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Short Communication

Nash-profit efficiency: A measure of changes in market structures

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ABSTRACT

Imperfectly competitive markets can be characterized by endogenous prices, limited or no competition, and the exercise of market power. To address the resulting dysfunctionality, this study proposes an alternative efficiency measure estimated by the directional distance function (DDF) with the direction toward Nash equilibrium, and develops the Nash-profit efficiency (NPE) and its decomposition which complements the typical profit efficiency measure. We model the production possibility set and the price functions of inputs and outputs, and then develop the mixed complementarity problem (MiCP). We validate the model with an empirical study of the oil and natural gas industry in New York State between 1981 and 1989. The results show that before 1984, firms exploited a less competitive market; that between 1984 and 1986, the number of new entrants transformed the market; and that after 1986, no firms could exercise market power due to market restructuring (deregulation) and an unforeseen oil glut. Based on the results, we conclude that the direction toward Nash equilibrium can be justified for efficiency estimation in imperfectly competitive markets, and that NPE is appropriate for investigating changes in market structures.

1. Introduction

Data envelopment analysis (DEA) is a nonparametric technique used to estimate the efficiency score of a decision making unit (DMU) in the production possibility set (PPS). Three issues, however, need to be addressed to extend DEA for new applications. First, determining the orientation for projecting an inefficient firm to the frontier may significantly affect the result of efficiency estimation, although choosing the direction vectors when estimating the directional distance function (DDF) is unsolved (Färe, Grosskopf, & Whittaker, 2013). Second, while DEA implicitly assumes an exogenous price (Cherchyea, Kuosmanen, & Post, 2002) without considering demand function, in the case of an imperfectly competitive market, firms may try to control the output level affecting the market price (i.e., price is endogenous). A non-cooperative game results when firms can change their corresponding outputs level to affect the market price in oligopoly (Lee & Johnson, 2015; Nash, 1951). From an output aspect, a firm may overestimate the revenue when expanding output toward the production frontier using exogenous output price in oligopoly. Third, the typical two-step analysis, which suggests improving technical efficiency by reducing inputs or expanding output in the first step, and freely changing the input and output mixes along the frontier to improve allocative efficiency in the second step, is inconsistent with theoretical analysis and empirical experience (Zofio, Paster, & Aparicio, 2013).

Motivated by these three issues, we present an alternative direction (i.e., orientation) toward the Nash equilibrium used in DDF (Luenberger, 1992; Chambers, Chung, & Färe, 1996). Specifically, assuming that firms are profit maximizers, we identify a Nash equilibrium where each firm cannot improve its profits by changing production levels within the PPS. In this case, the Nash equilibrium provides a profit-maximizing allocative efficient benchmark in an imperfectly competitive market even though a set of firms will choose not to produce on the production frontier. In an imperfectly competitive market, a non-cooperative game is formulated and the mixed complementarity problem (MiCP) can be used to identify a Nash equilibrium within the PPS (Facchinei & Pang, 2003; Lee & Johnson, 2015). Thus, we can estimate the efficiency via the direction toward the Nash solution and thereby develop Nash-profit efficiency (NPE) to measure the changes in market structure.

Understanding the relationship between competition and market structure is useful for two reasons. First, industrial organization theory states that a firm wants to know how its competition affects efficiency and productivity growth in order to devise survival strategies in different market structures. Second, since the intensity of competition is not independent of firm behavior, a high-performing firm may gain market power in the long run (Nickell, 1996).

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The proposed Nash direction is different from the directions proposed in previous studies. Chung, Färe, and Grosskopf (1997) use a firm-specific direction, implying that each firm determines its own direction based on current input and output levels. Färe, Grosskopf, and Weber (2006) suggest the direction with increasing one unit of desirable output and decreasing one unit of undesirable output simultaneously. Zofio et al. (2013) use the direction toward the profit-efficient benchmark with exogenous price and it supports the economic interpretation. Lee (2014), based on the practical wait-and-see decision-making process, suggests the direction toward marginal profit maximization. These studies, however, implicitly assume a perfectly competitive market, whereas this paper considers the endogenous price and suggests a direction toward Nash equilibrium in an imperfectly competitive market.

This paper contributes to the existing literature by (1) considering the efficiency analysis in an imperfectly competitive market with endogenous price; (2) providing an alternative orientation (i.e., direction toward Nash equilibrium) which can be extended to other variants of the distance function for technical efficiency measurement; (3) developing NPE and its decomposition assessing the change in market structure from a productivity analysis perspective, and (4) validating the model with an empirical study of the oil and natural gas industry operating in New York State from 1981 to 1989.

