The Impact of Technology Investments on a Firm's Production Efficiency, Product Quality, and Productivity

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ABSTRACT: For over a decade, empirical studies in the information technology (IT) value literature have examined the impact of technology investments on various measures of performance. However, the results of these studies, especially those examining the contribution of IT to productivity, have been mixed. One reason for these mixed empirical findings may be that these studies have not effectively accounted for the impact of technology investments that increase *production efficiency* and improve *product quality* on firm productivity. In particular, it is commonly assumed that such investments should lead to gains in both profits and productivity. However, using *a closed-form analytical model* we challenge this underlying assumption and demonstrate that investments in certain efficiency-enhancing technologies may be expected to decrease the productivity of profit-maximizing firms. More specifically, we demonstrate that investments in technologies that reduce the firm's fixed overhead costs do not affect the firm's product quality and pricing decisions but do increase profits and improve productivity. In addition, we demonstrate that investments in technologies that reduce the variable costs of designing, developing, and manufacturing a product encourage the firm to improve product quality and to charge a higher price. Although this adjustment helps the firm to capture higher profits, we show that it will

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also increase total production costs and will, under a range of conditions, *decrease* firm productivity. Finally, we show that the direction of firm productivity following such investments depends upon the relationship between the fixed costs of the firm and the size of the market.

KEY WORDS AND PHRASES: analytical modeling, information technology value, product quality, production efficiency, productivity paradox, technology investments.

FOR OVER A DECADE, EMPIRICAL STUDIES in the information technology (IT) value literature have attempted to quantify the benefits realized from IT investments. Although the intent of much of this work has been to demonstrate positive relationships between IT investments and economic performance measures (e.g., profits and productivity), the results of these studies, especially those related to the contribution of IT to productivity, have been mixed. For example, early studies examined the contribution of aggregate IT spending on economy-level 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, 21, 23, 31, 35, 36, 37]. These early studies led to the coining of the term "IT productivity paradox" and initiated a long stream of empirical work "focused on describing the paradox, denying the paradox, solving the paradox, and burying the paradox" [8]. For example, several studies that followed examined the productivity question at the firm level. Although some of these studies found a significant correlation between IT spending and productivity [3, 7, 19, 29], others were still unable to identify productivity gains from IT [29, 33, 34]. Similarly, findings from recent empirical studies at the application level of analysis continue to be mixed with some studies finding significant contributions and others finding either no contribution at all or negative contributions [2, 9, 10, 14, 30, 33, 38]. Although IT researchers have put forth several explanations for these seemingly contradictory and paradoxical findings (e.g., mismeasurement of economic performance, lags due to learning and adjustment) [5], little work has been done to identify the conditions under which managers should expect IT investments to contribute to productivity.

In this paper we suggest that one reason for these mixed empirical findings is that the studies have not effectively differentiated among (and often confuse) the goals of increasing *production efficiency,* improving *product quality,* and increasing *productivity.* Firms typically invest in technologies to help them earn more profits and realize higher levels of productivity. It is commonly assumed that such improvements in economic performance are realized by increasing the *efficiency* of production and service provision processes and by improving the *quality* of the products and services offered to consumers. However, in this paper we challenge this underlying assumption using a closed-form analytical model by demonstrating the complex, and sometimes counter-intuitive, interaction among efficiency, quality, and productivity.

Efficiency improvements are realized when a technology investment enables a firm to produce a *given* product or service (of given quality) with fewer resources. For example, high efficiency means minimizing inputs for a given level of output. In other words, measures of efficiency involve comparisons to a standard. Examples of technologies that improve efficiency include investments in:

- Machinery that enables farmers to produce a given amount of wheat (of the same quality) at lower costs,
- Back-office automation that enable firms to complete traditional administrative functions, such as payroll processing, faster and cheaper,
- Prototyping tools, usability labs, and computer-aided design (CAD) tools that enable firms to design and develop a given product at lower cost, and
- E-commerce tools, electronic reservation systems, web-based support tools, and other technologies that enable firms to distribute a given product (or provide a given service) at lower cost.

Quality improvements are realized when a technology investment leads to the creation of new products, or new features for existing products, which directly increase human desire to consume those products. Garvin [12] presents the following definition of quality: "the capability of a product or service to knowingly satisfy those preconceived composite wants of the user(s) that are intelligibly related to characteristics of performance or appearance and do not cause covert or overt reaction by other people." Garvin supplements this definition by identifying eight dimensions of quality: performance, features, reliability, durability, conformance, serviceability, aesthetics, and perceived quality. Since it is difficult for products to rate highly along all dimensions, firms spend significant resources on market research to identify those combination of dimensions that best meet the customers' needs and requirements.[1] Examples of technology investments that improve product quality include investments in:

- Patient-tracking systems by hospitals that enable emergency room (ER) doctors to provide better care in a more-timely manner to those patients in greatest need.
- Data mining tools by credit card companies and grocery stores to sift through customer data (e.g., demographics, past consumption behaviors, and credit history) to identify patterns that allow them to develop targeted product offerings.
- Interactive TV technologies and advanced internet services by telecommunications providers that enable them to provide new product features to consumers.
- Decision support systems (DSS) and group decision support systems (GDSS) that enable individuals and groups to organize data and communicate ideas more effectively, leading to better decision-making capabilities.

Productivity improvements are realized when a technology investment leads to an increase in 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 per quantity of related input (e.g., units/hour). However, quantity in many cases, especially in the service sector, is not considered a good proxy for value. In fact, productivity measures for individual firms usually define both output and input values in dollars (e.g., sales dollars or value to customers divided by the cost to producer).

The difference between the meaning of efficiency and productivity is subtle but very important. Efficiency is a measure of the amount of inputs required to produce a standard, fixed output. If a firm improves its production efficiency, it simply means that it can now produce a given product with fewer resources than it could previously. The efficiency measure is independent of the quality decisions made by a firm and independent of the actual output value generated by the firm. Alternatively, productivity is a measure of the actual output value generated by the firm per unit of related input value. According to Klassen et al. [17], "It is apparent that efficiency and productivity are linked and will often move in the same direction (although not always), but they are different measures and it is impossible to say one is a component of the other." In this paper, we identify three types of technologies that increase production efficiency and identify the conditions under which these investments will increase firm productivity and the conditions under which they will decrease firm productivity (assuming a profit-maximizing firm). We accomplish this through a *closed-form analytical model* that examines the impact of various technology investments on a firm's (1) production efficiency, (2) product quality and pricing decisions, (3) production costs, and (4) profits and productivity.

