"THE STATE OF THE ART AND FUTURE DIRECTIONS IN COMBINING FORECASTS"

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The State of the Art and Future Directions in Combining Forecasts

Abstract

Numerous empirical studies conducted since the late 1960's have shown, beyond a reasonable doubt, the benefits from combining the forecasts of several methods. Such benefits (in terms of improved accuracy and reduced variance of errors) have made combining a popular area of academic research and have provided a practical alternative to that of forecasting using a single, most appropriate method. In this paper the reasons for combining forecasts are discussed, the various approaches to combining are summarized, and methodological issues are explored. We also classify and evaluate empirical studies, discuss managerial implications, and present directions for future research. Finally an appendix lists and describes major studies, and summarizes their major finding(s) as well as relative inefficiencies.

[FORECASTING; COMBINING FORECASTS; COMPOSITE FORECASTS; FORECAST IMPROVEMENT; ACCURACY OF FORECASTING]

1. Introduction

Recent years have witnessed a phenomenal growth in combining forecasts (see Figure 1). In this paper we explore the reasons for this interest. Theoretical work and empirical studies have demonstrated beyond reasonable doubt that there are considerable benefits to be gained from combining forecasts. We consider how such benefits are being achieved by discussing several methodological issues and then classifying and summarizing empirical studies about combining forecasts. Finally, we review the managerial implications of these studies, and present some directions for future research. An appendix lists and summarizes major studies as well as their finding(s) and relative inefficiencies.

We believe that a survey paper on combining will help those interested in forecasting, as well as newcomers in the field, to review and more easily digest the huge literature on combining. We also hope that it will allow practitioners to judge more objectively the possible benefits if they employ combining in their organizations.

2. Why Combine Forecasts?

Combining is achieved when two or more forecasts for the same variable are aggregated to produce a single forecast. Such forecasts can be an amalgamation of different models of the same method, various methods and/or judgmental predictions. The empirical finding that combining improves accuracy and reduces the variance of forecasting errors attests to the fact that no single model/method and/or forecaster have been found to consistently outperform the rest. The effect of combining is that the forecasting errors of the various models/methods and/or people included are "averaged out" making the composite error smaller on the average. Thus, if a method overextends the trend in the data and another underestimates it, their average might produce a more accurate forecast. Similarly, if a person is over-pessimistic and another is over-optimistic their average will stand a better chance of being closer to the actual outcome than if the forecast had been based on the prediction of a single person only.

If we could assure that established patterns and/or relationships would not change in the future it is doubtful that combining would have helped. However, in the economic/business

environment, patterns and/or relationships are rarely constant (Makridakis, 1981) making it extremely difficult, at present, to select a best model/method in order to forecast. Combining, on the other hand, presents a robust alternative to a single model/method because it reduces the risk of "putting all the eggs in one basket" by "averaging" more than one forecast.

Combining provides maximum improvements when each of the forecasts that are combined contain independent information. On the other hand, if the forecasts are redundant no benefits can be expected. In reality predictions are neither completely independent nor entirely redundant, thus providing benefits which are in between those that could be expected theoretically (if independence could be assumed) and those of using a single model/method or person.

3. Available Approaches for Combining Forecasts

Researchers have proposed and tested several approaches for combining forecasts (Bates and Granger, 1969; Reid, 1969; Newbold and Granger, 1974; Doyle and Fenwick, 1976; Makridakis et. al., 1982; Mahmoud, 1982, 1984; Makridakis and Winkler, 1983; Winkler and Makridakis, 1983; Granger and Ramanathan, 1984; Zarnowitz, 1984; Bunn, 1985; and Gupta and Wilton, 1987). These approaches can be summarized as follows:

Averaging (Doyle and Fenwick, 1976; Gupta and Wilton, 1978; Makridakis and Winkler, 1983): Two or more methods can be easily combined by taking a simple arithmetic average of their forecasts. For a given number (p) of forecasts from different methods the average, for period t, can be calculated as:

$$F_t^c = \frac{F_t^{(1)} + F_t^{(2)} + \ldots + F_t^{(p)}}{p} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where F_t^c is the combined forecast for period t.

Historical weightings (Doyle and Fenwick, 1976): Weights are assigned on the basis of past forecasting accuracy, as measured by the best fit of each method to past data. For instance, if a quadratic loss function is desired each forecasting method should be weighted by the ratio of one minus its mean squared error to the total mean squared

error for all the forecasting models being combined. Thus, the combined forecasts could be calculated as follows:

$$F_t^c = W_1 F_t^{(1)} + W_2 F_t^{(2)} + \ldots\ldots + W_p F_t^{(p)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where W_1, W_2, ...W_p are weights assigned to each forecasting model which are found as:

$$W_i = 1 - \frac{MSE_i}{\Sigma\ (\ MSE_1 + MSE_2 + \ldots + MSE_p\ )} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Subjective weights (Doyle and Fenwick, 1976): Decision makers may prefer to weight the forecasting models based upon their personal judgment as to which methods more closely reflect reality. Thus, each of the weights in (2) are estimated judgmentally.

An alternative to the judgmental weights is to compute them in a Bayesian manner using the variance-covariance matrix which can be defined as (see Morris, 1977):

$$f_t^c = (e\ \ \Sigma^{-1}\ e)^{-1}\ (e\ \ \Sigma^{-1}\ f_t^{(i)}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where $e = (1, 1, \ldots\ldots 1)$, $f_t^{(i)} = f_t^{(1)}, f_t^{(2)}, \ldots, f_t^{(p)}$ and Σ is the error variance-covariance matrix.

Odds-Matrix Method: Gupta and Wilton (1987) proposed the Odds-Matrix method. This method uses a matrix of pairwise odds on outperformance to derive the required weights for combining. The estimation of the pairwise odds that one model will outperform the other is based on binomial probabilities. These probabilities can be determined from available data, managerial judgment, or both. For details, see Gupta and Wilton (1987).