The remainder of this paper is organized as follows. Section 2 defines NPE and its decomposition. Section 3 validates the NPE model with an empirical study of the oil and natural gas industry operating in New York State. Section 4 concludes and offers suggestions for future research.

2. Nash profit efficiency and its decomposition

This section develops NPE. The notations, formulation of MiCP identifying Nash equilibrium in an imperfectly competitive market, formulation of DDF, and the directional Nash technical efficiency (TE) using the direction toward the Nash solution appear in the Appendix.

According to productivity analysis, the profit maximization function presents the maximal return to dollars achievable with the given input and output prices. Here, we define the profit efficiency (PE) (or Nerlovian efficiency) as the difference between the profit of an observation r and the maximum profit in PPS, i.e., $\text{PE}(\boldsymbol{P}_y, \boldsymbol{P}_x; \boldsymbol{x}_r, \boldsymbol{y}_r) = \text{PF}^* - \text{PF} = (\boldsymbol{P}_y\boldsymbol{y}^* - \boldsymbol{P}_x\boldsymbol{x}^*) - (\boldsymbol{P}_y\boldsymbol{y}_r - \boldsymbol{P}_x\boldsymbol{x}_r)$. If $\text{PE} = 0$, the firm is efficient; otherwise, $\text{PE} > 0$ and the firm is inefficient. Based on the definitions of economic efficiency (Chambers, Chung, & Färe, 1998; Ferrier & Lovell, 1990; Nerlove, 1965), we decompose the profit efficiency into allocative efficiency (AE) and technical efficiency (TE), i.e., PE = AE + TE. Note that when using DDF with direction toward the profit maximization, the profit efficiency measure can be either technical or allocative (Zofio et al., 2013). Thus, we need only measure TE without distinguishing the AE effect from TE, namely, PE is equal to TE measured by the profit-maximized direction.

Recalling that $(x_{ri}^{N*}, y_{rj}^{N*}) \in \tilde{T}$ is the Nash solution obtained from MiCP (see Appendix), we define the Nash-profit maximization function (NPF*), the Nash-profit function (NPF), and the current-profit function (CPF) of specific firm r as:

$$\begin{aligned}\text{NPF}^* &= \sum_j P_j^Y\left(\bar{Y}_j^{N*}, \bar{\boldsymbol{Y}}_{(-j)}^{N*}\right)y_{rj}^{N*} - \sum_i P_i^X\left(\bar{X}_i^{N*}, \bar{\boldsymbol{X}}_{(-i)}^{N*}\right)x_{ri}^{N*}\\ &= \boldsymbol{P}_y^{N*}\boldsymbol{y}_r^{N*} - \boldsymbol{P}_x^{N*}\boldsymbol{x}_r^{N*};\\ \text{NPF} &= \sum_j P_j^Y\left(\bar{Y}_j^{N*}, \bar{\boldsymbol{Y}}_{(-j)}^{N*}\right)y_{rj} - \sum_i P_i^X\left(\bar{X}_i^{N*}, \bar{\boldsymbol{X}}_{(-i)}^{N*}\right)x_{ri}\\ &= \boldsymbol{P}_y^{N*}\boldsymbol{y}_r - \boldsymbol{P}_x^{N*}\boldsymbol{x}_r;\end{aligned}$$

$$\text{CPF} = \sum_j P_j^Y(\bar{Y}_j, \bar{\boldsymbol{Y}}_{(-j)})y_{rj} - \sum_i P_i^X\left(\bar{X}_i, \bar{\boldsymbol{X}}_{(-i)}\right)x_{ri} = \boldsymbol{P}_y^N\boldsymbol{y}_r - \boldsymbol{P}_x^N\boldsymbol{x}_r,$$

where $\bar{Y}_j^{N*} = \sum_{k\neq r} y_{kj}^{N*} + y_{rj}^{N*}$ and output price function $\boldsymbol{P}_y^{N*} = P_j^Y(\bar{Y}_j^{N*}, \bar{\boldsymbol{Y}}_{(-j)}^{N*}) = P_j^{Y_0} - \alpha_{jj}\bar{Y}_j^{N*} - \sum_{h\neq j}\alpha_{jh}\bar{Y}_h^{N*}$ with respect to Nash solution $(\boldsymbol{x}^{N*}, \boldsymbol{y}^{N*})$. Similarly, we can set the input price function $P_i^X(\bar{X}_i^{N*}, \bar{\boldsymbol{X}}_{(-i)}^{N*})$ with respect to the Nash solution. Next, we define and decompose NPE into efficiency on quantity change (EQC) and efficiency on price change (EPC) as:

$$\begin{aligned}\text{NPE} &= \text{NPF}^* - \text{CPF} = (\text{NPF}^* - \text{NPF}) + (\text{NPF} - \text{CPF})\\ &= \text{efficiency on quantity change (EQC)}\\ &\quad + \text{efficiency on price change (EPC)}.\end{aligned} \tag{1}$$