The model demonstrates that firms investing in technologies that improve production efficiency realize an increase in profits. However, the impact of these efficiency-enhancing investments on the other factors identified above depends upon the technology implemented. More specifically, technology investments that reduce the firm's fixed overhead costs do not affect the product quality and pricing decisions of the firm, but do improve firm productivity as measured by the ratio of output value to its related input value. Alternatively, technology investments that increase production efficiency by reducing the unit cost of designing, developing, and manufacturing a product, encourage the firm to offer a better quality product to consumers and to charge a higher price than before the investment. Although these adjustments to quality and price stimulate demand and enable the firm to capture higher profits, we show that it will also increase total production costs and will, under a range of conditions, decrease firm productivity. More specifically, we show that the direction of firm productivity following such investments depends upon the relationship between the fixed costs of the firm and the size of the market. 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.

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. In this section we briefly review the empirical studies in the IT value literature.

Economy- and Industry-Level Studies

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 [5, 8, 10]. At the economy level, Baily [1] found that productivity declined in the 1970s, while it grew in the prior two decades. In addition, Jorgenson and Stiroh [16] found that productivity growth dropped from 1.7 percent per year for the 1943 to 1973 period to about 0.5 percent for the 1973 to 1992 period. This decline in productivity took place despite massive investments in IT during this period. Roach [35] measured the productivity of information workers against that of production workers. He found that while the output of production workers increased by 16.9 percent during the 1970s through the mid-1980s, the output of information workers dropped by 6.6 percent during the same period.

Loveman [21] found that despite increasing IT spending in the manufacturing sector, the marginal contribution of IT to productivity was zero (or even negative). Strassmann [37], in an empirical study of 38 service sector firms, found no correlation between IT and return on investment and concluded that "there is no relation between spending for computers, profits, and productivity." Similarly, Roach [36], using government statistics from the Labor Bureau, found that productivity in the services sector showed little or no improvement in the 1980s despite massive investments in technology. More specifically, the statistics showed that productivity, measured as output per hour, had increased at an annual rate of around one percent since the early 1970s. Hackett [13] also reported that productivity in the service sector has shown little growth since 1977 and further observed that service industry operating expenses had "dramatically increased, outpacing both inflation and revenue growth" during this time. In addition, Panko [31] found a negative relationship between IT and the productivity of office workers. Finally, according to official numbers from the Bureau of Economic Analysis (BEA), the output of the broad banking sector—banks plus related industries such as nonbank credit-card issuers and mortgage bankers—has been flat since 1990 despite significant IT investments [23]. Brynjolfsson [5] summarized the problem—or "paradox"—identified in these aggregate-level studies as follows: "Delivered computing power in the U.S. has increased by more than two orders of magnitude since 1970, yet productivity, especially in the service sector, seems to have stagnated."

These early studies led to the coining of the term "IT productivity paradox" and initiated a long stream of empirical work "focused on describing the paradox, denying the paradox, solving the paradox, and burying the paradox" [8]. Although many explanations have been put forth, the primary explanation for the IT productivity paradox has been that data collection at the economy level and industry level has led to the mismeasurement of inputs and outputs in the productivity measures used in the early studies [5, 6, 7, 24, 26, 27, 31].[2] More specifically, according to Brynjolfsson [5, 6], the benefits often associated with technology investments, such as improvements in product quality, variety, customer service, timeliness, and responsiveness, are poorly accounted for in traditional (or aggregate) productivity statistics used in the early studies, leading to an underestimation of IT productivity gains.[3] Metcalfe [26] summarizes the problem as follows: "The real meaning of the Productivity Paradox is that the statistics available to macroeconomists do not measure the kinds of productivity that are improved by computers."

Firm-Level Studies

IT researchers have attempted to address the mismeasurement problems identified with the economy-level and industry-level studies by addressing the IT productivity question with firm-level data, with several studies finding a significant correlation between IT spending and productivity. For example, Brynjolfsson and Hitt [7] performed a study of 380 large firms between 1987 and 1991 and found that the return on investment for IT capital was more than 50 percent per year for the sample, and more than 60 percent per year for service firms in the same sample. Barua and Lee [3], using the same data set used by Loveman [21], showed that large, successful firms in the manufacturing sector made sizable productivity gains from IT investments. In addition, Lehr and Lichtenberg [17, 19] found that computers, especially personal computers, do contribute significantly to productivity growth.

Although more encouraging than the economy-level and industry-level studies, the results continue to be mixed at the firm level of analysis. For example, Mukherjee et al. [29] explored productivity growth for a group of 201 large U.S. commercial firms from 1984 to 1990. They found that overall productivity grew at the rate of about 4.5 percent per year on average, but productivity declined by 7.61 percent between 1984 and 1985, and by 0.33 percent between 1988 and 1989. Further analysis revealed that larger asset size and specialization of product mix were associated with higher productivity growth while a higher ratio of equity to assets was associated with lower productivity growth. Finally, Rai [33, 34], using IS budget as a measure of IT investment, found no relationship between IT and financial performance measures at the firm level but did find a relationship between IT and sales performance (or the level of output). Rai noted that improvements from IT may not be reflected in improved financial performance at the firm-level data because benefits may be redistributed within or across organizations or passed on to consumers. Therefore, he suggested that disaggregating IT investments in terms of specific activities and IS applications might offer significant measurement advantages.

IT Application and Activity-Level Studies

Several studies have analyzed data at the application level to identify the impact of IT investments on intermediate and activity-based measures of performance. The findings from these studies have been very mixed. For example, in Rai's [33] IT budgets were further disaggregated into key elements of IT infrastructure (hardware, software, telecommunications, and IS staff) to examine the contribution of each type of technology investment to economic performance measures. In his analysis, Rai found that IT budget allocations to IS staff, telecommunications, and hardware were positively correlated to firm output and labor productivity. However, he found no (or even a negative) correlation between software investments and labor productivity. Rai identified this as a particularly interesting finding and stated that it should be investigated further.

