

The Impact of Technology on Product Design, Productivity, and Profits: A Duopoly Model of Price-Quality Competition

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Abstract

This paper develops a two stage economic model of duopoly competition to examine the impact of technology investments in product design tools on product quality and price, firm productivity and profits, and consumer welfare. In the first stage the firms simultaneously choose product quality and in the second stage, after observing each other's quality choices, the firms simultaneously set prices. This model captures the firm's option to leverage technology tools to improve product quality and tracks the effect of such quality adjustments on measures of firm performance and consumer welfare. More specifically, the findings show that profit-maximizing firms will leverage technology-based design tools to improve product quality, resulting in higher levels of firm profits and consumer welfare; however, these improvements come at the expense of productivity. Alternatively, the findings show that firms that fail to improve quality, and instead leverage the tools to reduce production costs, will realize higher levels of productivity; however, this improvement in productivity comes at the expense of profits and consumer welfare. The results of the analytical model cast a new light on why it may be reasonable to empirically observe reductions in firm productivity following investments in IT tools that improve production capabilities.

1. Introduction

For over a decade empirical studies in the information technology (IT) value literature have attempted to quantify the economic benefits realized by firms and industries from IT investments. However, the results of these studies, especially those related to the contribution of IT to various measures of productivity, have been mixed. This has led to the coining of the term *IT productivity paradox*. The premise, or commonly accepted opinion, underlying this paradox is that IT investments should lead to gains in productivity. However, in this paper we demonstrate that, consistent with economic theory, there may be many reasonable conditions under which IT investments, even when properly managed by rational, profit-maximizing firms,

may actually reduce productivity. We formally characterize these conditions using a closed-form, analytical model. Therefore, while recognizing the many measurement problems facing empiricists, we argue that the mixed empirical findings in the IT value literature do not necessarily reflect a paradox. As we will see, they may in fact reflect the underlying truth of the relationship between IT and productivity. That is, accepting the unconditional premise that IT investments should improve productivity may lead to an inappropriate interpretation of previous empirical findings and, as pointed out by Strassmann[30], may lead to an inappropriate criticism of the use of IT by firms and industries.

This paper builds on previous analytical models of IT value developed by Thatcher and Pingry[34] and Thatcher and Oliver[32,33]. These authors modeled the impact of technology-based design tools (that enhance production capabilities) by a single product monopolist on economic performance including profits, productivity, and consumer surplus. They showed that a monopolist leverages these tools to design better quality products that they offer to consumers at higher prices. Although this adjustment to product design maximizes firm profits and improves consumer welfare it adversely affects measures of productivity, defined as the ratio of output value to input value.

This paper extends this formal analysis of IT value to a two-stage model of duopoly competition in which firms set product qualities in the first stage and product prices in the second stage. More specifically, the duopoly model examines the impact of technology-based design tools on product design (e.g., product quality and pricing choices), firm performance (e.g., demand, production costs, profits, and productivity), and consumer welfare. This model shows that the "counter-intuitive" results found in the monopoly case are robust to a more competitive market setting. That is, the model shows that competing, profit-maximizing firms will leverage technology tools to offer better quality products to consumers at higher prices. Although these adjustments stimulate demand, increase revenues and consumer surplus, and maximize profits they also increase production costs in a way that adversely affect various well-established measures of productivity (even when accounting for benefits passed

on to consumers in the output value). Alternatively, a simple extension of this model shows that firms that fail to improve product quality, and instead leverage the tools to reduce production costs, will realize higher levels of productivity; however, this improvement comes at the expense of profits and consumer welfare. In summary, the results of the analytical model cast a new light on why it may be reasonable to empirically observe reductions in firm productivity following investments in technology tools that improve production capabilities. Furthermore, our model identifies conditions under which productivity improvements should be expected.

Unfortunately, firms often struggle to understand these complex and sometime counter-intuitive relationships among technology investments, cost structure, product design, and productivity. However, based on these analytical results, it should not be surprising that the empirical findings in the IT value literature, especially those related to the contribution of IT investments to productivity, have been so mixed. We hope that the model presented in this paper will help interpret current and future empirical work in the IT value area.

2. Literature Review

For over a decade, empirical studies in the IT value literature have attempted to quantify the benefits realized from IT investments by analyzing data collected at the economy level, industry level, firm level, and IT application (or process) level. However, the results of these studies, especially those related to the contribution of IT to productivity, have been mixed. It has often been suggested in the literature that these mixed findings may be the result of factors such as methodological problems with the studies (i.e., empirical mismeasurement of outputs and inputs) or mismanagement problems within the firms. While we acknowledge the validity of these arguments, we suggest in this paper that these mixed findings may actually be consistent with economic theory and should be expected even when problems of mismeasurement and mismanagement are eliminated. Therefore, in this section we briefly review the empirical studies in the IT value literature that have motivated our work.