Weighted average based on the sample covariance matrix (Newbold and Granger, 1974; Makridakis and Winkler, 1983): The idea behind this approach is that the combined forecasts can be improved by taking into account the relative (percentage errors) accuracy of each method and the covariance between the errors of various models/methods calculated from historical data.

Linear combination: Holden and Peel (1986) among others applied linear combinations of forecasts. The weights of the forecast

models to be combined can be determined by:

$$A_t = \beta_0 + \beta_1 F_t^{(1)} + \beta_2 F_t^{(2)} + \ldots\ldots \beta_p F_t^{(p)} + \mu_t \ldots\ldots\ldots\ldots (5)$$

where $F_t^{(1)}$, $F_t^{(2)}$,.....$F_t^{(p)}$ denotes the forecast methods of each of the p methods in reference to period t. This approach requires that there are n forecasts available for each of the methods. A_t is the outcome of the combined forecasts, where the β's represent the weights assigned to the forecasts of each method. The β are estimated using regression analysis.

Constrained versus unconstrained weights (Nelson, 1972; Makridakis et al., 1982; Granger and Ramanathan, 1984): The 'constrained form' requires restricting the weights of (2) to sum to one while the 'unconstrained form' does not. The unconstrained form is more relevant when the components of the combined forecast cannot be assured to be unbiased.

Focus forecasting (Smith and Wright, 1978): In focus forecasting a weight of 1 is assigned if the forecast method to be combined has the minimum absolute forecast error in the preceding period, otherwise the weight becomes zero. Thus one needs only to keep track of which model/method was most accurate in the previous period. A variation has also been proposed in which the weights are computed by using the median, in addition to the average error, to assign the weights of 1 or 0.

Historical record of the most accurate forecast in all previous periods (Bunn and Kappos, 1982; Ringuest and Tang, 1987a): The historical record of the most accurate forecast in all previous periods can be used to compute the weights in (2). This can be done as follows:

$$W_p = \Sigma_p \; A_{ip} / n$$

where i = 1, 2,.....n (n = the number of periods available)

A_{ip} = 1, if method p yields the minimum absolute forecast error in period i, otherwise = 0 and

$A_{1p} = 1/p$

Composite predictors: A linear composite predictor can be used. Such a predictor can be found as follows (Moriarty and Adams, 1984; Phillips, 1987):

$$Y_t^c = \beta_1 \hat{Y}_t^{(1)} + \beta_2 \hat{Y}_t^{(2)} + \varepsilon_t \ldots\ldots\ldots\ldots (6)$$

where β_1 and β_2 are the weights attached to each forecast of the variables Y_t^c (composite predictor). The least squares estimate of β_1 is defined (see Cooper and Nelson, 1975) as:

$$\hat{\beta}_1 = \frac{\hat{\sigma}^{2(1)} - (\sigma^{(1)} \sigma^{(2)} \hat{\rho})}{\sigma^{2(1)} + \sigma^{2(2)} - (\sigma^{(1)} \sigma^{(2)} \hat{\rho})} \quad .....(7)$$

Weighting based upon actual forecast error: Russell and Adam (1987) proposed the following weighting procedure to combine forecasts:

$$WT(I) = \frac{1/EF(I)}{1/EF(1) + 1/EF(2) + ...1/EF(n)} \quad ....(8)$$

where WT(I) = weight placed upon the individual model forecast in combination, and

EF(I) = error function of the individual model under consideration.

The denominator contains the sum of the error functions of the 1 to n models to be combined. In Russell and Adam's (1987) study n was three, four or five models. In addition, they used nine different combination schemes. The weight, WT(I), was determined differently according to the different weighting schemes and different conditional accuracy measures (i.e. MSE, MAE, MAPE, etc.).

Multiple objective linear program model (MOLP): Reeves and Lawrence (1982) and Gulledge et al. (1986) introduced a MOLP model as an alternative weighting method to obtain an efficient linear combination of forecasts. Thus the decision variables for the MOLP are the weights assigned to the various forecasts. Let w_i = the weight assigned to forecast j = 1, 2,....p. Also, let A_i = the actual value in time period i = 1, 2,....m; and F_{ij} = the forecasted value by technique or model j in time period i. The model can be stated:

$$\text{minimize } f^{(1)}(d^+, d^-)$$

$$f^{(2)}(d^+, d^-)$$

$$f^{(p)}(d^+, d^-)$$

subject to

$$\sum_{j=1}^{n} F_{ij} W_j + d_i^- - d_i^+ = A_i \qquad i = 1,2,\ldots\ldots m$$

$$\sum_{j=1}^{n} W_j = 1$$

$$W_j \geq 0$$

$$d_j^+ , d_j^- \geq 0$$

where d_i^- = the underachievement by the combined forecast of the observed value in time period i, and

d_i^+ = the overachievement by the combined forecast of the observed value in time period i.

4. Methodological Issues in Combining Forecasts

In the previous section we have described a large number of combining approaches currently available in the forecasting literature. It is obvious that much research has been conducted in seeking the best way to combine forecasts. In this section, we discuss a series of methodological issues: constancy, efficiency, stability, and the number of forecasts to be combined.

Constancy of Patterns and/or Relationships

Any attempt to predict through statistical modelling requires the examination of the data structure and the ability of the different models to capture such structure. The notion of constancy of patterns or relationships is critical (see Makridakis, 1981; and Lawrence et al., 1986). The assumption of constancy may adequately describe data from physical, natural, and most engineering related applications, but it is rarely applicable in business and/or economic applications. Thus, predicting a continuing pattern is easier than predicting a turning point, such as a recession or a change in trend. However, changes from established patterns and/or relationships can

greatly affect forecasting accuracy and cannot be ignored.

When patterns and/or relationships change most forecasting techniques perform poorly (since they assume constancy). In their study of combining judgmental and statistical forecasts, Lawrence et al. (1986) found that the greatest improvement in forecasting accuracy was to be obtained in the short run and not, as they had anticipated, in the long run. An examination of the reasons for such findings revealed many cases of failure of the assumption of constancy. When patterns and/or relationships change, the forecast errors of various methods have the same sign. Thus, the advantage of combining forecasts is reduced.

