This article examines the statistical issues surrounding the Bank of England’s density forecast of inflation and its presentation as a “fan chart”. The Bank’s preferred central projection is the mode of the density, but this underestimates “average inflation over a number of years” in terms of which monetary stability is defined. An alternative fan chart based on central prediction intervals is presented, better reflecting the extent to which the overall balance of risks is on the upside of the inflation target. An “all-or-nothing” loss function is seen to be implicit in the Bank’s choices of statistical measures, but is unrealistic.
1. Introduction

Since February 1996 the Bank of England has published in its quarterly *Inflation Report* a density forecast of inflation, that is, an estimate of the probability distribution of possible outcomes for future inflation. Publication of a density forecast is a welcome development, because it acknowledges the uncertainty that is inherent in any forecast but that remains unacknowledged when only a point forecast is presented, as is too often the practice among economic forecasters. The density forecast is represented graphically as a set of prediction intervals covering 10, 20, 30, …, 90 per cent of the probability distribution, coloured red, of lighter shades for the outer bands. This is done for inflation forecasts one to eight quarters ahead, and since the distribution becomes increasingly dispersed and the intervals “fan out” as the forecast horizon increases, the result has subsequently become known as the “fan chart”: an example is reproduced in Chart 1 (not in colour).

An important feature of the density forecast is its asymmetry. The probability distribution is positively skewed, towards higher values of inflation, and the accompanying discussion often emphasises the distinction between the “upside risks” and the “downside risks” to the forecast. The density forecast is represented analytically by choosing a particular probability density function – the two-piece normal – and once values have been assigned to the underlying parameters that describe its location, dispersion and skewness, probabilities can be readily calculated. This contrasts with the purely numerical formulation used in surveys of forecasters, in which respondents are asked to attach a probability to each of a number of intervals, or bins, in which future inflation might fall. The longest-running survey of this kind is the US Survey of Professional Forecasters, formerly known as the ASA-NBER survey, begun in 1968 and recently evaluated by Diebold, Tay and Wallis (1997), while the Bank of England has included such survey responses in the *Inflation Report*, again since February 1996.
The asymmetry of the distribution implies that the familiar measures of central tendency - mean, median and mode - do not coincide, and the Bank chooses the mode of the density forecast as its preferred central projection; with positive skewness this is the smallest of the three measures. The asymmetry of the distribution also implies that the prediction intervals are asymmetric, explained in the footnote accompanying the fan chart as follows “... if the risks are more on one side than the other, then the remaining bands will be wider on that side of the central band”. Or, in the words of the authors of a recent explanatory article in the Bank’s Quarterly Bulletin (Britton et al., 1998), “each pair of bands covers 10% of the distribution but, if the risks are unbalanced, the same colour bands are not of equal width (representing unequal probability intervals)”. This is not the whole of the story, however, and an additional reason that emerges from their technical account is that each 10% is not equally divided between the upper and lower bands, in other words the prediction intervals are not based on a regular sequence of percentiles. This article considers the issues surrounding these choices and in particular argues for replacing the Bank’s intervals by “central” intervals so that, for example, the 90% prediction interval is formed by the 5th and 95th percentiles. In our judgement, many readers of the Inflation Report already interpret the 90% interval in this way, that is, as implying a 5% probability that inflation will exceed the upper limit of the fan chart, but this is wrong - in fact, the probability is greater than this, as we show below.

The article proceeds as follows. Section 2 reviews the choice of central measure or point forecast and the loss function associated with each possibility: an “all-or-nothing” loss function is seen implicitly to underlie the Bank’s preferred measure. Section 3 considers the competing forms of prediction interval, and presents an alternative fan chart for one of the Bank’s recent forecasts. Section 4 concludes by discussing the relation between these statistical questions and the Bank’s monetary policy objectives. The properties of the two-piece normal distribution, used by the Bank to represent its density forecast, are described in
Box A, while Box B contains the algebra of best prediction intervals. Further concerns about Bank forecasts, such as the fact that the forecast is a projection of inflation conditional on unchanged interest rates rather than a pure forecast, the calibration of the underlying volatility of inflation and the choice of forecast horizon, are left on one side for the time being.