Early studies examined the contribution of aggregate IT spending on economy and industry level performance measures and typically found little or no improvement in productivity despite massive investments in IT since the early 1970s [1, 13, 24, 26, 27, 31, and see 10 for a review of the empirical work]. These early studies gave rise to the IT productivity paradox and initiated a long stream of empirical work attempting to explain the paradox.

The primary explanation for these mixed findings was that the collection of data aggregated at the economy and industry levels had led to the mismeasurement of inputs

and outputs in the productivity measures and, therefore, the underestimation of productivity gains from IT investments [8, 9, 10, 19, 20, 21]. Therefore, later work examined the IT productivity question using firm level (or disaggregated) data. While some of these studies have found significant correlations between IT spending and firm productivity, other studies have not [e.g., 3, 8, 9, 16, 17, 18].

More recently, several studies have analyzed data at the application level to identify the impact of specific IT investments on intermediate and activity-based measures of firm performance. Interestingly, the findings from these studies have also been very mixed. For example, Rai [25] found that IT budget allocations to IS staff, telecommunications, and hardware were positively correlated to firm output and labor productivity. However, he found a negative correlation between software investments and labor productivity. Banker and Kauffman [2] found that ATM network membership had a positive impact on a bank's local deposit market share but a negative impact on labor productivity of branch tellers. In contrast, Haynes and Thompson [15] found robust and statistically significant productivity gains from the introduction of ATMs to UK building societies. Weill [35] found no productivity gains from investments in data processing systems or strategic systems and identified CASE tools as particularly disappointing in terms of their contributions to productivity. Mukhopadhyay et al. [23] found that investments by the U.S. Postal Service in optical character recognition and bar code sorting technologies led to significant increases in mail sorting output and improvements in quality. Finally, Devaraj and Kohli [11] found that investments by eight hospitals in decision support systems (DSS) used to help evaluate contracts led to higher revenues and better quality products and services.

While the studies reviewed above have examined the impact of IT on various measures of firm performance, it is important to note that firms do not capture all the benefits created by IT. That is, much of the value created is passed on to consumers through competition. Therefore, measures of economic performance such as revenues, profits, and productivity collected at the firm- or even application-level tend to underestimate IT value since these measures do not fully incorporate consumer welfare. Brynjolfsson [6] addressed this issue empirically by estimating four measures of consumer surplus (generated by integrating the area under the demand curve for IT) using data from the U.S. Bureau of Economic Analysis. He found that IT investments generate approximately three times their cost in value to consumers. Hitt and Brynjolfsson [7] extended this work to more carefully examine the relationships among productivity, business profitability, and consumer welfare. Using data collected from 370 firms over the period 1988-

1992, they found that IT contributed significantly to firm productivity and created substantial value for consumers, but they did not find evidence that IT had an impact on firm profitability.

Despite the plethora of empirical studies on IT value and despite the improvements in the measurements used in these studies, the empirical findings seem to be more mixed than ever. Based on these observations, Thatcher and Pingry[34] and Thatcher and Oliver[32, 33] developed analytical models of IT value in monopoly settings. They showed that a monopolist leverages technology-based design tools to design better quality products that they offer to consumers at higher prices. Although this adjustment to product design maximizes firm profits and improves consumer welfare it adversely affects various measures of productivity. These findings suggest that the IT productivity paradox may not be so much a paradox but instead the product of a conscious decision by rational firms to maximize profits (through quality improvements), sometimes at the expense of productivity.

In the following section we extend this formal analysis to a more competitive setting – a two-stage model of duopoly competition in which firms set product qualities in the first stage and product prices in the second stage. Although work in the economics literature has examined similar duopoly models of two-stage non-cooperative games (first quality, then price) [e.g., 14, 28, 29] it does not specifically examine the impact of technology tools on firms' quality and pricing decisions and the resulting impact on measures of productivity. However, using a simple two-stage model of duopoly competition we can formalize how firms leverage technology to improve product design (i.e., quality and pricing choices) and the resulting impact on firm performance (i.e., profits and productivity) and consumer welfare. Formalizing these complex relationships is a critical contribution of this paper.

3. Model

We consider a two-stage model of duopoly competition. In the first stage, firms 1 and 2 simultaneously choose a level of product quality. In the second stage, upon observing the quality of its competitor, the firms simultaneously set prices. As we will see below, the degree of differentiation between the firms' products is represented by parameters in the demand functions.

We now formally describe the game, beginning with the second stage. If, at the first stage, Firm 1 chooses product quality s_1 and Firm 2 chooses product quality s_2 , then the demand for Firm 1's product at the second stage is given by

$$Q_1 = a - p_1 + bp_2 + s_1 - cs_2,$$

with demand for Firm 2 (symmetrically) given by

$$Q_2 = a - p_2 + bp_1 + s_2 - cs_1,$$

where a represents the size of the market, b measures the price sensitivity of demand, c represents the quality sensitivity of demand, and p_1 and p_2 are the prices set by Firm 1 and Firm 2, respectively. These demand functions imply that, all else equal, a decrease in p_1 or an increase in p_2 will increase the quantity demanded for Firm 1's product while an increase in s_1 or a decrease in s_2 will increase the demand for Firm 1's product. This is similar for Firm 2. Given the above demand functions we make assumption $A(1): 0 < b, c < 1$, which implies that a firm's own investment and pricing decisions have greater impact on its own demand than do the decisions made by its rival.