Banker and Kauffman [2] examined the impact of ATM network investments on banks. In their studies they found that ATM network membership did have a positive impact on a bank's local deposit market share. However, they also reported that introducing ATM technology at a branch contributed little to a bank's economic performance. For example, they found that the presence of an ATM was associated with a decrease in labor productivity of branch tellers. Haynes and Thompson [14], in an effort to circumvent the measurement problems associated with both IT inputs and outputs in IT-intensive industries, took "the ATM as a clearly defined embodied IT application and then [used] an augmented production function approach to isolate its productivity effects across a sample of UK building societies, over the period of the ATM's diffusion." Unlike Banker and Kauffman, they found robust and statistically significant productivity gains associated with ATM introduction.

Weill [38] performed a study in which he found a significant relationship between investments in data processing systems and productivity. However, he was unable to identify gains associated with strategic systems or informational investments. In addition, Weill claimed that investments in technologies, such as computer-aided systems engineering (CASE) tools, have been particularly disappointing in terms of their contributions to productivity. Mukhopadhyay et al. [30] performed an application level study that examined the benefits of the optical character recognition and bar code sorting technologies used to sort mail at the U.S. Postal Service. They found that investments and use of such IT led to significant increases in mail sorting output and improvements in quality. Devaraj and Kohli [10] performed a study of eight hospitals that had recently implemented a decision support system (DSS) to help evaluate contracts. They found that such investments in DSS led to higher revenues and better quality products and services.

Finally, David et al. [9] used surveys to examine how chief financial officers of hotels measured productivity, what technology applications they have implemented, and what effect on productivity the respondents saw arising from technology. The responses identified IT investments that centered around reservation management, room management, and guest accounting modules. These included investments in automated reservation systems, in-room vending, safes, electronic locking systems, in-room entertainment, and automatic check-in/check-out devices. According to the surveys:

> In many cases, the respondents noted improvement in productivity as a result of installing certain back-office computer modules. . . . [However,] guest-operated technology was not a productivity plus, in the estimation of most respondents. . . . Two respondents reported that guest-operated systems such as in-room

information, vending, and entertainment, as well as check-in and check-out devices, served actually to decrease productivity. . . .

. . . The survey indicates that information-system technology is not always purchased to improve hotel productivity, but those systems are also aimed at boosting customer-service levels and augmenting the number of services offered.

Contributions of This Work

Despite the plethora of empirical studies on IT value and the improvements in the measurements used in these studies, the empirical findings seem to be more mixed than ever. Unfortunately, there is little theory driving these empirical studies or explaining the results. In particular, there is little work that develops analytical models to better understand the impact that various types of IT investments *should be expected* to have on measures of firm profitability and productivity. We propose such an analytical model in the following section. In particular, in this model we challenge the following assumptions underlying these empirical studies:

- IT investments should have a positive impact on productivity, and
- Improvements in product or service quality enabled by IT investments should have a positive impact on productivity.

The model presented in the following section will examine whether or not these assumptions are appropriate (or consistent with economic theory). That is, although IT investments may enable improvements in efficiency and quality, economic theory suggests that such improvements may not necessarily lead to productivity gains, as we will see. In fact, we will show that the IT productivity paradox is not so much a paradox, but instead a conscious decision by profit-maximizing firms to invest in technologies that may improve profits, but sometimes at the expense of productivity (even when accounting for product quality in the productivity measure). In the following sections we formalize these relationships analytically and characterize the conditions under which productivity losses from IT investments should be expected. As we will see in the section "Research and Managerial Implications," the model results are consistent with many of the seemingly paradoxical findings in the IT value literature.

Model

WE CONSIDER A SINGLE-PRODUCT MONOPOLIST that designs and produces a single product or service characterized by two attributes: quality and unit price. Both are determined by the firm.[4] In this paper we model product quality as a numeric level that may be thought of as the overall evaluation of a product, exclusive of price, as *Consumer Reports* might provide. That is, quality is a composite measure of some vector of attributes (e.g., features, performance, reliability, and responsiveness) valued by consumers [12].

Demand

The quantity demanded by consumers for this product depends on both the quality and price of the product as determined by the firm. If the firm lowers the price or improves the product quality, demand for the product increases. More specifically, we assume the demand (D) for the product is [20]

$$D = a - bP + cQ, \tag{1}$$

where $a, b, c > 0$ are parameters that can be determined empirically for each industry, P is the unit price of the product, and Q is the quality level of the product. More specifically, a represents the size of the market, b measures the sensitivity of demand to the price charged by the firm, and c measures the sensitivity of demand to the quality of the product offered to the market. In this model the firm chooses a price-quality combination (P^*, Q^*) that maximizes its profits.

Production Costs

The firm has several cost components and may invest in different types of technologies to increase production efficiency and to improve product quality, with the hope of realizing gains in profits and productivity from the investments. We assume that the total cost (C) to the firm is

$$C = F + fQ^2 + eQD, \tag{2}$$

where $f, e > 0$ are parameters that characterize the firm's production capabilities (to be discussed in more detail later in this section), and $F > 0$ represents the amortized fixed costs associated with running the business.

We can qualitatively interpret this cost function as follows. The first term, F, represents the amortized fixed costs of running the business or the *indirect costs of production,* including building leases, equipment depreciation and maintenance, and utility expenses. In addition, the cost term F includes costs of acquiring, implementing, and maintaining technologies (e.g., hardware, software, processes, and methodologies) to support or improve the firm's production capabilities. The firm must incur these costs to enable production, but these costs do not depend on the quality or quantity of products manufactured by the firm.

Alternatively, the second and third terms in the cost function represent the *direct costs of production* incurred by the firm. In order for the firm to offer a product to consumers it must first *design* and *develop* the product to be offered. That is, the firm must determine the combination of attributes (e.g., features, performance, reliability, responsiveness, convenience, variety, and customer support) that defines a product of a specified quality level and that meets customer requirements. This process represents a significant setup cost and may include functions such as research and development, prototyping, and usability testing. The second term, fQ^2, in the cost function represents this cost. This cost component is assumed to be quadratic because improving the overall quality of a product becomes increasingly difficult (and increasingly costly) as product quality increases. The convex form of this cost component is common in other streams of literature [4, 11].

