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Optimal Production Under Uncertainty *

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Optimal Production Under Uncertainty

Abstract

To overcome long-standing obstacles in the literature about the current unusual and uncertain state of the world, in this paper, we generalize and extend the previous results of the theory of the competitive firm under uncertainty. In particular, we consider simultaneous output, output price, and input price and provide important comparative statics. We prove that the level of the risk is negatively related to optimal output, whereas the expected output price is positively related to optimal output. In addition, to relax the non-increasing absolute risk aversion assumption in the literature, our results do not require any restriction on the firm's utility.

Keywords: Multiple uncertainties, comparative statics, risk, firm, risk aversion.

JEL Classification: D21, D24, D81.

1 Introduction

Given the current unusual and uncertain state of the world, this topic is very timely and useful. This is especially true for price uncertainty and quantity uncertainty. Nowadays, it seems that simultaneous output, output price, and input price uncertainties are a plausible assumption for modelling the theory of the firm.

The literature has extended Sandmo's pioneering article (Sandmo, 1971) that considered output price uncertainty. For example, Dalal and Alghalith (2009) provided comparative statics under output price and output uncertainty, while placing a restriction on the coefficient of relative risk aversion. Álvarez-López and Rodríguez-Puerta (2011) discussed comparative statics under output price uncertainty.

Furthermore, Guo, *et al.* (2015) proved that the separation theorem holds, but the full-hedging theorem does not always hold under regret aversion. They also showed that regret-averse firms with more regret aversion will hold smaller optimal hedging positions in an unbiased futures market and showed that banning firms from forward trading affects their production level in both directions. Alghalith (2016) adopted output price uncertainty and *additive* output uncertainty. Guo, *et al.* (2018) developed two test statistics to test the production frontier function even under heteroscedasticity. Guo, *et al.* (2019) developed some properties of regret-aversion on production. First, they proved that the linear-regret firms will surely produce more than their purely risk-averse counterparts and surely produce less than firms under certainty, and provided sufficient conditions to ensure the regret-averse firms produce more than the purely risk-averse firms and study the comparative statics of the optimal production. Harri *et al.* (2020) considered production with output price uncertainty and input price uncertainty under a set of technical assumptions. Moreover, Guo, *et al.* (2021) focused on disappointment aversion under output price uncertainty. To contribute to the theory, Martins (2024) used a mean-variance approach, Hibiki and Miyawaki (2025) considered a Bayesian (statistical) method, and Gauchon, *et al.* (2024) adopted a stochastic-order framework under price uncertainty. Both Gallenstein, *et al.* (2024) and Lien, *et al.* (2023) used an empirical approach. Readers may read Kumbhakar (2023) and Wibowo, *et al.* (2023) for an excellent review of the literature.

On the other hand, there are many applications of using production functions. For example, Franses and Janssens (2018) examined which past data are more useful for predicting the future of a variable by using monthly industrial production series. Mahasinghe and Sarathchandra (2020) showed that different industrial requirements impose different conditions and lead to different production plans. Salisu, *et al.* (2022) showed the predictability of monthly industrial production growth and quarterly real GDP growth during the period of the COVID-19 pandemic. Silvia, *et al.* (2023) applied Cobb-Douglas's production function and found that land area, labor, financial capital, and fertilizer positively impacted patchouli production, but education had no effect on patchouli production in the Aceh Jaya Regency. In addition, Ajmal, *et al.* (2024) examined the impact of the exchange rate, oil imports, oil demand by different sectors, industrial production, and oil inventory on crude oil prices for the USA, China, Germany, Japan, and India.

In this paper, we overcome long-standing obstacles in the field. To do so, we first generalize and extend the previous results of the theory of the competitive firm under uncertainty. Thereafter, we provide some important comparative statics. We also consider simultaneous output, output price, and input price uncertainties. In doing so, we prove that the level of the risk is negatively related to optimal output, whereas expected output price is positively related to optimal output. Our results do not impose any typical restrictions on the firm's preferences. Furthermore, we introduce a new mathematical technique that can be utilized in numerous future research extensions.