The products offered by the firms are differentiated. The parameters b (price sensitivity) and c (quality sensitivity) capture the degree of product differentiation between the firms (or the substitutability of the firms' products). For example, very low values of b and c (i.e., close to zero) imply that the services offered by the firms are completely differentiated (or less substitutable); in this case the demand for a firm's product is not affected by the quality or pricing decisions made by its rival. That is, each firm essentially acts as a monopolist. On the other hand, larger values of b and c imply that the firms' products are less differentiated or more substitutable. Therefore, the quality and pricing decisions made by a firm's rival will have a larger impact on demand for the firm's own product.

Given the demand functions presented above we assume that consumer demand for a firm's product is relatively more sensitive to price than to quality by making Assumption $A(2): b > 2c$. We assume a price-sensitive market because, even though quality criteria are important, the actual quality offered by a firm is not as salient to consumers as are the prices charged by the firms. Consumers typically are not fully informed about the quality of various products. Becoming better informed is costly (e.g., obtaining information from free trials, magazines, consumer reports, or friends and family). Without precise information about the product quality, many products appear to provide similar features. However, product prices are easier to identify and interpret.

At the first stage, the cost to Firm i of designing and developing a product of quality s_i is given by

$$C_i = \frac{k}{2} s_i^2,$$

where k is a technology cost coefficient that characterizes the rate at which the marginal cost of further improvements in product quality rise as quality increases. We will refer to the technology coefficient, k , as the *design cost of quality*.

We note at this point that unlike past studies that examine the impact of IT investments on economic performance, this paper does **not** model IT investment explicitly. That is, IT investment is not a decision variable in this model. Instead, we assume that technology investments made by a firm affect the level of k , the design cost of quality. More specifically, we model investments in technology as improvements to a firm's production capabilities, or a reduction in k . Examples of technology investments that lower cost parameter k are Computer-Aided Design (CAD) and Computer-Aided Systems Engineering (CASE) tools, prototyping tools, decision support systems, and usability testing technologies. Ideally, these tools enable a firm to design and develop a product (or service) of a given level of quality faster and cheaper. Based on this discussion, in Section 4 we will examine the economic value of technology investments by deriving the impact of changes in k on various measures of economic performance.

We note that the cost function presented above is assumed to be quadratic because improving the overall quality of a product becomes increasingly difficult (and increasingly costly) as product quality increases [4, 12, 22]. In addition, we assume the marginal cost of manufacturing and distributing the product in the second stage to be zero.

Therefore, the total profit function of Firm i is given by

$$\Pi_i = p_i(a - p_i + bp_j + s_i - cs_j) - \frac{k}{2}s_i^2.$$

We now derive the consumer surplus function of Firm i 's customers. Figure 1 maps the quantity demanded (x-axis) for Firm i 's product for each price (y-axis) charged by Firm i given the firm's own quality and the price and quality of its rival. The intercept of the price axis is determined by setting $Q_i = 0$ and solving for p_i . Therefore, solving

$$Q_i = a - p_i + bp_j + s_i - cs_j = 0$$

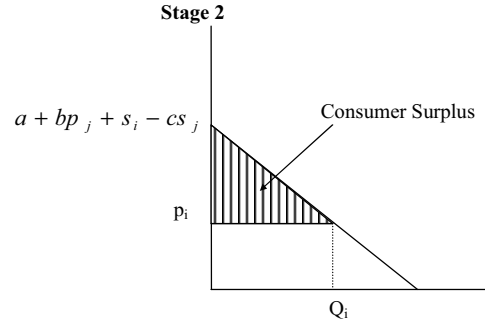
leads to

$$p_i = a + bp_j + s_i - cs_j.$$

The aggregate consumer surplus realized by consumers who purchase Firm i 's product at price p_i is given by the area of the shaded triangle in Figure 1. Therefore, the consumer surplus function for consumers that purchase Firm i 's product is given by

$$Y_i = \frac{1}{2}Q_i[(a + bp_j + s_i - c_j) - p_i]$$

Figure 1: Consumer Surplus



Productivity is defined as the ratio of output value to its related input value. When quantity is assumed to be a good proxy for value, productivity is defined as quantity of output (e.g., number of widgets, lines of programming code, number of checks processed) per quantity of related input (e.g., labor hours, number of employees). Early studies that examined IT value used economy- or industry-level measures of productivity that were based on **counts** and **numbers** [see 5, 10 for a more detailed discussion].

