PRODUCTION AND OPERATIONS MANAGEMENT
POMS
Vol. 13, No. 3, Fall 2004, pp. 245–259
ISSN 1059-1478 | 04 | 1303 | 245$1.25

The Creation of Output and Quality in Services: A Framework to Analyze Information Technology-Worker Systems

Karen Napoleon • Cheryl Gaimon
Terry College of Business, University of Georgia, Athens, GA 30602-6256, USA
DuPree College of Management, Georgia Institute of Technology, Atlanta, GA 30332-0520, USA
knapol@terry.uga.edu • cheryl.gaimon@mgt.gatech.edu

Information technology has profoundly impacted the operations of firms in the service industry and service environments within manufacturing. Two models are introduced that establish a conceptual framework linking firm profit to attributes of the IT-worker system. The framework considers the impact of IT capabilities (such as functionality and ease-of-use) and worker skill as drivers of output volume and quality. The framework contrasts attributes of the IT-worker systems when services are mass-produced (flow shop) versus customized (job shop). Mathematical models are introduced to formalize the conceptual framework. Numerical examples are presented that illustrate the types of insights that can be obtained from the models.

Key words: service operations; services; worker skill; information technology; flow shop; job shop
Submissions and Acceptance: Received June 2003; revision received October 2003, January 2004; accepted January 2004

1. Introduction

The advent of information technology has fundamentally changed the nature of resource management for firms in the service sector as well as for service units within the manufacturing sector. According to Froehle et al. 2000, "the role of IT is especially critical to services as it has quickly become one of the most important infrastructural elements of service firms." For example, the use of PCs or computer workstations to perform statistical, optimization, simulation, or computer-aided-design analysis is pervasive among knowledge workers employed in management consulting, R&D, and engineering design. In addition, networked systems running transactions based software or linked to point of sale devices and operated by clerical workers or cashiers are widespread in banking (Huete and Roth 1988), insurance (Teal 1991), and retail domains (Bradley et al. 1996). (Also see Fitzsimmons and Fitzsimmons 2001 and Metters et al. 2003). Unfortunately, despite substantial investments in IT, for many firms, the realization of performance gains has been elusive (Brynjolfsson and Hitt 1996).

Limited empirical research exists that delineates the performance benefits in services obtained from investment in IT. Baldwin 1997, Brynjolfsson and Hitt 1996, Dvorak et al. 1997, and Hoffman 1997 have shown that, with the support of IT, the speed that white-collar workers generate output improves. According to Beatty 1988, the average volume of output per unit time generated by the design engineer increases by 50% with the use of CAD (also see Ebel and Ulrich 1987). In their study of banking services, Huete and Roth 1988 showed that IT was a vital part of the production and delivery process impacting a variety of performance dimensions including the speed that transactions were processed. Kentucky Fried Chicken invested in IT (pack monitors) to improve the speed of workers stationed at drive through windows (Apte and Reynolds 1995). Based on his study of aggregate industry data, Stiroh 2001 concludes that the introduction of IT has driven much of the productivity gain in IT intensive services including public utilities, communications, business services, legal services, retail, and entertainment.

Beyond impacting the speed output is generated by the workforce, the use of IT also affects the service unit's ability to generate high performance and consistent quality. According to Roth and Jackson 1995, the extensive use of IT enables banks to improve performance quality by offering customers 24-hour access to services through ATMs and on-line banking. The level of consistent quality achieved by the U.S. Postal Service has dramatically improved due to the use of optical character readers and barcode sorters (Mukhopadhyay et al. 1997). UPS has improved performance quality by providing customers with 24-hour access to its on-line tracking system. Beyond improving consistent quality by reducing input errors, the use of bar coding, scanning, and computerized inventory and distribution systems has enabled retailers such as Wal-Mart to enhance performance quality by reducing the likelihood of stockouts (Bradley et al. 1996).

The speed and quality of the output generated in services is also affected by employee selection and training. Worker skill is measured based on a variety of dimensions such as years of education, years of work experience, or scores on specially designed tests. Gatewood and Field 1994 provide a comprehensive taxonomy of the many instruments available to assess employee skill. By deploying a multidimensional skill measurement system, Microsoft Corporation identifies the skills needed to improve performance and makes hiring decisions accordingly (Stross 1996, Seligm 1997). Investments in worker knowledge such as training in statistical quality control have led to substantial improvements in consistent quality (Apte and Reynolds 1995), whereas enrollment in executive degree programs enables workers to create services that embody superior performance quality (Thatcher and Oliver 2001).

In this paper, a framework is introduced for analyzing IT-worker systems in services. The framework shows that the extent to which a service domain benefits from IT depends on how the operations manager resolves a multitude of challenges that characterize the IT-worker interface in the production domain (at the process level). Our framework recognizes that the operations manager determines workforce attributes including size and skill level, and attributes of the IT such as the overall availability, functionality, connectivity, and ease of use. As described later, these attributes of the *IT-worker system* drive the performance of the service operations domain.

We consider two drivers of firm profit in our framework: *output volume* and *premium quality*. Output volume refers to the maximum output that can be generated by the IT-worker system. For example, if the speed with which the service worker processes transactions increases, then output volume increases. Premium quality is a composite measure of two forces. First, the firm that is capable of producing a service with superior performance quality commands a higher price in the marketplace. Second, if the consistency of output quality improves then the marginal production cost declines as a result of savings associated with defective output, yield loss, and rework. Therefore, premium quality measures the firm's ability to generate marginal net revenue (the price charged for output less the marginal production cost).

In the next section, two conceptual models of service operations are given that establish a framework linking firm profit to attributes of the IT-worker system. In Section 3, the conceptual models are formalized in two mathematical models that provide a rigorous foundation for further study. In Section 4, we illustrate the type of analysis that may be conducted based on numerical examples. (A more preliminary treatment of this topic appears in Gaimon and Napoleon 2000.)

Lastly, while the research presented here primarily lies in the domain of service operations, our work also relates to research in IT that measures the impact of IT on firm performance. Typically in this research, the firm is the unit of analysis, models estimate the input-output relationships based on the Cobb-Douglas production function, and variables are measured in dollars. In contrast, the general production and quality functions introduced in this paper are inspired by the dynamic production function given in Gaimon 1997. Devaraj and Kohli 2003 show that the impact of IT is better estimated by measuring IT usage as opposed to spending. Our approach is consistent with this result. Dewan and Kraemer 2000 find that less economically developed nations realize less benefits from the same IT spending as compared with more developed nations, in part due to the lower level of worker knowledge. Similarly, our framework and models capture the impact that the level of worker knowledge has on the performance gains realized from IT usage. Mukhopadhyay, Rajiv, and Srinivasan 1997 state that the impact of IT may be obscured in studies that focus on the firm as the unit of analysis. Instead they measure the impact of IT on output volume (productivity) at the process level. (Also see Kohli and Devaraj 2003). These results support our use of process level measures (output volume and quality) to assess the impact of IT. (For a comprehensive review of this area of IT research, see Kohli and Devaraj 2003.)

2. Two Models of IT-Worker Systems

In this section, we present the salient features of the simple and complex IT-worker systems. For a table summarizing the conceptual relationships, see Napoleon and Gaimon 2004.

2.1. The Simple IT-Worker System

The simple IT-worker system is characterized by structured (Simon 1979) or programmable (Stohr and Konsynski 1992) decision making in which elements of the service delivery process are automated (Zuboff 1988). Bowen and Lawler 1992 refer to this as the "production line" approach to services whereas Chase and Garvin 1989 call it "the service factory." The standardization of service operations is most appropriate in environments that generate mass produced services such as transactions processing in banks (Bowen and Lawler 1992, Chase 1978, Chase and Hayes 1991, Chase and Stewart 1996, Schmenner 1986) or mass produced support services such as inventory and materials management in high-volume manufacturing domains.