2 Generalizing the Classical Results

Under the assumption of decreasing absolute risk aversion, Sandmo (1971) showed that the impact of a small change in the expected price on optimal output is positive. Using Sandmo's model, Ishii (1977) showed that the impact of a small change in the price risk on optimal output is negative under the assumption of non-increasing absolute risk aversion. In this paper, we relax these assumptions. That is, we generalize the results of both Sandmo and Ishii.

Using Sandmo (1971), the profit is given by

$$\pi = px - c(x) - B, \tag{2.1}$$

where p is the random output price, x is output, B is fixed cost and $c\left(x\right)$ is the variable cost function ($c''\left(x\right) > 0$). Also, $p = \bar{p} + \sigma\epsilon$, where $\bar{p}$ is expected price, σ is its standard deviation, and ϵ is random ($E\epsilon = 0$); E is the expectation operator. The risk-averse firm maximizes the expected utility of the profit $EU\left(\pi\right)$, where $U'\left(\pi\right) > 0$ and $U''\left(\pi\right) < 0$ (U is differentiable). Under this model setting, one can easily show that the first-order condition of the expected utility of the profit $EU(\pi)$ is

$$EU'(\pi)(p - c'(x^*)) = \int_{\varepsilon} U'(\pi(\varepsilon))(\bar{p} + \sigma\varepsilon - c'(x^*)) f(\varepsilon) d\varepsilon = 0 \tag{2.2}$$

where ε is the outcome of ϵ, f is the probability density function, and $*$ denotes the optimal value.

Under this model setting, we first develop the following proposition:

Proposition 2.1 *Assuming differentiability and risk aversion, the optimal output x^* is increasing with the price $\bar{p}$ and is decreasing with the standard deviation, σ, of the price $\bar{p}$; that is, $\frac{\partial x^*}{\partial \bar{p}} > 0$ and $\frac{\partial x^*}{\partial \sigma} < 0$, respectively.*

Proof. By the continuity of ε, $EU'(\pi)(p - c'(x^*))$ in Equation (2.2) becomes a specific outcome of $U'(\pi)(p - c'(x^*))$, such as $U'(\pi(\hat{\varepsilon}))(\bar{p} + \sigma\hat{\varepsilon} - c'(x^*))$, where $\hat{\varepsilon}$ is a specific outcome of ϵ. Thus, we have

$$EU'(\pi)(p - c'(x^*)) = U'(\pi(\hat{\varepsilon}))(\bar{p} + \sigma\hat{\varepsilon} - c'(x^*)) = \bar{p} + \sigma\hat{\varepsilon} - c'(x^*) = 0 \ , \tag{2.3}$$

and thus, we have

$$[\bar{p} - c'(x^*)] EU'(\pi) + cov(U'(\pi), pq) = 0 \ .$$

This implies that

$$\bar{p} - c'(x^*) > 0 \ . \tag{2.4}$$

In addition, by Sandmo (1971), we have $\hat{\varepsilon} < 0$.

Moreover, the first-order condition after the change in $\bar{p}$ is

$$\bar{p} + d\bar{p} - c'(x_1^*) + \sigma\hat{\varepsilon}_1 = 0 \equiv \bar{p}_1 - c'(x_1^*) + \sigma\hat{\varepsilon} = \bar{p} - c'(x^*) + \sigma\hat{\varepsilon} \ .$$

In addition, if the expected price increases; that is, $\bar{p}_1 > \bar{p}$, we have $c'(x_1^*) > c'(x^*)$; this implies that $x_1^* > x^*$, which, in turn, implies that the optimal output will increase, and vice versa.

