Draft: Please send comments. I am interested in sins of omission, especially on missing evidence. I will be happy to acknowledge substantive contributions. This is version 37.

Findings from Evidence-based Forecasting: Methods for Reducing Forecast Error

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Abstract

Empirical comparisons of reasonable approaches provide evidence on the best forecasting procedures to use under given conditions. Using this evidence, I summarize the progress made over the past quarter century with respect to methods for reducing forecasting error. Seven well-established methods have been shown to improve accuracy: combining forecasts and Delphi help for all types of data; causal modeling, judgmental bootstrapping and structured judgment help with cross-sectional data; and causal models and trend-damping help with time-series data. Promising methods for cross-sectional data include damped causality, simulated interaction, structured analogies, and judgmental decomposition; for time-series data, they include segmentation, rule-based forecasting, damped seasonality, decomposition by causal forces, damped trend with analogous data, and damped seasonality. The testing of multiple hypotheses has also revealed methods where gains are limited: these include data mining, neural nets, and Box-Jenkins methods. Multiple hypotheses testing should be conducted on widely used but relatively untested methods such as prediction markets, conjoint analysis, diffusion models, game theory, and leading indicators. Replications are needed to determine whether the promising methods do in fact, provide improvements. Finally, multiple hypotheses testing is needed in nearly all areas to determine the most effective ways of implementing the methods and to identify the conditions under which various methods can contribute to accuracy.

Keywords: causal models, causal forces, combining forecasts, conjoint analysis, damped trend, damped seasonality, data mining, Delphi, diffusion, game theory, judgmental decomposition, leading indicators, multiple hypotheses, neural nets, prediction markets, replication, segmentation, simulated interaction, structured analogies.

This paper summarizes what has been learned over the past quarter century about the accuracy of forecasting methods. To do so, it relies on what I believe to be a cornerstone of the research published in the journals sponsored by the International Institute of Forecasters:

> " . . For empirical studies, the journal gives preference to papers that compare 'multiple hypotheses' (two or more reasonable hypotheses)."

This method of reasonable alternatives implies that the current method is included along with other leading methods. In these comparisons, the journal would favor papers with empirical evidence, hopefully using many data sets, and offering full disclosure of the data and procedures. Finally, the hypotheses should specify the conditions in which the findings apply. I will refer to this approach as *multiple hypotheses* for the rest of this paper. References to evidence are restricted to findings from studies using multiple hypotheses.

Evidence-based findings

In judging progress in a field, one might look at new methods and develop a rationale on why they should be useful. Consider an analogy to medical research: one could develop new treatments in the lab based on reasoning about what treatments should be most effective. In a like manner, Fildes (2006) examined the most influential new treatments in forecasting. Peer review has supported these approaches. Is this sufficient?

Continuing with the analogy to medicine, Avorn (2004) reports the following, which I have paraphrased: "In a former British colony, most healers believed the conventional wisdom that a distillation of fluids extracted form the urine of horse, if dried to a powder and fed to aging women, could . . . preserve youth and ward off a variety of diseases." The preparation became very popular. Many years later, experimental studies concluded that the treatment was had little value and that it caused tumors and blood clots. The former colony is the United States and the drugs were hormone replacement products. The treatment seemed to work because those who used the drug tended to be healthier than those who did not. This was because they were people who, in general, were more interested in taking care of their health.

I have little faith in forecasting treatments until they have been empirically tested. Wildly popular techniques have often failed when subjected to testing. So in this paper, I examine only those methods that have been shown to be useful (or not useful) and under what conditions. As is the case for most research in the social and managements sciences, only a small percentage of papers are concerned with evaluation. Most are concerned with developing new or refined methods.

I looked primarily for studies that used real data to compare the *ex ante* forecasting accuracy of alternative methods. When possible, I relied upon published reviews and meta-analyses. My focus is primarily on unconditional (ex ante) forecasts because they lend themselves more more closely represent the actual situation. Due to limitations of time and space, I do not address the issue of the assessment of uncertainty in forecasting.

My search for evidence-based findings was intended to include all types of forecasting methods. Using the forecasting methodology tree at forecastingprinciples.com, I examined 17 basic methods: role playing, intentions/expectations surveys, conjoint analysis, prediction markets, Delphi, structured analogies, game theory, decomposition, judgmental bootstrapping, expert systems, extrapolation models, data mining, quantitative analogies, neural nets, rule-based forecasting, causal models, and segmentation. Brief summaries of these methods are available at forecastingprinciples.com with additional details in Armstrong (2001).

While this review focuses on the first 25 years of the International Institute of Forecasters (from its founding in 1981), many of the advances are built upon earlier work. Some earlier contributions, such as the classical decomposition of time series (mean, trend, and seasonality) are not discussed if I was unable to obtain evidence from the past 25 years that related to the use of the methods or to the conditions under which they are useful.

The initial base of findings is drawn from Armstrong (2001). In that book, 39 academic researchers in forecasting summarized evidence-based principles in their areas. They were supported by 123 reviewers in an effort to ensure that all relevant evidence on the principles had been included. The principles were initially posted on an open website, forecastingprinciples.com, and appeals were made for peer review as to any information that had been overlooked.

I began to update the review in early 2005 by searching literature, contacting key researchers, and requesting help through various email lists (e.g., the Associate Editors of the *International Journal of Forecasting*, and the authors and reviewers of the *Principles of Forecasting* book). An early version of this paper was presented as a keynote address at the International Symposium on Forecasting along with an appeal for peer review. In addition, a draft was posted on forecastingprinciples.com to solicit reviews. I also asked a number of experts to act as reviewers on this paper. I am indebted to the 22 reviewers who provided substantive contributions to the paper as well as to others who made smaller contributions. Some of these reviewers read more than one version of the paper.

Advances have been made in methods for improving forecast accuracy in the past 25 years, as summarized below. The list begins with methods that are well established, moves to “promising methods,” proceeds to those that have been tested but found to offer only limited gains, and concludes with methods that have been widely used but not well-tested.