Strong parallels exist between simple IT-worker systems in services and flow shops in manufacturing. In both domains, the key competitive priorities are to generate high volumes of standardized and low cost output. Therefore, a firm creates mass produced services by deploying repetitive and routine procedures to increase throughput, reduce waste, and achieve consistent quality. The service workers employed largely fill entry-level positions and earn relatively low wages. According to Bowen and Lawler 1992, the orientation of the service delivery system is to ensure *control* of the process (workforce) in order to provide consistent quality of the high-volume service. The IT used consists of customized (tailored) hardware and software to facilitate the automation of routine decisions and to enhance the speed of repetitive activities. The service firm incurs a substantial cost to purchase and deploy the dedicated IT system. However, due to the capability of the tailored IT to support high-volume, efficient and consistent operations, the unit production cost is low (economies of scale). In conclusion, as in manufacturing flow shops, the technology in simple IT-worker systems is procedural in nature and supports less skilled workers to complete simple and standard operations.

To illustrate, in fast food environments, keystrokes on cash registers link customer purchases to a price list database and reduce service time and increase accuracy. Scanning devices used by cashiers increase both the number and accuracy of transactions processed per unit time. Moreover, each time the cashier scans a customer's purchase, inventory control is initiated and the retailer's internal database is updated. Restocking decision rules embedded in the IT reduce the likelihood of merchandise stock out so that the retailer incurs lower costs for lost sales and service quality improves. (See Fitzsimmons and Fitzsimmons 2001.)

The insurance and banking industries have derived significant benefits from simple IT-worker systems (Zuboff 1988, Teal 1991). Prior to the introduction of IT, workers responsible for making customer loan decisions performed a series of routine and time consuming data collection and information processing activities. Quality problems were common due to the manual processing of large amounts of data and since reliance on worker judgment led to inconsistent and uninformed loan decisions. In contrast, with a dedicated IT system, custom software prompts employees to request customer profile information and substantially increases the speed and accuracy of processing. The diverse locations of customer contact (different branch banks) are electronically linked to the firm's home office computer (internal networking) which generates a complete customer credit profile by accessing databases such as those offered by Equifax and Experian (external networking). The relative risk of the loan request is assessed automatically (built-in software) based on the customer credit profile and the firm's actuarial tables. Beyond reducing the likelihood of fraud, banks and insurers realize a lower default rate due to the comprehensive and automated IT-based risk assessment processes (Day 1993). Lastly, in contrast to the days or weeks needed to process a loan application prior to IT, the loan approval or denial is electronically transferred to the employee and the customer in a matter of minutes.

2.1.1. Quality and Output Volume. The service provider's ability to generate high-volume and consistent quality output is primarily driven by the dedicated IT capabilities and the overall level of IT accessibility. The amount of IT (the extent that the IT is readily available to the workforce) substantially affects output volume. For example, additional bank tellers have no impact on output volume once all terminals are busy. In addition, the IT system may include functionality that enables the lesser skilled worker to increase the scope of activities performed. For example, with bar coding and scanning (dedicated and automated IT), less skilled workers complete transactions faster and with more accuracy. Moreover, the processing by cashiers is linked to an inventory control system and replenishment orders are placed automatically. Lastly, while worker skill is not the key driver of performance in simple IT-worker environments, skill is needed to properly operate the IT system and answer customer queries.

2.2. The Complex IT-Worker System

The unstructured (Simon 1979) or unprogrammable (Stohr and Konsynski 1992) service domain is characterized by unpredictable, non-routine decision-making. The complex IT-worker system produces small volumes of custom high performance quality services. The competitive priorities, therefore, parallel those in manufacturing job shops (Gaimon 1997, Chase et al.

2001). Due to the nonstandard and custom services provided, the firm's ability to realize the efficiency benefits of batch processing are limited (Chase 1978).

Complex IT-worker systems exist throughout the service industry and in service support units in the manufacturing sector. By employing computer-aided-design (CAD) technologies, engineers and architects generate product and process designs to meet the needs of both internal (manufacturing support) and external clients. Biological and chemical scientists use statistical software packages to analyze data in medical, pharmaceutical, and R&D laboratories. Management scientists employed by consulting firms or acting as internal consultants solve complex problems using a variety of optimization, simulation and statistical packages.

The above examples establish that complex IT-worker environments employ highly skilled and highly paid workers (Sulek and Maruchek 1992). In fact, the skill level of the *knowledge worker* in the complex IT-worker domain drives the firm's ability to create the high performance custom services demanded by the consumer. According to Bowen and Lawler 1992, the orientation of this service delivery system is employee *empowerment* since it measures workforce performance in terms of outcomes as opposed to process control. New employees are selected based on their skill level as indicated by advanced academic degrees and prior work experience. Existing employees are rewarded for the development of new skills obtained from internal job transfers, continuing education, or attendance at professional conferences.

The role of IT in unstructured services is to "informate" (see Zuboff 1988) as opposed to automate decision-making. In other words, in complex IT-worker systems, the service creation process undertaken by knowledge workers is supported by hardware (networked PCs or workstations) and software packages (simulation, CAD, or statistical analysis). Fundamentally, the IT is general purpose and consists of hardware purchased from a catalog and 'off the shelf' software. As a result, the IT system is far less costly to purchase and deploy than the dedicated IT used in production line services. Moreover, the ability of the firm to generate high performance custom services is driven by the worker's ability to create application specific solutions that meet consumer needs. Again, the analogy between the complex IT-worker domain and the manufacturing job shop is evident.

2.2.1. Quality and Output Volume. Consider the service environment in design-based engineering domains. By replacing manual drafting with CAD software running on computer workstations, the output per unit time generated by the design engineer dramatically increases. Also, the CAD system enables the engineer to complete 3-dimensional visuals and thereby improve performance quality. However, without the considerable talent of the knowledge worker to operate the CAD system, improvements in output volume and quality would not occur. This helps to explain the wide range of performance improvements reported in the literature following the introduction of CAD (Beatty 1988, reports a range of 50–100% increase in output per unit time). Clearly, a firm purchasing IT must carefully assess whether training is needed to acquaint knowledge workers with new system features and capabilities.

The size of the workforce and the extent that the IT support is accessible to that workforce also impact output volume in complex IT-worker domains. For convenience, we measure the amount of IT in terms of the number of PC's or workstations that are made available to the workforce. Often, a considerable amount of the knowledge worker's time does not involve direct usage of the IT system (for example, the time spent in meetings, reading journal articles, writing technical reports). The portion of time the worker spends independent from the IT depends on the tasks involved, the capabilities of the IT, the skill level of the worker, and the worker's style of creative thinking. It is not surprising, therefore, that in some complex-IT worker domains, the size of the workforce exceeds the number of IT units available.

3. The Mathematical Models

In this section, we introduce mathematical models that provide rigor to the conceptual framework discussed above for simple and complex IT-worker systems.

3.1. Primary Variables: Workforce and IT Decisions

The volume of workforce, w, is a continuous decision variable indicating the number of workers or worker hours employed. With $w \in (0, \overline{W}]$, $\overline{W}$ represents the maximum workforce size and may reflect a limited labor pool or budget limitations. Second, the average level of workforce skill is a continuous decision variable denoted by s, where $s \in [1, \overline{S}]$. The level of workforce skill must meet or exceed the base skill level, $s = 1$. By definition, while a workforce with the base skill level has sufficient knowledge to generate output, it cannot generate premium quality. In other words, only a workforce whose skill level exceeds the base ($s > 1$) is capable of generating premium quality output. The upper bound, $\overline{S}$, represents the maximum skill level, which may reflect workforce availability or budget limitations. Clearly, the bounds on w and s have different interpretations in simple versus complex IT-worker systems. For instance, the base skill level of a design engineer reflects substantially different attributes than that of a cashier.