If constancy of patterns and/or relationships cannot be assured, elaborate combining schemes do not work better than simple averaging because past accuracies and/or error structures will not necessarily be the same during the future while forecasting.

The Efficiency of Forecasts and Combined Forecasts

Forecast improvement rarely occurs without additional costs. Forecast efficiency can therefore be defined as the trade-off between improved accuracy and the additional incremental costs required to achieve such higher accuracy. In the case of combining, a forecaster should compare a single forecasting method with that of combining. Moriarty and Adams (1984) suggested that if the variance of the combined forecast error is not significantly less than that of the single model, then the forecaster should use the single model. Granger and Newbold (1973, 1977) called this concept "conditional efficiency" and proposed a practical way for testing it. They also argued that forecasting optimality is not a practical concept. Instead they aimed at forecast improvement which can be more easily achieved through combining which "satisfies" rather than "optimizes" the goal of improved forecast accuracy. Granger and Newbold demonstrated that using simple linear combinations of forecasts could achieve higher forecasting efficiency than following a policy of trying to identify and use the single best method.

Studies by Newbold and Granger (1974), Bunn (1978), Reinmuth and Guerts (1979), Bessler and Brandt (1981), Farmer et al. (1981), Bunn and Seigal (1983), Winkler and Makridakis (1983) and Fildes and Fitzgerald (1983) have provided additional evidence supporting Granger and Newbold's claim. Efficiency was confirmed empirically using small samples as well as large samples.

Clemen (1986) concluded that imposing restrictions on combining is necessary because of the potential decreases in

forecasting efficiency. His study showed that combined forecasts can suffer from inefficiency if the forecasts being combined were redundant. However, when Clemen and Winkler (1986) examined this issue in more detail and applied a Bayesian model they found improvements in the performance of a combined forecast, although redundancy was present.

Bunn (1985) stated that several interrelated factors need to be considered when efficiency is studied. These factors include: dependence between models, error variance ratios, size of sample, and presence of outliers. Forecasters should also take particular care to insure unbiasedness. If one of the individual forecasts consistently under or over predicts, this will result in a composite forecast which will also be biased (Falconer and Sivesind 1977) if another forecast cannot cancel the consistent over or under estimation.

Stability of Weights

In combining forecasts by other means than a simple arithmetic average it must be assumed that the weights are stable over time. However, in practice this is rarely the case. In Winkler (1984) and Figlewski and Urich (1983), a simple average outperformed the weighted combination due to instability of the weights.

Kang (1986), in his study of a series of Monte Carlo experiments as well as combining the nominal GNP forecasts of four macro economic forecasters, showed that the weights were unstable over time and that there is no guarantee that the combined forecasts will have the optimal property of having the smallest variance or the best accuracy (see also Winkler, 1984; Figlewski and Urich, 1983; and Zarnowitz, 1984). Thus, the fact that weight stability (as with constancy of patterns and/or relationships) cannot be assured complicates matters and tends to favor simple averaging schemes over sophisticated weighting procedures.

The Number of Forecasts to be Combined

Several studies have investigated the question of how many forecasts should be included in combining. Researchers have examined the relative improvements in accuracy associated with different numbers of combinations. Makridakis and Winkler (1983) found that the variability associated with the choice of methods is reduced as more methods are included. Thus, the risk of not choosing the best forecasting method decreases rapidly when more methods are being combined. The impact of adding an extra method, however,

reaches a plateau after three or four methods have been combined.

Support for Makridakis and Winkler is provided by Granger and Ramanathan (1984), Ashton and Ashton (1985) and Lawrence et al. (1986). These researchers found that the combination of three forecasts is better than any combination of a pair. Holden and Peel (1986) also showed that as the number of forecasts being combined increases the average root mean squared error falls. They considered averages of up to six forecasts.

Ringuest and Tang (1987b) and Russell and Adam (1987) conducted empirical studies which suggested that whichever number of forecasts combined is most accurate depends to some degree on the methods used to combine the forecasts. Bopp (1985) noted that situational factors also play a role. He found that a two model combination contained as much information as a three model combination, but stated that this particular finding was only relevant to his study. The implication is, however, that perhaps two lesser expensive models can produce a more efficient forecast than that forthcoming from a third but more expensive model. The issue of cost as related to the number of forecasts to be included in a combination is discussed by Ashton and Ashton (1985). They explained that although accuracy can be improved by adding more forecasts, the trade-off between increased accuracy and the cost of the individuals' time must be taken into account.

5. Classifying and Evaluating Empirical Studies About Combining Forecasts

The body of literature dealing with combining is extensive. Thus, there is a strong need to classify and evaluate such studies so that their usefulness and relevance (see next section) can become clear. Empirical studies can be classified by the type of combining they do. Thus, a categorization can include studies combining judgmental methods only, quantitative methods only, and quantitative and judgmental methods together. (Appendix 1 summarizes all major empirical studies following this classification).

Combining studies can also be grouped according to the combining method used. Appendix 2 summarizes the relative efficiency of various studies and combining procedures. The efficiency of each method relative to a simple average method is noted, when comparisons are possible.

Most studies have shown that a simple arithmetic average is superior in comparison to individual models alone. However,

more complex or sophisticated combining approaches have been shown to produce more accurate results relative to simple averaging. Winkler and Makridakis (1983), for example, found that weighted average schemes based on the covariance matrix outperformed that of a simple arithmetic average. However, improvements were generally small to make such sophisticated combining a practical alternative. This was also confirmed by Clemen and Winkler (1986). Also, Kang (1986) found simple averaging a more desirable alternative because the weights in other methods are so unstable.

We might expect that as more knowledge about combining is accumulated we would eventually be able to devise combining procedures that are superior to simple arithmetic averaging. This has been the case in some studies. For instance, Russell's and Adam's (1987) weighting schemes, especially the one that is based upon the inverse proportions of the mean absolute error, provide encouraging results and might be useful for practical applications. Similarly, studies by Gulledge et al. (1986) and Reeves and Lawrence (1982) employing multiple objective linear programming suggested that the combined forecasts were more accurate than simple averages. They also indicated the necessity for decision makers to provide implicit information regarding their preference and the assignment of weights to various forecasts as a means of optimizing forecasting objectives.