Similarly, the first-order condition after the change in σ is

$$\bar{p} - c'(x_2^*) + (\sigma + d\sigma)\hat{\varepsilon}_2 = 0 \equiv \bar{p} - c'(x_2^*) + \sigma_1\hat{\varepsilon} = \bar{p} - c'(x^*) + \sigma\hat{\varepsilon} \ . \tag{2.5}$$

If the level of risk σ increases; that is, $\sigma_1 > \sigma$, we have $c'(x_2^*) < c'(x^*)$, which implies that the optimal output will decrease, and vice versa. ■ Therefore, the assumption of non-increasing absolute risk aversion is not necessary. It is well known that Sandmo (1971) assumed decreasing absolute risk aversion for the first result, while Ishii (1977) assumed non-increasing absolute risk aversion for the second result. We contribute to the literature by revising the results as shown in Proposition 2.1.

3 Multiple Uncertainties

In this section, we extend the theory by considering price, output, and cost risks. We first extend the theory to include price and output uncertainties as discussed in the next subsection.

3.1 Price and Output Uncertainties

In this section, we will consider the case of multiplicative output uncertainty q, because it is common in the literature to do so, see, for example, Dalal and Alghalith (2009) for more information. To explore it, We first modify the definition of profit from Equation (2.1) to be

$$\pi = pqx - c(x) - B \ , \tag{3.1}$$

in which q is a random variable representing the output uncertainty with $q = 1 + \theta\eta$, where η is random with $E\eta = 0$ and θ, a measure of output risk, is the standard deviation of q and $p = \bar{p} + \sigma\varepsilon$, where $\bar{p}$ is its mean and σ is its standard deviation with $E\varepsilon = 0$. We note that Equation (3.1) and Equation (2.1) are the same because this holds with and without output uncertainty. In this paper, we assume the variables are independent.

Recalled from Equation (2.2), the first-order condition of the expected utility of the profit $EU(\pi)$ is

$$EU'(\pi)(pq - c'(x^*)) = 0 \ . \tag{3.2}$$

Recalled from Equation (2.4), we have

$$\bar{p} - c'(x^*) > 0 \ . \tag{3.3}$$

From the above results, we develop the following proposition:

Proposition 3.1 *Under the above model setting, assuming differentiability and risk aversion, the optimal output x^* is increasing with the price $\bar{p}$, decreasing with the standard deviation, σ, of the price $\bar{p}$, and decreasing with θ, a measure of output risk and the standard deviation of q; that is, $\frac{\partial x^*}{\partial \bar{p}} > 0$, $\frac{\partial x^*}{\partial \sigma} < 0$, and $\frac{\partial x^*}{\partial \theta} < 0$, respectively.*

Proof. Using the method in the previous section, the first-order condition can be expressed as

$$\begin{aligned} & EU'(\pi)(pq - c'(x^*)) = 0 \\ \equiv\ & U'(\hat{\pi})(\hat{p}\hat{q} - c'(x^*)) = \hat{p}\hat{q} - c'(x^*) = \\ & (\bar{p} + \sigma\hat{\varepsilon})\,\hat{q} - c'(x^*) \ , \end{aligned} \tag{3.4}$$

where the superscripts denote optimal outcomes of the random variables. By continuity, we have

$$\hat{p}\hat{q} - c'(x^*) = \bar{p}\check{q} - c'(x^*) = \bar{p} + \bar{p}\theta\check{\eta} - c'(x^*) = 0 \ . \tag{3.5}$$

Moreover, Equation (2.4) implies that $\check{\eta} < 0$. Also, Equation (3.4) can be rewritten as

$$\bar{p} + \sigma\check{\varepsilon} - c'(x^*) = 0 \ . \tag{3.6}$$

Therefore, we have $\check{\varepsilon} < 0$. In addition, as shown before, we have

$$\bar{p} + d\bar{p} - c'(x_1^*) + \sigma\check{\varepsilon}_1 = 0 = \bar{p}_1 - c'(x_1^*) + \sigma\check{\varepsilon} = \bar{p} - c'(x^*) + \sigma\check{\varepsilon} \ . \tag{3.7}$$

If the expected price increases; that is, $\bar{p}_1 > \bar{p}$, then we have $c'(x_1^*) > c'(x^*)$, and thus, the optimal output increases, and vice versa.