2. Central measures and associated loss functions

The loss function or cost function associated with a prediction problem is usually set up so that the loss is zero for a correct prediction and is positive for a wrong prediction. If the loss is proportional to the square of the forecast error then we have a quadratic loss function and the forecast which minimises the expected loss is the conditional expectation or mean of the forecast density. Then the expected forecast error is zero and the forecast is unbiased. Statistical prediction theory predominantly adopts a quadratic loss function - a least squares criterion of optimality - and in situations where the conditional expectation cannot be conveniently analysed attention is typically restricted to linear least squares prediction, using the same criterion but considering only linear functions of observed values, as in the classic exposition by Whittle (1963). Associated with a quadratic loss function is the use of the sample mean square error (or its square root) as a summary measure of forecast performance.

In the forecasting literature the leading alternative to the quadratic loss function is the linear loss function. If this is assumed to be symmetric, like the quadratic loss function, then the loss is proportional to the absolute value of the forecast error and the optimal point forecast is the median of the conditional distribution. The corresponding summary measure of forecast performance is the sample mean absolute error. Based on forecast errors over the preceding ten-year period, these measures are published alongside the Government’s economic forecasts in the Financial Statement and Budget Report, for example.
The loss function associated with the third of the traditional measures of central tendency, namely the mode, is the “all-or-nothing” or step loss function. This is motivated by Aitchison and Dunsmore (1975, p.46), for example, by asking “how should a predictor be constructed if it is desperately important to predict the true outcome?”. The natural formulation is a loss function which takes the value $0$ if the prediction is within $\varepsilon$ of the outcome and a positive constant otherwise. In the limit as $\varepsilon \to 0$ the expected loss is minimised by the mode of the predictive distribution, the single most likely outcome.

Comparisons among the three measures in the econometric forecasting literature are driven by nonlinearity in the equations of the underlying econometric models, which is the source of their divergence, and concern their statistical properties more than their associated loss functions. The mode scarcely features in this literature, due to computational difficulties in the multivariate case (see Calzolari and Panattoni, 1990). Attention usually focuses on the differences between the deterministic forecast, obtained by solving the equations of the model once their random disturbance terms have been set to zero, and the estimate of the conditional expectation obtained by stochastic simulation techniques. The deterministic forecast is often the median of the forecast density and is biased, but it is easier to compute. A further practical consideration is the internal coherency of a forecast, by which is meant that the solution values should satisfy the identities and definitional equations of the model. If any of these are nonlinear, perhaps through the appearance of quantity variables measured in both real and nominal terms and the relation of one to the other via a price index, then they are not satisfied by the conditional expectation, whereas the deterministic forecast is internally coherent in this sense. This is also a difficulty for the mode forecast even in the linear case: for random variables $X$ and $Y$ with asymmetric distributions it is in general not true that the mode of $X+Y$ is equal to the mode of $X$ plus the mode of $Y$, for example.
3. Prediction intervals

Most of the statistical literature on prediction intervals considers only the symmetric case. In his survey article, for example, Chatfield (1993) mostly considers models and methods for the calculation of the mean square forecast error on which to base a symmetric prediction interval. Some of the literature he cites, however, does treat the asymmetric case, and here the prediction intervals that are constructed are invariably based on percentiles of the forecast distribution, irrespective of the underlying approach to the construction of the distribution.

From a Bayesian perspective, for example, Thompson and Miller (1986) find that a “natural” way to summarise the predictive distribution is by presenting selected percentiles, and their chart of percentile forecasts for various lead times is a forerunner of the Bank of England’s fan chart. Using bootstrap methods to estimate the forecast distribution, Thombs and Schucany (1990) likewise summarise it through its quantiles. Similarly, using an empirical method that was probably “ahead of its time” (Chatfield, 1993, p.127), Williams and Goodman (1971) present “standard” 80, 90 and 95 percent intervals, that is, with equal tail probabilities of 10, 5 and 2.5 percent respectively.

We describe all these examples of prediction intervals for asymmetric distributions as central prediction intervals, adopting the same usage as the literature on confidence intervals (Stuart and Ord, 1991, p.746). A central 100\(p\)% prediction interval covers the stated proportion in the centre of the distribution, with equal probability in each of the tails. Thus, as in a final example, that of Tsay in discussion of Chatfield (1993), the 95% prediction interval lies between the 2.5th and 97.5th percentile.