6. Implications for Managers

Georgoff and Murdick (1986) emphasized that combining forecasts is a useful way for managers to improve the accuracy of their projections. This view is certainly supported by the empirical studies reviewed in this paper. Combining different methods improves forecasting accuracy and decreases the variance of forecasting errors. This is often with little or no increase in associated costs. Simpler approaches to combining provide adequate improvements; thus, managers with relatively little experience can use these approaches in practice

In addition, combining is valuable in judgmental forecasting. Ashton and Ashton (1985) show that aggregating judgmental forecasts avoids the detrimental effects of unknowingly relying on the worst of the available individuals.

Researchers have commented that, in practice, most forecasts are a combination of a judgmental forecast and a quantitative forecast (Lawrence et al. 1986, Jenkins 1982). Yet, there is little evidence of how and when managers combine forecasts in a formal manner. Winkler (1984) cites Koten (1981) who reported that combinations

involving only subjective forecasts are currently used by some companies for major decisions. In a survey of sales practices in the U.S., Dalrymple (1987) found that respondents used an average of 2.7 forecasting methods on a regular basis. Clearly, managers recognize the dangers of applying one single technique as a base for their predictions.

Managerial adjustments, a common approach of forecasting in practice, should be done with caution. Empirical results are mixed. Armstrong (1982) indicated that subjective revision of objective forecasts involves considerable risk because it often reduces accuracy. An experimental study by Carbone et al. (1983) found that judgmental adjustment by student subjects did not improve accuracy. Mathews and Diamantopoulos (1986), however, showed that managerial manipulation led to improvement in forecasting performance. They explained this result by suggesting that individual expertise in the form of situation-specific knowledge may be the key element underlying forecast improvement. Certainly, the fact that different forecasting models provide different information is fundamental to the success of combining. However, combining through judgmental adjustments ought to be formalized so that such adjustments can be made objectively, thus avoiding judgmental biases.

It is advisable that managers prepare a judgmental forecast separately and then formally combine it with a quantitative forecast. Makridakis (1987) emphasizes that, instead of approaching each forecasting situation on an ad hoc basis, it is preferable to develop rules for dealing with forecasting tasks. Such a systematic approach is important when combining, especially when combining managerial judgment with some other method. Humans tend to be optimistic and underestimate uncertainty. Tyebjee (1987) and Moriarty (1985) have suggested procedures to improve judgmental forecasting systems.

Managers should also consider the costs involved in combining forecasts. While combining quantitative forecasts generally adds little cost over the cost of making individual forecasts, this is not the case with judgmental forecasts whose costs can be substantial. Thus, trade-offs between higher costs and improved accuracy need to be considered.

7. Future Directions

The review of the literature on combining has illustrated that there are some general guidelines for combining. These "rules," however, are not clearly defined or universally applicable. Questions

remain as to the preferred procedures for combining and the ability of a model or group of models to capture changes in data patterns in a superior way so that combining will be of lesser value. Thus, the field of forecasting needs not only further insights into combining techniques, but considerable effort into improving single forecast methodology.

Some of the research in combining can nevertheless have implications for individual model selection. For example, Gardner's (1986) interpretation of Makridakis' and Winkler's (1983) results is that the combined forecasts improved accuracy because they avoided extrapolating too much trend at long term horizons. In effect, Gardner noted, the constant-level models damped the rate of growth in the forecasts, which were made from extremely noisy data. Gardner suggests building one such model that damps the trend extrapolated from noisy data (see Gardner 1985). Instead of using combining, Gardner's model seems to provide accurate results when tested empirically. Schnaars (1986) found that rules that involve dampening the trend also led to substantial improvement in accuracy in comparison with the rule "pick the model that provides the best fit to the historical sales."

It might be necessary to reverse the trend towards combining forecasting models and concentrate rather on the ability of specific methods or integrated systems to deal with the reality and the complexity of real life forecasting. Combining forecasts should be viewed as a way of learning about the deficiency of single forecasting methods, or group of methods, and helping us devise new models or variations of existing ones in order to improve forecasting accuracy. Thus, we see that the biggest benefit of combining has come by letting us realize that single models were not more accurate than combining several of them and in doing so averaging their errors. Once the reasons why combining works better than single methods have been understood, new ways of improving accuracy could be found.

Thus, the future of research into combining forecasts should not focus exclusively on the averaging of different kinds of forecasts. Rather, researchers should evaluate how their work on combining could help towards learning and improving individual forecasting methods. In addition they should consider how their results could contribute towards the development of integrated forecasting systems, for special and general applications. That combining provides more accurate results than single models/methods and/or forecasters attests to the fact that such models/methods or people are biased in a consistent way and their errors need to be averaged in order to cancel them out. If this is the case, however,

the alternative exists to find effective ways of reducing or eliminating consistent biases by better, more effective selection, or methods that can provide equally or more accurate forecasts than combining.

8. Conclusions

In summary, the following conclusions can be drawn:

(a) For all types of combinations (judgemental only, quantitative only, and quantitative and judgmental), considerable improvements in forecasting accuracy over individual forecast performance are demonstrated by empirical studies.

(b) There is no one best method for combining forecasts. However, simple methods of combining, such as the simple average, are equally as good as or better than more complex methods. Simple averaging is superior to judgmental methods of combining in most cases.

(c) Combining forecasts gives improved performance even if only a small number of forecasts are combined. Further improvements are achieved with additional numbers of forecasts in the combination, but increases in accuracy occur at a diminishing rate.

(d) One reason that combining different types of forecasts (for example, quantitative and judgmental) provides improved performance is that more information is included in the combination.

(e) Combining a simple model with a complex one provides a better forecast than the complex one generates alone.

(f) Composite forecasts have been shown to be superior to combined forecasts in some cases.

(g) Whether restricted or unrestricted linear combinations of forecasts provide better performance seems to depend on situational factors.

