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Forecasting and inventory performance in a two-stage supply chain with ARIMA(0,1,1) demand: Theory and empirical analysis

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ABSTRACT

The ARIMA(0,1,1) demand model has been analysed extensively by researchers and used widely by forecasting practitioners due to its attractive theoretical properties and empirical evidence in its support. However, no empirical investigations have been conducted in the academic literature to analyse demand forecasting and inventory performance under such a demand model. In this paper, we consider a supply chain formed by a manufacturer and a retailer facing an ARIMA(0,1,1) demand process. The relationship between the forecasting accuracy and inventory performance is analysed along with an investigation on the potential benefits of forecast information sharing between the retailer and the manufacturer. Results are obtained analytically but also empirically by means of experimentation with the sales data related to 329 Stock Keeping Units (SKUs) from a major European superstore. Our analysis contributes towards the development of the current state of knowledge in the areas of inventory forecasting and forecast information sharing and offers insights that should be valuable from the practitioner perspective.

1. Introduction

The classical approach towards inventory forecasting considered by researchers and practitioners alike consists of selecting an accurate forecasting method that is subsequently used for stock control purposes. However, it should be noted that this approach tends to look at demand forecasting and inventory management as two independent stages without interactions, which may lead to a sub-optimal performance of the whole system (Syntetos et al., 2010). In fact, previous research has shown that forecast accuracy is to be distinguished from the performance of the forecasts when utility measures are employed, especially in an inventory management context where the interactions between forecasting and stock control are not yet fully understood (Syntetos et al., 2009b; Babai et al., 2010; Ali et al., 2011). That is to say, forecast accuracy improvements do not necessarily imply inventory cost savings and/or a service level increase.

Ali et al. (2011) have investigated the scale of inventory savings according to the degree of improvement in forecasting accuracy by analysing a two-stage supply chain where two information sharing strategies are considered. The first, termed as No Information Sharing (NIS), relates to not sharing any information with the downstream supply chain members. Under such a strategy, the upstream members base their forecasts on the orders received from the downstream members and no information sharing mechanisms are employed. The second strategy, termed as Forecast Information Sharing (FIS), relates to the supply chain members (say a retailer and the manufacturer) using the same forecasts to place orders. The research under concern was conducted assuming stationary demand processes (Auto-Regressive, AR(1); Moving Average, MA(1) and ARMA(1,1)) and it resulted in some very important findings: (i) there is a substantial forecast-accuracy related benefit resulting from FIS and the relevant gains depend on the demand process; (ii) the percentage reductions in inventory holdings and costs are generally less than the percentage gains in forecasting errors; (iii) the translation of the accuracy gains to inventory savings depends on the magnitude of the forecast accuracy improvement, regardless of the demand process. Non-stationary processes though were not considered.

The (Auto-Regressive Integrated Moving Average) ARIMA(0,1,1) demand model in particular has been analysed extensively by researchers and used widely by forecasting practitioners due to its attractive theoretical properties and empirical evidence in its support. It is important to note that the optimal estimator for an

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ARIMA(0,1,1) model is the Simple Exponential Smoothing method that is widely used in practise. A well known result in the supply chain inventory forecasting literature (see Graves, 1999; Gilbert, 2005) shows that, for an order-up-to level (OUT) system, the orders resulting from a downstream stage facing an ARIMA(0,1,1) demand process follow also an ARIMA(0,1,1) process. Based on this mathematical relationship, various papers have argued that there is no benefit from any information sharing between downstream and upstream stages (e.g. Graves, 1999). However, it has recently been shown in the academic literature that orders faced by an upstream stage in the supply chain that follow an ARIMA(0,1,1) process may be generated from various demand processes at the downstream stage (including the ARIMA(0,1,1)) (Ali and Boylan, 2011). As such, it may not be possible for the upstream stage to infer the demand at the downstream stage rendering FIS a potentially very beneficial strategy that may result in reduced forecasting errors and inventory costs. Addressing the plausibility of this assumption constitutes the aim of this work. To the best of our knowledge, there have been no attempts in the academic literature to analyse empirically inventory systems with ARIMA(0,1,1) demand data. It is our aim to attempt to fill this gap. In more detail, the aim of this paper is twofold: (i) to analyse the scale of inventory savings according to the degree of improvement in forecasting accuracy for an ARIMA(0,1,1) demand process; and (ii) to assess the inventory benefits of information sharing under an ARIMA(0,1,1) structure. Our analysis is conducted analytically but also empirically by means of experimentation with the sales data related to 329 Stock Keeping Units (SKUs) from a major European superstore.

