The Economics of Modern Manufacturing: Reply

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In our 1990 paper (Milgrom and Roberts, 1990a), we offered a model of a manufacturing firm that selects a large number of human-resource, manufacturing, marketing, and organizational policy variables. We then sought to develop a set of assumptions under which these variables would all move together monotonically in response to posited variations in technology and input prices. The idea was to use the methods of the theory of supermodular functions (Donald M. Topkis, 1978) to show that observed patterns of change in manufacturing that we labeled the adoption of a "modern manufacturing strategy" could be understood in terms of profit-maximizing responses to these supply-side factors if plausible complementarities were present. Unfortunately, our major result, theorem 7, is incorrect as stated, as P. Timothy Bushnell and Allen D. Shepard (1995) and Topkis (1995) independently discovered. We thank them for their careful reading of our paper, for pointing out the error, and for offering ways of recovering the desired conclusion by imposing further conditions beyond those we had assumed.

As Bushnell and Shepard (1995) and Topkis (1995) indicate, the problem is in attempting to show that output price in our model is monotonically decreasing as technology improves. One effect in our model arises from the fact that, as technology improves, firms are led to reduce their marginal costs, which favors lowering prices. However, the improving technology also makes it cheaper for firms to increase quality, and this can have an ambiguous effect on the price choice. In particular, if increased quality makes demand less elastic, this second effect would make the firm want to increase its prices.

The extra conditions suggested by Bushnell and Shepard (1995) focus on the operating profit function (price minus average variable cost, all times demand). They require first that, when price is higher than its optimal value as a function of the other variables in the model, lowering price and increasing (an aspect of) quality should be complements in increasing operating profit, so that a higher quality leads to a cut in price being more profitable. For this it is sufficient that, on this range of prices, demand should become more price-elastic as quality increases. (For prices outside this range, complementarity of price reductions and quality increases in generating profits is inconsistent with the complementarity between other pairs of variables that is needed to apply the mathematical theorem underlying the result. This difficulty is handled by Bushnell and Shepard as we did in our original paper—by replacing the true profit function by another that has the same optimizers and for which the desired complementarity does hold.) The second part of Bushnell and Shepard's condition requires that, if demand is changing over time, than it is becoming more price-elastic over the specified range of prices.

The second part of the Bushnell-Shepard condition seems especially appealing if one thinks that competitors of the firm (which are not modeled in our paper) may also be adopting a modern manufacturing strategy that leads to their offering closer, better substitutes to the firm's offerings. The first part is less readily interpretable, but as we argue below, it is hard to replace with anything weaker.

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Topkis's (1995) resolution of the problem focuses on the demand function. He relaxes a number of assumptions we had made but adds a condition that the log of the demand function is supermodular in price and each of the other determinants of demand, which he shows is sufficient for the desired monotonicity result.[1] Even though the profit function in our paper cannot be supermodular when p is treated as a choice variable, the determination of the optimal p depends only on the operating profits. If the log of demand is supermodular, then the log of operating profits inherits this property, and so the optimizing values of the price variable (which are the same as those of the original problem) behave monotonically. The log-supermodularity condition is equivalent to the demand becoming more price-elastic as each of the other determinants of demand increases.

Our original paper, the Bushnell-Shepard comment, and much of Topkis's comment focus on sufficient conditions for monotonicity in our model or extensions of it. This raises the question of what the weakest sufficient conditions might be, that is, whether the sufficient conditions may be extended to be necessary and sufficient for monotonicity. What properties must hold in a model if monotone comparative-statics conclusions can be obtained? Our approach to this problem, which was also addressed by Topkis, follows Milgrom and Chris Shannon (1994) and Milgrom and Roberts (1994).

Generally, the task of identifying interesting necessary conditions for monotonicity of the solutions of a model in its parameters is made complicated by the fact that monotonicity might obtain in a particular instance because of a fortuitous choice of parameters, even though any general, global, sufficient condition failed to hold. This has led us to consider "critical sufficient conditions" (Milgrom and Roberts, 1994; see also Milgrom and Shannon, 1994). These are conditions that are sufficient to imply the desired comparative-statics conclusion in the particular instance being studied and that must hold if the conclusion is to be "general," that is, if it is to remain true even under variations in the specific details of the model's formulation. Such variations might reflect the modeler's inherent uncertainty about exactly which assumptions are empirically justified. With such uncertainty, we want to know which assumptions of the model are critical for the conclusion being derived and which are, instead, merely simplifying ones.

In the present instance, consider the issue of whether the optimal price will be a decreasing function of the other (sign-adjusted) variables in the model and the underlying exogenous parameter. Using the notation from our earlier paper, and recalling that only the operating profits are relevant for the determination of the price, we are interested in how p changes when we decrease c, $r\rho$, and ι/m and increase q and τ in the problem

$$\max_p (p - c - r\rho - \iota/m)\mu(p,q,\tau)\,\delta(\mathbf{x})$$

where $\mathbf{x}$ is a set of variables not including p and where we can assume without loss of generality that each of the terms in the product is positive. By inspection, the δ term also does not affect the optimal choice of p and so it can be ignored when focusing on monotonicity conclusions about p. Suppose now the modeler is uncertain about the actual elasticity of demand and so desires that conclusions about the behavior of p should be robust to variations in the elasticity. In this model, we represent this uncertainty by replacing the single function $\mu(p,q,\tau)$ by a parameterized family of functions such as $\nu(p,q,\tau;\alpha) \equiv \mu(p,q,\tau)\cdot p^{\alpha}$. Varying α adds to or subtracts from the previously assumed price elasticity. By theorem 2 of Milgrom and Roberts (1994), if

[1] Topkis (1995) actually obtains a somewhat weaker conclusion than we had sought, namely, that the largest and smallest optimizing choices move monotonically. If there is a unique optimizer, then his conclusion is that it is monotone.

$\log(\mu(\cdot))$ is a concave function of p and if the optimal price choice $p^*(-c, -r\rho, -\iota/m, q, \tau|\alpha)$ is increasing in its arguments for all values of α, then the function $\log(\mu(\cdot))$ must be supermodular in (p, q) for all τ and in (p, τ) for all q. Moreover, the same condition is sufficient regardless of whether $\log(\mu(\cdot))$ is concave.[2]

As noted, supermodularity of the log of demand in p and each of the other variables is equivalent to the condition that the absolute value of the price elasticity of demand, $(-p\mu_p/\mu)$, is nondecreasing in the other variables. Thus, if we require the chosen price to be decreasing in the parameters even when we add an arbitrary constant to the elasticity of demand, we are forced to assume that the demand becomes more elastic as we increase the other variables. Similarly, Topkis (1995) has shown that robustness against variations in the marginal production cost, c, leads to the necessity of the log of demand being supermodular. In these senses, the condition identified by Bushnell and Shepard (1995) and by Topkis is the weakest sufficient condition for robust monotonicity, and Bushnell and Shepard's remark that "assumptions concerning trends in the price elasticity of demand are *required* to generate [our] desired results" (italics added) is correct.

[2]A closely related condition, log-supermodularity of each firm's demand in its own price and the prices of other firms, was used in Milgrom and Roberts (1990b) to establish strategic complementarity in certain Bertrand oligopoly games. Strategic complementarity implies increasing best-reply functions, and more.

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