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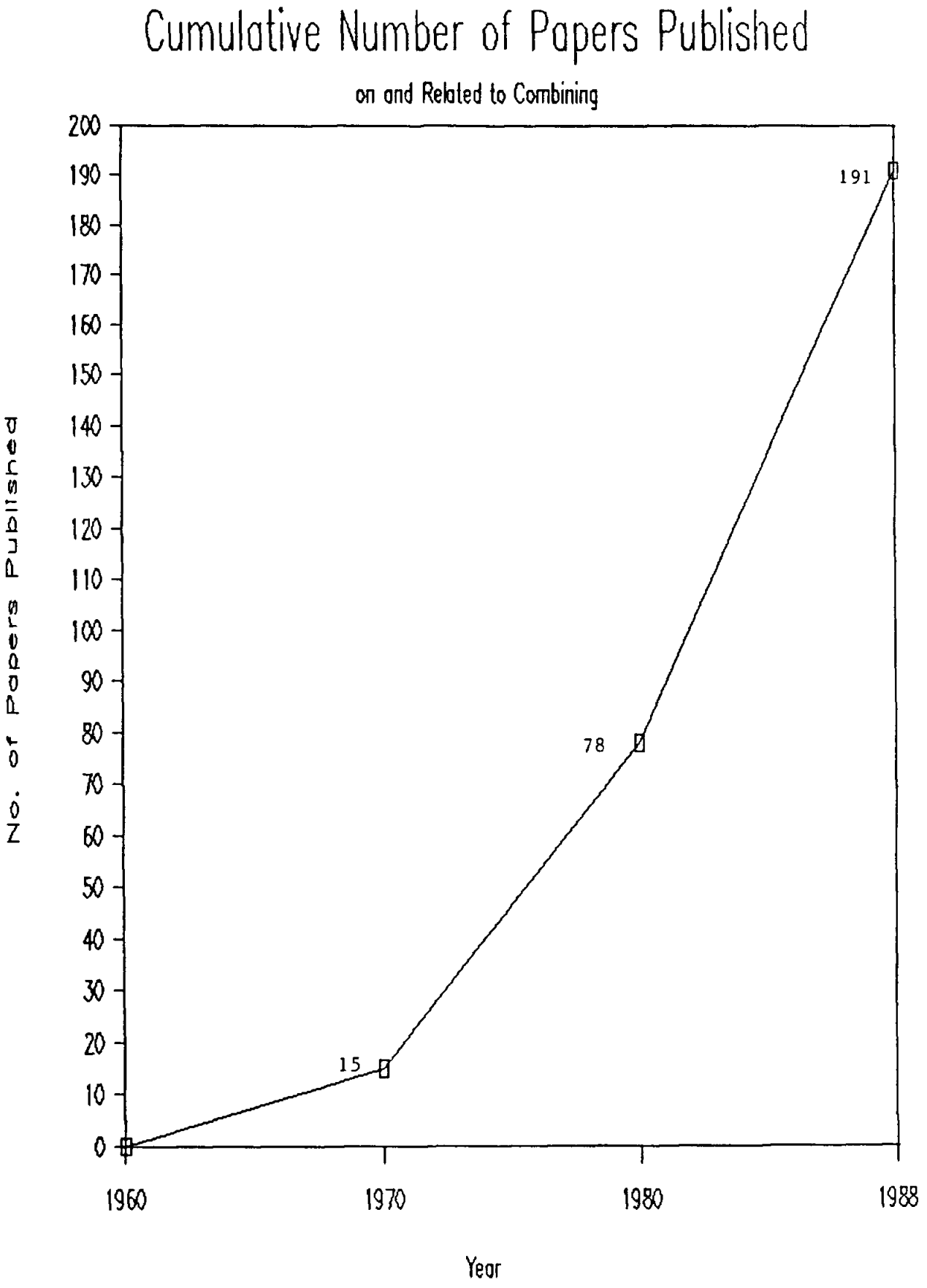
Figure 1


Cumulative Number of Papers Published
on and Related to Combining
No. of Papers Published
200
190
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191
78
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1960
1970
1980
1988
Year