Within each of these areas, the methods are organized by those that apply for all types of data, followed by those relevant primarily for cross-sectional data, and then those primarily applicable to time-series data. In assessing improvements, I sought evidence primarily on the percentage reduction in the absolute *ex ante* forecast error. When there was little evidence of error reduction, I report on the percent of the time the specified method improved accuracy. In addition to examining evidence on the accuracy of the methods, I also sought evidence on how the research over the past quarter of a century has contributed to a more effective use of the methods and to better defining the conditions under which the methods are most effective.

Well-established methods

All types of data

Combining forecasts

Combining forecasts call for developing forecasts from different methods or data, then using a typical forecast from these methods (usually a simple average, but sometimes a median or trimmed average). When using simple averages, the absolute error of the combined forecast can be no worse than the average of the absolute errors of the components. In cases where all of the errors for all of the methods all biased in the same direction for all methods, such combining would not improve upon the average of the components. However, this does not apply to all ways of combining (e.g., the mode or median).

Combining is expected to be most useful when it draws upon a diversity of forecasts such as when the methods differ substantially. Batchelor and Dua (1995) found that the accuracy of combined forecasts is expected to be much greater when using *a number of methods* (up to five) and *different types of data*.

Equal-weights combining has been shown to be effective at reducing forecast error under most conditions. However, differential weights are occasionally useful when they allow one to draw upon information as to which methods are most appropriate for a situation. They were used successfully to tailor the weights to the situation in rule-based forecasting (e.g., when uncertainty was high, less weight was placed on trend extrapolations and more on the naïve extrapolation).

A meta-analysis based on 30 studies (24 of which were conducted in the past quarter century) estimated a 12% reduction in error in comparison to the average error of the components (Armstrong 2001b). The error reductions ranged from 3 to 24%. Since this analysis, Makridakis and Hibon (2000) reported a 4.3% error reduction in the large scale M3-Competition with its 3,003 series. In some studies, combined forecasts were more accurate than even the most accurate of the component methods. Combining forecasts produced similar gains in accuracy for cross-sectional data as for time-series data.

Combining forecasts emerges as one of the most important ways to improve forecast accuracy. Interestingly, combining can improve accuracy even if one knows in advance which single method is most accurate.

Further research on combining should examine different ways of combining (e.g., mean vs. median) and also the conditions under which differential weights are justified.

Delphi

In the Delphi procedure, at least two rounds of forecasts are obtained independently from a small group of experts. After each round, the experts' forecasts are summarized and reported back to all of the experts. The group of experts is also informed about the reasons behind these predictions. All of the inputs are anonymous to reduce group pressure.

The Delphi procedure was developed at RAND in the 1950s and it has been widely used in businesses. There have been only a small number of multiple hypotheses tests on Delphi, with most of these of recent origin; Rowe and Wright (2001) identify ten of these in the past 25 years.

Given the research on the problems that traditional groups have with making predictions, one would expect that Delphi, with its structured judgment, would improve accuracy. Rowe and Wright (2001) found that Delphi improved accuracy over traditional groups in five studies, worsened accuracy in one, and was inconclusive in two. Using an alternative benchmark, they found Delphi to be more accurate than one-round expert surveys for 12 of 16 studies. There were two ties and two cases in which Delphi was less accurate. Over the 24 comparisons, Delphi improved accuracy in 71% and harmed it in 12%. Few studies allowed for estimates of the error reductions, although one study [cite?] found an error reduction of about 40%.

As might be expected, when the forecasts were in an area in which the panelists had *no* expertise, Delphi was of little value.

Much remains to be done on Delphi. What type of feedback will help to improve accuracy? Does the use of a trimmed mean lead to better results than using an average or median? How much expertise is needed? Under what conditions is Delphi most useful?

Well-established methods for cross-sectional forecasting

Causal Models

To use causal models, one must identify the dependent and causal variables, and then estimate the direction and size of the relationships. This requires much data in which there are substantial variations in each of the variable and the variations in the causal variable are independent of one another. For example, causal models might be used to predict the success of prospective job candidates based on data on the success among a wide group of previous jobholders and using data on causal variables such as intelligence and prior job success, where the variations in the causal variables are large and somewhat independent of one another.

Studies on the effectiveness of causal models date at least from the 1940s and research has continued since that time. This research shows that causal models reduce errors in comparison to unaided judgments (the most common approach to making forecasts with cross-sectional data). Grove et. al's (2000) meta-analysis, based on 136 studies (primarily from psychology, personality assessments, educational achievement, mental health, and medicine), found that causal models based on regression analysis reduced errors by 10% on average. The causal models were more accurate than unaided judgment in 88% of the comparisons.

Perhaps the most important gain in knowledge over the past quarter century has been in identifying the conditions under which unaided expert judgments are more accurate than the models (Grove et. al's 2000). For example, for the few [say how many or cite?] studies in which judgment was more accurate than the models, the judges generally had more information.

Research is needed on how to gain acceptance for causal models. Some organizations, such as football and baseball teams have adopted causal models with much success; but those who use this method are a small minority. Mostly, however, these findings are met with incredulity by practitioners, who counter with situations where they think that causal models would not improve accuracy.

Judgmental bootstrapping

What if there is insufficient information to develop causal variables either due to a lack of useful data on the dependent variable or to a lack of independent variation in the causal variables? This issue was solved in the early 1900s with a method that is now known as judgmental bootstrapping. It involves developing a model of an expert by regressing his forecasts against the information that he used. The general proposition seems preposterous: It is that the model of the man will be more accurate than the man. But there is some sense to it: The model applies the man's rules more consistently than he does.

Judgmental bootstrapping has been found to be more accurate than unaided judgment (the normal forecasting method for these situations) in 8 of 11 comparisons, with two tests showing no difference, and one showing a small loss. The typical error reduction was about 6% (Armstrong 2001a).

