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Joint pricing-procurement control under fluctuating raw material costs

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ABSTRACT

We consider a firm that periodically procures raw material units, stores them, and processes them into finished products upon order arrivals. The raw material cost evolves in a Markovian fashion, whereas the demand process is influenced by both the raw material cost and sales prices charged by the firm. The firm controls both the raw material procurement activity and sales price in each period. We show the optimality of base-stock-list-price type of policies with the additional raw-cost dependence. Under conditions that are verifiable when the firm engages in price competition with other firms tapping into the same raw material market and when the raw material cost process has time-continuity and mean-reversion tendencies, we identify two monotone patterns in which policy parameters should follow as the raw material cost fluctuates. Cost increases are also shown to translate into price increases at low inventory levels. In other circumstances, however, there does not appear to be a clear pattern as to how the firm should pass cost increases on to end customers. Our numerical evidence unequivocally supports the adaptation of procurement and pricing controls to changing raw material costs.

1. Introduction

Most firms in the manufacturing and wholesale businesses face the challenges as well as opportunities posed by fluctuating raw material costs. Hard-to-predict cost movements make raw material acquisition a nontrivial matter. Moreover, firms are often engaged in intense competition for price-sensitive customers. As the raw material cost changes, the profit under a certain sales price for a finished product unit would change too. On the other hand, customers are attracted by low sales prices. Thus, when the raw material cost varies, the demand curve for any particular firm would differ due to competitors' price adjustments. This means that a firm facing fluctuating raw material costs has to deal with oscillating customer demand curves too.

We can use a stylized model in the spirit of Hotelling (1929) and Salop (1979) to further motivate the impact of a commonly felt input cost on the demand curve of a firm under price competition. Suppose firms occupy integer positions on the real line, and customers uniformly distributed on the line choose to purchase from firms with the least price-distance sums. Then, detailed analysis in Appendix A reveals that, for each participating firm, a demand curve $w(\pi,\cdot)$ that is influenced by the prevailing raw material cost π will emerge. In particular, it is of the form

$$w(\pi,p)=\pi-p+2. \tag{1}$$

Naturally, the demand level $w(\pi,p)$ is decreasing in the firm's sales price p. That $w(\pi,p)$ is increasing in the input cost π at every fixed sales price p is a more noteworthy phenomenon. It can be explained by the tendency for a raised input cost to push competitors' prices higher, thus making it easier for the current firm to attract demand at any particular price level. In Appendix C, we show that this trend can be backed up by data from Bloomberg Terminal on China Iron Ore Spot Price Shandong/Zibo (π) and China Domestic Hot Rolled Steel Sheet Spot Average Price (p). Indeed, an increased raw iron price π will make it easier for a steel manufacturer to raise its finished steel product price p.

In this paper, we consider the simultaneous control of acquisition and pricing activities for a firm which not only faces fluctuating raw material costs but also possesses demand curves that vary with raw material costs. We can think of the firm, for instance, as a steel manufacturer that turns iron ore purchased from one single spot market into a finished steel product. It competes on the finished product market with other steel manufacturers with access to the same spot market for iron ore. Particularly, we concentrate on a firm which periodically procures raw material units from a spot market, stores them, and processes them into finished products upon order arrivals. We let the raw material cost follow a Markov process, and assume that the demand process is influenced by both raw material costs and sales prices. We let the firm control both the raw material procurement level and unit

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sales prices in each period. During production whose lead time we assume to be zero, each unit of raw material is converted into one unit of the finished product. Any unsatisfied demand is backlogged.

The raw material cost process being Markovian simply means that, when given past and present cost information, future raw material costs are only dependent on the present raw material cost. In Appendix B, we use auto-regression studies of real price data on copper and iron ore to provide empirical support to the Markovian assumption. Allowing the firm to deal solely with a spot market rather than futures or other contracts simplifies the problem. Real data indicate this modeling feature has left enough latitude for applications. For instance, according to a Wharton report (Anonymous, 2009), steel makers in China purchased 60% of iron ore from the spot market in 2009. A U.S. Department of Agriculture report (GIPSA, 2007), on the other hand, indicates that a number of meat packers in the United States rely heavily on the spot market for their physical supply.

We assume zero fixed ordering cost in raw material procurement. For a steel plant, huge transaction volumes associated with modern steel manufacturers would make each period's variable purchase cost much greater than the fixed book keeping or order entering cost. Also, transportation or handling cost can be considered as proportional to volumes. We assume zero lead time in raw material delivery as well. According to a report by the Pennsylvania Economy League of Southwestern Pennsylvania (2011), 99% of iron ore used in the United States comes from mines in Minnesota and Michigan; whereas, a huge concentration of steel plants are located around these states, making shipping accomplishable in days. In addition, we suppose the firm carries out make-to-order production, a practice that is common among steel plants (Hintsces et al., 2010).