However, quantity in many cases, especially in the service sector, is not considered a good proxy for the value created by IT for consumers [5, 10]. Therefore, later empirical studies used firm-level data to measure at least some of the intangible value that was being created by computers [e.g., 6, 8, 9, 17]. That is, if consumers are willing to pay more for increases in quality or convenience, then a firm's **revenue** will reflect some of this increase in intangible value. Therefore, these studies measured output value based on firm revenues to capture at least some of the intangible value of IT in productivity measures (e.g., sales dollars divided by the cost to the producer).

Finally, some of the value created through IT investments are passed on to consumers through competition and will not be captured in measures of firm revenues. Therefore, Brynjolfsson[6] and Brynjolfsson and Hitt[7] attempted to measure the impact of IT investments on not only firm revenues but also **consumer surplus**.

Based on this discussion, in this model we consider three measures of productivity which we term *output productivity*, *firm productivity*, and *social productivity*. Output productivity is defined as the ratio of the number of products produced to its related input value, with inputs measured in dollars. In this paper, we are interested in measuring the productivity of the production process, or the output value generated per unit of production cost.

Therefore, the output productivity function for Firm i is given by $\rho_{1,i} = Q_i/C_i$.

Firm productivity is defined as the ratio of output value to the firm to its related input value, with both inputs and outputs measured in dollars. In our model, the output value to the firm of the production process is the revenue (or sales dollars) generated. Therefore, the firm productivity function for Firm i is given by $\rho_{2,i} = R_i/C_i$.

Social productivity is defined as the ratio of output value to society to its related input value, with both inputs and outputs measured in dollars. In our model, the output value to society of a firm's production process is the sum of a firm's revenue and consumer surplus. Therefore, the social productivity function for Firm i is given by $\rho_{3,i} = (R_i + Y_i)/C_i$.

Finally, in this model technology investments undertaken by the firm (which are represented as changes in k , the technology coefficient, in the cost function) are assumed to be costless. That is, the costs of acquiring, implementing, and maintaining the technology will not affect production costs (or input value) and, therefore, will not adversely affect the denominator of the productivity measures presented above. We note that this assumption provides the best case scenario for observing improvements in productivity from investments in technology tools.

The competition between firms is analyzed by solving for the sub-game perfect equilibrium of the two-stage game. After determining equilibrium qualities and prices we use comparative static analysis to investigate the impact of the model parameters on the equilibrium decisions.

4. Results

4.1. Equilibrium Quality and Pricing Decisions

At the second stage, the second derivatives of the profit function with respect to (w.r.t) prices are negative, $\frac{\partial^2 \pi_1}{\partial p_1^2} = \frac{\partial^2 \pi_2}{\partial p_2^2} = -2$. Therefore, we derive both firms' price reaction functions¹ given the product quality decisions (s_1, s_2) made in stage 1 by solving the first order conditions (F.O.C.)

$$\frac{\partial \pi_1}{\partial p_1} = a - 2p_1 + bp_2 + s_1 - cs_2 = 0 \text{ and}$$

$$\frac{\partial \pi_2}{\partial p_2} = a - 2p_2 + bp_1 + s_2 - cs_1 = 0.$$

Solving gives the price reaction functions

$$p_1(p_2) = \frac{1}{2}(a + bp_2 + s_1 - cs_2) \text{ and}$$

$$p_2(p_1) = \frac{1}{2}(a + bp_1 + s_2 - cs_1).$$

We observe that both reaction functions have positive slopes and that prices are positively correlated. The point at which the price reaction curves intersect determines the unique price equilibrium in stage 2. Therefore, the equilibrium pricing decisions (p_1^*, p_2^*) in stage 2, given the quality decisions (s_1, s_2) made in stage 1, are

$$p_1^*(s_1, s_2) = \frac{a(b+2) + s_1(2-bc) + s_2(b-2c)}{4-b^2} \text{ and}$$

$$p_2^*(s_1, s_2) = \frac{a(b+2) + s_2(2-bc) + s_1(b-2c)}{4-b^2}.$$

Assumptions $A(1) - A(2)$ ensure positive prices in equilibrium.

At the first stage, we derive both firms' quality reaction functions by solving the first order conditions (F.O.C.)

$$\frac{\partial \pi_1}{\partial s_1} = -s_1 \frac{\{k(b-2)^2(b+2)^2 - 2(2-bc)^2\} + 2s_2(2-bc)(2c-b) + 2a(2+b)(bc-2)}{(4-b^2)^2} = 0$$

and

$$\frac{\partial \pi_2}{\partial s_2} = -s_2 \frac{\{k(b-2)^2(b+2)^2 - 2(2-bc)^2\} + 2s_1(2-bc)(2c-b) + 2a(2+b)(bc-2)}{(4-b^2)^2} = 0.$$

Solving gives the quality reaction functions

$$s_1(s_2) = \frac{2s_2(2-bc)(b-2c) + a(b+2)(2-bc)}{k(2-b)^2(b+2)^2 - 2(2-bc)^2} \text{ and}$$

$$s_2(s_1) = \frac{2s_1(2-bc)(b-2c) + a(b+2)(2-bc)}{k(2-b)^2(b+2)^2 - 2(2-bc)^2}.$$

The point at which the quality reaction curves intersect determines the quality equilibrium in stage 1. Therefore, the equilibrium quality decisions (s_1^*, s_2^*) in stage 1 are

$$s_1^* = s_2^* = \frac{2a(2-bc)}{k(2+b)(2-b)^2 - 2(1-c)(2-bc)}.$$

¹ Recall that the price reaction curve $[p_1(p_2)]$ for Firm 1 maps out Firm 1's best, or profit-maximizing, response to each price that could be charged by Firm 2.