The volume of IT, denoted by x, is a continuous decision variable indicating the extent of IT accessible to the workforce. The volume of IT can be measured as the number of hours the workforce has access to IT or as the number of personal computers, work stations, cash registers, etc. that are shared by the workforce. The volume of IT satisfies $x \in [0, \bar{X}]$ where the maximum level of IT accessibility may reflect space constraints or budget limitations.

The technology choice decision is a discrete variable denoted by i, with $i \in [1, 2, \ldots, I]$. Therefore, the firm selects a particular IT capability from a set of I alternatives where each technology choice impacts output volume and premium quality differently. Let the continuous parameter $j \in (0, \bar{J})$ measure the extent that an IT alternative contributes to output volume and the continuous parameter $k \in (0, \bar{K})$ measure the impact of the IT choice on premium quality. Therefore, a pair of IT attributes (j, k) is associated with each technology choice decision, i. IT options may be sequenced such that as i increases, either output volume (j) or premium quality (k) increases or both increase. If the IT sequences differ with respect to the impact on premium quality and output volume, then the firm faces a technology choice tradeoff.

3.2. Secondary Variables: Output Volume and Premium Quality

The workforce and IT attributes selected by the service operations manager determine the levels of output volume and premium quality. First, we consider premium quality, denoted by $Q_i(s)$, reflecting the ability of the IT-worker system to increase marginal net revenue either by charging a premium price or by reducing the production cost. Premium quality is expressed as a function of the skill level of the workforce s and the quality enhancing capability of the IT choice as indicated by k. For example, if both s and k satisfy their upper bounds, then the output generated provides the maximum possible level of premium quality. If both the workforce skill and the IT quality related capability satisfy their respective base levels ($s = 1$ and $k = 0$ for $i = 1$), then while minimally acceptable to the customer, output quality does not enhance the firm's ability to increase marginal net revenue and premium quality is zero ($Q_1(1)=0$).

The output volume generated, denoted by $P_i(w, x, s)$, is a function of workforce volume (w), workforce skill (s), the amount of IT available to the workforce (x), and the output enhancing capability of the IT choice i as indicated by j. For example, if w, s, x, and j satisfy their upper bounds, then the service domain generates the maximum output volume possible.

3.3. The Objective Function

The profit-maximizing objective for the service operations domain is given in Equation (1a) and reflects the revenue earned (first term), the cost incurred for wages (second term), the cost incurred for IT (third term), and the return function (fourth term). The bounds on the primary decision variables are summarized in Equation (1b). Naturally, the manner in which the primary and secondary decision variables impact terms in the objective differs for the simple versus complex IT-worker systems. In the remainder of this section, we explore these dimensions of profit. The use of detailed notation is suppressed whenever possible.

$$\text{Maximize: } \Phi = \pi[P_i(w, x, s), Q_i(s)] - C_1(w, s) - C_{2i}(x) + R_i(x) \quad (1a)$$

$$\text{with } w \in (0, \bar{W}], x \in [0, \bar{X}], s \in [1, \bar{S}], \text{ and } i \in [1, 2, \ldots, I]. \quad (1b)$$

From the first term in (1a), total net revenue is a function of output volume (P) and premium quality (Q). Consistent with standard usage, total net revenue is the difference between the total revenue earned and the total production cost. In contrast to the norm, however, our total production cost includes the costs for input materials, yield loss, and rework but excludes the costs associated with the workforce (wages) and IT (equipment operating and maintenance costs). As output volume increases, we assume that the total net revenue increases at a non-increasing rate. The second order condition may occur for several reasons (Bairam 1994). First, it may reflect the saturation of demand where the firm must lower its price to sell larger quantities of output. Second, it may occur if, as output volume increases, the firm is forced to pay higher prices for inputs. Third, it may occur if, for higher volumes of output, the firm's finite resources are stressed so that less efficient or more costly production methods are used. Lastly, if learning occurs, while total net revenue increases as output increases, it does so at a decreasing rate. Mathematically, we have $\partial\Phi/\partial P \geq 0$ and $\partial^2\Phi/\partial P^2 \leq 0$.

Next, consider how premium quality impacts the service domain's ability to earn net revenue (Brandyberry et al. 1999, Flynn et al. 1995, and Hendricks and Singhal 1997). If both the workforce skill and the IT quality enhancement capability are defined at their base levels, then premium quality is not generated (marginal net revenue is minimal and $Q = 0$). Alternatively, if either worker skill or the IT quality enhancement capability exceeds their base levels, then $Q > 0$ and premium quality increases the total net revenue earned. For example, in the complex IT-worker domain, highly skilled workers may create high performance services that command premium prices in the marketplace. In contrast, in the simple IT-worker domain, built-in features of the IT system may lead to a higher level of consistent quality and thereby reduce the portion of the production cost associated with yield loss or rework. In both service domains, we assume that as premium quality increases, net revenue increases at a non-increasing rate so that $\partial\Phi/\partial Q \geq 0$ and $\partial^2\Phi/\partial Q^2 \leq 0$. The second order condition occurs since, beyond some level, additional quality neither appeals to the consumer nor affords cost savings to the firm (diminishing returns).

The second term in the objective represents the cost associated with labor, C_1, and is driven by the size (w) and skill level (s) of the workforce. In general, as the size of the workforce increases, the cost for wages increases ($\partial C_1/\partial w > 0$) at non-decreasing rate ($\partial^2 C_1/\partial w^2 \geq 0$) (see Bairam 1994). The second order condition occurs because the firm must offer a higher wage rate to attract a larger workforce. Similarly, as the average workforce skill level increases, the cost for wages increases ($\partial C_1/\partial s > 0$) at a non-decreasing rate ($\partial^2 C_1/\partial s^2 \geq 0$). The second order condition reflects the scarcity of highly skilled labor as well as the increasingly costly activities that must be undertaken to enhance the skill of the existing workforce. Lastly, $\partial^2 C_1/\partial w \partial s \geq 0$ holds since the cost incurred for wages increases for a larger and more skilled workforce.

The cost associated with information technology, denoted by C_2 and given in third term of Equation (1a), is a function of the technology choice decision (i) and the level of IT accessibility (x). First, as the number of PCs, workstations, etc. made available to the workforce increases, the cost of purchasing, operating, and maintaining the IT system increases ($\partial C_2/\partial x > 0$) at a non-decreasing rate ($\partial^2 C_2/\partial x^2 \geq 0$). The second order effect arises since, as x increases, the marginal cost incurred in relation to the space requirements, networking complexity, administrative and maintenance activities increases, (Gaimon 1998). Second, consider how the technology choice impacts C_2. As the output volume or quality enhancement capability increases, (i.e., $j \in (0, \bar{J})$ or $k \in (0, \bar{K})$ increases), the associated IT cost increases ($\partial C_2/\partial j > 0$, $\partial C_2/\partial k > 0$) at a non-decreasing rate ($\partial^2 C_2/\partial j^2 \geq 0$, $\partial^2 C_2/\partial k^2 \geq 0$). For example, in the simple IT-worker domain, the second order condition occurs because it is increasingly costly to add built-in features to drive an ever-increasing yield or speed of output creation.

The last term in the objective, R, represents the monetary return realized by the service domain that makes x units of technology choice i available to the workforce. The return function captures the cost reduction obtained from the transfer of operations activities in another part of the firm to the IT-worker system or from the integration of information between the IT-worker system and other parts of the firm. For example, in the simple IT-worker retail environment, while scanning merchandise, the cashier automatically updates inventory records. As a result, the firm reduces the costs incurred to manually monitor merchandise levels on stores shelves. McAfee 2002 describes the cost savings realized when a firm introduces IT that integrates several functions involved in order fulfillment so that the separate data entry is eliminated and the flow of information is enhanced. In the complex-IT worker domain, suppose the IT system provides knowledge workers with access to library databases and journal articles. As a result, the support staff that was previously responsible for performing database searches and retrieving journal articles is reduced. Continuing with the latter example, suppose the firm purchases a single workstation that is networked to the library databases. Due to its limited availability, some knowledge workers will continue to rely on the support staff for information retrieval. Therefore, as the amount of IT accessibility (x) increases, the return increases ($\partial R_i/\partial x \geq 0$). Due to diminishing returns, the return function satisfies the second order condition ($\partial^2 R_i/\partial x^2 \leq 0$).