APPENDIX 1

A Classification of Empirical Studies about Combining Forecasts

Area of Application	Description	Main Findings	Literature Sources
A. Combining Judgmental Methods Only			
Aggregation of subjective forecasts made by executives.	Data were short-run forecasts of advertising sales for TIME magazine. 5 weighting methods used to combine forecasts.	Aggregating a small number of subjective forecasts found to be more accurate than the individuals' forecasts that comprised the aggregates. This occurred regardless of weighting method employed.	Ashton and Ashton (1985)
Examination of accuracy in the Delphi method.	3 experiments assessed accuracy of group predictions over 1, 2, and 3 month time spans.	Predictions derived from the group were more accurate than those of 95% of the individual panelists, but did not exceed in accuracy the best panelists.	Parente, Anderson, Myers and O'Brien (1984)
Consensus of experts' judgments	Experiment using student subjects. Combinations of a number of distributions into a single distribution to be used as an input to a formal Bayesian analysis.	Different methods of combining (math. formulae; feedback/ group discussion) may produce different results.	Winkler (1968)
Combining sets of judgmental forecasts obtained using students and	Data obtained using Graph and Table techniques (see Lawrence et al., 1985). Combining	A combination of judgmental forecasts always improved accuracy over the	Lawrence, Edmundson and O'Conner (1986)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
the authors.	methodologies were simple averaging and judgmental.	constituent forecasts, for all time horizons. Showed ineffectiveness of judgmentally combining forecasts compared with simple averaging.	
Experiment comparing the accuracy of combining forecasts formed with objective versus subjective methods.	Forecasts combined were judgmental forecasts of two time series (Dow Jones Industrial Index and mini-computer log-ins). Produced by student subjects. Comparison of subjectively combined forecasts (produced by student subjects) and objectively combined forecasts (produced using 4 different ex ante weights).	Subjective combination of forecasts give as accurate, or more accurate, results than the objective combinations. Any combination of forecasts gives more accurate results than the individual forecasts.	Flores and White (1987)
B. Combining Quantitative Methods Only			
Combining forecasts using simple or weighted average	Makridakis et al. (1982, 1984) addressed the issue of combining forecasting techniques in order to improve accuracy. They used "Combining A" method which consisted of a	Both combining methods indicated that the resulting forecasts perform very well overall and better than the individual methods included in the average. Combining A performed	Makridakis et al. (1982, 1984)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	simple average of 6 methods and "Combining B" method using a weighted average of 6 methods based on the sample covariance matrix of fitting errors.	better than Combining B.	
	Ten forecasting methods were applied to 1001 time series. A combination rule was developed to find combined forecasts for several periods ahead. Five procedures were used for estimating weights when combining methods.	Of the five weighting procedures used, two outperformed the others. The combined forecasts were more accurate than forecasts from individual methods under most conditions with large time horizons providing some exceptions. The accuracy of weighted averages outperformed that of the simple average. It appears that differential weighting can lead to improved forecasts.	Winkler and Makridakis (1983)
	Simple average used to combine the forecast of the various methods considered in the study. 14 forecasting methods and 111 time series were used.	The accuracy of combined forecasts was little influenced by the specific methods included in the combination. Accuracy improved with the increases in the number of methods	Makridakis and Winkler (1983)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
		being combined, although a degree of saturation was reached after about four or five methods. The variability of accuracy among different combinations decreased as the number of methods included in the combination increased.	
	Examined accuracy and properties of forecasts of UK economy produced by 15 organizations.	Study provided empirical support for taking a simple average of a number of forecasts rather than forming a weighted combination of them.	Holden and Peel (1988)
Stability of weights used in combination of forecasts.	A series of Monte Carlo experiments as well as combinations of nominal GNP forecasts from 4 well-known macro forecasters.	The weights used in the combination of forecasts are shown to be very unstable. They are generally so unstable that the combined forecasts often do not perform better than some of the individual forecasts or a simple average of the forecasts in practice. The Monte Carlo experiments show that when the	Kang (1986)

Area of Application	Description	Main Findings	Literature Source
		underlying models are known, a composite forecast from a composite model is generally more accurate than the combination of the individual forecasts. A simple average technique is shown to be the best technique to use in practice, because the weights in the combination are so unstable.	
Comparing different approaches to combining quantitative methods.	Different approaches for combining two or more forecasts.	Some applications of combinations of methods demonstrated improvements of forecasts.	Reid (1969)
	Used a recursive regression algorithm for two or more forecasts and creating a multideterministic forecasting model.	Empirical results involving three data sets suggested that the regression combination procedure provided substantial improvement over those obtained by using a unideterministic forecast model.	Reinmuth and Geurts (1979)
	Makridakis et al. (1982) 111 time series used to evaluate 5 procedures	Showed value of the simple averaging approach, using a combination of	Ringuest and Tang (1987a)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	for combining individual forecasts produced by 8 different techniques.	relatively few individual forecasts. Method suggested by Bunn and Kappos (1982) provided best overall performance. This method produced the only true weighted average considered, thus it was the only combination considered that could utilize all of the available information.	
	Comparison of 6 methods: "equal weighting," "optimal," "optimal with independence assumption," and three variations on the formulation of a Bayesian combination based upon posterior probabilities.	There is no one best method of combination. In terms of forecasting efficiency, factors to consider include dependence between models, error variance ratios, size of observation base and incidence of outliers.	Bunn (1985)
	Examines bias in forecasting. Develops procedures to determine optimal combining weights. These are applied to forming a combined forecast based on forecasts from 5 economic organizations.	The combined forecast using the developed procedures did not perform as well as the individual models or the simple mean.	Holden and Peel (1989)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	Empirical comparison of 3 rules (a simple average forecast, a median forecast, and a focus forecast) for aggregating forecasts of 4 economic variables.	An average forecast will not perform as well as previous studies indicate if all or most of the individual forecasts tend to over - or under - predict simultaneously. Little evidence to suggest that median forecast is a viable alternative to the mean forecast. Focus, forecasting, however is a reasonable alternative to simple averaging.	Ringuest and Tang (1987b)
Combining forecasts using decision support system approach	Developed a model to help decision makers through an expanded decision support system. The methodology used was multiple objective linear programming (MOLP). They used three different forecasting methods (exponential smoothing, harmonic smoothing and multiple regression).	The conclusion was that combined forecasts would be preferred to individual forecasts in a wide variety of decision environments.	Reeves and Lawrence (1982)
	Empirical study of combining naive forecasting models.	Results support using a model combination that (1) selects the	Russell and Adam (1987)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	Demonstrated a 5 step decision procedure for combining simplistic forecasting models. Procedure for choosing and weighting individual models. 9 combination models tested.	best 3 to 5 models studied and (2) weights the selected models based upon the inverse proportion of their individual accuracy as measured by MSE, MAE and MAPE.	
Using multiple objective linear programming (MOLP) to determine weighted linear combinations of forecasts to be used for policy analysis.	MOLP model is developed and tested on forecasts for several economic policy variables.	Showed the dominance of combined forecasts over a single forecast; the necessity for policy makers to provide implicit information regarding their preferences for forecasting objectives; and the assignment of weights to various forecasts as a means of minimizing the forecasting objectives.	Gulledge, Ringuest and Richardson (1986)
Box-Jenkins with other techniques	Combined Box-Jenkins projection with those generated by other forecasting techniques. Also introduced the weighted average of forecasts that minimizes the variance of the combined forecast error.	The combining procedure provided the best overall forecasts. Box-Jenkins forecasts can frequently be improved upon by combinations with either Holt-Winters or stepwise autoregressive forecasts. Indicated that combining is well worth try-	Dalrymple (1978), Binroth et al. (1979), Newbold and Granger (1974), Mahmoud (1982)