Similarly, one can easily get

$$\bar{p} - c'(x_2^*) + (\sigma + d\sigma)\,\check{\varepsilon}_2 = 0 \equiv \bar{p} - c'(x_2^*) + \sigma_1\check{\varepsilon} = \bar{p} - c'(x^*) + \sigma\check{\varepsilon} \ . \tag{3.8}$$

If the level of risk σ increases; that is, $\sigma_1 > \sigma$, then we have $c'(x_2^*) < c'(x^*)$, and thus, the optimal output decreases, and vice versa.

On the other hand, using Equation (3.5), we obtain

$$\begin{aligned} & \bar{p} + \bar{p}(\theta + d\theta)\check{\eta}_1 - c'(x_3^*) = 0 \\ \equiv \quad & \bar{p} + \bar{p}\theta_1\check{\eta} - c'(x_3^*) = \bar{p} + \bar{p}\theta\check{\eta} - c'(x^*) = 0 \ . \end{aligned}$$

Thus, if θ increases; that is, $\theta_1 > \theta$, then we have $c'(x_3^*) < c'(x^*)$, and vice versa. Thus, we conclude that an increase (decrease) in the output risk will lead to the decrease (increase) in the optimal output.

Once again, the results do not require the assumption of non-increasing absolute risk aversion. ■

3.2 Price and Cost Uncertainties

We turn to consider the case when both output price and input price are uncertain (see Alghalith (2007) among others). To do so, we first modify the definition of profit from Equation (2.1) to get

$$\pi = pf(z) - wz - B \ , \tag{3.9}$$

where w is the random input price, $f(z)$ is the production function with $f'(z) > 0$ and $f''(z) < 0$, z is the non-random input quantity, $w = \bar{w} + \delta\epsilon$, where $\bar{w}$ is the mean of w, ϵ is random with $E\epsilon = 0$, and δ is the standard deviation of w.

As shown before, the risk-averse firm maximizes the expected utility of the profit such that

$$\max_z EU(\pi) \ . \tag{3.10}$$

The first-order condition of Equation (3.10) is

$$EU'(\pi)\left(pf'(z^*) - w\right) = 0 \ , \tag{3.11}$$

which is equivalent to

$$[\bar{p}f'(z^*) - \bar{w}]\, EU'(\pi) + f'(z^*)\, cov\,(U'(\pi), p) - cov\,(U'(\pi), w)\ .$$

Therefore, we have

$$\bar{p}f'(z^*) - \bar{w} > 0\ . \tag{3.12}$$

From the above, we obtain the following proposition:

Proposition 3.2 *Under the above model setting, assuming differentiability, statistical independence, and risk aversion, the optimal input z^* is increasing with the price $\bar{p}$, decreasing with the input price $\bar{w}$, decreasing with the standard deviation δ of w, and decreasing with the standard deviation, σ, of the price $\bar{p}$; that is, $\frac{\partial z^*}{\partial \bar{p}} > 0$, $\frac{\partial z^*}{\partial \bar{w}} < 0$, $\frac{\partial z^*}{\partial \delta} < 0$, and $\frac{\partial z^*}{\partial \sigma} < 0$, respectively.*

Proof. From Equation (3.11), we know that the first-order condition is

$$\begin{aligned} & EU'(\pi)\,(pf'(z^*) - w) = 0 \\ \equiv\ & U'(\hat{\pi})\,(\hat{p}f'(z^*) - \hat{w}) = \hat{p}f'(z^*) - \hat{w}\ . \end{aligned}$$

By continuity, we have

$$\hat{p}f'(z^*) - \hat{w} = \bar{p}f'(z^*) - \check{w} = 0\ . \tag{3.13}$$

We can rewrite Equation (3.13) as

$$\bar{p}f'(z^*) - \bar{w} - \delta\check{\epsilon} = 0\ . \tag{3.14}$$

This implies that $\check{\epsilon} > 0$. Similarly, we rewrite Equation (3.13) as

$$\dot{p}f'(z^*) - \bar{w} = 0 = (\bar{p} + \sigma\ .\dot{\varepsilon})\, f'(z^*) - \bar{w}\ . \tag{3.15}$$

This implies that $\dot{\varepsilon} < 0$.