The remainder of the paper is organised as follows: in the next section the background of our work is briefly discussed followed, in Section 3, by the presentation of the assumed supply chain structure and the theoretical analysis of forecasting and inventory performance. In Section 4 we analyse the scale of inventory savings according to the degree of improvement in forecasting accuracy along with the inventory benefits of information sharing in the supply chain. This is conducted by means of simulation on theoretically generated and empirical data. The paper concludes, in Section 5, with a discussion of our main findings and the natural next steps of research.

2. Research background

In this section the literature pertinent to our research is briefly reviewed. First, we refer to general studies dealing with forecasting and stock control in relation to ARIMA models. Then, forecasting performance and the effects of information sharing in supply chains are discussed. For more details on the relevant literature, interested readers are referred to a recent review paper by Syntetos et al. (2009a).

2.1. Forecasting

The relevant literature dealing with statistical forecasting extends to the development of the simple exponential smoothing method by Brown (1959) in the 1950s and some of its extensions by Holt (1957) and Winters (1960). In the 1970s, ARIMA models were developed and have been studied extensively by many researchers. Their theoretical underpinnings were described by Box and Jenkins (1970) and later by Box et al. (1994). Please note that most linear exponential smoothing models have equivalent ARIMA models with the only notable exception being the multiplicative form of Holt–Winters. However, a state-space model underpinning multiplicative Holt–Winters, characterised by a single source of randomness, was identified by Ord et al. (1997). State-space models for exponential smoothing may also be formulated based on multiple sources of error. For example, single exponential smoothing is optimal for a model with two sources of error (Muth, 1960). Finally, it should be noted that evidence from the M1 and M3 forecasting competitions has shown the ARIMA methodology to be competitive in terms of forecast accuracy (Makridakis et al., 1982; Makridakis and Hibon, 2000) and, hence, it provides support for the assumption of such processes.

2.2. Stock control

The assumption of an OUT policy is a common one in nearly all the papers mathematically analysing supply chains under ARIMA demand processes and the bullwhip effect. Disney (2007) has found that products accounting for 65% of the sale value at a major UK retailer, Tesco, follow forms of an OUT inventory policy. Dejonkheere et al. (2003) have shown that an OUT policy will always result in demand variability amplification. They demonstrate the existence of the bullwhip effect for other stock control policies but claim that using replenishment rules that smooth the order patterns based on fractional adjustments may reduce demand variance amplification. Chandra and Grabis (2005) compared, under an autoregressive demand model at a downstream supply chain level, the OUT policy with a Material Replenishment Planning (MRP) scheme and show the existence of the bullwhip effect in both policies. More recently, an adapted OUT policy has been investigated by Gaalman and Disney (2009) where a proportional inventory position feedback controller is used. The dynamic behaviour of this so-called proportional OUT policy has been analysed for several ARMA demand models and it has been shown that, for a correct choice of the feedback parameter, the bullwhip effect can always be avoided.

2.3. Forecast utility performance

Academic studies investigating the performance of forecasting methods have traditionally focused on the accuracy of the forecasts. However, forecasting practitioners are mostly concerned with the empirical utility of these methods paying attention, for example, to the resulting trade-off between inventory costs and achieved service levels.

As forecasting is the driving force of all planning and control activities in a firm, it may be reasonably expected that an improvement in forecast accuracy will enhance operational performance. The implications of forecast accuracy for stock control performance in particular have attracted a lot of attention in recent years and many studies have been concerned with the interactions between these two areas. The rules governing this relationship are still not completely understood; however, many papers have shown that the performance of a stock control system does not always relate directly to the forecasting accuracy as calculated by standard measures (see, for example, Eaves and Kingsman, 2004; Flores et al., 1993; Gardner, 1990; Mahmoud and Pegels, 1989; Sani and Kingsman, 1997; Syntetos and Boylan, 2006). That is to say, the fact that a forecasting method outperforms one other in terms of accuracy does not imply that this superiority will necessarily be reflected in terms of reduced inventory cost and/or an increased service level.

Ali et al. (2011) recently showed mathematically and by means of simulation on both theoretically generated and empirical data that an improvement in forecasting accuracy achieved by means of Forecast Information Sharing (FIS) will translate to inventory cost savings. Assuming some Auto-Regressive Moving Average (ARMA) representations for the demand process, they showed that the gains in accuracy (as measured by the Mean Squared Error—MSE) depend on the particular ARMA process.