The Bank of England’s fan chart is not based on central prediction intervals, however. Instead, the intervals are chosen to be the shortest possible for the assigned probabilities. Since the shortest interval for given coverage \(p\) does not coincide with the central interval if the distribution is asymmetric, its tail probabilities are unequal. For the Bank’s forecasts, the
probability that inflation will lie above the interval exceeds the probability that inflation will lie below the interval, as shown in Box B. If a central interval is constructed by sharing the excess equally between the tails, then it lies above the shortest interval. Table 1 presents a comparison of the two sets of prediction intervals for the final quarter of the forecast illustrated in Chart 1, calculated from the formulae in Box A.

An alternative fan chart based on central prediction intervals is presented in Chart 3. In comparing the two fan charts it is important to remember that they are simply different graphical representations of the same density forecast. Chart 3 nevertheless gives the impression of a forecast of higher inflation than Chart 1, since the central intervals are above the Bank’s intervals, as noted above, and as the coverage is reduced they converge on the median rather than the mode, the median exceeding the mode.

Central prediction intervals are regarded as a “natural” or “standard” way of summarising a forecast density in the forecasting literature, as noted above, and the accompanying discussion typically does not justify them as “best” with respect to a particular loss function. The exposition of statistical prediction analysis from a decision theoretic point of view by Aitchison and Dunsmore (1975) specifically eschews the time-series forecasting problem, yet with this particular perspective they show how a loss function (or utility function, in their formulation) can be associated with an interval prediction problem: “often there may be no great pressure to pinpoint the actual outcome ... but rather a need to ensure that an interval, region or set is provided which contains the realised outcome”(1975, p.54). Derivations for the two cases they consider are presented in Box B. For an all-or-nothing loss function, in which the cost of a mistake does not depend on its magnitude, the best prediction interval is the shortest, whereas for a linear loss function, in which the cost of a mistake is directly proportional to its size, the central prediction interval is best.
4. Discussion

The introduction of new arrangements for the operation of monetary policy in 1997 saw the establishment of the Monetary Policy Committee (MPC), which in particular adopted the Bank’s existing forecasting practice. The publication of a density forecast aims to convey a fuller account of the MPC’s subjective assessment of inflationary pressures, recognising its imprecision. In discussing its relation to an inflation target, many commentators treat the forecast as a pure forecast rather than a projection conditional on unchanged interest rates; like them, we continue to ignore this distinction.

The inflation target, as determined by the Government and defined by the 12-month increase in the Retail Prices Index excluding mortgage interest payments (RPIX), is 2½ per cent. It is recognised that temporary deviations from target may occur as a result of shocks and disturbances. But if inflation is more than 1 percentage point above or below the target, then the Governor of the Bank will send an open letter to the Chancellor explaining the causes and consequences of this divergence. The thresholds do not define an *ex ante* target range, but are concerned with *ex post* accountability. Achievement of monetary stability is taken to mean, “if shocks or errors are random on either side, that on average over a number of years inflation should come out at 2½ per cent on this RPIX measure plus or minus a bit, but it is not biased in one direction or the other” (Governor’s evidence to the Treasury Committee inquiry on the July 1997 Budget).

The discussion in the preceding sections is concerned with the distribution of inflation at a particular point in time, whereas in this quotation the Governor is concerned with the behaviour of observed inflation over time. For time series that comprise only a single observation at each point in time, statistical theory connects the two concepts via a stationarity condition. The theoretical mean \( E(x_i) = \mu \), assumed constant over time, can then be consistently estimated by the sample average over a series of observations \( \{x_i; t = 1, \ldots, n\} \), with
corresponding equivalences for variances, distributions, and so forth. The Governor’s interpretation of bias is then completely conventional, so it is surprising that the Bank places so much emphasis on the mode rather than the mean of the forecast density. With positive skewness the mode is biased downwards, and evidence of this may be beginning to emerge, the MPC observing in the minutes of its July 1998 meeting that, since its inauguration in May 1997, “inflation had been at or above the target, and month-by-month inflation had tended to turn out slightly higher than the Committee had expected”.