3.4. The Production Functions

Six production function attributes are introduced that characterize the technical relationships between the workforce and technology decision variables and the creation of output volume (P). We assume the production function is continuous and twice differentiable with respect to w, x, and s. To distinguish between Models 1 and 2, we let $P_i^1(w, x, s)$ and $P_i^2(w, x, s)$ denote the output volume generated in simple and complex IT-worker systems, respectively. In both models, the volume of output is expressed as the sum of two terms as shown in Equations (2a) and (2b). The first terms denote the contribution to output derived solely from the workforce and independent of IT. The second terms denote the impact on output volume due to the workforce enhancement provided by IT. A complete discussion follows.

$$P_i^1(w, x, s) = p_1^1(w, s) + p_{2i}^1(w, x) \quad (2a)$$

$$P_i^2(w, x, s) = p_1^2(w, s) + p_{2i}^2(w, x, s) \quad (2b)$$

The first production function attribute characterizes the impact on output volume if either the level of workforce is close to zero or the level of IT accessibility is zero. If IT is unavailable ($x = 0$), the output generated solely reflects manual efforts by the workforce ($w > 0$). Here, the first terms in Equations (2a) and (2b) are positive, whereas the second terms are zero. In contrast, if w is close to zero, then the first terms in (2a) and (2b) approach zero. In addition, in complex IT-worker systems, workers are required to operate the IT and generate high performance custom output so that the second term in (2b) approaches zero when w is close to zero. In contrast, in a limited number of simple IT-worker systems known as self-serve, the customer performs the service operation. For example, customers routinely pump their own gas and process the corresponding credit card transactions. Workers are needed when customers cannot properly operate the self-serve system or if the system fails. Therefore, in some simple IT-worker domains with highly specialized IT systems, p_{2i}^1 may be positive even if w is close to zero.

The second production function attribute depicts the effect on output as the nonzero workforce level increases. Suppose, we hold constant the amount of IT accessibility (x), the level of worker skill (s), and the technology choice decision (i). In either the simple or complex IT-worker domains, an increase in worker hours leads to an increase in output volume ($\partial p_1^1/\partial w \geq 0$, $\partial p_{2i}^1/\partial w \geq 0$, $\partial p_1^2/\partial w \geq 0$ and $\partial p_{2i}^2/\partial w \geq 0$). In other words, the output volume generated by the workforce both with and without technological support is a non-decreasing function of the size of the workforce. However, since all other inputs are fixed, the increase in output volume occurs at a decreasing rate as the size of the workforce increases (i.e., diminishing returns). This gives us $\partial^2 p_1^1/\partial^2 w < 0$, $\partial^2 p_{2i}^1/\partial^2 w < 0$, $\partial^2 p_1^2/\partial^2 w < 0$ and $\partial^2 p_{2i}^2/\partial^2 w < 0$.

A third production function attribute reflects the relationship between worker skill (s) and the portion of output created manually (i.e., the first terms in Equations (2a) and (2b)). While holding constant the size of the workforce (w), as worker skill increases, the contribution to output generated by the workforce without IT support increases at a decreasing rate. Again, the second order effect reflects diminishing returns. Naturally, the extent to which worker skill drives the manual creation of output is far greater in Model 2 than in Model 1. Mathematically, we have $\partial p_1^1/\partial s \geq 0$, $\partial p_1^2/\partial s \geq 0$, $\partial^2 p_1^1/\partial^2 s < 0$, and $\partial^2 p_1^2/\partial^2 s < 0$.

Next, we consider the impact of workforce skill on the portion of output created with IT support as shown in the second terms of Equations (2a) and (2b). First, in simple IT-worker systems, worker skill beyond the base level is not needed to operate IT and generate output so that $\partial p_{2i}^1/\partial s = 0$ holds. Also, by definition, a workforce with the base skill level has sufficient knowledge to generate output though it cannot generate premium quality. In the simple IT-worker system, different IT choices may be associated with different base skill levels. In particular, an IT choice may have built-in features such that output can be generated with a lesser skilled workforce. For example, by introducing cash registers with automatic change makers, lesser skilled workers may be employed. In fact, firms offering mass-produced services often invest in additional built-in IT features to reduce the base skill (and wage) level of the workforce (Metters et al. 2003). Alternatively, in the banking industry, Roth and Jackson 1995 found that additional worker skill was needed to effectively operate newly installed IT.

In sharp contrast, in complex IT-worker systems, the speed that a worker operating IT generates output depends heavily on the extent that worker skill exceeds the base level. For example, a highly skilled engineering specialist may generate more output volume per unit time from a CAD system than a lesser skilled worker operating the same technology. Specifically, while holding constant the size of the workforce (w), IT accessibility (x), and the IT choice (i), the volume of output in a complex IT-worker system is a non-decreasing function of worker skill ($\partial p_{2i}^2/\partial s \geq 0$). However, increasing worker skill while holding other inputs fixed leads to diminishing returns so that $\partial^2 p_{2i}^2/\partial^2 s < 0$.

The fourth production function attribute characterizes the effect on output volume in relation to the level of IT accessible to the workforce (x). Suppose we hold fixed the size (w) and skill (s) of the workforce and the technology choice decision (i). In both simple and complex IT-worker domains, the volume of output increases at a non-decreasing rate as the amount of IT available to the workforce increases so that $\partial p_{2i}^1/\partial x \geq 0$ and $\partial p_{2i}^2/\partial x \geq 0$. Since other inputs are fixed, the increase in output volume occurs at a decreasing rate (diminishing returns) giving us $\partial^2 p_{2i}^1/\partial^2 x < 0$ and $\partial^2 p_{2i}^2/\partial^2 x < 0$. The following discussion illustrates these relationships.

Consider an architectural firm (Model 2) where the number of CAD workstations is smaller than the number of design engineers employed so that IT sharing occurs (Herzberger 1998). Typically, worker productivity suffers since the IT sharing causes problems with coordination and conflicts with worker scheduling. However, as the number of CAD workstations (x) increases, the problems associated with sharing IT decline and the fixed workforce generates output at a faster rate. Of course, since the workforce does not require the use of CAD at all times, as x increases, the rate of increase in output declines.

The above discussion introduces the concept of an *IT saturation level*. A saturation level is reached when any additional increase in IT accessibility provides no increase in output volume. Continuing the Model 2 example, once each design engineer has access to her own CAD workstation, the availability of additional IT does not increase output. It follows that, in Model 2, the IT saturation level is a function of the size of the workforce. Moreover, worker skill and IT functionality also impact the Model 2 saturation level. For example, engineers may benefit from more accessibility to CAD workstations if that technology offers expanded functionality. Let $x = \hat{X}_1^2(w, s)$ denote the saturation level of IT accessibility for Model 2.

The notion of a saturation level also holds in the simple IT-worker domain. For example, wait-staff in restaurants rely on shared workstations to place food orders, prints bills, and process customer payments. If few workstations are available, then the staff waits for IT accessibility and productivity suffers. As the number of workstations increases, wait-staff productivity increases. However, beyond some point, additional workstations do not increase output volume. Therefore, the saturation level in the simple IT-worker domain is also function of the size of the workforce. Suppose the IT system is not user friendly (technology choice decision) so that many keystrokes are needed to complete the average operation. Since each wait-staff needs more access to the IT system, workstation sharing is more of a problem and productivity suffers. Therefore, the IT saturation level is also a function of the technology choice decision. Let $x = \hat{X}_1^1(w)$ denote the IT saturation level for Model 1. Lastly, in contrast to Model 2, since the IT is specially designed to be used by low skilled workers, the Model 1 saturation level is independent of worker skill.