After designing the product, the firm must then *manufacture* the product (or provide the service) for consumption. This represents the variable (or per unit) cost of production. The third term, eQD, in the cost function represents the variable costs associated with manufacturing products (or providing services) of a given quality level for distribution. This term implies that variable production costs increase with product quality.

In summary, the monopolist spends a fixed cost (F) in support of the general business enterprise, a cost (fQ^2) to design and develop a product of a specified quality, and a per unit cost (eQD) to manufacture the product to meet demand. Similar cost functions have been used in the context of IT investments [4].

Production Efficiency

In general, efficiency is defined as the input value necessary to produce a given output [17]. Therefore, we define production efficiency to measure the input value (in dollars) necessary to design, develop, and manufacture a product of a specified level of quality. In our model, the realization of parameters F, f, and e in Equation (2) determine the firm's production efficiency. In turn, the realization of these three cost parameters depends on, among other factors, the technology implemented by the firm. In the next section we consider changes to each parameter—realized through investments in specific types of technologies—separately to develop some initial insights as to their individual effects on the firm's product quality and pricing decisions, production costs, profits, and productivity. Toward this end we examine three types of technology investments—those associated with

- *Automation of overhead tasks*—A technology investment that decreases the overhead costs of operating the firm is represented by a decrease in F. An example of this type of investment would be the traditional investment in back-office automation of the firm's payroll function or accounting process, assuming that the functions are an overhead cost of doing business and are independent of product demand and product quality.
- *Design (or start-up) and development of a product/service*—A technology investment that decreases the costs of designing, setting up, and developing a product with a specified level of quality is represented by a decrease in f (we refer to this parameter as the fixed cost of quality). Examples of this type of technology are CAD and CASE tools, prototyping tools, and usability testing technologies. Ideally, these tools enable a firm to design and develop a product of a given level of quality faster and cheaper, which implies higher efficiency.
- *Improvement in the manufacturing or service provision capability*—A technology investment that decreases the variable (or unit) cost of quality is represented by a decrease in e. That is, a decrease in e enables the firm to manufacture a

product (or provide a service) of a given quality level at lower cost. An example of this type of investment may be a computer system (or set of technology tools) that enables a stockbroker or a reservation agent to provide customer service at lower cost.

In summary, technology investments that decrease the cost parameters e and f essentially expand (or enhance) the firm's production capabilities while investments that decrease the cost parameter F reduce the firm's overhead costs without affecting its production capabilities. As we will see later, the firm may leverage efficiency improvements from some of these technology investments to improve product quality and adjust price. Such strategic adjustments will affect the input and output values realized by the firm, therefore, affecting firm productivity. We formalize these relationships in the next section.

Revenues, Profits, and Productivity

Based on Equations (1) and (2), the firm's revenue (R) is

$$R = PD = P(a - bP + cQ), \tag{3}$$

and the firm's profit (π) is

$$\pi = R - C = (P - eQ)(a - bP + cQ) - F - fQ^2. \tag{4}$$

In addition to revenue and profit, we measure total productivity [17, 28]. We define total productivity as the ratio of output value to its related input value, with outputs and inputs measured in dollars. In our model, the output of the production process is the *revenue* (or sales dollars) generated from the process; alternatively, the inputs are the *total costs* of production. Therefore, in our model productivity (ρ) will be defined as

$$\rho = \frac{R}{C}. \tag{5}$$

We note that our model provides a best-case scenario for observing productivity gains from technology investments because:

- The firm is more likely to retain the benefits from technology investments—in the form of increased revenue—instead of passing them on to consumers, due to the absence of competitive pressures. That is, we mitigate the problems associated with the redistribution of revenues and profits.
- The firm may vary its product quality and price instantaneously in response to a technology investment. That is, we assume that there are no lags in observing changes in productivity or profit due to learning and adjustment in this model.

- Technology investments undertaken by the firm are assumed to be costless. That is, the cost of the technology and the costs of implementation and maintenance will not affect the indirect costs of production and, therefore, will not adversely affect the firm's total costs—the denominator of our productivity measure.

Table 1 lists the measures, decision variables, and parameters used in the analytical model.

Results

Equilibrium Quality and Pricing Decisions

GIVEN EQUATIONS (1) THROUGH (4), the firm's equilibrium choice of quality is [see Appendix for all derivations]

$$Q^* = \frac{a(c-be)}{4bf-(c-be)^2}, \tag{6}$$

and the firm's equilibrium choice of price is

$$P^* = \frac{a\left[e(c-be)+2f\right]}{4bf-(c-be)^2}. \tag{7}$$

The denominator $4bf-(c-be)^2$ of both the equilibrium choice of quality and price in the above equations is the determinant of the 2x2 Hessian matrix. According to Assumption (1) in the Appendix, this term must be positive to guarantee concavity of the profit function in price and in quality, and to guarantee a unique maximum. Therefore, Assumption (2), $c>be$, ensures that the equilibrium level of quality chosen by the firm is positive. This assumption also ensures that the firm charges a positive price for the product.[5]

Substituting the equilibrium values for P^* and Q^* into Equations (1) through (5) yields the firm's equilibrium demand,

$$D^* = \frac{2abf}{4bf-(c-be)^2}, \tag{8}$$

total costs,

$$C^* = F + \frac{a^2 f(c-be)(c+be)}{\left[(c-be)^2-4bf\right]^2}, \tag{9}$$

Table 1. Model Measures, Decision Variables, and Parameters

D	Quantity demanded for the product
C	Total costs of production (or input value)
R	Revenues (or output value)
π	Profits
ρ	Total productivity
Q	Product quality
P	Price
a	Market size
b	Price sensitivity parameter
c	Quality sensitivity parameter
F	Fixed costs of overhead
e	Unit cost of quality
f	Fixed cost of quality

revenues,

$$R^* = \frac{2a^2bf\left[e(c-be)+2f\right]}{\left[4bf-(c-be)^2\right]^2}, \tag{10}$$

profits,

$$\pi^* = \frac{a^2 f}{4bf-(c-be)^2} - F, \tag{11}$$

and productivity,

$$\rho^* = \frac{2a^2bf\left[2f+e(c-be)\right]}{F\left[(c-be)^2-4bf\right]^2 + a^2 f\left(c^2+b^2e^2\right)}. \tag{12}$$

In the following sections we examine the impact that investments in various technologies have on the firm's equilibrium choice of product quality and price, and the demand, production costs, profits, and productivity that result from these choices. We accomplish this through comparative static analysis.