Note PE must be non-negative, but NPE can be positive or negative due to the endogenous price. When NPE > 0, a firm should change its input or output mix toward a Nash solution, meaning that competition is increasing and will benefit the firm's profit. When NPE < 0 implies a poor Nash solution and a firm should maintain its current competence because competition is destructive and will undermine the firm's profit. Therefore, NPE is a good indicator for planning and adjusting a firm's inputs and outputs according to a Nash equilibrium in an imperfectly competitive market. In particular, we can investigate EQC and EPC for the detailed effects of efficiency affected by quantity change and price change between the Nash solution and the observation.

If using a Nash direction for DDF estimation, the efficiency score is equal to NPE. Therefore, we formulate Proposition 1, which also shows that Nash profit inefficiency is either technical or allocative.

Proposition 1. *The DDF estimated by Nash direction* $\frac{(\boldsymbol{x}-\boldsymbol{x}^{N*}, \boldsymbol{y}^{N*}-\boldsymbol{y})}{(\boldsymbol{P}_y^{N*}\boldsymbol{y}^{N*}-\boldsymbol{P}_x^{N*}\boldsymbol{x}^{N*})-(\boldsymbol{P}_y^{N}\boldsymbol{y}-\boldsymbol{P}_x^{N}\boldsymbol{x})}$ *is equal to NPE. Similarly, using the direction* $\frac{(\boldsymbol{x}-\boldsymbol{x}^{N*}, \boldsymbol{y}^{N*}-\boldsymbol{y})}{(\boldsymbol{P}_y^{N*}\boldsymbol{y}^{N*}-\boldsymbol{P}_x^{N*}\boldsymbol{x}^{N*})-(\boldsymbol{P}_y^{N*}\boldsymbol{y}-\boldsymbol{P}_x^{N*}\boldsymbol{x})}$ *generates the DDF equal to EQC.*

Proof. See Appendix. □

Defining market preference in efficiency (MPE) to be equal to the difference between NPE and PE reveals the preference of market structure from the economic efficiency perspective. We decompose MPE into the efficient benchmark effect (EBE) and the endogenous price effect (EPE) as:

$$\begin{aligned}\text{MPE} &= \text{NPE} - \text{PE}\\ &= \left(\boldsymbol{P}_y^{N*}\boldsymbol{y}_r^{N*} - \boldsymbol{P}_x^{N*}\boldsymbol{x}_r^{N*}\right) - \left(\boldsymbol{P}_y^{N}\boldsymbol{y}_r - \boldsymbol{P}_x^{N}\boldsymbol{x}_r\right)\\ &\quad -[(\boldsymbol{P}_y\boldsymbol{y}^* - \boldsymbol{P}_x\boldsymbol{x}^*) - (\boldsymbol{P}_y\boldsymbol{y}_r - \boldsymbol{P}_x\boldsymbol{x}_r)]\\ &= \left(\boldsymbol{P}_y^{N*}\boldsymbol{y}_r^{N*} - \boldsymbol{P}_x^{N*}\boldsymbol{x}_r^{N*}\right) - (\boldsymbol{P}_y\boldsymbol{y}^* - \boldsymbol{P}_x\boldsymbol{x}^*)\\ &\quad -\left[\left(\boldsymbol{P}_y^{N}\boldsymbol{y}_r - \boldsymbol{P}_x^{N}\boldsymbol{x}_r\right) - (\boldsymbol{P}_y\boldsymbol{y}_r - \boldsymbol{P}_x\boldsymbol{x}_r)\right]\\ &= \text{efficient benchmark effect (EBE)}\\ &\quad - \text{endogenous price effect (EPE)}.\end{aligned} \tag{2}$$

MPE shows the preference of profit efficiency in different market structures (i.e., imperfect competition with endogenous price, and perfect competition with exogenous price). If MPE < 0, firm r favors the imperfectly competitive market where firms exercising market power will receive a higher profit efficiency than in a perfectly competitive market. This market may attract new entrants and competition increases. If MPE > 0, firm r favors the more competitive market since PE shows a small gap between the allocatively efficient benchmark and the observation. When MPE is close to zero, no difference between NPE and PE usually implies a perfectly competitive market. In fact, EBE = MPE + EPE, that is, the gap of ideal benchmarks is compounded with the gap of individual performance and the gap of market price in different market structures.