The fifth production function attribute reflects cross-derivative relationships. Consider the impact of IT accessibility on the marginal contribution to output from an additional worker hour. An increase in the size of the workforce necessitates a greater sharing of the fixed amount of IT. Therefore, if a larger amount of IT exists, then a greater increase in output volume is realized for the same increase in workforce. Mathematically, this gives us $\partial^2 p_{2i}^1/\partial w \partial x \geq 0$ and $\partial^2 p_{2i}^2/\partial w \partial x \geq 0$.

Next, consider the impact of worker skill on the marginal contribution to output from an additional worker hour. Typically, an increase in the size of the workforce necessitates more coordination among workers and requires workers have the ability to operate as a team. Therefore, as the size of the workforce increases, new dimensions of skill contribute to the creation of output so that $\partial^2 p_1^1/\partial w \partial s \geq 0$, $\partial^2 p_1^2/\partial w \partial s \geq 0$ and $\partial^2 p_{2i}^2/\partial w \partial s \geq 0$.

The impact of worker skill on the marginal contribution to output from an additional unit of IT accessibility differs for Models 1 and 2. First, in the complex IT-worker domain, suppose additional CAD workstations are made available to a fixed size workforce with the base skill level. As skill increases, the same increase in IT accessibility provides greater enhancement for the creation of output volume so that $\partial^2 p_{2i}^2/\partial s \partial x \geq 0$. In contrast, for example, in a retail environment, additional worker skill has no effect on the increase in output obtained as the number of cash registers increases. In general, in Model 1, additional skill is not needed to obtain an increase in output volume from additional IT accessibility so that $\partial^2 p_{2i}^1/\partial s \partial x = 0$.

Lastly, the sixth production function attribute reflects the impact on the creation of output in relation to the technology choice decision, *i*. Suppose the set of I technology options are sequenced so that, as *i* increases, output volume increases (*j* increases). The same workforce (size and skill held constant) given the same amount of IT accessibility may generate a higher volume of output as a result of the more advanced technology. However, in the complex IT-worker domain, the extent that more advanced IT increases output may be limited if worker skill is insufficient. Mathematically, this means that, as *j* increases, p_{2i}^1 in Equation (2a) increases whereas the increase in p_{2i}^2 in Equation (2b) is a function of the skill level of the workforce.

3.5. The Quality Functions

In this section, three quality function attributes are given that characterize the technical relationships between workforce skill and IT capability (*s* and *i*) and the creation of premium quality (Q). The attributes are expressed as first or second order derivative relationships so that we assume the quality function is continuous and twice differentiable with respect to *s* and *k*. Let $Q_i^1(s)$ and $Q_i^2(s)$ denote the level of premium quality generated in simple and complex IT-worker systems, respectively, as shown in Equations (3a) and (3b). The first terms denote the contribution to quality derived solely from workforce skill and independent of IT. The second terms reflects the impact of IT on quality.

$$Q_i^1(s) = q_1^1(s) + q_{2i}^1 \tag{3a}$$

$$Q_i^2(s) = q_1^2(s) + q_{2i}^2(s) \tag{3b}$$

First, if the workforce has the base skill level ($s = 1$) and the IT choice is not capable of providing premium quality ($k = 0$ for $i = 1$), then premium quality is not generated by the IT-worker system (i.e., $q_1^1(1) = q_{21}^1 = Q_1^1(1) = 0$ and $q_1^2(1) = q_{21}^2(1) = Q_1^2(1) = 0$).

The second quality function attribute characterizes the creation of premium quality in relation to worker skill but without IT support. In both Models 1 and 2, the portion of premium quality that is generated independent from IT support (first terms in (3a) and (3b)) is a non-decreasing function of workforce skill ($\partial q_1^1/\partial s \geq 0$ and $\partial q_1^2/\partial s \geq 0$). In Model I, workers with a higher skill level may be capable of generating output with fewer errors so that the amount of rework decreases and the firm realizes a lower marginal production cost (Stewart and Chase 1999). In Model 2, as a result of extensive training or years of experience, highly skilled management consultants are capable of creating premium quality services. However, diminishing returns occur since it becomes increasingly difficult to increase premium quality (command higher prices or reduce production costs) by increasing worker skill ($\partial^2 q_1^1/\partial s^2 < 0$ and $\partial^2 q_1^2/\partial^2 s < 0$).

The third quality function attribute (second terms in Equations (3a) and (3b)) connotes the contribution to premium quality driven by IT. In Model 1, this term is expressed independent from worker skill, whereas in Model 2, the contribution to premium quality from IT is a function of worker skill. First, consider an IT upgrade introduced in a retail chain. Suppose that if a stock-out occurs at one store, the IT system now has a built-in-feature that instructs the employee to direct the customer to other store locations where the merchandise is available (i.e., the IT inventory system is networked). As a result, the level of customer service quality increases. Moreover, in simple-IT worker systems, the new IT feature is typically part of a menu-driven system upgrade that does not require additional worker skill to operate. Mathematically, this gives us $\partial q_{2i}^1/\partial s = 0$ and q_{2i}^1 increases as k increases.

Next, consider the complex IT-worker domain where the extent that IT provides premium quality depends heavily on knowledge worker skill. For example, only a highly skilled engineer may be capable of performing complex functions on an advanced CAD system. Similarly, consider client recommendations developed by a junior versus a senior management consultant assuming both use the same simulation software running on the same computer (same i). Due to her considerable experience and deep skills, the senior consultant is able to generate a client report embodying premium quality beyond that created by the junior employee. These examples demonstrate that, even with the same technology, in Model 2, worker skill enhances the contribution to premium quality ($\partial q_{2i}^2/\partial s \geq 0$). However, the extent that skill drives premium quality in the complex IT-worker system exhibits diminishing returns ($\partial^2 q_{2i}^2/\partial^2 s < 0$).

Lastly, in complex IT-worker systems, consider the impact on premium quality when an IT upgrade is introduced. Suppose the set of I technology options are sequenced so that, as i increases, premium quality increases (k increases). If sufficient skill exists, then the knowledge workers are able to use the additional functionality embedded in the IT system so that premium quality increases and the service commands a higher price in the marketplace. Alternatively, if insufficient skill exists to operate the additional functionality, then premium quality does not increase. In conclusion, in complex IT-worker systems, as k increases, q_{2i}^2 increases or remains the same depending on the skill level of the workforce.

3.6. Diminishing Returns

When defining attributes of the output volume and quality functions as well as characteristics of the profit-maximizing objective, we frequently invoke the notion of diminishing returns (Bairam 1994). In contrast, Milgrom and Roberts 1990 and Arthur 1996 suggest that increasing returns may occur in relation to IT. We believe that diminishing returns is consistent with our focus on the *process level*. For example, increasing returns to investment in IT may occur at the *firm level* because of synergies that are created between different functions of the organization. In our models, benefits such as these (e.g., cost savings) that occur outside the specific IT-worker system under investigation are captured in the return function. Lastly, mathematically, diminishing returns occur only in second order derivatives. Therefore, the first order conditions of optimality do not depend on the assumption of diminishing returns.

3.7. The Analytic Solutions

Two mathematical models have been introduced that capture the salient attributes of the conceptual framework for simple and complex IT-worker systems in service domains. We have shown that a firm's ability to generate output and premium quality differs for simple versus complex IT-worker systems (Equations (2) and (3)). Therefore, while the general forms of the objectives are the same for both models (Equation (1)), the analytic solutions differ. Moreover, even those terms in the solution that appear the same analytically are substantially different in magnitude as a result of the different application domains under consideration.