The question of the choice of prediction interval and the appearance of the fan chart is more a question of statistical presentation and is less directly related to the objectives of monetary policy. Standard statistical practice in reporting a probability distribution is to use intervals based on percentiles. The three associated probabilities, that an observation lies below, within, or above the interval, are then clearly specified. The Bank’s prediction intervals are less preferred since only the coverage is specified and the separate probabilities that inflation will fall below or above the limits are not given; in any event it is more likely that inflation will lie above than below the interval, as shown above. The “open letter” thresholds represent an interval for which the Bank might consider reporting a probability, although they do not define a target range and, unlike the other possibilities considered here, they represent a symmetric interval around the target. As for the fan chart itself, these statistical considerations clearly indicate a preference for the alternative in Chart 3 over the Bank’s presentation in Chart 1. Moreover, in respect of its impact on public perceptions of inflation expectations, Chart 1 underplays the extent to which the overall balance of risks is on the upside of the target.

The final question is whether the Bank’s choice of summary measures can be better understood in relation to the loss functions associated with the different possibilities. The Bank’s choices can be associated with the all-or-nothing loss function, the need to hit the inflation target being seen as “desperately important”, in Aitchison and Dunsmore’s phrase
quoted above. But this loss function is completely indifferent to the actual magnitude of any non-zero error, which is unrealistic. Nevertheless it seems to reflect the MPC’s interpretation of its brief, at least to the extent that it underlies the way the density forecast of inflation is presented. A more conventional choice of loss function by the MPC would conform to the conventional notion of monetary stability defined with reference to average inflation over a number of years. It would also lead to presentation of the density forecast in the alternative manner recommended here.
Box A. The two-piece normal distribution

A random variable $X$ has a two-piece normal distribution with parameters $\mu, \sigma_1$ and $\sigma_2$ if it has probability density function (pdf)

$$f(x) = \begin{cases} 
A \exp\left[-\frac{(x - \mu)^2}{2\sigma_1^2}\right] & x \leq \mu \\
A \exp\left[-\frac{(x - \mu)^2}{2\sigma_2^2}\right] & x \geq \mu 
\end{cases}$$

(A.1)

where $A = \left(\frac{\sqrt{2\pi} (\sigma_1 + \sigma_2)}{2}\right)^{-1}$ (John, 1982; Johnson, Kotz and Balakrishnan, 1994). The distribution is formed by taking two halves of normal distributions with parameters $(\mu, \sigma_1)$ and $(\mu, \sigma_2)$ respectively and scaling them to give the common value $f(\mu)$ as in (A.1). Chart 2 gives an illustration with $\sigma_2 > \sigma_1$ so that the two-piece normal distribution has positive skewness; this example corresponds to the final quarter of the forecast in Chart 1. The scaling factor applied to the normal pdf (dashed line) on the left is $2\sigma_1 / (\sigma_1 + \sigma_2)$ while that applied on the right is $2\sigma_2 / (\sigma_1 + \sigma_2)$. Relative to the normal pdf, the area on the left (right) is decreased (increased) hence the mean and the median exceed the mode, which remains equal to $\mu$.

The two-piece normal distribution is a convenient way of representing departures from the symmetry of the normal distribution since probability calculations can still be based on the published tables of the standard normal distribution. Denoting the cumulative distribution function (cdf) of the latter as $\Phi(z)$ and defining quantiles by $\Phi(z_\alpha) = \alpha$ then the lower $100\alpha\%$ point of the two-piece normal distribution, for $\alpha < \sigma_1 / (\sigma_1 + \sigma_2)$, is

$$x_\alpha = \sigma_1 z_\beta + \mu$$

(A.2)

where $\beta = \alpha (\sigma_1 + \sigma_2) / 2\sigma_1$. Similarly $x_{1-\alpha}$, the upper $100\alpha\%$ point, is given for $\alpha < \sigma_2 / (\sigma_1 + \sigma_2)$ as

$$x_{1-\alpha} = \sigma_2 z_{1-\delta} + \mu$$

(A.3)
where \( \delta = \alpha (\sigma_1 + \sigma_2) / 2\sigma_2 \). With positive skewness \( (\sigma_2 > \sigma_1) \), the median is given by this latter calculation with \( \alpha = 0.5 \) or \( \delta = (\sigma_1 + \sigma_2) / 4\sigma_2 \). Although \( z_{\alpha} = -z_{1-\alpha} \) by the symmetry of the standard normal distribution, the lower and upper quantiles of the two-piece normal distribution given above are symmetric around neither the mode nor the median.