Using the approach we shown before, we have

$$\begin{aligned} & (\bar{p} + d\bar{p} + \sigma\dot{\varepsilon}_1)\, f'(z_1^*) - \bar{w} = 0 \\ \equiv\ & (\bar{p}_1 + \sigma\dot{\varepsilon})\, f'(z_1^*) - \bar{w} = (\bar{p} + \sigma\dot{\varepsilon})\, f'(z^*) - \bar{w}\ . \end{aligned}$$

Thus, we have

$$\bar{p} = \frac{\bar{w}}{f'(z^*)} - \sigma\dot{\varepsilon} \quad \text{and} \quad \bar{p}_1 = \frac{\bar{w}}{f'(z_1^*)} - \sigma\dot{\varepsilon} \ . \tag{3.16}$$

This implies that $z_1^* > z^*$ if $\bar{p}_1 > \bar{p}$, and vice versa.

Similarly, we can obtain

$$\sigma = \frac{\frac{\bar{w}}{f'(z^*)} - \bar{p}}{\dot{\varepsilon}} \quad \text{and} \quad \sigma_1 = \frac{\frac{\bar{w}}{f'(z_2^*)} - \bar{p}}{\dot{\varepsilon}} \ . \tag{3.17}$$

This implies that $z_2^* < z^*$ if $\sigma_1 > \sigma$, and vice versa.

Using the same argument, we can obtain

$$\bar{w} = \dot{p}f'(z^*) \quad \text{and} \quad \bar{w}_1 = \dot{p}f'(z_3^*) \ . \tag{3.18}$$

This implies that $z_3^* < z^*$ if $\bar{w}_1 > \bar{w}$, and vice versa.

Moreover, we have

$$\delta = \frac{\bar{p}f'(z^*) - \bar{w}}{\check{\epsilon}} \quad \text{and} \quad \delta_1 = \frac{\bar{p}f'(z_4^*) - \bar{w}}{\check{\epsilon}} \ . \tag{3.19}$$

This implies that $z_4^* < z^*$ if $\delta_1 > \delta$, and vice versa.

We note that the results are perfectly intuitive. ■

Remark 3.1 $x = f(z)$.

3.3 Output, Price and Cost Uncertainties

We turn to consider that output, output price and input price are uncertain simultaneously. The profit is given by $\pi = pqf(z) - wz - B$, where the variables are defined as before.

The first-order condition is

$$EU'(\pi)(pqf'(z^*) - w) = 0 \ , \tag{3.20}$$

and thus, we get

$$\left[\bar{p}f'\left(z^*\right)-\bar{w}\right]EU'\left(\pi\right)+cov\left(U'\left(\pi\right),pq\right)-cov\left(U'\left(\pi\right),w\right)=0\ . \tag{3.21}$$

Thus, we have

$$\bar{p}f'\left(z^*\right)-\bar{w}>0\ . \tag{3.22}$$

From the above, we obtain the following proposition:

Proposition 3.3 *Under the above model setting, assuming differentiability, statistical independence, and risk aversion, the optimal input z^* is increasing with the price $\bar{p}$, decreasing with the input price $\bar{w}$, decreasing with the standard deviation δ of w, decreasing with the standard deviation, σ, of the price $\bar{p}$, and decreasing with θ, a measure of output risk and the standard deviation of q; that is, $\frac{\partial z}{\partial \bar{p}}>0$, $\frac{\partial z}{\partial \bar{w}}<0$, $\frac{\partial z}{\partial \delta}<0$, $\frac{\partial z}{\partial \sigma}<0$, and $\frac{\partial z}{\partial \theta}<0$.*