The optimal solution to the problem given by Equations (1a) and (1b) can be derived using constrained calculus. The necessary conditions for optimality (the Karush-Kuhn-Tucker conditions) for w, s, and x are given in Napoleon and Gaimon 2004. Due to the mathematical complexity, we cannot analytically show that the necessary conditions are sufficient. Lastly, to identify the best technology choice, the model must be resolved for each technology option. Clearly, an IT alternative is characterized by its impact on cost (C_{2i}), return (R_i), output (P_i) and premium quality (Q_i). In other words, for each $i = 0, 1, \ldots, I$, the optimal solution for w, s, and x is obtained. The technology choice (value of i) and the corresponding solutions for w, s, and x that are associated with the maximum objective value are optimal. However, note that if a solution is obtained in which $x = 0$, then $j = 0$ and $k = 0$ must hold. In other words, the benefits to output and premium quality from IT are realized only if $x > 0$.

4. Numerical Analysis

To demonstrate the usefulness of the models as a means of providing managerial insights and to illustrate key distinctions that arise between the structured (Model 1) and unstructured (Model 2) decision-mak-

Table 1 **Functions for Numerical Examples Models 1 and 2**

$$P_i^1(w, x, s) = w^{\alpha^1} s^{\beta^1}[p_0^1] + w^{\alpha^1}[p_{1i}^1(1 - e^{-p_{2i}^1(x/w)})] \quad (4)$$

$$P_i^2(w, x, s) = w^{\alpha^2} s^{\beta^2}[p_0^2 + p_{1i}^2(1 - e^{-p_{2i}^2(x/w)})] \quad (5)$$

$$Q_i^1(s) = q_1^1(s - 1)^{q_0^1} + q_{2i}^1(1 - e^{-q_{3i}^1}) \text{ and } Q_i^2(s) = (s - 1)^{q_0^2}[q_1^2 + q_{2i}^2(1 - e^{-q_{3i}^2})] \quad (6)$$

$$\pi^1(Q_i^1, P_i^1) = \pi_1^1(1 + \pi_2^1 Q_i^1)(P_i^1)^{\gamma 1} \text{ and } \pi^2(Q_i^2, P_i^2) = \pi_1^2(1 + \pi_2^2 Q_i^2)(P_i^2)^{\gamma 2} \quad (7)$$

$$C^1(s, w) = c_0^1[1 + c_1^1(s - 1)]w \text{ and } C_1^2(s, w) = c_0^2[1 + c_1^2(s - 1)]w \quad (8)$$

$$C_{2i}^1(x) = c_{2i}^1 x \text{ and } C_{2i}^2(x) = c_{2i}^2 x \quad (9)$$

$$R_i^1(x) = r_{0i}^1 + r_{1i}^1 x \text{ and } R_i^2(x) = r_{0i}^2 + r_{1i}^2 x \quad (10)$$

where $\pi_1, \pi_2 > 0$; $c_0, c_1, c_{2i} > 0$; $r_{0i}, r_{1i} > 0$; $\alpha, \beta, \gamma \in (0, 1]$; $p_0, p_{1i}, p_{2i} > 0$; and $q_0 \in (0, 1]$, $q_1, q_{2i}, q_{3i} > 0$ for Models 1 and 2 and for $i = 1, 2, \ldots, I$. Also, given the nature of the simple and complex IT-worker domains, it is likely that: $\pi_1^1 < \pi_1^2$, $\pi_2^1 < \pi_2^2$, $c_0^1 < c_0^2$, $c_1^1 < c_1^2$, $c_{2i}^1 > c_{2i}^2$, $r_{0i}^1 > r_{0i}^2$, $r_{1i}^1 > r_{1i}^2$, $\alpha^2 > \alpha^1$, $\beta^2 > \beta^1$, $\gamma^1 \geq \gamma^2$, $p_0^1 > p_0^2$, $p_{1i}^1 > p_{1i}^2$, $p_{2i}^2 > p_{2i}^1$, $q_0^2 > q_0^1$, $q_1^2 > q_1^1$, $q_{2i}^2 > q_{2i}^1$, and $q_{3i}^2 > q_{3i}^1$, for $i = 1, 2, \ldots, I$.

ing domains, numerical examples are introduced based on special cases of the general functions. The particular functions assumed are motivated by actual firm data obtained from surveys and face-to-face interviews (Napoleon 1997). To maintain confidentiality of our sources, the actual data has been disguised.

For the complex IT-worker domain, surveys were conducted with architectural and engineering firms whose knowledge workers employed CAD systems. For the simple IT-worker domain, data was collected from a major distributor of pet products prior to, during, and following implementation of an IT system. The simple IT-worker domain consisted of low skilled employees in the shipping and receiving departments who operated scanning equipment and accessed menu-driven software for purchasing and inventory control.

The particular functions used in the numerical examples (Equations (4)–(10)) satisfy the first and second order conditions described earlier and appear in Table 1. A detailed discussion of these functions and a complete statement of notation are given in Napoleon and Gaimon 2004.

4.1. Numerical Examples

Numerical examples are presented to compare the optimal solutions obtained for Model 1 (denoted by M^1) and Model 2 (M^2) in response to different conditions that characterize the service operations domain. For Model 1, we have the following bounds on the decision variables: $w \in (0,24]$, $s \in [1,5]$, and $x \in [0,12]$. For Model 2, the bounds are: $w \in [0,18]$, $s \in [1,10]$, and $x \in [0,18]$. All other input parameter settings appear in Table 2 (only those input values that differ from Example M_0^1 or M_0^2 are indicated). The numerical inputs and solutions represent daily values. All of the solutions in Table 3 satisfy the first order conditions of optimality and are interior (none are boundary solutions). While the models are too complex to prove sufficiency, we have demonstrated that the objective is concave at each numerical solution (i.e., using the standard notation for Hessians, we obtained $|H_1| < 0$, $|H_2| > 0$, and $|H_3| < 0$). Moreover, for each numerical example, we can show that the solutions reported in Table 3 lead to higher objective values than any of the 26 boundary solutions. This gives us confidence that the solutions reported in Table 3 are global optimum.

4.1.1. Model 1 (Simple IT-Worker System). The IT purchase reflected as we shift from Example M_0^1 to

Table 2 **Numerical Inputs for Simple (Model 1) and Complex (Model 2) IT-Worker Systems**

MODEL 1	Net revenue			Worker cost		IT cost	Output volume (workforce)			Output volume (IT)		Premium quality (workforce)		Premium quality (IT)		Return	
Example	π_1^1	π_2^1	γ^1	c_0^1	c_1^1	c_{2i}^1	p_0^1	α^1	β^1	p_{1i}^1	p_{2i}^1	q_0^1	q_1^1	q_{2i}^1	q_{3i}^1	r_{0i}^1	r_{1i}^1
M_0^1 (baseline)	15	.5	1	5.25	.5	20	25	.2	.05	25	5	.1	.05	.05	.05	15	.2
M_1^1		.6				30				35							5
M_2^1		5	.95	6.00													
M_3^1				7.50													
M_4^1				7.50		40				30				.25			
MODEL 2	**Net revenue**			**Worker cost**		**IT cost**	**Output volume (workforce)**			**Output volume (IT)**		**Premium quality (workforce)**		**Premium quality (IT)**		**Return**	
Example	π_1^2	π_2^2	γ^2	c_0^2	c_1^2	c_{2i}^2	p_0^2	α^2	β^2	p_{1i}^2	p_{2i}^2	q_0^2	q_1^2	q_{2i}^2	q_{3i}^2	r_{0i}^2	r_{1i}^2
M_0^2 (baseline)	300	50	1	30	.2	10	.1	.45	.1	.1	12	.2	.1	.3	.1	.1	.02
M_1^2		55	.85														
M_2^2		55	.85	40		20				.15				.35			
M_3^2				40													
M_4^2				40		20				.15				.35			

Table 3 Optimal Solutions for Simple (Model 1) and Complex (Model 2) IT-Worker Systems