Four of these bootstrapping studies were done in the last quarter century. They have helped to demonstrate the improved accuracy due to bootstrapping as the new evidence supported previous findings, extended the work to an applied management problem (e.g., advertising), and showed a condition under which it does not help. The failure occurred when experts used incorrect rules (Ganzach et al 2000); in this case, bootstrapping applied incorrect rules more consistently and thus harmed accuracy.

While additional research is needed on the conditions under which judgmental bootstrapping is most useful, the primary need is to determine how to most effectively gain acceptance of bootstrapping. Although this approach can greatly reduce costs for repetitive forecasts (because the model can be used automatically), the method violates our common sense. How could a computer model of our forecasts make better forecasts than we can?

Practitioners seldom use judgmental bootstrapping, although it has had high profile uses by the Dallas Cowboys football team. The owner of the Philadelphia Flyers hockey team told me that he uses it and freely discusses it with other owners, secure in the belief that none of them will try to use it.

One possibility for implementation would be to develop freeware to guide people through this process. The freeware could provide instructions as for example conditions where bootstrapping is relevant, instructions for the selection of experts, forms for the collection of relevant information, a regression program, and a report writing template. Links would be provided to relevant literature.

Structured judgment

Structure can come in a variety of forms. Some of the key elements involve providing checklists, using systematic and well-summarized feedback on the accuracy of an expert's forecasts (used effectively in weather forecasting), helping experts to focus on relevant information (used by structured employment interviews), asking experts to justify their predictions, using independent experts with a diversity of information (hopefully with different biases), decomposing the problems, and using simple heuristics.

Although much pop management literature extols the value of intuition or gut feelings, a substantial amount of evidence, much from the past 25 years, suggests that a number of approaches to structured judgments are substantially more accurate than unstructured judgments. For summaries of this evidence, see the section on Expert Opinions in Armstrong (2001).

Structure can sometimes improve the accuracy of judgment to the extent that it is comparable to that from causal models. Jørgensen (2004) examined 12 guidelines for structuring experts' judgmental predictions of time to complete software projects. Using findings from 15 studies on software development costs, he found that structured judgments were more accurate than those from causal models in five studies, the same as causal in five, and less accurate in five.

Well-established methods for time-series forecasting

Causal Models

Causal models have been widely used for time-series forecasting. Much research has been done on causal models, including many multiple hypotheses studies. Allen and Fildes (2001) found that where there were good data, causal models were more accurate than non-causal extrapolations. For the 534 comparisons from a variety of studies involving long-range forecasts (most related to economics), causal models were more accurate than extrapolative models by a 2 to 1 ratio. Allen and Fildes did not, however, provide estimates of the expected error reduction; perhaps the obsession with statistical significance led researchers to overlook the need to assess effect sizes when evaluating forecasting methods.

Because they can include policy variables (such as the price of a product), causal methods are useful for forecasting the effects of decisions in government and business. This is particularly true when one has good domain knowledge, accurate data, the causal variable has a strong effect on the dependent variable and the causal models will change substantially (as is common when forecasts cover a lead time of many years). For example, causal models should be useful for a situation in which a manager would like to know the effects of a large change in prices.

Econometricians have devoted enormous efforts over the past 25 years in searching for ways to improve econometric methods. Unfortunately, while the complexity of the methods has increased, these efforts have not been shown to improve accuracy. There is a danger that the added sophistication of the methods leads forecasters to rely more on the data analysis and less on prior knowledge. In addition, with some exceptions (e.g., Allen and Fildes 2001), little attention has been paid to studying the conditions under which econometric methods are most useful.

Damped trend

Damped trend involves putting less emphasis on the trend extrapolation as uncertainty increases. Gardner (1985) showed that trend damping improves accuracy for extrapolation models. Gardner's exponential smoothing with damped trends was tested in a study involving the 1,001 series from the M-Competition (Gardner and McKenzie, 1985). Trend damping reduced forecast errors by 10.5% (average over forecast horizons 1-18) when compared with traditional exponential smoothing with a linear trend (Makridakis et al., 1982). In the M3-Competition (Makridakis and Hibon 2000), trend damping reduced forecast errors by 6.6% compared to traditional exponential smoothing. Gardner (1990) also tested trend damping in a Navy distribution system with more than 50,000 inventory items; implementation of trend damping reduced Naval inventory investment by 7% ($30 million) compared to the method that had been used previously, simple exponential smoothing. In addition, compared to reasonable benchmarks, trend damping has been successful on data related to annual consumer product sales (Schnaars 1986), cookware sales (Gardner and Anderson, 1997), computer parts (Gardner, 1993), and process industry sales (Miller and Liberatore 1993).

However, Fildes et al. (1998), in a study involving 261 telecommunications series for horizons of up to 12 months, found that damping *reduced* the accuracy of Holt's exponential smoothing by 16.8% (based on the two criteria in their table 4). In all, there have been ten multiple-hypotheses studies on damped trend. They have led to an average error reduction of about 4.6%.

Further research would be useful to determine the conditions under which damping is most useful. In addition, there may be other ways to use trend damping. For example, because uncertainty increases over the forecast horizon, it would seem desirable to do more damping as the horizon increases.

Promising findings with limited evidence on accuracy

This section contains forecasting methods that show promise, but where the evidence is limited. In my search, I favored methods that showed large improvements in accuracy. I avoided one-shot studies with small improvements, especially when there was no prior reason to expect that they would be more accurate. I also avoided murky papers: It is the responsibility of researchers to ensure that their papers are clearly written.

Promising methods for cross-sectional data

Damped causality

One of the basic generalizations in forecasting is to be conservative given uncertainty. This rule is incorporated into regression so that as the uncertainty due to errors in the variables increases, the estimated relationship decreases in absolute magnitude. However, regression estimates provide insufficient adjustments for the errors. Statisticians have long been aware of this problem and have recommended methods for shrinking the estimates.

