long run hedge ratios based on the contemporaneous observation and the first five lags.

Figure 20 shows two versions of estimates of the probability of a move in the price of an individual name, based on the underlying loan data. One cumulates

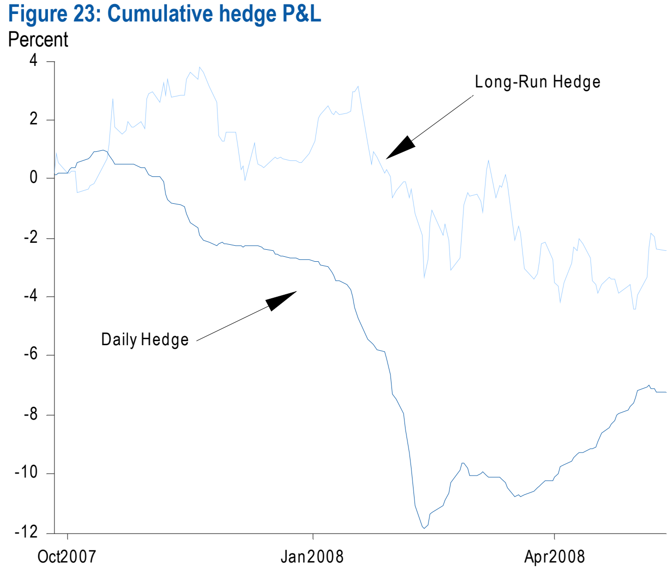
[2] Figure 19 suggests something fishy about the loan price data: it seems to respond to news one day late. That is, the contemporaneous (zero-lag) correlation is zero, whereas it should be the largest. Its cross correlation with the LCDX (loan CDS index) reveals the same pattern. So far, we have not been able to get to the bottom of this anomaly.

Figure 22: Hedge P&L over daily evaluation horizon



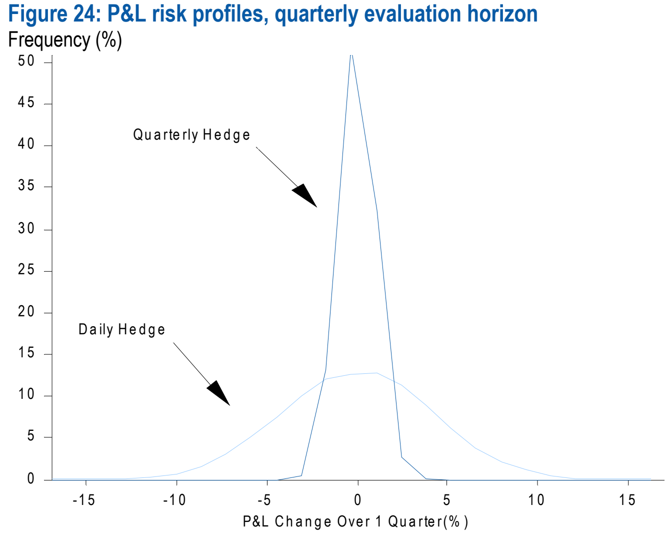
Source: JPMorgan

Figure 23: Cumulative hedge P&L



Source: JPMorgan

Figure 24: P&L risk profiles, quarterly evaluation horizon



Source: JPMorgan

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information from July 2007 onward, the other uses a rolling 60-day window, starting in September 2007. The range of variation is very small in each case, all estimates lying between 0.31 and 0.33. Figure 21 shows the result of combining these probability estimates with the respective regressions of asset return on lagged hedge returns. The variation in the cumulative estimate of the hedge ratio is minimal, and its average is 0.95. Fluctuations in the rolling hedge ratio estimate are greater, the average is 0.85, and the range is 0.2:1.4. Nevertheless, these figures accord more with the intuitive view of Figure 7, that some hedge is better than none (which is close to the recommendation of the independent returns framework), and do not help themselves to hindsight.

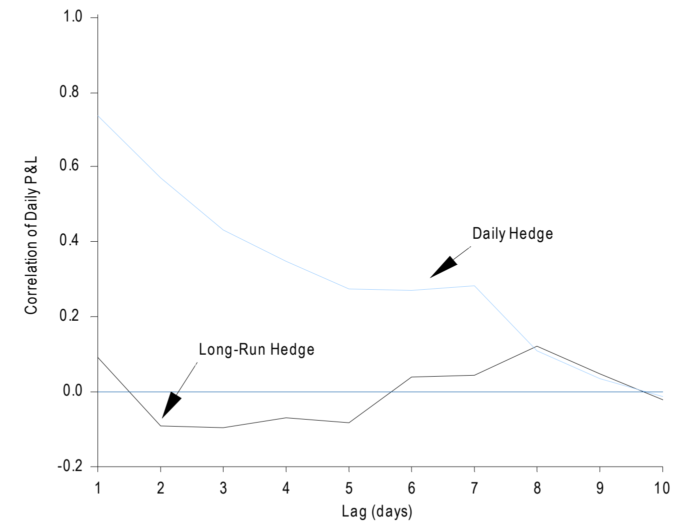
Evaluating Hedge Performance

Figures 22 and 23 compare the realized P&L of the cumulative long-run hedging strategy to the simple hedge based on daily returns, depicted in Figure 8. In each case, the hedge ratio is calculated from data available up to a given date, and then used over the next day. (In other words, the hedge horizon and evaluation period are both one day.) The long run hedge P&L is much more volatile from day to day, although cumulative P&L is higher by the end of the history. While these considerations would doubtless weigh heavily on anyone involved in hedging, they need to be put in the correct perspective when evaluating performance.