To ensure a **unique** and **positive** equilibrium in quality competition we assume $A(3): k > \frac{2(2-bc)(1-c)^2}{(2+b)(2-b)^2}$. That

is, this assumption guarantees that the denominator of the quality equation above is positive and that the second derivatives of the profit functions w.r.t. qualities are negative,

$$\frac{\partial^2 \pi_1}{\partial s_1^2} = \frac{\partial^2 \pi_2}{\partial s_2^2} = -\frac{k(2-b)^2(2+b)^2 - 2(2-bc)^2}{(4-b^2)^2} < 0.$$

Given that both firms invest in the same level of product quality in equilibrium in stage 1 and given the equilibrium pricing equations presented earlier, both firms will charge the same price in stage 2,

$$P_i^* = \frac{ka(2-b)(2+b)}{k(2+b)(2-b)^2 - 2(1-c)(2-bc)}.$$

4.1. Economic Value of IT Investments

In this section we examine the impact of investments in technology-based design tools [represented by changes in the technology coefficient (k) in the cost function] on various measures of economic performance.

Proposition 1: IT investments that lower the design cost (k) of quality will increase profits and consumer surplus.

The partial derivatives of Firm i 's profit function w.r.t. k is

$$\frac{\partial \pi_i}{\partial k} = -\frac{2a^2(2-bc)\{k(b+2)(b-2)^2(b(2-c)+2(1-2c))-2(1-c)(2-bc)^2\}}{[k(b+2)(b-2)^2 - 2(1-c)(2-bc)]^3} < 0$$

Assumptions $A(1) - A(3)$ ensure that these partial derivatives are negative, implying that an improvement in a firm's production capability (or a reduction in k) will **increase profits**. Each firm's optimal response to an improvement in k is to offer a better quality product at a higher price. Assuming optimal adjustments to product design are made, each firm realizes an increase in product demand. Since more products are sold at a higher price revenues increase as well. More interestingly, the improvement in product quality and the resulting increase in demand together lead to an increase in production costs despite the improvement in k . However, the increase in revenues is greater than the increase in costs, resulting in

higher profits. [See Appendix for mathematical derivations of these findings]

The consumer surplus function in equilibrium – where $s^* = s_1^*, s_2^*$ and $p^* = p_1^*, p_2^*$, for consumer's purchasing the product offered by Firm i is given by

$$Y_i^* = \frac{1}{2}Q \left(\frac{a+s^*(1-c)}{1-b} - p^* \right) = \frac{k^2 a^2 (4-b^2)^2}{2(1-b)[k(2+b)(2-b)^2 - 2(1-c)(2-bc)]^2}.$$

Assumptions $A(1) - A(3)$ ensure positive consumer surplus in equilibrium. The partial derivative of the consumer surplus function w.r.t. k is

$$\frac{\partial Y_i}{\partial k} = -\frac{2a^2 k(2-b)^2(2+b)^2(1-c)(2-bc)}{(1-b)[k(b+2)(b-2)^2 - 2(1-c)(2-bc)]^3} < 0.$$

Assumptions $A(1) - A(3)$ ensure that the partial derivative is negative, implying that that an improvement in a firm's production capability (or a reduction in k) will **increase consumer surplus**. That is, the increases in product quality and product demand for each firm result in higher aggregate consumer surplus despite the higher prices charged to consumers. The above analysis demonstrates that IT investments that improve firms' production capabilities benefit the firms and consumers alike.

Proposition 2: IT investments that lower the design cost (k) of quality will decrease productivity.

The partial derivatives of Firm i 's three productivity functions – output productivity, firm productivity, and social productivity – w.r.t. k are

$$\frac{\partial \rho_{1,i}}{\partial k} = \frac{(b+2)^2(2-b)^3}{2a(2-bc)^2} > 0, \quad \frac{\partial \rho_{2,i}}{\partial k} = \frac{(4-b^2)^2}{2(2-bc)^2} > 0,$$

$$\text{and } \frac{\partial \rho_{3,i}}{\partial k} = \frac{(3-2b)(4-b^2)^2}{4(1-b)(2-bc)^2} > 0.$$