In a large-scale study of cross-sectional data, Dana and Dawes (2004) showed that the gain from equal weights is larger when sample sizes are smaller and predictability is poor. These studies compared two extremes: equal weights versus regression weights. The optimal approach most likely lies in between these two methods.

Damped estimates of causality should also be relevant for time-series data because one must contend with the uncertainty involved in forecasting the causal variables. This suggests damping coefficients toward zero or damping the forecasts of the changes in the causal variables. However, this is speculative as I was unable to find multiple hypotheses tests on real-world data.

Simulated interaction

Simulated interaction is a form of role-playing. To use simulated interaction, an administrator obtains a description of the target situation, descriptions of the main protagonists' roles, and a list of possible decisions. Role players adopt a role and read about the situation. They then improvise realistic interactions with the other role players until they reach a decision. The role players’ decisions are used to develop a forecast. The typical session lasts less than an hour.

A similar procedure has been used by the military since the 1920s and in jury trials since the 1970s. It has rarely been used in businesses although there have been published reports on its use in marketing and personnel selection. Despite this long-term use, no multiple hypotheses tests were published prior to 1987.

Simulated interaction is expected to be particularly useful in conflicts (such as in buyer/seller negotiations, union/management relations, legal cases, wars, and terrorism) because it is so difficult to think through the many actions and reactions among the parties involved. Simulated interactions allow for a more realistic representation. Relative to the current forecasting method (expert judgment) simulated interactions reduced forecast errors by 57% in the eight situations tested to date (Green 2002, 2005). The gains were achieved even though the roles were played by university students who had little knowledge of the types of conflict situations being used. Further information is available at conflictforecasting.com.

Structured analogies

In everyday life, people often refer to analogies when making forecasts. For example, some advised against a military action in Iraq because they saw it as similar to Viet Nam. However, this is usually done in an unstructured manner. The assumption behind structured analogies is that experts can provide useful information about analogies, but they are not effective at translating this information into forecasts. The latter task should be done in a mechanical manner to avoid biases.

In order to use the structured analogies method, an administrator prepares a description of the target situation and selects experts who have knowledge of analogous situations. Then, the experts identify and describe analogous situations, rate their situation’s similarity to the target situation, and match the outcomes of their analogies with potential outcomes in the target situation. The administrator then derives forecasts from the information the experts provided about their most similar analogies.

Green and Armstrong (2005) obtained structured analogies forecasts for eight conflict situations (e.g., one of the situations involved a country in the Middle East that built a dam that reduced water to a country downstream; how would the conflict be resolved?) When experts were able to report on two or more analogies, and where a mechanical rule was then used to make a forecast, there was a 41% reduction in error as compared to using unaided experts to make the forecasts.

Judgmental decomposition

Judgmental decomposition refers to the multiplicative breakdown of a problem. Experts make estimates of each component, and these are multiplied. For example, one could estimate a brand's market share and the total market, and multiply estimates to get a sales forecast. This method is relevant for situations where one knows more about the components than about the target variable. Thus, the analyst should identify segments that are easy to predict.

Decomposition was especially important when there was high uncertainty in predicting the target variable. MacGregor (2001, Exhibit 2) summarized results from three studies (two done since 1988) involving 15 tests and found that judgmental decomposition led to a 42% reduction in error under high uncertainty.

Summary of promising methods for cross-sectional data

Table 1 summarizes the gains in accuracy for the promising methods that relate to cross-sectional data. The table list the gains that were achieved for the conditions stated. The conditions were narrow. Given the evidence to date, simulated interaction and structured analogies apply only to conflict situations, and the gains for judgmental decomposition apply only when there is high uncertainty and when one has better knowledge of the components than of the global values.

Insert Table 1 about here

Promising methods for time-series data

Segmentation

Segmentation is based on an old idea: spread your risk. It would seem advantageous because the forecasting errors in the different segments may offset one another. Assume that you had ten divisions in a company. You might improve accuracy by forecasting each division separately, then adding the forecasts. But there is a problem. If the segments are based on small samples and erratic data, the segment forecasts might contain very large errors. However, segmentation can often allow for more effective use of information. Jorgensen (2004) for example, reports that experts prefer the bottom-up approach as it allows them to more effectively use their knowledge about the problem.

Armstrong (1985, p. 287) reported three comparative studies on segmentation that were conducted in the past quarter century. A typical study would break the problem into segments, and then forecast each segment either by extrapolation or regression. Segmentation improved accuracy for all three studies. In addition, Dangerfield and Morris (1992), in their study on bottom-up forecasting, found that segmentation was more accurate for 74% of 192 monthly time series from the M-Competition. In a study involving seven teams making estimates of the time required to complete two software projects, Jorgensen (2004) found that the error from the bottom-up forecast was 51% less than that for the top-down approach.

Structured judgmental adjustments

Forecasters often make unstructured judgmental adjustments to times-series forecasts. These can be a source of bias. For example, managers could inflate a sales forecast in the belief that this will motivate employees. Salesmen might deflate a forecast so it is easier to exceed. Therefore, it was not surprising when some early studies concluded that unstructured adjustments often harmed forecasts.

There are several ways to structure judgmental adjustments. These include providing written instructions for the task, soliciting written adjustments, requesting adjustments from a group of experts, asking for adjustments to be made prior to seeing the forecasts, and recording reasons for revisions.

In Goodwin (2005), 14 papers published since 1989 provided evidence on judgmental adjustments. It is difficult to summarize the results because the studies used different ways to structure judgment. However, adjustments seemed useful when:

a) recent events were not fully reflected in the data. Thus, adjustments might be made to revise the current level of the variable being forecast.
b) historical data were limited.
c) experts possessed good domain knowledge about future changes that have not been included in the model (e.g., last-minute price reductions for a product).

Findings to date suggest that minor revisions should be avoided, perhaps because they lead to over-adjustments.