First, there was never any presumption that the long-run hedge would be less volatile evaluated over a daily horizon. The long-run hedge is for controlling long-horizon P&L volatility. In fact, the daily P&L figures for the long run hedge are slightly negatively correlated, which means that long horizon volatility will be daily volatility multiplied by something less than the square root of the horizon. Likewise, for the simple daily returns hedge, P&Ls are highly persistent, meaning that long-horizon volatility will be larger than daily times the square root of the horizon.

Second, all the hedges we have discussed so far abstract from expected returns, and are designed only to control P&L volatility over different horizons. Where total returns end up is just the luck of the draw of the particular history under consideration, and is neither a feature of the hedges in question, nor can it be extrapolated to other stretches of data.

Figure 25: Serial correlation of daily LLP/HYCDX P&L



Source: JPMorgan

Table 1: Value at Risk for Alternative Hedges and Horizons

Value-at-Risk		Hedge Horizon			
		Daily		Quarterly	
Hedge ratio optimal for ...	Daily	1	1	2.2	1
	Quarterly	2	1	0.5	1

Source: JPMorgan

All the long-run hedge guarantees is that, if you repeat the "experiment" of Figure 23 many times, the volatility of the terminal P&L *across* these experiments will be less than the volatility of the short-run hedge terminal P&L across the same experiments.

Of course, it is not practical to repeat these experiments in the time frame of real hedging decisions. In contrast, the large *daily* moves in long-run hedge P&L (Figure 22) would be readily apparent in this time frame, and would compare adversely on a daily basis to the short run hedge. Knowing what we know, however, we can run a simulation that repeats the experience of the last year over many random histories created using the intermittent price move model, calibrated to the LLP/HYCDX example. The result is shown in Figure 24, which compares hedge ratios that are optimal over daily and quarterly hedge horizons, the example

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discussed in the Introduction. It should be read as depicting the range of cumulative P&Ls that could result, as it were, on the right side of Figure 23. The average P&L for both the daily and quarterly hedges is zero. (In other words, the outperformance of the long run hedge in Figure 23 is not to be relied on.) However, the range of variation for the daily hedge is much greater than for the quarterly. In other words, following the daily hedge strategy leads to a higher long-horizon value at risk.

Table 1 contains the figures on which the Introduction's discussion of consequences for capital was based. The body of the Table contains P&L volatility or VaR figures based on the assumption of a 30% daily probability of a price change for each individual loan. The quarterly figures are translated to a daily average (divided by $\sqrt{60}$) to make them comparable with the daily numbers, and are expressed as a multiple of the daily VaR of the daily hedge. Figures in italics represent the predictions of the liquid markets model, which are the same for all four combinations. At a quarterly horizon, the daily hedge is 4+ times more risky than the quarterly hedge (2.2 *vs.* 0.5). On top of this, its realized quarterly volatility is more than double the prediction of the liquid markets framework (2.2 *vs. 1*), which means a high likelihood that allocated capital will be inadequate. Similarly at a daily horizon, the value-at-risk of the quarterly hedge is double (2 *vs.* 1). If you pursue the quarterly hedge but allocate capital in line with daily VaR, over 3 months you will tie up four times too much capital (2 *vs.* 0.5).

It is evident from Table 1 that it is necessary to choose a time horizon, and associated hedge ratio, and live with its adverse consequences for VaR at the other time horizon. No such hard choice is required if a liquid asset is being hedged.

The reason for (or a symptom of) the configuration in Table 1 is the correlation of hedge errors over time, depicted in Figure 25 for the loan portfolio example. What is shown is the correlation of the P&L in Figure 22 with its value 1 through 10 days earlier. These correlation numbers are predicted to be zero by the liquid markets model. Daily hedge P&Ls evidence strong positive serial correlation, meaning that as the hedge horizon increases, P&L volatility does not "average out" as it does in the liquid markets case, and in fact accumulates faster than the $\sqrt{\text{horizon}}$ the liquid markets model would predict. This is evidenced by the figure of 2.2 in the top right of Table 1. Conversely, quarterly hedge P&Ls are negatively serially correlated, so as the horizon increases, P&L volatility more than averages out, accounting for the figure of 0.5 in the bottom right of Table 1.