Technology Investments and Profits

We will now consider the impact of various technology investments on profits. The impact on equilibrium profits of a change in the cost parameter F is

$$\frac{\partial \pi^*}{\partial F} = -1 < 0. \tag{13}$$

The impact on equilibrium profits of a change in the cost parameter *f* is

$$\frac{\partial \pi^*}{\partial f} = \frac{-a^2 (c - be)^2}{\left[(c - be)^2 - 4bf\right]^2} < 0. \tag{14}$$

Finally, the impact on equilibrium profits of a change in the cost parameter *e* is

$$\frac{\partial \pi^*}{\partial e} = \frac{-2a^2 bf (c - be)}{\left[(c - be)^2 - 4bf\right]^2} < 0. \tag{15}$$

The partial derivatives of the profit function with respect to each of the cost parameters are all negative. (Note: Equation (15) is negative given Assumption (1).) These results imply that improvements (i.e., decreases) in any of the cost parameters, *F, e,* or *f,* will lead to an increase in firm profits. A decrease in *F* (i.e., an investment that reduces overhead costs) *does not* affect the quality and pricing decisions (Q^*, P^*) made by the firm; therefore, it does not affect the quantity of products (D^*) demanded or the revenue (R^*) earned in equilibrium. That is,

$$\frac{\partial Q^*}{\partial F} = \frac{\partial P^*}{\partial F} = \frac{\partial D^*}{\partial F} = \frac{\partial R^*}{\partial F} = 0. \tag{16}$$

However, a decrease in *F* does reduce the total costs (C^*) incurred by the firm in equilibrium,

$$\frac{\partial C^*}{\partial F} = 1 > 0, \tag{17}$$

which leads to a corresponding increase in profits.

Proposition 1: IT investments reducing the costs of overhead will increase firm profits.

Alternatively, a decrease in *f* (i.e., an investment that reduces the cost of designing and developing a product of a specified quality level) *does* affect the quality and pricing decisions made by the firm. More specifically, a decrease in *f* will encourage the profit-maximizing firm to improve product quality,

$$\frac{\partial Q^*}{\partial f} = \frac{-4ab(c - be)}{\left[(c - be)^2 - 4bf\right]^2} < 0. \tag{18}$$

Since demand is relatively sensitive to quality (i.e., Assumption (1)) the firm charges a higher price (P^*) for the improved product,

$$\frac{\partial P^*}{\partial f} = \frac{-2a\left(c^2 - b^2e^2\right)}{\left[\left(c - be\right)^2 - 4bf\right]^2} < 0, \tag{19}$$

and still realizes an increase in the number of products sold,

$$\frac{\partial D}{\partial f} = \frac{-2ab\left(c - be\right)^2}{\left[\left(c - be\right)^2 - 4bf\right]^2} < 0. \tag{20}$$

Since more products are sold at a higher price, revenue for the firm increases,

$$\frac{\partial R^*}{\partial f} = -2a^2b\frac{4cf\left(c - be\right) + e\left(c - be\right)^3}{\left[4bf - \left(c - be\right)^2\right]^3} < 0. \tag{21}$$

In addition, the improvement in product quality and the increase in demand together lead to an overall increase in production costs despite the technology investment that expands the firm's production capabilities (i.e., decreases the cost parameter, f),

$$\frac{\partial C^*}{\partial f} = -a^2\left(c - be\right)\frac{4bf\left(c + be\right) + \left(c + be\right)\left(be - c\right)^2}{\left[4bf - \left(c - be\right)^2\right]^3} < 0. \tag{22}$$

Finally, the firm realizes an increase in profits because the increase in revenue generated by the quality and pricing adjustments is greater than the corresponding increase in costs (see Appendix for proof).

Proposition 2: IT investments reducing the costs of product/service design and development will increase firm profits.

A decrease in e (i.e., an investment that reduces the variable cost of producing a product of a specified quality level) affects the firm's quality and pricing decisions similarly. A decrease in e will encourage the firm to devote resources to improving product quality,

$$\frac{\partial Q^*}{\partial e} = -ab\frac{4bf + \left(c - be\right)^2}{\left[\left(c - be\right)^2 - 4bf\right]^2} < 0. \tag{23}$$

Since demand is relatively sensitive to quality, the firm charges a higher price for the better quality product,

$$\frac{\partial P^*}{\partial e} = -a\frac{4b^2ef + c(be-c)^2}{\left[(c-be)^2 - 4bf\right]^2} < 0, \tag{24}$$

and still sells more products,

$$\frac{\partial D^*}{\partial e} = -4ab^2f\frac{c-be}{\left[(c-be)^2 - 4bf\right]^2} < 0, \tag{25}$$

earns more revenue,

$$\frac{\partial R^*}{\partial e} = -2a^2bf\frac{4bcf + (c+2be)(c-be)^2}{\left[4bf - (c-be)^2\right]^3} < 0, \tag{26}$$

and incurs more costs,

$$\frac{\partial C^*}{\partial e} = -2a^2bf\frac{4b^2ef + (2c+be)(be-c)^2}{\left[4bf - (c-be)^2\right]^3} < 0. \tag{27}$$

However, the firm still realizes an increase in profits because the increase in revenue generated by these changes is greater than the corresponding increase in total costs (see Appendix). Note that this result depends on Assumption (1), or that market demand is relatively sensitive to product quality.

Proposition 3: IT investments reducing the variable costs of product/service provision will increase firm profits.