Little is known about the amount of improvement possible from structured judgmental adjustments to time-series forecasts. Further research is also needed on the conditions under which judgmental adjustments are useful. For example, there may be cases, such as adjusting for recent events, where mechanical adjustments might be superior to judgmental adjustments.

Rule-based forecasting

Rule-based forecasting (RBF) is a method for weighting and combining extrapolation methods based on features of time-series (Collopy & Armstrong 1992). It integrates judgment and statistical procedures to tailor forecasts to the domain. RBF does this primarily by identifying key features in time series such as irregularities and instabilities and by capturing managers' knowledge of the domain and expectations about direction of the trend (causal forces). The knowledge is captured in production rules. Some of the rules can be applied in a simple manner. For example, when managers' knowledge about causal forces (expected direction of trend) conflicts with historical trends, a situation referred to as "contrary series," traditional extrapolation methods produce enormous errors. A simple rule for contrary series is to forecast that there will be no trend. When tested on M-Competition data (Makridakis et al 1982) along with data from four other data sets, the median Absolute Percentage Error (MdAPE) was reduced by 17% for one-year-ahead forecasts and by over 40% for six-year-ahead forecasts (Armstrong & Collopy 1993). Further information is provided on the Rule-based Forecasting Special Interest Group at forecastingprinciples.com.

Empirical results on multiple sets of time series have indicated that RBF produces forecasts that are more accurate than traditional methods and equal weights combining. RBF is most useful when one has good domain knowledge, the domain knowledge has a strong impact, the series is well-behaved, and there is a strong trend in data. When these conditions do not exist, RBF neither harms nor improves accuracy (Collopy and Armstrong, 1992). Given only a modest amount of domain knowledge, for one-year ahead ex *ante* forecasts of 90 annual series, the MdAPE for RBF was 13% less than that from equally weighted combined forecasts. For six-year ahead *ex ante* forecasts, it had an MdAPE that was 42% less. In comparison with equal-weights combining, RBF was more accurate only for those series for which there was domain knowledge (Collopy and Armstrong, 1992). Adya (2000) replicated these findings after correcting minor mistakes in the rule-base. In the M3-Competition, RBF was run using automatic procedures (Adya et al. 2001) and without any domain knowledge. RBF was the most accurate of the 22 methods for annual forecasts involving 645 series and six-year horizons (Makridakis and Hibon, 2000; Adya, et al. 2000). Its symmetric MAPE (Mean Absolute Percentage Error) was 3.8% less than that for combining. Vokurka, et al (1996) tested an alternative version of RBF using the same 126 series as used by Collopy and Armstrong (1992). Although they did not use domain knowledge, the MdAPE for six-year ahead annual forecasts was 15% less for RBF than that for combined forecasts.

Decomposition by causal forces

Contrary series are defined as those in which causal forces drive the series in opposite directions. If the components of a contrary series can be forecast more accurately than the global series, it helps to decompose the problem by causal forces (Armstrong, Collopy and Yokum 2005). For example, to forecast the number of people that die on the highways each year, forecast the number of passenger miles driven (a series expected to grow), and the death rate per million passenger miles (a series expected to decrease), then multiply these forecasts. When tested on five time series that clearly met the conditions, decomposition by causal forces reduced forecast errors by two-thirds. For the four series that partially met the criteria, the errors were reduced by one-half.

Although the gains in accuracy were large, there is only a single study on decomposition by causal forces. In addition, contrary series are not common. Perhaps the most common situation is when forecasting revenues of a product (such as computer software) where the price is decaying, the number of units and inflation are growing, and market share trends depend on the comparative advantages of the software. When contrary series do occur, the forecasting errors from traditional methods tend to be large.

Damped seasonal factors

Miller and Williams (2003, 2004) developed a procedure for damping seasonal factors. Given uncertainty and errors in the historical data, their procedure damps the seasonal factors (e.g., multiplicative factors are drawn towards 1.0 and additive seasonal factors towards zero). This is useful because otherwise the estimated seasonal factors are affected by errors in the data. The Miller-Williams procedures reduced forecast errors by about four percent in tests involving the 1,428 monthly time series from the M3-Competition. The damped seasonal forecasts were more accurate for 68% of the series.

Bunn and Vassilopoulos, (1999) damped seasonal estimates by averaging those for a given series with seasonal factors estimated for a set of related series. This approach reduced forecast error by about 20%. When Gorr, Oligschlager & Thompson (2003) pooled monthly seasonal factors for crime rates for six precincts of a city, the forecasts were 7% more accurate than when the seasonal factors were estimated individually for each precinct. On average then, averaging seasonal factors across series led to a 13.5% error reduction.

This area is promising because the estimation of seasonal factors might be improved through the use of domain knowledge, especially for short series. For example, experts can avoid the use of seasonal factors in areas where there is no reason to expect seasonality (such as in the stock market) and rely on them in areas where seasonal factors are obvious, such as for ice cream sales. Finally, because uncertainty increases over time and seasonal influences might change, increased damping might improve accuracy for longer time horizons.

Summary of promising methods for time-series data

Table 2 summarizes the gains for the promising methods for time series. The gains apply only for the conditions stated. These are narrow for rule-based forecasting and for decomposition by causal forces. In other words, the gains would be expected to be small as one departs from these ideal conditions.

Insert Table 2 about here

Tested areas with little gain in accuracy

Evidence–based forecasting can also show what does not work. Some areas with much research efforts have shown limited gains in accuracy. In some cases, this may be due to the small number of papers testing multiple hypotheses. In other cases it might simply be that the effects on accuracy are so small that they are difficult to measure.

Time-series forecasts

Data mining

The key assumption of data mining is that, given large amounts of data, statistical analysis can determine patterns that will aid in forecasting. Similar to the approach used in stepwise regression, data mining ignores theory and prior knowledge. It merely searches for pattern in the data.