Proof. The first-order condition is

$$EU'\left(\pi\right)\left(pqf'\left(z^*\right)-w\right)=0=\hat{p}\hat{q}f'\left(z^*\right)-\hat{w}\ . \tag{3.23}$$

Also, by continuity, we have

$$\hat{p}\hat{q}f'\left(z^*\right)-\hat{w}=\bar{p}f'\left(z^*\right)-\breve{w}=0\ . \tag{3.24}$$

We rewrite Equation (3.24) as

$$\bar{p}f'\left(z^*\right)-\bar{w}-\delta\breve{\epsilon}=0\ . \tag{3.25}$$

This implies that $\breve{\epsilon}>0$. Similarly, we rewrite Equation (3.24) as

$$\dot{p}f'\left(z^*\right)-\bar{w}=0=\left(\bar{p}+\sigma\dot{\varepsilon}\right)f'\left(z^*\right)-\bar{w}\ . \tag{3.26}$$

This implies that $\dot{\varepsilon}<0$. Now, we express Equation (3.24) as

$$\bar{p}\check{q}f'\left(z^*\right)-\bar{w}=\bar{p}\left(1+\theta\check{\eta}\right)f'\left(z^*\right)-\bar{w}=0 \tag{3.27}$$

This implies that $\check{\eta}<0$. Using the method in the previous proofs completes the proof.
■

Clearly, the results do not require the assumption of non-increasing absolute risk aversion.

3.4 The Impact of Adding a Risk to Another Risk

For example, we can show that starting with the price risk, adding output risk reduces optimal output. To do so, consider Equation 3.5 such that

$$\bar{p} + \bar{p}\theta\check{\eta} - c'\left(x^*\right) = 0 \ . \tag{3.28}$$

Now, adding output uncertainty is equivalent to a change in θ from zero to a positive value (and thus a change in $\theta\check{\eta}$ from zero to a negative value). Differencing the above equation (holding $\bar{p}$ constant) yields

$$\Delta\bar{p}\theta\check{\eta} = \Delta c'\left(x^*\right) \ . \tag{3.29}$$

If θ changes from a positive value to zero ($\theta\check{\eta}$ changes from a negative value to zero), $\Delta\theta\check{\eta} > 0$ and thus $\Delta x > 0$ (output increases); and vice versa.Needless to say, the results are perfectly intuitive.

4 Concluding Remarks

Given the current unusual and uncertain state of the world, especially with price uncertainty and quantity uncertainty, it is important to develop a theory of the production function that simultaneously solves for output, output price, and input price uncertainties for modelling the theory of the firm. To do so, we first extend the theory by considering price, output, and cost risks. We prove that under our model setting and assumptions, the optimal output increases with the price, decreases with the standard deviation of the price, and decreases with the standard deviation of the output.

Thereafter, by considering that both output price and input price are uncertain, we find that the optimal input increases with the price, decreases with the input price, decreases with the standard deviation of the input quantity, and decreases with the standard deviation of the price.

We then consider that output, output price, and input price are uncertain simultaneously and find that the optimal input increases with the price, decreases with the input price, decreases with the standard deviation of the input price, decreases with the standard deviation of the price, and decreases with the standard deviation of the output. Lastly, we study the impact of adding a risk to another risk.

The results are perfectly intuitive for the risk-averse firm. The risk level is negatively related to the optimal quantities. The mean of the input price is negatively related to the optimal quantity, but the mean of the output price is positively related to the optimal quantity.

Furthermore, the partial derivatives of the comparative statics are far simpler than the ones obtained by traditional methods. They do not depend on the preferences. Thus, it is much easier to empirically estimate them.

Moreover, unlike previous literature, our results do not depend on the sign of $U'''(\pi)$ or whether the firm exhibits decreasing absolute risk aversion.

A possible future study is to apply these methods to the case of imperfect competition such as monopoly.

Competing interests:

The authors have no competing interests to declare that are relevant to the content of this article.

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