Model 1 Example	w	s	x	P	Q	Net revenue	Wages	IT cost	Total return	Gross profit
M_0^1	17.7	1.16	8.0	84.5	.044	1295.83	100.36	160.00	16.60	1052.07
M_1^1	17.5	1.22	8.4	101.2	.045	1558.90	101.48	252.00	57.00	1261.92
M_2^1	12.0	2.14	6.1	80.5	.053	1227.69	113.04	122.00	16.22	1008.87
M_3^1	14.2	1.10	7.0	81.6	.042	1249.66	111.83	140.00	16.40	1014.24
M_4^1	9.6	1.24	4.3	81.9	.055	1262.04	80.64	172.00	15.86	1025.26
Model 2 Example	w	s	x	P	Q	Net revenue	Wages	IT cost	Total return	Gross profit
M_0^2	14.1	9.58	5.6	.821	.198	2680.36	1148.87	56.00	.212	1475.70
M_1^2	10.3	13.53	4.3	.739	.213	2950.57	1083.35	43.00	.186	1824.41
M_2^2	8.6	14.39	3.5	.856	.224	3499.76	1265.23	70.00	.170	2164.70
M_3^2	8.7	9.34	3.6	.660	.196	2142.03	928.46	36.00	.172	1177.73
M_4^2	12.3	10.14	4.7	.970	.208	3306.96	1391.38	94.00	.194	1821.78

M_1^1 is inspired by the experience of the pet food distributor. From Example M_0^1, initially, the firm maintained a large warehouse in which low wage workers were employed to fill orders generated by the sales force. Unfortunately, the order filling process was replete with errors. Also, additional workers were employed who performed inventory planning and control. Lastly, sales, order filling, and inventory planning were supported by unconnected IT systems so that separate data entry was necessary for each function.

The firm purchased a new IT system whose attributes are captured in Example M_1^1. The new IT system had scanning equipment that increased the speed of worker processing (p_{1i}^1 is higher in M_1^1 than in M_0^1) and assured that the items picked from the warehouse matched the orders so that processing costs declined and marginal net revenue increased (π_2^1 is higher in M_1^1). The new IT system was designed to be user-friendly so that the base skill level did not change. Moreover, a considerable return was generated since the new IT system integrated sales, order filling, and inventory planning data and automated some inventory planning and control decisions (r_{1i}^1 is higher in M_1^1) (also see McAfee 2002). Naturally, however, the firm incurred a substantial increase in the cost of IT for the greater functionality (c_{2i}^1 is higher in M_1^1).

Driven primarily by the increased speed with which workers processed order filling, the distributor increased output volume considerably with a slightly smaller workforce. The higher number of orders processed along with the lower processing costs incurred (higher contribution to marginal net revenue from output) led to a considerable increase in total net revenue. As a result of the IT ability to integrate and automate elements of sales, order filling, and inventory planning, the pet food distributor realized a very substantial increase in the return function. Overall, the distributor's gross profit increased considerably by using the enhanced IT system.

To broaden our numerically based insights, we use the functional forms introduced for the pet food distributor to analyze other simple IT-worker systems. In contrast to M_0^1 and M_1^1 where the input was inspired by actual firm data, in the next examples input were selected to illustrate specific situations commonly encountered by decision makers in simple IT-worker systems.

Let M_0^1 and M_2^1 represent two retail environments that differ with respect to attributes of their consumer target markets and the base skill levels of their workforce. Suppose M_0^1 reflects a retailer such as Sears, whereas M_2^1 reflect a retailer such as Nordstrom (Simons and Weston 1999). First, the customers' willingness to pay for premium quality service is higher in M_2^1 (π_2^1 is larger in M_2^1). Second, the potential size of the customer base experienced by the firm in example M_2^1 is smaller (γ^1 is smaller in M_2^1). Third, since the base skill worker in example M_2^1 is more skilled than the base skill worker in example M_0^1, the base wage rate (c_0^1) is higher.

The solutions in Table 3 indicate that the retailer whose attributes are consistent with Nordstrom employs a smaller but higher skilled workforce than the retailer whose attributes are consistent with Sears. The higher skill leads to a higher total cost for wages in M_2^1 relative to M_0^1. While both the size of the workforce and the IT accessibility are lower for M_2^1 relative to M_0^1, the technology made available per worker (x/w) is higher. Despite the somewhat smaller volume of sales (output), the firm in Example M_2^1 earns only slightly less total net revenue than M_0^1 due to its ability to charge higher prices for premium quality service.

A comparison of Examples M_0^1 and M_3^1 illustrates the effect of higher wages on the composition of the IT-worker system. Suppose that the base wage rate increases from 5.25 in M_0^1 to 7.50 in M_3^1. As a result, the firm in M_3^1 optimally employs considerably fewer workers. While the smaller workforce requires less IT, the decrease in x is modest. Therefore, the ratio of technology per worker is higher for M_3^1 relative to M_0^1.

There are two interpretations of this result. First, in a sense, we observe a substitution of technology for workers in M_3^1 relative to M_0^1. Second, the firm given by M_3^1 optimally invests in more IT per worker in order to enable each worker to generate a higher volume of output and thereby justify the higher wage rate.

In our final example of the simple IT-worker system, we extend our analysis of a firm's response to a high wage rate. With a wage rate of \$7.50 (as in Example M_3^1), the firm in Example M_4^1 considers investment in an expensive IT upgrade that enhances the speed and consistent quality of output generated by the workforce. In response to the higher wage rate and the opportunities afforded by the IT, the firm in M_4^1 employs a substantially smaller workforce that requires much less IT accessibility relative to M_3^1. However, despite the large reductions in w and x, the reduction in output volume is negligible due to the greater speed with which workers create output. Primarily due to the enhanced capability of IT to generate consistent quality, the firm in M_4^1 realizes a higher level of quality than M_3^1. The reduction in the size of the workforce leads to a considerable reduction in the cost for wages. While the amount of IT accessibility is substantially lower in M_4^1 than in M_3^1, the greater functionality of the IT leads to a considerable increase in its total cost. Lastly, note that gross profit is slightly higher in M_4^1 as compared to M_3^1 but slightly lower than in M_0^1. By comparing the solutions in M_0^1, M_3^1 and M_4^1, we see that while the IT upgrade is justified for the firm with the relatively high wage rate (M_3^1), it is *not* justified for the firm with a lower wage rate (M_0^1.). This illustrates a situation frequently observed in practice: the substitution of IT functionality for expensive workers.

4.1.2. Model 2 (Complex IT-Worker System). The situations reflected in Examples M_0^2, M_1^2, and M_2^2 are inspired by what we observed in our study of architectural firms whose highly skilled engineers employed CAD to generate output in the form of design drawings. The initial position of the firm is captured by example M_0^2 whereas example M_1^2 represents the firm's response to a shift in market characteristics. The firm observed a market segment that was willing to pay a premium price for output of higher performance quality, (π_2^2 is higher in M_1^2 than in M_0^2). Specifically, some customers were willing to pay higher prices for 3-dimensional design drawings. (Although the CAD system owned by the firm was capable of generating 3-dimensional drawing, the workforce was not familiar with this element of the system functionality and persisted in creating 2-dimensional drawings.) However, the potential size of the new market segment was somewhat smaller than the market currently served by the firm (γ^2 is lower in M_1^2 than in M_0^2).

After analyzing the opportunities presented by the different markets embodied in M_0^2 and M_1^2, the firm decided to modify its resource capabilities to meet the premium price but smaller target market. The firm in M_1^2 heavily invested in workforce training so that its employees would be capable of generating 3-dimensional drawings. However, the firm also reduced the size of its workforce considerably as compared with M_0^2. Driven by the higher workforce skill, the level of premium quality output increased in M_1^2 relative to M_0^2. But, with the reduced workforce, the total volume of output decreased somewhat. The increase in the level of premium quality compensated for the reduction in output volume so that the firm in M_1^2 earned higher total net revenue than M_0^2. Relative to M_0^2, while the higher skill level drove a substantial increase in the wage rate, the firm in M_1^2 incurred a lower total cost for wages as a result of the smaller workforce. Since the smaller workforce requires less IT accessibility, the total cost for IT was lower in M_1^2 relative to M_0^2. Overall, by shifting its resource capabilities to meet the smaller sized but premium price target market, the firm realized a considerable increase in gross profit.