Data mining is popular. On September 5, 2005, a Google search using the term "data mining" resulted in seven million sites. When specified that either prediction or forecasting be included in the search, Google produced half a million sites. The interest in data mining is aided by the availability of large data sets such as those found with scanner data in stores.

Keogh and Kasetty (2002) conducted a comprehensive search for empirical comparisons of data mining. They criticize the failure of data mining researchers to test alternative methods. To address this problem, they found procedures from two dozen papers on data mining, which they then tested on 50 real-world data sets. Keogh (personal correspondence) concluded:

> "[Professor X] claimed to be able to do 68% accuracy. I sent them some "stock" data and asked them to do prediction on it, they got 68% accuracy. However, the "stock" data I sent them was actually random walk! When I pointed this out, they did not seem to think it important. The same authors have another paper in [the same journal], doing prediction of respiration data. When I pointed out that they were training and testing on the same data and therefore their experiments are worthless, they agreed (but did not withdraw the paper). The bottom line is that although I read every paper on time-series data mining, I have never seen a paper that convinced me that they were doing anything better than random guessing for prediction. Maybe there is such a paper out there, but I doubt it."

I have been unable to find evidence that data-mining techniques improve forecasting accuracy for time series. In general, methods that have ignored theory, prior evidence, and domain knowledge have had a poor record in forecasting. For example, stepwise regression has proven to be detrimental to forecasting accuracy.

Neural nets

Neural nets, which are designed to pick up nonlinear patterns from long time series, have been an area of great interest to researchers. Wong, Lai & Lam (2000) found over 300 research papers published on neural nets during 1994-1998. Early reviews on the accuracy of neural nets were not favorable (Chatfield 1993 refers to some of these). However, Adya and Collopy (1998) found eleven studies that met the criteria for a comparative evaluation, and in 8 of these (73%), neural nets were more accurate. There were no estimates of the error reductions versus alternative methods although Liao and Fildes (2005), in a test involving 261 series, 18 horizons, and 5 forecast origins, found impressive gains in accuracy for neural nets with an error reduction of 56% compared to damped trends. Chatfield (personal correspondence) suspects that there is a ‘file-drawer problem,’ saying that he knew of some studies that failed to show gains and were not submitted for publication, and there is a well-known bias by reviewers against papers with null results. Also, the comparisons were sometimes against less effective forecasting methods, not against damped trend or combining.

Because all studies are not equal, I turned to the large-scale M3-Competition with its 3,003 varied time series. Here, neural nets were 3.4% less accurate than damped trends and 4.2% less accurate than combined forecasts.

Given, the mixed results on accuracy and the difficulties in using and understanding neural nets, my conclusion is that too much research effort is being devoted to this method. On the other hand, the impressive findings from Liao and Fildes (2005) deserve further attention in an effort to discover the conditions under which neural nets are useful. For the latest on neural nets, see the special interest group at forecastingprinciples.com.

Box-Jenkins methods

Researchers have published an immense number of studies using Box-Jenkins methods for the extrapolation of time series. The interest has spread beyond academics: a general Google search on “Box-Jenkins” in November 2005 produced over 110,000 hits. Some early small-scale studies showed promise. However, using the M-Competition study (Makridakis et al. 1982), I compared average MAPE for Box-Jenkins (BJ) with combining over the 18 forecast horizons for the 111 series in which there were comparisons. In this analysis, the BJ forecasts were 1.7% less accurate. In the M2-Competition, with 29 series (23 from companies), I examined the MAPE over 15 horizons for the 3-year period; the BJ forecasts were 27% less accurate than either damped trend or combined exponential smoothing (Makridakis, et al. 1994). For the M3-Competition, none of the BJ models yielded forecasts that were as accurate as the combined forecasts for any of the ten forecast horizons reported in the table. As a crude measure, I averaged the symmetric MAPE errors across the 3,003 series and 18 forecasts horizons and found that the four BJ models were, on average, 7.6% less accurate than damped trends and 8.3% less accurate than combining (Makridakis and Hibon 2000, Table 6).

Widely used methods that have been subject to little testing

The following areas represent methods that are widely used, but in which there has been little testing. Further multiple hypotheses studies are needed in these areas.

All types of data

Prediction markets

Studies in the early 1900s by psychologists showed that accuracy could be improved by aggregating across a large number of people. But this had been obvious many years before as people had used markets to predict what would happen in politics and sports. If you want to get an unbiased forecast of future events by judgment, create a market and let people bet on possible outcomes.

Most comparative testing of prediction markets (information markets) has been done in financial and commodities markets and in sports. While I was unable to find a meta-analysis in these areas, a large number of studies have been published in which forecasters have struggled in vain since the 1920s to develop methods that are superior to financial markets. In addition, small-sample studies show that betting markets were more accurate than political polls for forecasting political elections (Wolfers and Zitewitz 2004).

Over the past quarter century, little research has been done to improve our knowledge about the use of prediction markets. It would be useful to test prediction markets against other structured group methods, such as Delphi. In addition, we know little about the conditions under which prediction markets are most useful. It seems likely, for example, that if people know little about a situation, there would be little to gain from a prediction market. In addition, if their knowledge were generally wrong, there would seem to be little benefit. For example, contrary to a large body of empirical research, most people believe that a minimum wage law is good for the economy and for poor people. What could a prediction market add if a forecast was needed on the impact of a change in the minimum wage? Another issue is how to deal with cascades. These occur because people in a market base their predictions on their own information and on the decisions by others. If information is weak and some people make poor predictions, this will be observed by others who may believe that the predictions were based on good information, so they might follow them.

According to Surowiecki (2004), prediction markets are being used for forecasting within companies. It seems reasonable to expect them to be more accurate than traditional meetings, but this would apply to nearly any structured method.