Conclusion

With this framework laid out, we can restate in its arid statistical language the problems illiquid assets create for hedging.

- The hedge ratio between two assets, traded in efficient markets, whose prices refresh daily, will be driven by their (perceived) common fundamentals, and there will be no conflict between short and long run hedging.

- One measure of illiquidity is the probability that the price of an individual security refreshes on any given day. If this probability is not 1, it contaminates estimated hedge ratios. The shorter the sampling interval, the more the hedge ratio is driven to zero.

- These short-run hedge ratios appear sensible viewed one day at a time: their P&L volatility is lower than the information fundamentals -based (long-run) hedge ratio viewed in the same way. But it only makes sense to do this if P&Ls are uncorrelated over time, and here they are not.

  – The P&Ls of the short-run hedge are positively correlated over time, which means that its risk scales up at a larger rate than the square-root-of-time horizon associated with independent P&Ls over time (which are relevant to the liquid case).
  – The reverse is true for the long-run hedge: day to day, its P&Ls are negatively correlated, which means long run volatility is less than $\sqrt{\text{horizon}}$ times short-run volatility.

- Hence the added complication with illiquid asset hedging: you have to know your time horizon.

This language is, of course, a far cry from the way hedging decisions are made when real money is on the line, and arguing about regressions seems like nitpicking. But the chances are that hedging and risk management practice involve rules of thumb derived from the liquid assets framework. Rules shunt the reasons for using them to the background, which is efficient when fundamental conditions justify using the rules, detrimental when they do not. An example is the practice of basing decisions on daily returns, which is sound statistics in liquid and informationally efficient markets such as government bond, FX, and equities, where financial risk management

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started. Daily returns also provide the most historical data to work with, and data are always at a premium. The rules thus have acquired the flavour: "Look after the short run, and the long run will take care of itself". As we have seen, this will end in tears when illiquidity sets in: the short run volatility of the fundamentals hedge will rise, forcing a decrease in the hedge ratio, and a loss of control of long run volatility, to which the standard rules are blind in the short run.

The illiquid assets framework developed here underpins new rules for hedging liquid assets: you can calculate your hedge ratio once you factor in stale prices. But effective hedging now requires you to choose a hedge horizon.

Appendix: Calculating the Long-Run Hedge Ratio

We assume that each name in the asset portfolio (for example, LLP) has a "true" price (as opposed to its observed price, which is potentially stale) whose daily return is correlated *only* contemporaneously with the hedge index, via an unobserved common market shock. Each name's true price also experiences its own idiosyncratic shock, which is uncorrelated with the market shock (by definition) and with the idiosyncratic shock of any other name (an assumption, potentially quite a strong one). Define the variance of the asset's markets and idiosyncratic shock components as M_a and I_a, respectively. M_h and I_h represent the corresponding terms for the hedge, and M_{ah} is the covariance of the market shocks of the asset and hedge.

The long run hedge ratio is the same as would result if the probability of a name experiencing a price move, 'p', were equal to 1. This hedge ratio is $L=M_{ah}/(M_h+I_h)$. The denominator is simply the daily variance of hedge returns. So, if we can estimate the numerator, we are done.

The covariance between the asset's daily return and that of the hedge k days earlier is

$$Cov(a,h,k) = M_{ah}.p(1-p)^k$$

So, if we can estimate p for the asset, we can extract an estimate of M_{ah} from the estimate of the covariance between a and h.

There are two ways to go about this. One uses the asset's name-level data to estimate the average length of a spell of constant price. Call this μ, then under the assumptions of our simple price change model, $p=1/(1+\mu)$. As Figure 20 shows, these estimates are very stable over time, at least for the LLP data. This may not be the case for other asset portfolios.

Another method, which can be used if the name-level data are not available, is to extract an estimate of p from yet another correlation over time, on this occasion, the serial correlation of the asset's daily returns. Under our simple price move probability model, the asset's autocorrelation at lag k is

$$r(a,k) = C.(1-p)^k,$$

where C depends on M_a and I_a, but not on k. An estimate of p follows from calculating r(a,k) for a number of lags, say 10, and fitting the above equation using a regression (on 10 observations), where the unknown parameters are a and p. This regression can be run either in the nonlinear form above, or in logarithms, in which case it is linear. For the full 7/2007 – 5/2008 period, we estimate p to be 0.22 with the non-linear model, and 0.32 with the logarithmic one. Neither has any exclusive claim, so an average of the two might be as decent a compromise as any.

With the estimate of p in hand, we now can extract an estimate of M_{ah} from the asset-hedge return covariance. In fact, we have many estimates, one for lag k=1, one for k=2, and so on. Again, there is no reason to prefer one against others, so the simplest thing to do is to average the resulting M_{ah} estimates over a set of lags. In the analysis in the paper, we use the first five lags.

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