Assumption $A(1)$ ensures that the partial derivatives of all three productivity functions are positive, implying that an improvement in a firm's production capability (or a reduction in k) will **decrease productivity**, even when accounting for output value passed on to consumers through competition. This seemingly counter-intuitive result is driven by the firms' profit-maximizing adjustments to product design. That is, each firm's optimal response to an improvement in k is to offer a better quality product at a higher price. Proposition 1 showed that these adjustments generate higher profits despite a realization of higher production costs. However, the positive signs of the three partial derivatives presented above shows that while the *absolute* increase in revenues

² We note that Assumption $A(3)$ implies that to ensure positive quality choices in equilibrium the design cost of quality must be "substantial". More specifically, depending upon the realization of the differentiation parameters, b and c , in the demand function the minimum level of k required to ensure a unique and positive equilibrium ranges as follows: $[1/2 < k < 4/3]$.

is greater than the *absolute* increase in costs, the *percentage increase* in costs is greater than the *percentage increase* in revenues (and the other output values). In other words, while a reduction in k leads to an increase in the *difference* in revenues and costs, it simultaneously leads to a decrease in the *ratio* of output values to costs.

Together, Propositions 1 and 2 demonstrate that firms maximize profits by leveraging technology investments to offer better quality products at higher prices, but at the expense of productivity.

4.2. Economic Value of IT Investments When Holding Product Quality Constant

In Section 4.2, we show that the decrease in productivity following a reduction in k is driven by the firm's adjustments to product design. Below we clarify this relationship by considering the impact of a reduction in k on economic performance when firms hold product quality **constant** following an IT investment. This reduces the two-stage model presented in Section 3 to a one-stage model of price competition. Therefore, the analysis below is based on equations derived from the stage 2 results presented in Section 4.1. That is, the equilibrium pricing decisions (p_1^*, p_2^*) , given fixed product qualities (s_1, s_2) are

$$p_1^*(s_1, s_2) = \frac{a(b+2) + s_1(2-bc) + s_2(b-2c)}{4-b^2}$$

and

$$p_2^*(s_1, s_2) = \frac{a(b+2) + s_2(2-bc) + s_1(b-2c)}{4-b^2}.$$

Proposition 3: Given fixed product qualities, IT investments that lower the design cost (k) of quality will increase profits but will not affect consumer surplus.

Given product qualities (s_1, s_2) , the partial derivative of Firm i 's profit function w.r.t. k is $\frac{\partial \pi_i(s_1, s_2)}{\partial k} = -\frac{s_i^2}{2} < 0$. This partial derivative is negative, implying that an improvement in a firm's production capability (or a reduction in k) will increase profits. Each firm's optimal response to an improvement in k when keeping product quality constant is to offer the same product at the same price, implying that firms will realize the same product demand and revenues as before the IT investment. In addition, given fixed product quality the reduction in k leads to a decrease in costs (i.e., $\frac{\partial C_i(s_1, s_2)}{\partial k} = \frac{s_i^2}{2} > 0$). Since revenues remain unchanged, the decrease in costs results in higher profits. Of course,

since quality, prices, and demand remain unchanged following the reduction in k , consumer surplus remains unchanged as well.

The above analysis demonstrates that IT investments that improve firms' production capabilities holding product quality constant benefit the firms without hurting consumers.

Proposition 4: Given fixed product qualities, IT investments that lower the design cost (k) of quality will increase productivity.

Given fixed product qualities, the partial derivatives of the three productivity functions – output productivity, firm productivity, and social productivity – w.r.t. k are

$$\frac{\partial \rho_{1,i}(s_1, s_2)}{\partial k} = -2 \frac{s_i(2-bc) + s_j(b-2c) + a(2+b)}{k^2 s_i^2 (4-b^2)} < 0,$$

$$\frac{\partial \rho_{2,i}(s_1, s_2)}{\partial k} = -2 \frac{(s_i(2-bc) + s_j(b-2c) + a(2+b))^2}{k^2 s_i^2 (4-b^2)^2} < 0,$$

and

$$\frac{\partial \rho_{3,i}(s_1, s_2)}{\partial k} = -3 \frac{(s_i(2-bc) + s_j(b-2c) + a(2+b))^2}{k^2 s_i^2 (4-b^2)^2} < 0.$$

Assumptions $A(1) - A(2)$ ensure that the partial derivatives of all three productivity functions given fixed product qualities are negative, implying that an improvement in a firm's production capability (or a reduction in k) will increase productivity. Here in the one-stage model productivity increases because the output values remain unchanged while costs decrease.

Together, Propositions 3 and 4 demonstrate that when holding product quality constant, firms maximize profits by leveraging IT investments to minimize costs given a fixed product design, resulting in an increase in both profits and productivity. This analysis further demonstrates that the adverse affects of IT investments on productivity shown in Section 4.2 are driven by the firms' profit-maximizing adjustments to product quality and price.