Cross-sectional data

Conjoint analysis

In conjoint analysis, people are asked to state their preferences from pairs of offerings. For example, various features of a personal digital assistant (PDA), such as price, weight, and battery life might be varied to develop a set of offerings. The values for the features are varied so that they do not correlate with one another. These offerings would then be presented to a sample of potential customers to assess the likelihood that they would purchase each offering. Their responses can be analysed by regressing their choices against the product features. The method is called “conjoint analysis” because respondents *consider* the product features *jointly*. This forces them to consider tradeoffs among the various features.

Conjoint analysis is analogous to judgemental bootstrapping except that one is examining customers’ preferences rather than experts’ judgments about the sales volumes for each offering. The approaches can be used on similar problems, such as for new product forecasting. However, I have been unable to find any comparisons of these methods. Certainly the judgmental bootstrapping approach should be much less expensive as needs only about 5 to 20 experts, where as conjoint analysis might require hundreds of carefully selected customers.

Although conjoint analysis seems to be based on solid principles, there have been no tests against alternative methods, despite repeated calls for such research (Wittink & Bergestuen 2001).

Game theory

Game theorists have studied the behavior of subjects in various games, such as the Prisoners’ Dilemma. A number of researchers and consultants have suggested that the behavior in such games can be used to predict behavior in the real world. While this approach has much intuitive appeal, attempts to find comparative studies on the value of game theory for forecasting have been unsuccessful.

In a related study, however, Green (2005) asked game theorists to use game theory to make predictions for eight conflict situations. The game theorists were also expected to benefit from their long experience with conflict situations as well as by their ability to use game theory. As it turned out, their predictions were no more accurate than those made by university students.

Structured judgmental adjustments

Judgmental adjustments of cross-sectional predictions are common. For example, one might have a model to rate whether someone should undergo a medical operation. In contrast to time-series forecasting, however, judgmental adjustments do not seem to improve cross-sectional predictions. Meehl (1956), in reviewing the evidence on predictions about people, concluded “ . . . it almost looks as if the first rule to follow in trying to predict the subsequent course of a student’s or patient’s behavior is to carefully avoid talking to him, and the second rule is to avoid thinking about him.” This conclusion also applies to personnel predictions because employers over-ride the forecasts with irrelevant information. Grove et al. (2000), in their meta-analysis, found further support; when judges had access to interviews with the subject, their predictions were less accurate.

Meehl’s advice was followed with great success by the general manager of the Oakland Athletics baseball team (Lewis 2004). He intentionally avoided watching games so his evaluation of a player would not be affected by his judgment; instead, he used statistics to make his decisions.

Time series data

Diffusion models

Diffusion models assume that a series will start slowly, begin a rapid rise, and then gradually approach a saturation level. This has great intuitive appeal as one can see when plotting the historical sales of products such as refrigerators, TVs, and personal computers. However, despite the substantial research on diffusion models, there have been few tests of comparative forecast accuracy to date, and these tests have produced mixed results. Meade and Islam (2001), in their review of the accuracy of alternative methods, found that no one diffusion model dominated, that simpler models were about as accurate, and that the gains were small compared to simple benchmark models. [Refer instead to Meade 2006?].

Leading indicators

While leading indicators have been widely used since the 1930s, few multiple hypotheses tests have been conducted. Tests done in the 1990s caused some concern. However, McGuckin and Ozyildirim (2004) provide evidence that leading indicators improve accuracy for macroeconomic forecasts.

Discussion

In November 2005, I searched for “forecasting OR predicting” among the titles and topics on the Social Science Citation Index (SSCI): This yielded over 15,000 papers. In addition, many papers that contribute to forecasting do not contain these keywords in the title or topic; Armstrong and Pagell (2003) estimated that only 42% of the relevant papers do so. Thus, there may have been about 35,000 papers relevant to forecasting (that excludes the Science Citation Index, which has substantially more such studies than the SSCI). Based on this paper, I made a rough estimate that there are about 300 multiple hypotheses papers related to assessing accuracy; this represents less than one percent of the total papers published on forecasting. Perhaps there is an additional one percent of multiple hypotheses studies related to other aspects of forecasting such as assessing uncertainly or gaining acceptance. Using a much different approach, Armstrong and Pagell (2003) estimated that only 3% of the papers in forecasting assessed which methods contribute to the development for principles for forecasting.

As can be seen from Fildes (2006), the assessment of usefulness is not a prime consideration among academic researchers. Many people have noted this problem over the years, but there is little evidence that things are changing. Compare our papers and you will see that there is little overlap between papers that are influential among academics and those that have been demonstrated to better forecasting procedures. This is not to imply that the advances noted by Fildes will not be shown to be useful, but merely that the jury awaits findings from evaluation research.

Undoubtedly, despite the extensive help on this paper from colleagues, relevant papers have been overlooked here. Undoubtedly there are useful methods that have not been properly tested.

The methods that I referred to as promising are in need of replication. As has been shown in other fields, promising findings often fail when attempts are made at replication. My expectation is that additional research will identify conditions under which these methods fail.

A number of seemingly useful methods (such as prediction markets and conjoint analysis) will continue to be applied even though research lags. Given that these methods are consistent with basic forecasting principles, I applaud their use. Nevertheless, we could learn much about the conditions under which they are most useful.

The findings over the past quarter century are not so surprising as might seem at first glance. The successful methods follow some basic generalizations in forecasting:

- *Be conservative when uncertain*: Damping methods are based on the need to be conservative in the face of uncertainty.
- *Spread risk*: Decomposition, segmentation and combining are based on spreading risk, while efforts to find the single best method often lead one astray.
- *Use realistic representations of the situation*: Simulated interaction and structured analogies are consistent with developing methods that represent situations in a realistic manner, while game theory fails on this.
- *Use lots of information*: Methods that use more information (e.g., combining, prediction markets) are superior to those that rely on a single source (e.g., exponential smoothing).
- *Use prior knowledge:* Methods based on prior knowledge about the situation and relationships (e.g., econometric methods) are superior to those that rely only on the data (e. g., exponential smoothing, Box-Jenkins).
- *Use structured methods:* Structured methods are more accurate than unstructured methods. This shows up, for example, in the judgmental adjustments to forecasts.