Although it is not surprising that investments in each of the three technology types will increase profits, the model has helped to formalize this intuition and has explained the mechanism through which these profit improvements may be achieved. In particular, the model demonstrates that a firm investing in technologies that expand the firm's production capabilities (or reduces the unit cost of designing, developing, and manufacturing a product) must use that investment to improve product quality to *maximize* its profits. Alternatively, a firm investing in technologies that reduce overhead costs maximizes profits through the realization of reduced costs while leaving product quality unchanged.

Technology Investments and Productivity

We now consider the impact of various technology investments on firm productivity. The impact on equilibrium productivity of a change in the cost parameter F is,

$$\frac{\partial \rho^*}{\partial F} = \frac{-2a^2 bf\left[2f + e(c - be)\right]\left[(c - be)^2 - 4bf\right]^2}{\left[\left[(c - be)^2 - 4bf\right]^2 + a^2 f\left(c^2 - b^2 e^2\right)\right]^2} < 0. \tag{28}$$

Assumption (1) implies that the sign of Equation (28) is negative. This implies that investments in technologies that reduce fixed overhead costs will lead to an increase in firm productivity. This result is quite intuitive since, as we saw earlier, these investments do not affect the quality and pricing decisions of the firm and, therefore, do not affect the firm's revenues. Such investments enable the firm to produce the same revenues at lower total costs which implies an increase in productivity. In this special case efficiency and productivity are equivalent.

> **Proposition 4:** IT investments reducing the costs of overhead will increase firm productivity.

The impact on equilibrium productivity of a change in f is

$$\frac{\partial \rho^*}{\partial f} = \frac{2a^2 b\left[F(c - be)\left[4cf + e(-c + be)^2\right]\left[-4bf + (-c + be)^2\right] + 2a^2 f^2 (c - be)(c + be)\right]}{\left[-F\left[-4bf + (-c + be)^2\right]^2 - a^2 f\left(c^2 - b^2 e^2\right)\right]^2} \tag{29}$$

Although we are unable to sign Equation (29) we are able to specify the conditions that determine the direction of total productivity for a profit-maximizing firm following an investment that lowers f. The sign of Equation (29) depends upon the relationship between the size of the firm's fixed costs (F) and the size of the market (a). That is, a firm that invests in technology to reduce f will realize productivity gains if its fixed costs are sufficiently large. Otherwise, the firm will realize losses in productivity from such investments. More specifically, by setting Equation (29) equal to zero and solving for F we determine that

$$\text{If } F > \frac{2a^2 f^2 (c + be)}{\left[4cf + e(c - be)^2\right]\left[4bf - (c - be)^2\right]}, \text{ then } \frac{\partial \rho^*}{\partial f} < 0.$$

Finally, the impact on equilibrium productivity of a change in e is

$$\frac{\partial \rho^*}{\partial e} = \frac{2a^2bf\left[F\left[-4bf+(-c+be)^2\right]\left[4bcf+(c+2be)(-c+be)^2\right]+a^2f\left[4b^2ef+c(-c+be)^2\right]\right]}{\left[-F\left[-4bf+(-c+be)^2\right]^2-a^2f\left(c^2-b^2e^2\right)\right]^2}. \tag{30}$$

We are also unable to sign Equation (30) but we are again able to specify the conditions that determine the direction of productivity. Similar to the findings above, the sign of Equation (30) depends on the relationship between the size of the firm's fixed costs (F) and the size of the market (a). That is, a firm that invests in technology to reduce e will realize productivity gains if its fixed costs are sufficiently large. More specifically, by setting Equation (30) equal to zero and solving for F we determine that

$$\text{If } F > \frac{a^2f\left[4b^2ef+c(c-be)^2\right]}{\left[4bf-(c-be)^2\right]\left[4bcf+(c+2be)(c-be)^2\right]}, \text{ then } \frac{\partial \rho^*}{\partial e} < 0.$$

Therefore, Equations (29) and (30) show that the impact of a technology investment that expands (or enhances) the production capabilities on firm productivity depends on the size of the firm's fixed costs relative to the size of the market.

The intuition behind these results can be explained as follows. As we saw earlier, a decrease in either cost parameter, e or f, will encourage the profit-maximizing firm to improve product quality and charge a higher price. These adjustments increase both the revenue earned and the total costs incurred by the firm.[6] Since revenue represents output value and total costs represent its related input value, the impact of these investments on productivity will depend on the percentage increases in revenue and total costs realized by the firm. That is, if revenue increases by a higher percentage than total costs that implies a productivity gain for the firm. Otherwise if total costs increase by a higher percentage than revenue that implies a productivity loss for the firm. This can be written as

$$\text{If } \frac{\frac{\partial R}{\partial f}}{R} > \frac{\frac{\partial C}{\partial f}}{(F+C_d)}, \text{ then } \frac{\partial \rho}{\partial f} < 0,$$

and,

$$\text{If } \frac{\frac{\partial R}{\partial e}}{R} > \frac{\frac{\partial C}{\partial e}}{(F+C_d)}, \text{ then } \frac{\partial \rho}{\partial e} < 0,$$

where $C_d = fQ^2 + eQD$, or the direct production costs. These equations show that as fixed costs become large, the percentage increase in total costs from investments that lower e of f becomes smaller. However, the percentage increase in revenues from

Table 2. The Effect of Decreasing *e* (assuming $F = 100$)

	Initial equilibrium values	Decrease in *e*
e	1.0	**0.8**
P	$14.29	$15.12
Q	2.86	3.66
D*	57.14	60.98
C*	$344.90	$412.31
R*	$816.33	$922.07
ρ^*	**2.37**	**2.24**
π^*	$471.43	$509.76

Note: This table shows the effect of a decrease in the cost parameter *e* on firm performance measures. The first column shows the equilibrium values under the following parameter assumptions: $F = 100$, $a = 100$, $b = 5$, $c = 10$, and $f = 10$. The second column shows the new equilibrium values after a 20 percent reduction in *e*. This numerical example supports the analytical results presented in the fourth section and, in particular, shows a set of parameter values under which IT investments that decrease *e* will lower firm productivity.

these same investments remain unchanged since they do not depend on *F*. Therefore, when *F* is sufficiently large, growth in revenue will outpace growth in total costs, implying an increase in productivity.

> **Proposition 5:** IT investments reducing the costs of product/service design and development will increase firm productivity if the firm's overhead costs are sufficiently large (relative to market size). Otherwise, such investments will decrease productivity.