Our model accommodates the case involving one main raw material with volatile costs and other minor material types with stable costs. We can simply treat the combination convertible into one unit of finished product as one raw material unit. Therefore, when small quantities of carbon, copper, manganese, and some other metals are needed in the conversion to steel, we can define a unit of raw material as the one more ton of iron ore plus the aforementioned small quantities of other elements that help produce one ton of steel. The main driver of cost volatility in the raw material can be seen to come from the volatility of iron ore prices. Take the example of carbon steel, which, according to Ashby and Jones (1992), accounts for 90% of steel production. In it, elements other than iron ore, such as carbon and various additive ingredients, occupy a very small proportion of the whole weight (Carbon and Alloy Steel, http://www.onealsteel.com/carbon-and-alloy-steel.html).

Our analysis on a dynamic programming formulation of the joint control problem leads to the following main findings regarding the firm's operational strategy:

I. It is optimal for the firm to acquire raw material in a base-stock fashion. When its starting inventory level is below the base-stock point, the firm should charge a list price for its finished product. This price is subject to downward adjustments if the firm's starting inventory level increases beyond the base-stock point. Both the base-stock point and sales prices are functions of the current raw material cost.
II. When the firm is engaged in price competition with other firms tapping into the same raw material market as exemplified by the motivational example and when the raw material cost process exhibits reasonable trends, the optimal policy should let both the base-stock level and the expected next-period inventory level drop as the raw material cost increases. Also, the list price the firm charges should increase with the raw material cost when its inventory level is below the base-stock level. On the flip side, numerical analysis shows that relaxation of some of the conditions could jeopardize the monotone behaviors of the control policies.

The above suggests that a firm has certain monotone rules to follow in its dealings with raw material procurement and finished product sales. With regard to whether cost increases should be passed on to end customers, the rules spell out a definitive yes at low inventory levels. At the same time, our numerical study shows that the rules are more nuanced at high inventory levels, even though the general trend leans on the affirmative side. We also have numerical evidence to indicate that in environments with random raw material costs, the adoption of cost-dependent joint pricing-production policies can help boost profitability, with the benefit even more pronounced under stronger raw material cost volatilities.

Overall, our research contributes to joint pricing and procurement with a random price-dependent demand of the finished product and a Markovian raw material cost process which also influences customers' choices due implicitly to price competition from other firms. Policy guidelines and insights derived here can be applied by firms ranging from steel mills to food processing plants and oil refineries in their day-to-day operations.

The remainder of the paper is organized as follows. Section 2 surveys the relevant literature, and Section 3 provides the general setup of the problem. We formulate the problem and give its preliminary analysis in Section 4. The paper's main results on the policies' cost-dependent components are derived in Section 5. We conduct a computational study in Section 6. The paper is concluded in Section 7.

2. Literature survey

Dynamic pricing without inventory replenishment is a big concern for revenue management. Important works include Gallego and van Ryzin (1994), Feng and Gallego (1995), and Zhao and Zheng (2000). Many authors have worked on pricing problems involving procurement as well; see, e.g., Eliashberg et al. (1993). On this subject, major breakthroughs were made by Federgruen and Heching (1999) and Chen and Simchi-Levi (2004). For a joint control problem, Federgruen and Heching (1999) characterized one optimal policy as base-stock-list-price. Chen and Simchi-Levi (2004) extended the above work to the case with fixed costs and introduced the concept of symmetric-k-convexity to cope with the added difficulty. Chen et al. (2014) studied a joint pricing and inventory control model with both an on-site sales market and a long-distance market.

Quite a few works have dealt with inventory management under fluctuating raw material costs. Golabi (1985) considered a problem with an independent cost process and deterministic but variable demand. Li and Kouvelis (1999) compared two types of contracts when the raw material cost process follows a geometric Brownian motion. Guo et al. (2011) used control theory on a one-period problem involving random demand and purchasing cost.

Kalymon (1971) considered fixed costs during acquisition and showed the optimality of a cost-dependent (s, S) policy; however, his results did not offer insights into how the policy parameters would change with costs, except for the degenerate case where auto-correlations between costs disappear. Ozekici and Parlar (1999) proved the optimality of an (s, S) policy when both purchasing costs and demand are stochastic and state-dependent. Also, Song and Zipkin (1993) studied a continuous-review inventory control problem where a worldly state evolves as a Markov process and demand arrival rates are state-dependent.