Speculation

What new areas might lead to improved accuracy over the next 25 years? Two areas stand out in my judgment: index methods and combined methods.

Index methods

Consider a situation where you have many variables that affect an outcome. This occurs, for example, when forecasting growth in national incomes: By my count, there are at least 50 causal variables. Alternatively, consider the U.S. presidential election where there are a host of factors that influence votes. In such cases, there is not enough data to obtain estimates for traditional causal models (such as those estimated by regression). However, such problems have been approached through the use of index methods.

To use an index method, an analyst prepares a list of all variables that might have an effect of the variable to be forecast (e.g., national income), then determine for each observation (e.g., France) whether each variable is favorable (+1), unfavorable (-1) or indeterminate (0). He would then add the scores and use the total in making forecasts. Thus, each variable has the same weight. Applied to forecasting, this use of judgmental indexes has been called “experience tables” or “index methods.”

This simple, easily understood method is expected to aid forecasting in situations where there are many causal variables, good domain knowledge about which variables are important and about the direction of effects, and limited amounts of data. These conditions apply where discrete choices must be made, such as for the selection of personnel, retail sites, investment opportunities, product names, or advertising campaigns. In addition, they can be used to prepare quantitative forecasts.

Lichtman (2005) reported that his “Keys model,” based on a subjective index of 13 variables, picked the winner of every U. S. presidential election since 1860 (retrospectively through 1980 and prospectively from 1984-2004). This record cannot be matched by any of the traditional quantitative models, which are based on regression analyses involving three or four variables.

Combined methods

There may be benefits in combining forecasting methods. For example, judgmental bootstrapping might be used along with regression analysis to develop a hybrid causal model. Judgmental bootstrapping could be used to obtain estimates for variables for which there is insufficient information (for example, a causal variable such as price might have remained constant over a given time series).

The integration of judgment and quantitative methods provides another promising area for combining methods. Indeed, this has been one of the key areas for research over the past quarter century. A review by Armstrong and Collopy (1998) found 47 papers related to the integration of judgment and quantitative methods; all but 2 of these studies were published in the last quarter century.

Conclusions

Studies that have used multiple reasonable hypotheses for important problems have led to much progress. These studies are especially helpful when they describe the conditions under which hypotheses apply.

Over the past quarter century, substantial evidence from comparative studies has supported seven forecasting methods. Two of these methods apply to all types of data: combined forecasts with an estimated 12% error reduction, and Delphi, which improved accuracy in of 19 of 24 comparisons (79%), though there was insufficient information to estimate the amount of error reduction. Three methods apply to cross-sectional data: causal models with a 10% error reduction, judgmental bootstrapping at 6%, and structured judgment for which I had no estimate of the savings. Two methods apply to time series data: damped trend with a 5% error reduction, and causal models with improved accuracy for 2/3 of the 534 comparisons (no estimates were made of the size of the error reductions). These methods apply to a broad range of conditions. Practitioners should implement these well-established methods.

Researchers should give particular attention to the methods designated as promising. In contrast to the error reductions of 5% to 12% for the well-established findings, the gains in these promising areas ranged from 4% to 67%.

In judging the value of these promising methods, one should consider the conditions. For example, while damping with analogous series produced only a 5% error reduction, the conditions are quite common. The same applies to the 4% error reduction when using damped seasonality. In contrast, decomposition by causal forces produced large error reductions but the conditions are not common.

The evidence is sparse in most of these promising areas (e.g., there is only one study on decomposition by causal forces). However, the size of the gains suggests that they are worthy of use in firms. In addition, each of these methods is consistent with basic principles of forecasting.

Implementation of the promising methods can be done at low risk by using the methods experimentally as part of a combined forecast. In addition to replications and extensions, further research is needed on the extent of the gains, the conditions under which these methods are appropriate, and the most effective way to apply these methods.

The testing of multiple reasonable hypotheses has also identified areas that offer little promise even after much research. These include neural nets, data mining, and Box-Jenkins methods.

Some widely used methods, such as prediction markets, conjoint analysis and game theory, would benefit from multiple hypotheses testing. Do they improve accuracy, and if so, under what conditions? What are the most effective ways to use these methods?

Multiple hypotheses studies have proven to be useful for advancing knowledge on the accuracy of forecasting methods. We need more of these studies, especially when they produce surprising results for important problems. Imagine the gains if ten percent of the papers used the method of multiple hypotheses, rather then the current level of perhaps two percent.

Table 1: Promising methods for cross-sectional data

Method	Conditions	General research effort	Multiple hypotheses studies	Multiple hypotheses tests	Alternative methods	Percent error reduction
Simulated interaction	Conflicts with 2 or more parties	Low	6	9	unaided judgment	57
Structured analogies	Conflicts with 2 or more analogies per expert	Very low	1	8	unaided judgment	41*
Judgmental decomposition	very large or small numbers; knowledge of components	Low	3	15	unaided judgment	42

*Based on single study

Table 2: Promising methods for time-series data

Method	Primary Conditions	General research effort	Multiple hypotheses studies (tests)	Alternative methods	% error reduction (% better)
Segmentation	none	Low	6	top down; global	51* (74)*
Structured adjustments	Recent events, limited data & domain knowledge	Moderate	14	unadjusted forecasts	NA
Rule-based forecasting/ causal forces	domain knowledge, annual data & long-term	Low	5/1	combining	42
Decomposition by causal forces	conflicting forces	Very low	1 (5)	global forecasts	67*
Damped trend with analogous data	small samples	Low	1	undamped trend	5*
Damped seasonality	uncertainty; analogous data	Low	3	undamped seasonality	4*; 13 (68)*

* Based on single studies

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[All papers by Armstrong are available in full-text at jscottarmstrong.com]

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