4.3. Economic Impact of Quality Sensitivity

Given the importance of the firms' product quality decisions in determining the direction of productivity, in this section we return to the two-stage model and consider the impact of changes in c , a parameter in the demand function, on productivity. One can interpret c in a variety of ways: (i) as a measure of the consumer's tastes for product quality, with c larger as consumers value better quality more highly, (ii) as a measure of the differentiation of firm's products, with c larger as the

products are less differentiated, and (iii) as a measure of the consumer's information about product quality, with c larger as consumers are better informed about each firm's product quality. Here we will focus on the first interpretation and consider c as a measure of the consumer's tastes for product quality.

Proposition 5: An increase in consumer's tastes (c) for product quality will increase productivity.

The partial derivatives of the three productivity functions – output productivity, firm productivity, and social productivity – w.r.t. c are,

$$\frac{\partial \rho_1}{\partial c} = \frac{bk(b+2)^2(2-b)^3 + (2+b)(2-bc)(2-b)^2}{a(2-bc)^3} > 0,$$

$$\frac{\partial \rho_2}{\partial k} = \frac{kb(4-b^2)^2}{(2-bc)^3} > 0, \text{ and } \frac{\partial \rho_3}{\partial k} = \frac{kb(3-2b)(4-b^2)^2}{2(1-b)(2-bc)^3} > 0$$

Given Assumptions $A(1) - A(2)$, the partial derivatives of all three productivity functions are positive, implying that an increase in consumer sensitivity to product quality will lead to an increase in productivity. Again, the mechanism driving this result is the firms' profit-maximizing adjustments to product design to such a shift in consumer tastes. Each firm's optimal, profit-maximizing response to an increase in c is to offer a **lower quality product at a lower price** [see Appendix for all mathematical derivations]. Of course, a decrease in product quality and price will have the opposite impact on output values and input value than observed in Section 4.2. That is, such adjustments lead to decreases in demand, revenues, consumer surplus, and costs. However, the positive signs of the three partial derivatives presented above imply that the *percentage decrease* in costs is greater than the *percentage decrease* in revenues, resulting in an increase in the *ratio* of revenues to costs (and an increase in the *ratio* of other output values to costs).

This finding further supports our claim that a firm's choice of product quality directly affects various measures of productivity. However, it may seem counter-intuitive to the reader that as consumers become more quality sensitive (i.e., c becomes larger), firms will choose to develop and offer lower quality products at lower prices. To understand the intuition behind this result we refer to Figures 2 and 3.

Figure 2 shows that, holding stage 1 qualities fixed at (s_1, s_2) , an increase in c causes each firm's price reaction curve to shift inward. This inward shift occurs because an increase in c , holding (s_1, s_2) fixed, leads to a decrease in demand for each firm's product. Hence, in each subgame (s_1, s_2) both firms set lower prices given an increase in c .

From Figure 2 we know that increasing c leads to lower prices in each sub-game (s_1, s_2) and, it can also be shown, leads to lower profits for each firm. In fact, holding a competitor's quality fixed, an increase in c leads to a lower marginal (stage 2) profit per unit of quality. Hence, holding the competitor's quality fixed, each firm's optimal product quality decreases as c increases. Figure 3 shows the inwards shifts of each firm's quality reaction curves in stage 1 when consumer sensitivity to quality increases. The shifts in the quality reaction curves lead to a new equilibrium in which both firms invest in lower levels of quality than they would have before. The decrease in both product quality and price that results from an increase in c drives the productivity gain realized from the change.

Figure 2. Impact of increasing c on pricing.

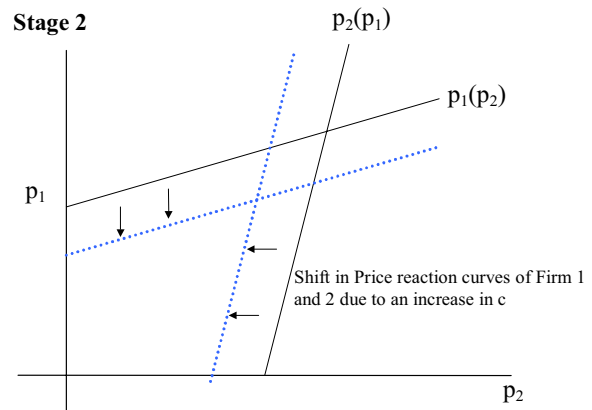
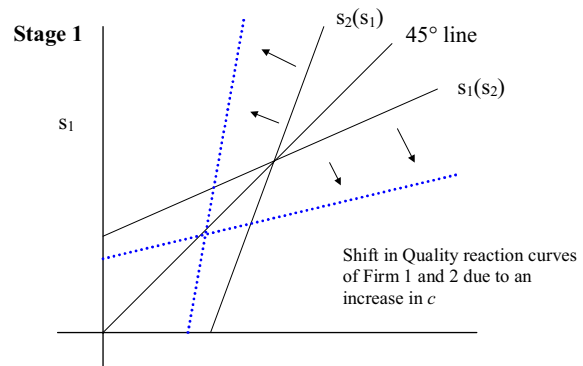


Figure 3. Impact of increasing c on product quality.