The fitting of the distribution is less convenient, either by the method of moments or by the maximum likelihood method, as indicated by John (1982). The first two moments are

\[
E(X) = \mu + \frac{\sqrt{2}}{\pi} (\sigma_2 - \sigma_1) \tag{A.4}
\]

\[
\text{var}(X) = \left(1 - \frac{2}{\pi}\right)(\sigma_2 - \sigma_1)^2 + \sigma_1 \sigma_2 \tag{A.5}
\]

The likelihood is a function of the sums of squares of deviations \((x_i - \mu)\), with the squares of positive and negative deviations cumulated separately, corresponding to the two pieces of the distribution: estimation of \( \mu \) corresponds to separation of the sample, and requires numerical methods.

The alternative parameterisation of the distribution used by the Bank of England (Britton et al., 1998) is

\[
f(x) = \begin{cases} 
\frac{A}{\sigma \sqrt{2\pi}} \exp\left[ -\frac{(x - \mu)^2(1 + \gamma)}{2\sigma^2} \right] & x \leq \mu \\
\frac{A}{\sigma \sqrt{2\pi}} \exp\left[ -\frac{(x - \mu)^2(1 - \gamma)}{2\sigma^2} \right] & x \geq \mu 
\end{cases}
\]

where \( A = \frac{2}{(1/\sqrt{1-\gamma}) + (1/\sqrt{1+\gamma})} \) and the sign of \( \gamma \) has been corrected so that positive values represent positive skewness, as in their discussion. Although the parameter \( \gamma \) provides a direct indicator of skewness, this parameterisation is no more convenient for either purpose. Clearly it is equivalent to (A.1) through \((1 + \gamma)\sigma_1^2 = \sigma^2\) and \((1 - \gamma)\sigma_2^2 = \sigma^2\) with \(-1 < \gamma < 1\), but note that \( \sigma^2 \) is not the variance of the distribution. Equations (A.4) and (A.5)
can be rewritten in terms of $\gamma$ and $\sigma$ rather than $\sigma_1$ and $\sigma_2$, and once numerical values have been assigned to the difference between the mean and the mode and to the variance, the resulting expressions are solved for $\gamma$ and $\sigma$ by numerical methods to calibrate the Bank’s density forecast of inflation.
**Box B. Best prediction intervals**

We consider the construction of a prediction interval \((a, b)\) which has a given probability \(p\) of containing the outcome \(x\), that is,

\[
Pr(a \leq x \leq b) = F(b) - F(a) = p
\]

where \(F()\) is the cumulative distribution function. This requirement does not by itself pin down the location of the interval, and the question is what is the best prediction interval. The two possibilities considered in this article are the shortest interval, with \(b - a\) as small as possible, and the central interval, with equal tail probabilities

\[
Pr(x < a) = Pr(x > b) = (1 - p) / 2.
\]

If the distribution of outcomes is symmetric these are the same; if the distribution is asymmetric then the shortest and central intervals do not coincide.

In a decision theory framework each can be justified as the best interval prediction with respect to a particular loss function or cost function, as we now show.

It is assumed that there is a cost proportional to the length of the interval, \(c_0(b - a)\), which is incurred irrespective of the outcome. The distinction between the two cases arises from the assumption about the additional cost associated with a mistake, that is, the interval not containing the outcome.