Area of Application	Description	Main Findings	Literature Sources
		ing and requires very little effort.	
Box-Jenkins and regression	Combined regression model with a univariate Box-Jenkins model.	The combined forecasts reduced the mean squared errors by a large factor.	Pindyck and Rubinfeld (1976), Adams (1978)
Box-Jenkins and exponential smoothing.	Combined forecasts from the application of exponential smoothing and B-J type models to airline traffic data.	Forecasting accuracy improved by combining the forecasts of both methods. Also emphasized the possibility of the relevant weights changing through time.	Bates and Granger (1969)
Bayesian adjustment to given Box-Jenkins univariate technique	Formal Bayesian adjustments were made to a given Box-Jenkins univariate technique.	The expected results were in favor of the combining approach.	Gregg (1980)
Exponential smoothing with regression.	Combined simple adaptive response exponential smoothing with a regression model to track historical check volume.	The combined approach provided better forecasts.	Mabert (1978)
	Developed the methodology of merging exponential smoothing models and multiple regression. The	The forecasted results were acceptable.	Crane and Crotty (1967), Bonini

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	development results in simple formulae that allow the user to update the regression coefficients in an adaptive fashion.		and Freeland (1979)
Time series ARIMA model (TSM) with an econometric model (SEM; the London Business School model of the U.K. economy).	Models combined using a linear composite predictor.	In all cases of one step ahead forecasts the TSM predictor can be added to that of the SEM to improve the fit of the equation. For 8 step ahead prediction errors, inference is hazardous because of the biases in the test statistics due to autocorrelation. However, in a number of cases, there is still additional information contained in the time series predictors which are not captured by SEM.	Longbottom and Holly (1985)
Combining an econometric model and an ARIMA model.	Forecasted value of personal income over a 6-quarter horizon. Composite prediction using weighted average with value of weights determined by OLS and restricted to unity.	Combined model outperforms either individual model. Greatest forecast improvement gained at longer lead times.	Falconer and Sivesind (1977)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
Combining econometric models	Tested a variety of methods for combining forecasts of GNP for 4 major econometric models. Methods include one in which forecasting errors are jointly normally distributed and several variants of this model as well as some simpler procedures and a Bayesian approach with a prior distribution based on exchangeability of forecasters.	Results indicated that a simple average, the normal model with an independence assumption, and the Bayesian model perform better than the other approaches studied.	Clemen and Winkler (1986)
Combining econometric, regression and time series models	Used Dept. of Energy's econometric model to forecast gasoline consumption. Also used a regression model and an ARIMA time-series model. Weights for combining these 3 models not constrained to add to one.	The 2-model combination with the highest R^2 is the econometric time series one. This 2-model combination contained as much information as the 3-model one. Combining a simple model with a complex one produces a better forecast than the complex one generates alone.	Bopp (1985)
Holt's smoothing with adaptive response	The study used a simple average for combining forecasting techniques.	The combined approach provided better MSE and reduction of the cost of the forecasting error.	Mahmoud (1982)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
rate of single exponential smoothing.			
Combining time series forecasts	Integration of two approaches: forecasting contemporaneously aggregated time series and combining alternative forecasts of a time series. Used models of 2 UK monetary aggregates M3 and M0.	Forecasts from a time series model for aggregate M3 were superior to aggregated forecasts from individual models fitted to either the components or counterparts of M3. An even better forecast was obtained by forming a linear combination of the 2 alternatives. For M0, however, aggregated forecasts from its components proved superior to either the forecast from the aggregate itself or from a linear combination of the 2.	Mills and Stephenson(1985)
Combining forecasts of mixed time frequency or aggregation level	Presented and tested a method allowing the forecaster to obtain pooled forecasts at the (time- or component-) disaggregated level.	Showed that the resulting aggregate pooled forecast is identical to the forecast which would be obtained by simply pooling 2 forecasts at the aggregate level, while the disaggregated forecast maintains the	Fuhrer and Haltmaier (1988)