> **Proposition 6:** IT investments reducing the costs of product/service provision will increase firm productivity if the firm's overhead costs are sufficiently large (relative to market size). Otherwise, such investments will decrease productivity.

We demonstrate these relationships (and conditions) in Tables 2 and 3.

Summary

In this section we have assumed a single-product monopolist that optimizes its profits by choosing (or adjusting) product quality and price. The model demonstrates that firms investing in technologies that improve production efficiency realize an increase in profits. However, the impact of these efficiency-enhancing investments on the other performance measures depends upon the technology implemented. More specifically, technology investments that reduce the firm's fixed overhead costs do not affect the product quality and pricing decisions of the firm, but do improve firm productivity as

Table 3. The Effect of Decreasing *e* (assuming $F = 350$)

	Initial equilibrium values	Decrease in *e*
e	1.0	**0.8**
P*	$14.29	$15.12
Q*	2.86	3.66
D*	57.14	60.98
C*	$344.90	$412.31
R*	$816.33	$922.07
ρ*	**1.37**	**1.39**
π*	$221.43	$259.76

Note: This table shows the effect of a decrease in the cost parameter *e* on firm performance measures assuming the same parameter values for *a, b, c,* and *f* used in Table 2. However, in this table we assume higher fixed costs for the firms: $F = 350$. The first column shows the equilibrium values under these initial parameter values. The second column shows the new equilibrium values after a 20 percent reduction in *e.* This numerical example shows that if fixed costs are sufficiently large that a decrease in *e* will lead to an increase in firm productivity.

measured by the ratio of output value to its related input value. Alternatively, technology investments that increase production efficiency by reducing the unit cost of designing, developing, and manufacturing a product, encourage the firm to offer a better quality product to consumers and to charge a higher price than before the investment. Although these adjustments to quality and price stimulate demand and enable the firm to capture higher profits, we show that it will also increase total costs and will, under a range of conditions, decrease firm productivity. More specifically, we show that the direction of firm productivity following such investments depends upon the size of the firm's fixed costs relative to the size of the market.

Research and Managerial Implications

Explanations for Past Empirical Findings and Examples

THE MODEL RESULTS SUPPORT SEVERAL FINDINGS in the IT value literature. In this section we briefly discuss a few of these studies. Hackett [13] reported that productivity in the service sector has shown little growth since 1977 and further observed that service industry operating expenses had "dramatically increased, outpacing both inflation and revenue growth" during this time. Our model captures this phenomenon as follows. The acquisition of technology is represented by a decrease in either *e* or *f.* In both cases (assuming the market size is sufficiently large relative to the firm's fixed costs) total costs increase by a larger percentage than revenues, leading to a decrease in productivity. However, this should not be cause for too much concern since the absolute difference between revenues and costs does increase, leading to an increase in profits—the real bottom-line for most firms.

Weill [38] found that significant productivity contributions could be attributed to data processing systems. However, he was unable to identify gains associated with strategic systems or informational investments that would correspond to changes in e and f in our model. In addition, Weill claimed that investments in technologies such as CASE tools (which would lead to a reduction in f in our model) have been particularly disappointing in terms of their contributions to productivity. Mukhopadhyay et al. [30] found that the use of optical character recognition and bar code sorting technologies used to sort mail at the U.S. Postal Service (or lower e in our model) led to significant increases in mail sorting output and improvements in quality. In addition, Devaraj and Kohli [10] showed that the implementation of DSS, which also reduce e, in the eight hospitals examined in his study led to higher revenues and better quality products and services.

David et al. [9], in his survey study of the productivity of hotel technologies, found that investments in back-office computer modules, which reduce F, led to productivity gains. However, guest-operated technologies such as in-room information, vending, and entertainment, as well as check-in and check-out devices (which correspond with decreases in e), served actually to decrease productivity. As is supported by our analytical model, David et al. concluded information-system technology is not always purchased to improve hotel productivity, but instead is also aimed at boosting customer service levels and augmenting the number of services offered.

Banker and Kauffman [2] reported two empirical findings related to our results. In their work, ATM networks are shown to be a factor that affects bank market share. This makes sense in the context of our model, which predicts that the higher service quality enabled by ATMs (which improve production capabilities) would lead to an increase in the quantity of services demanded in equilibrium. In addition, they found that introducing ATM technology at a branch was associated with a decrease in labor productivity of branch tellers. However, Haynes and Thompson [14] found significant productivity gains from ATM introduction in the United Kingdom. Although seemingly contradictory, both results could be consistent with our model depending upon the relationships between fixed costs and market size in these studies.

Strassmann [37] compared two corporate financial indicators, sales, general, and administrative costs (SG&A) and cost of goods (COG), at 66 corporations between 1987 and 1996. SG&A is a company's overhead (F in our model), which Strassmann believes to be a good stand-in for technology costs. In other words, Strassmann suggests that costs of acquiring, implementing, and maintaining systems are represented by these costs. This is similar to the way we assume such investment costs would be incorporated in the cost parameter F in our model. COG is a basic measure of the costs involved in the production of products or services similar to our concept of direct production costs. In his study, Strassmann finds that despite a massive investment in information technology (i.e., increases in the companies' SG&A expenses), their COG increased. However, this finding is consistent with our model which suggests that IT investments that lower e or f will lead to an increase in direct production costs (or COG).

In addition, according to McGee and Wilder [25], IT deployments at Prudential Insurance Corp. have eliminated manual procedures and paperwork, reducing the time it takes to accomplish tasks. Enabling agents to access coverage, customer, and company information from mobile notebooks has eliminated the need for the insurer to print and distribute millions of pages of documents annually. This has enabled agents to improve the quality of customer service by spending more face-to-face time with customers and taking advantage of more cross-selling opportunities. Ultimately, this has led Prudential to service more customers and realize more revenues, all of which is consistent with our model.

