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25 years of time series forecasting

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Abstract

We review the past 25 years of research into time series forecasting. In this silver jubilee issue, we naturally highlight results published in journals managed by the International Institute of Forecasters (*Journal of Forecasting* 1982–1985 and *International Journal of Forecasting* 1985–2005). During this period, over one third of all papers published in these journals concerned time series forecasting. We also review highly influential works on time series forecasting that have been published elsewhere during this period. Enormous progress has been made in many areas, but we find that there are a large number of topics in need of further development. We conclude with comments on possible future research directions in this field.

Keywords: Accuracy measures; ARCH; ARIMA; Combining; Count data; Densities; Exponential smoothing; Kalman filter; Long memory; Multivariate; Neural nets; Nonlinearity; Prediction intervals; Regime-switching; Robustness; Seasonality; State space; Structural models; Transfer function; Univariate; VAR

1. Introduction

The International Institute of Forecasters (IIF) was established 25 years ago and its silver jubilee provides an opportunity to review progress on time series forecasting. We highlight research published in journals sponsored by the Institute, although we also cover key publications in other journals. In 1982, the IIF set up the *Journal of Forecasting* (*JoF*), published with John Wiley and Sons. After a break with Wiley in 1985,[2] the IIF decided to start the *International Journal of Forecasting* (*IJF*), published with Elsevier since 1985. This paper provides a selective guide to the literature on time series forecasting, covering the period 1982–2005 and summarizing over 940 papers including about 340 papers published under the "IIF-flag". The proportion of papers that concern time series forecasting has been fairly stable over time. We also review key papers and books published elsewhere that have been highly influential to various developments in the field. The works referenced

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[2] The IIF was involved with *JoF* issue 44:1 (1985).

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comprise 380 journal papers and 20 books and monographs.

It was felt to be convenient to first classify the papers according to the models (e.g., exponential smoothing, ARIMA) introduced in the time series literature, rather than putting papers under a heading associated with a particular method. For instance, Bayesian methods in general can be applied to all models. Papers not concerning a particular model were then classified according to the various problems (e.g., accuracy measures, combining) they address. In only a few cases was a subjective decision needed on our part to classify a paper under a particular section heading. To facilitate a quick overview in a particular field, the papers are listed in alphabetical order under each of the section headings.

Determining what to include and what not to include in the list of references has been a problem. There may be papers that we have missed and papers that are also referenced by other authors in this Silver Anniversary issue. As such the review is somewhat "selective", although this does not imply that a particular paper is unimportant if it is not reviewed.

The review is not intended to be critical, but rather a (brief) historical and personal tour of the main developments. Still, a cautious reader may detect certain areas where the fruits of 25 years of intensive research interest has been limited. Conversely, clear explanations for many previously anomalous time series forecasting results have been provided by the end of 2005. Section 13 discusses some current research directions that hold promise for the future, but of course the list is far from exhaustive.

2. Exponential smoothing

2.1. Preamble

Twenty-five years ago, exponential smoothing methods were often considered a collection of ad hoc techniques for extrapolating various types of univariate time series. Although exponential smoothing methods were widely used in business and industry, they had received little attention from statisticians and did not have a well-developed statistical foundation. These methods originated in the 1950s and 1960s with the work of Brown (1959, 1963), Holt (1957, reprinted 2004), and Winters (1960). Pegels (1969) provided a simple but useful classification of the trend and the seasonal patterns depending on whether they are additive (linear) or multiplicative (nonlinear).

Muth (1960) was the first to suggest a statistical foundation for simple exponential smoothing (SES) by demonstrating that it provided the optimal forecasts for a random walk plus noise. Further steps towards putting exponential smoothing within a statistical framework were provided by Box and Jenkins (1970), Roberts (1982), and Abraham and Ledolter (1983, 1986), who showed that some linear exponential smoothing forecasts arise as special cases of ARIMA models. However, these results did not extend to any nonlinear exponential smoothing methods.

Exponential smoothing methods received a boost from two papers published in 1985, which laid the foundation for much of the subsequent work in this area. First, Gardner (1985) provided a thorough review and synthesis of work in exponential smoothing to that date and extended Pegels' classification to include damped trend. This paper brought together a lot of existing work which stimulated the use of these methods and prompted a substantial amount of additional research. Later in the same year, Snyder (1985) showed that SES could be considered as arising from an innovation state space model (i.e., a model with a single source of error). Although this insight went largely unnoticed at the time, in recent years it has provided the basis for a large amount of work on state space models underlying exponential smoothing methods.

Most of the work since 1980 has involved studying the empirical properties of the methods (e.g., Bartolomei & Sweet, 1989; Makridakis & Hibon, 1991), proposals for new methods of estimation or initialization (Ledolter & Abraham, 1984), evaluation of the forecasts (McClain, 1988; Sweet & Wilson, 1988), or has concerned statistical models that can be considered to underly the methods (e.g., McKenzie, 1984). The damped multiplicative methods of Taylor (2003) provide the only genuinely new exponential smoothing methods over this period. There have, of course, been numerous studies applying exponential smoothing methods in various contexts including computer components (Gardner, 1993), air passengers (Grubb &