**(i) All-or-nothing loss function**

If the costs associated with the possible outcomes have an all-or-nothing form, being zero if the interval contains the outcome and a positive constant \(c_1\) otherwise, then the loss function is

\[
L(x) = \begin{cases} 
  c_0(b - a) + c_1 & x < a \\
  c_0(b - a) & a \leq x \leq b \\
  c_0(b - a) + c_1 & x > b 
\end{cases}
\]

The expected loss is

\[
E[L(x)] = c_0(b - a) + \int_{-\infty}^{a} c_1 f(x) dx + \int_{b}^{\infty} c_1 f(x) dx \\
= c_0(b - a) + c_1 F(a) + c_1 [1 - F(b)]
\]
and the first-order conditions for minimum expected loss are

\[ f(a) = f(b) = c_0 / c_1. \]

Thus the limits of the interval correspond to ordinates of the probability density function (pdf) of equal height. If the cost associated with the length of the interval is excessive, such that \( c_0 / c_1 \) exceeds the maximum value of the pdf, given by its value at the mode, then the optimal interval prediction degenerates into a point prediction, namely the mode.

The equal height property is also a property of the interval with shortest length \( b - a \) for given coverage \( p \). To see this consider the Lagrangean

\[ L = b - a + \lambda[F(b) - F(a) - p]. \]

This is of similar form to the expected loss above, and the first-order conditions for a minimum again give \( f(a) = f(b) \) as required.

This requirement is not sufficient to determine \( a \) and \( b \) given \( p \), and numerical methods are used to locate the interval, as described by Britton et al. (1998, p.34). The imbalance in its tail probabilities for the two-piece normal distribution can be seen by comparison with (A.2) and (A.3) in Box A. From (A.1), we have \( f(a) = f(b) \) if \( -(a - \mu) / \sigma_1 = (b - \mu) / \sigma_2 \), and for lower limit \( a \) equal to \( x_\alpha \) given by (A.2) the corresponding upper limit \( b \) then satisfies

\[ (b - \mu) / \sigma_2 = -z_\beta \] with \( \beta = \alpha(\sigma_1 + \sigma_2) / 2\sigma_1 \). That is,

\[ b = -\sigma_2 z_{1-\beta} + \mu \]

\[ = \sigma_2 z_{1-\beta} + \mu = x_\alpha, \]

say, for upper tail probability \( \alpha^* \) such that \( \beta = \alpha^*(\sigma_1 + \sigma_2) / 2\sigma_2 \), as in (A.3). Thus \( \alpha^* = \alpha(\sigma_2 / \sigma_1) > \alpha \), and the upper tail probability exceeds the lower tail probability if the distribution is positively skewed, with \( \sigma_2 > \sigma_1 \).

(ii) Linear loss function
In this case it is assumed that the cost of a mistake is proportional to the amount by which the outcome lies outside the interval. Thus the loss function is

\[
L(x) = \begin{cases} 
  c_0(b - a) + c_2(a - x) & x < a \\
  c_0(b - a) & a \leq x \leq b \\
  c_0(b - a) + c_2(x - b) & x > b 
\end{cases}
\]

The expected loss is

\[
E[L(x)] = c_0(b - a) + \int_a^\infty c_2(a - x)f(x)dx + \int_0^a c_2(x - b)f(x)dx
\]

and the first-order conditions give

\[
c_0 = c_2 \int_a^\infty f(x)dx = c_2 \int_b^\infty f(x)dx.
\]

Hence the best prediction interval under a linear loss function is the central interval with equal tail probabilities \( Pr(x < a) = Pr(x > b) \). Again if the fixed cost is excessive, such that \( c_0 / c_2 > \frac{1}{2} \), then the optimal interval prediction degenerates into a point prediction, in this case the median.

The behaviour of the optimal intervals as the relative costs change matches their behaviour as the coverage, \( p \), is reduced, the shortest intervals converging on the mode and the central intervals converging on the median.
REFERENCES


### Table 1
Alternative prediction intervals for inflation
(August 1997 *Inflation Report* fan chart, final quarter)

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</tr>
<tr>
<td>40</td>
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<tr>
<td>45</td>
<td>2.78</td>
<td>10</td>
<td>3.10</td>
<td>45</td>
</tr>
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</table>

Note: (a) Row percentages may not sum to 100.0 due to rounding
Chart 1  The August 1997 Inflation Report fan chart

Chart 2  The probability density function of the two-piece normal distribution

- dashed line: two halves of normal distributions with $\mu = 2.5$, $\sigma_1 = 0.902$ (left) and $\sigma_2 = 1.592$ (right)
- solid line: the two-piece normal distribution
Chart 3  Alternative fan chart based on central prediction intervals

Increase in prices on a year earlier