Managerial Implications

The results of this paper have several implications for managers as well. As previously noted, managers should not expect that productivity, measured by the ratio of revenue to total costs, to necessarily improve or production costs to decrease with the adoption of certain technology innovations. Although managers may be legitimately concerned with costs and productivity, they should be wary of two traps. The first trap is that they may focus too heavily on reducing production costs and improving productivity, leading to potential under-investment in product quality. The second trap involves viewing productivity too narrowly based on the easy availability of revenue and cost information and weak availability of other relevant information. This encourages the use of simplistic productivity measures. Rewarding for productivity, whether at the business unit level or the corporate level, is also likely to result in an under-investment in product quality. In both cases, under-investment sacrifices profits. According to Brynjolfsson [6], "A single-minded focus on productivity can be counter-productive." We might adjust this statement to say, "A single-minded focus on productivity can be unprofitable."

Conclusions

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 a closed-form analytical model to help formalize the impact of various IT investments that improve production efficiency on product quality and pricing decisions, production costs, profits, and productivity. We showed that investments in each of the three technology types examined in the model are expected to increase firm profits. However, we also showed that the impacts of these investments on firm productivity vary and depend on the type of technology implemented and the relationship between the size of the firm's fixed overhead costs and the size of the market. That is, a profit-maximizing firm may make a conscious decision to invest in certain technologies that lead to product quality improvements to capture higher profits, but sometimes at the expense of firm productivity. We also showed that the model results are consistent with several empirical findings in the IT literature. We believe that this simple model helps to build intuition about the mechanisms driving these relationships. As we will see below in our discussion of model limitations, this model will also help to inform the development of more detailed and realistic models and help guide future empirical studies.

Although the analytical model presented in this paper has provided several important insights into the IT value debate there are several limitations that should be noted when interpreting the results. First, pure cases of a change in a parameter, such as e, are unlikely from a real world technology implementation. Typically, there will be interaction effects that we did not fully explore in this paper. Consider the effect of adopting CASE tools for a firm. In our model, we would suggest that such an investment would correspond with a decrease in f and, as a result, would increase the optimal level of product quality. However, this story is incomplete because it is likely that the manufacturing, marketing, and support of the higher quality product will require investments and changes in technology in other areas of the firm. These other technological and firm changes will also impact the other cost parameters, e and F.

Second, model Assumptions (1) and (2) characterize types of markets to which the model may apply. These assumptions essentially place boundaries on the sensitivity of demand to product quality. That is, the assumption implies a range of c for which demand is relatively sensitive to quality, but not too much so. Although this assumption appears consistent with many markets—including travel, credit card, health/medical services, and internet access—it may be less consistent with markets with higher price sensitivity such as traditional manufacturing (e.g., steel). In fact, we would expect efficiency improvements in relatively price-sensitive markets to be more likely to lead to productivity improvements than presented in this paper. We will focus on developing more extensive models that apply to a wider range of markets in future research.

Third, related to the last point, we assume in our model that the firm is able to adjust quality instantaneously in the short-run in response to technology investments. However, this may not be the case in practice as firms may be unable or unwilling to adjust quality in the short-run. If firms are unable to make the profit-maximizing adjustments to quality, the impact of investments that reduce e and f in our model may be more likely to lead to productivity gains.

Fourth, in our model we assume a single-product monopolist. In future work, it would be beneficial to extend the model to competitive, multi-product settings to account for the impact of strategic interactions and to increase the applicability of the model to real-world settings. In addition, future work should consider the impact of IT investments on alternative measures of productivity, such as the ratio of revenue to direct production costs and the ratio of (revenues + consumer surplus) to total costs. Comparing the impact of different IT investments on the various measures of productivity may provide further insights into the empirical findings in the IT literature.

Finally, 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 (e.g., profits and productivity) in real-world settings is moderated by the degree to which a firm improves its product and service quality.

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Notes

1. Devaraj and Kohli [10] recently noted that the impact of technology on nonfinancial outcomes such as customer satisfaction and quality is gaining interest in the IT literature.

2. Other explanations have suggested that the studies did not account for [5]:

- *Lags due to learning and adjustment:* Benefits from IT investments are often not realized immediately and may take several years to materialize in the productivity statistics because firms need time to learn how to use, and to gain experience with, the new technologies.
- *Redistribution and dissipation of profits:* Investments in IT may not improve an industry's total output. That is, firms that invest heavily in IT may benefit privately but at the expense of other firms in the industry (or they may pass some of the value on to consumers). Therefore, no net benefit will show up at the economy level and industry level of analyses. This explanation suggests that IT investments do not create value but instead redistributes value among firms within an industry.
- *Mismanagement of IT:* This lack of empirical support for IT productivity may be due to poor decision-making and poor project management by IT managers within firms. In addition, Isaac and Pingry [15] argue that typical organizational incentives may lead employees to divert IT from productive activities for the firm to activities (e.g., fancy presentations and complex models) in the employee's interest with respect to intra-organizational gaming and office politics.

3. Empirical studies on the impact of IT on quality are difficult to perform because of problems with accurately measuring quality improvement using available economic statistics [32]. That is, most empirical measures of quality improvement are based on changes in production costs. Such measures are unappealing since they make it difficult to tease apart the impact of IT investments on the quality improvement and cost reduction.

4. By considering a monopolist we eliminate the need to consider the impact of competitive pressures. For example, monopolists are considerably more flexible and autonomous than either competitive or oligopolistic firms and will not be forced into making investment decisions based on strategic necessity.

5. Assumptions (1) and (2) characterize the types of markets that the model may apply. We present these assumptions in this form to make interpretation of the comparative statics in the following sections more straightforward. However, combining the two assumptions provides a more clear interpretation. That is, Assumptions (1) and (2) imply that

$$be + 2\sqrt{bf} > c > be. \qquad \text{Assumption (2a)}$$

Recall c measures the sensitivity of demand to quality, b measures the sensitivity of demand to price, and e and f are the cost parameters for quality. This assumption essentially places boundaries on the sensitivity of demand to quality; that is, the assumption implies a range of c for which demand is relatively sensitive to quality, but not too much. This assumption appears consistent with many markets, including travel, credit card, health/medical services, and internet access. However, it may not be consistent with some markets related to traditional manufacturing such as steel.

6. We note that in this model the increase in total costs is due to the increase in direct production costs ($fQ^2 + eQD$) since technology investments are assumed costless and, therefore, do not adversely affect F, the indirect production costs.

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