5. Conclusions and Managerial Implications

The so-called productivity paradox has been hotly debated within and outside the academic community with many explanations having been put forth. We have deliberately simplified a complex situation by developing an analytical model to help formalize the impact of IT

investments that improve production capabilities on product design, production costs, profits, consumer surplus, and productivity.

A key implication of this work is that although managers should expect investments in technology-based design tools to improve firm profits and consumer value, they should not necessarily expect that these same investments, even when managed properly, to improve productivity or reduce cost. In fact, our model demonstrates that when firms leverage IT investments to improve product quality production costs increase and productivity decreases. Therefore, the mixed empirical findings in the IT value literature (reviewed in Section 2) regarding the relationship between IT and productivity are not so surprising, and, in fact, should be expected. For managers, focusing too heavily on improving productivity and reducing cost, whether at the business unit level or the firm level, is likely to lead to an under-investment in product quality, a sacrifice of profits, and a sacrifice of consumer value.

This paper has extended the monopoly model of IT value presented by Thatcher and Pingry[34] and Thatcher and Oliver[32, 33] to a duopoly setting and demonstrated that the impact of product quality adjustments on productivity is pervasive and is not restricted to monopoly markets. However, our model has limitations. For example, model Assumptions $A(1) - A(3)$ characterize the types of markets to which the model may apply. These assumptions essentially place boundaries on the sensitivity of demand to product quality and price and the efficiency of firms' cost structures (or production capabilities). While we recognize the limitations of our model we also note that the analysis of the impact of technology on productivity or profit cannot be complete without capturing the fact that IT enables the firm to inexpensively alter the quality as well as the quantity of its product. The purpose of this paper and its antecedents has been to capture the implications of that opportunity.

Future research should focus on empirically testing and validating the propositions derived from the analytical model presented in this paper. More specifically, empirical studies performed at the IT application (and activity) level of analysis may help explain whether or not the relationship between technology investments and firm performance in real-world settings is moderated by the degree to which a firm improves its product quality as described in this paper.

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Appendix

Equilibrium Values and Partial Derivatives (not presented in the main text)

Quality

$$\frac{\partial s_i^*}{\partial k} = -\frac{2a(2-bc)(b+2)(b-2)^2}{[k(b+2)(2-b)^2 - 2(1-c)(2-bc)]^2} < 0, \text{ and}$$

$$\frac{\partial s_i^*}{\partial c} = -2a \frac{kb(b+2)(b-2)^2 + 2(2-bc)^2}{[k(b+2)(2-b)^2 - 2(1-c)(2-bc)]^2} < 0.$$

Price

$$\frac{\partial p_i^*}{\partial k} = -2a \frac{(b-2c) + (2-bc)^2(2-b)}{[k(2+b)(2-b)^2 - 2(1-c)(2-bc)]^2} < 0,$$

and

$$\frac{\partial p_i^*}{\partial c} = -2ka \frac{(2-b)(2+b(1-2c))}{[k(2+b)(2-b)^2 - 2(1-c)(2-bc)]^2} < 0.$$

Demand

$$Q_i^* = \frac{k(4-b^2)}{k(2+b)(2-b)^2 - 2(1-c)(2-bc)},$$

$$\frac{\partial Q_i^*}{\partial k} = -\frac{2a(1-c)(2+b)(2-b)(2-bc)}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^2} < 0, \text{ and}$$

$$\frac{\partial Q_i^*}{\partial c} = -\frac{2ka[(2-b)(2+b)(2(1-bc)+b)]}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^2} < 0.$$

Revenue

$$R_i^* = \frac{k^2(4-b^2)^2}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^2},$$

$$\frac{\partial R_i^*}{\partial k} = -\frac{4ka^2(b-2)^2(b+2)^2(1-c)(2-bc)}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^3} < 0, \text{ and}$$

$$\frac{\partial R_i^*}{\partial c} = -\frac{4k^2a^2(b-2)^2(b+2)^2(2(1-bc)+b)}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^3} < 0.$$

Production Costs

$$C_i^* = \frac{2ka^2(2-bc)^2}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^2},$$

$$\frac{\partial C_i^*}{\partial k} = -\frac{2a^2(2-bc)^2[k(2+b)(2-b)^2 + 2(1-c)(2-bc)]}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^3} < 0,$$

and

$$\frac{\partial C_i^*}{\partial c} = -\frac{4ka^2[kb(2+b)(2-b)^2 + 2(2-bc)^2]}{(k(2+b)(2-b)^2 - 2(1-c)(2-bc))^3} < 0.$$

Productivity

$$\rho_{1,i}^* = (4-b^2) \frac{k(2+b)(2-b)^2 - 2(1-c)(2-bc)}{2a(2-bc)^2},$$

$$\rho_{2,i}^* = \frac{k(4-b^2)^2}{2(2-bc)^2}, \text{ and}$$

$$\rho_{3,i}^* = \frac{k(4-b^2)^2(3-2b)}{4(1-b)(2-bc)^2}.$$