Area of Application	Description	Main Findings	Literature Sources
		aggregation identity required by the problem.	
The Odds--Matrix (OM) method of combining forecasts	Description of the OM method. Testing via a simulation experiment to investigate behavior of combined estimates, combining method performance and weight interpretability.	Method allows easy inclusion of relevant subjective and empirical information about the forecasts, while providing weights which are intuitively meaningful and not dependent upon large numbers of observations of prior forecast accuracy. The experimental results showed the method to be highly robust and significantly superior to existing approaches under many conditions.	Gupta and Wilton (1987)
Linear constraints in combining methods	Discussion of how linear combinations of forecasts may be formed, properties of combined forecasts and how the results may be interpreted. An application using three different combined methods were performed.	The superiority of one of the three combined methods was demonstrated. It provides the smallest mean squared error and an unbiased combined forecast even if individual forecasts are biased. The best method is to add a constant term and not to constrain the weights to add to unity.	Granger and Ramanathan (1984)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	Test of Granger's and Ramanathan's (1984) proposal to include a constant term and not restrict the weights to sum to one in the linear combination of forecasts. Combination of GNP forecasts from 4 econometric models.	Small gains in forecasting efficiency can be obtained by restricting the linear combinations.	Clemen (1986)
	Empirical analysis of approaches to obtaining linear combinations of forecasts. Simulated quarterly earnings modeled using 3 ARIMA models. One-quarter ahead forecasts were combined using alternative approaches.	Most accurate forecasts obtained by adding a constant term and not constraining the weights to add up to one. The differences in the accuracy rankings were statistically significant.	Holmen (1987)
	Examination of effects of combining 3 econometric and 3 time-series forecasts of growth and inflation in the U.K.	A restricted linear combination of the econometric forecasts is superior to an unrestricted combination and also to the unweighted mean of the forecasts. However, it is not preferred to the best of the individual forecasts.	Holden and Peel (1986)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
C. Combining Quantitative and Judgmental Methods			
Guesswork and statistics (guesstics)	Involved a combination of guess work and statistics. The sales trend graph plays an important role in this technique (using the moving average method).	The approach showed improvement in forecasts.	Gold (1979)
Quantitative methods and qualitative methods	Forecasting techniques were combined using the simple average method.	The forecasted results showed improvement in accuracy.	Mahmoud (1982)
Combining corresponding sets of individual professional forecasts of economic variables.	Investigated the accuracy of combining corresponding predictions from different sources. Some forecasts were econometric; many were judgmental.	The results show that there are gains to the forecast users from combining predictions from different sources.	Zarnowitz (1984)
Box-Jenkins ARIMA method and management judgmental forecasts.	Discussed contrasts between management judgmental and systematic methods for forecasting sales. Introduced concept of composite sales forecasting which combines two (or more) separate sources of forecast inputs. Used the composite model as a standard for	Recommended consideration of a composite forecasting model in which inputs may include both systematic and judgmental factors. Under certain conditions, management judgmental forecasts will make strong contributions to forecast accuracy.	Moriarty and Adams (1984)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	testing the conditional efficiency of its constituent forecasts. Model empirically tested.		
	Combination of 3 judgmental forecasts and ARIMA forecast of U.K. balance of payments.	Performance can be improved by aggregation and it does not matter much that there is only a limited range of forecasts to aggregate.	Fildes and Fitzgerald (1983)
Forecasting livestock prices with individual and composite methods.	Several forecasting models combined using various weighting schemes (optimal, adaptive, simple average).	Composite forecasts help users avoid relatively large forecasting errors. Quantitative models outperformed expert judgment approach. Yet, explicit use of commodity experts with no formal model building expertise can improve overall quality of a set of forecasts.	Bessler and Brandt (1981), Brandt and Bessler (1983)
Composite forecasting as a criterion for retention of a forecasting method.	Comparison of management judgement and multiple time series forecasts of sales. Composite model applied to judge contribution of each type of forecast.	Results varied across years. The improvement in forecast performance using the composite model was not statistically significant in comparison with the judgment method. Therefore, both	Moriarty (1985)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
		judgment and time series methods should be retained.	
Combining sets of judgmental forecasts with forecasts from deseasonalized single exponential smoothing (DSE)	Database was 68 monthly series used in M-Competition (Makridakis et al. 1982). Judgmental data obtained using Graph and Table techniques with student subjects and the authors.(See Lawrence et al., 1985) Combining method used was simple averaging.	A combination of a statistical and a judgmental forecast improved accuracy over the constituent forecasts. Also provided greater improvement than a combination of purely judgmental forecasts. Combinations of 3 forecasts (DSE-Graph-Table) are more accurate than using only 2 forecasts. Greatest improvement in accuracy was obtained in the short run. Seasonality does not influence the benefit gained from combining forecasts.	Lawrence, Edmundson and O'Connor (1986)
Combining forecasting models of earnings per share.	Three types of forecasting models which use past historical growth rates, expected return model, time series ARIMA models) combined with estimates of the financial analysts of the Value Line Investment Survey. Alternative models combined in an OLS	Value line forecasts were more accurate than the other models However, Value Line does not make use of all the information inherent in historical earnings per share. Forecast errors were reduced when Value Line forecasts were	Newbold, Zumwalt and Kannon (1987)

Appendix 1 continued

Area of Application	Description	Main Findings	Literature Sources
	regression in an attempt to provide more accurate forecasts.	combined with the Brown-Rozeff ARIMA model.	

Appendix 2

Relative Efficiency of Different Combining Methods

Method	Findings (if any) showing efficiency of method relative to simple averaging	Sources
Simple averaging		Makridakis et al. (1982, 1983), Kang (1986), Clemen and Winkler (1986), Ashton (1982), Mahmoud (1982), Einhorn (1972), Lawrence et al. (1986), Carbone et al. (1983), Gupta and Wilton (1978), Holden and Peel (1986), Winkler and Makridakis (1983).
Historical weightings		
Subjective weights	Incremental accuracy of an ex ante subjective weighting method over simple averaging was small.	Ashton and Ashton (1985)
	Judgmental combination was more time consuming than a simple average and considerably less accurate.	Lawrence et al. (1986)
Odds-Matrix Method	OM method found to outperform simple averaging, with the reduction in combined forecast error particularly significant in the presence of nonstationary forecast errors.	Gupta and Wilton (1987)
Bayesian approach		Newbold and Granger (1974) Makridakis and Winkler (1983), Smith and Makov

Appendix 2 continued

Method	Findings (if any) showing efficiency of method relative to simple averaging	Sources
		(1978), Bunn (1978).
	No one best method of combination. Relative performance of simple average depends not only on variance ratio, but also on correlation coefficient.	Bunn (1985)
	A Bayesian model is roughly comparable to the simple average.	Clemen and Winkler (1986)
Weighted average based on the sample covariance matrix		Engle et al.(1985), Reid (1986), Diebold and Pauly 1987), Winkler and Makridakis (1983).
	A weighted average outperforms a simple average	Bates and Granger (1969), Newbold and Granger (1974), Makridakis and Winkler (1983).
	Weighted average based on the sample covariance matrix does not perform as well as simple average.	Makridakis et al. (1982)
	A simple average is best because the weights in a weighted average combination are so unstable.	Kang (1986)
Linear combination		Diebold and Pauly (1987), Granger and Newbold (1973, 1977), Winkler and Makridakis (1983), Reid (1969), Reinmuth and Guerts (1979), Bessler and Brandt (1981)

Appendix 2 continued

Method	Findings (if any) showing efficiency of method relative to simple averaging	Sources
		Bunn (1978), Farmer et al. (1981), Bunn and Seigal (1983).
Constrained vs unconstrained weights		Nelson (1972), Makridakis et al. (1982), Granger and Ramanathan (1984), Dickinson (1975), Holmen (1987).
	Restrained linear combination superior to simple average.	Holden and Peel (1986)
Focus forecasting		Smith and Wright (1978)
Historical record of the most accurate forecast		Bunn and Kappos (1982), Ringuest and Tang (1987a)
Composite predictor		Moriarty and Adams (1984) Phillips (1987)
Weighting based upon actual forecast error		Russell and Adam (1987)
Multiple objective linear programming		Reeves and Lawrence (1981, 1982), Gulledge et al. (1986)

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