In example M_2^2, we observe what happened when the architectural firm sought further enhancements in its ability to generate premium quality output by investing in an IT upgrade. The IT under consideration, while twice as expensive per unit as the current IT, offered considerable improvements in both the speed and quality of output generated by the workforce ($^2_{1i}$ and q_{2i}^2 are higher in M_2^2 than in M_1^2). The new IT had built-in features not available in the existing system that facilitated even more complex analysis of 3-dimensional drawings. However, to effectively operate the more sophisticated IT system, the firm recognized that an increase in the base skill level would be needed (the base wage rate is higher in M_2^2).

By comparing the solutions in M_2^2 and M_1^2, we see by purchasing the IT upgrade, the firm reinforced its strategy to employ a smaller but more highly skilled workforce, (w decreased by and s increased). In addition, the smaller but more productive workforce required less IT accessibility. Despite the smaller workforce, as a consequence of the enhancements afforded by the IT upgrade, output volume was higher in M_2^2 relative to M_1^2. Therefore, the firm was able to capture a larger portion of the smaller target market that was willing to pay a premium price for high quality output. The level of premium quality generated by the higher skilled workforce operating the enhanced IT increased. As a result of the higher levels of output and premium quality, total net revenue was higher in M_2^2 relative to M_1^2. Due to the higher skilled workforce, the total cost for wages increased. Similarly, due to the enhanced IT functionality, the total IT cost increased substantially. The increase in total net revenue easily offset the increased costs incurred for wages and IT so that gross profit was higher in M_2^2 relative to M_1^2.

To broaden the numerically based insights, two more examples are given based on the functional forms introduced for the engineering design firm. Unlike the input in M_0^2, M_1^2 and M_2^2 which were inspired by actual firm data, the input for the next examples are selected to illustrate situations commonly encountered by decision makers in complex IT-worker systems.

Next, we explore the impact to a firm that is forced to pay higher wages for its knowledge workers. As we shift from M_0^2 to M_3^2, the base wage rate increases from 30 to 40. In response, the firm reduced the size of its workforce substantially. The smaller workforce required less IT support so that x decreased substantially, as well. With the reduction in workforce and IT accessibility, the total output decreased considerably. However, given the need to generate premium quality output in this service operations domain, only a modest reduction in workforce skill occurred so that the reduction in premium quality was negligible. The substantial reduction in output volume led to a considerable decline in total net revenue. The savings realized in the total cost for wages and IT did not compensate for the reduction in total net revenue so that gross profit declined. Lastly, as indicated by the value x/w, the firm in M_3^2 allocated more technology per worker relative to M_0^2 so that the firm partially substitutes IT for workforce.

The final example allows us to assess the opportunity provided by an IT upgrade for a firm that must pay higher wages for its workforce. Specifically, with the high base wage rate in M_3^2, the firm in M_4^2 employs the IT upgrade described in M_2^2 having built-in features that increase both the speed and quality of output generated per worker.

Relative to the lower wage rate firm in M_0^2 and due to the enhanced IT, the firm in M_4^2 pursued a less drastic reduction in its workforce and IT accessibility than that undertaken by the firm in M_3^2. Also, despite the higher wage rate relative to M_0^2, to attain the potential benefits of the IT, the firm in M_4^2 invested in more workforce skill. The enhanced IT compensated for the smaller workforce so that output volume increased considerably in M_4^2 relative to M_0^2. Due to the higher skill and enhanced IT, premium quality increased. Total net revenue increased because of the higher levels of output and quality. Due to the higher skill level and despite the smaller workforce, the total cost for wages increased. Also, due to the greater functionality, the total IT cost increased by very substantially in M_4^2 despite a smaller level of IT accessibility relative to M_0^2. Lastly, the increase in total net revenue dominated the objective function so that gross profit was considerably higher for the firm in M_4^2 as compared to the firm in M_0^2.

5. Conclusions

Two formal models have been introduced that contribute to our conceptual understanding of service operations at the process level. The models establish a rigorous framework linking firm profit to attributes of the IT-worker system. In Model 1, simple IT is used by lesser skilled workers to support structured decision-making. The ability to standardize the service creation process, as in mass produced services, facilitates the development of the dedicated IT system (hardware, software). In contrast, in Model 2, complex ("off the shelf") IT is used by knowledge workers (e.g., consultants, scientists, engineers, etc.) to support unstructured decision-making.

The operations manager selects attributes of the workforce (number of workers and skill level) and IT attributes (IT accessibility, IT choice reflecting functionality, ease-of-use, connectivity, etc.) that jointly determine both the levels of output volume and premium quality. Due to fundamental conceptual differences between the structured versus unstructured environments, different mathematical functions denoting production and premium quality are introduced. Characteristics of these functions are captured in a series of first and second order derivative relationships. Support for the conceptual and mathematical models is given based on the empirical and anecdotal literature.

The objective in both mathematical models is to maximize profit. Total net revenue is expressed as a function of the firm's decisions regarding output volume and premium quality and external market conditions. Costs are incurred for the workforce (in relation to its size and skill level) and for the information technology employed (in relation to the amount made available to the workforce and the embedded features such as functionality). Lastly, a return function is introduced representing the cost reduction realized due to the transfer of operations activities from another part of the firm to the IT-worker system.

The models presented provide decision-makers with valuable templates to evaluate the impact on profit from various characterizations of the inputs to the service creation process. By formalizing the simple versus complex IT-worker systems mathematically, we have embedded the service firm's competitive priorities in the context of its resource-based decisions. As a result, the decision-maker can perform sensitivity analysis to derive a variety of important managerial insights. For example, in the context of the two profit maximizing models, a manager can explore how features of the IT-worker system impact a firm's ability to increase net revenue. The manager can assess the cost implications of the size and skill of the workforce as well as the operating costs associated with different types of IT under consideration. In particular, important tradeoffs associated with various technology choice decisions may be assessed.

Numerical examples are presented that validate the conceptual models introduced by illustrating results that are consistent with what is observed in practice. In several examples, we analyze situations where a firm undertakes the substitution of workforce with IT. For example, in the simple IT-worker domain, we show that an increase in profit occurs if dedicated IT is introduced that automates operations previously performed by a large number of low skilled workers or workers with a relatively high wage rate. The use of IT in domains where services are mass-produced is analogous to the substitution of capital for labor witnessed in direct manufacturing of high-volume commodity goods. According to Metters et al. 2003, "a cost leader aggressively tracks technology innovation in an attempt to substitute automation for labor." Moreover, in the simple IT-worker domain, we show the benefits afforded to the firm that deploys an IT system that integrates previously separate functions of the firm and thereby improves the efficiency of the service creation process (captured by the return function).

For the complex IT-worker domain, considerable analysis is given on a firm's response to a relatively high wage rate for its knowledge workers. First, assuming the firm makes no change in its IT system, we find that both the size of the workforce and the level of IT accessibility decrease. However, we also show that the firm allocates more technology per worker so that, in a sense, the firm partially substitutes IT for its relatively expensive workforce. Second, we show that in response to a high wage rate, a firm operating a complex IT-worker system should consider investing in an IT upgrade that enhances the speed or quality of the output generated. Here, the higher paid workforce is made more productive at generating output volume or quality. Moreover, we show that to justify the investment in the enhanced IT, despite the higher wage rate, the firm must increase the skill level of the workforce so that the potential benefits of the upgrade are realized. Lastly, in both the simple and complex IT-worker domains, we illustrate the impact on resource decisions in relation to market characteristics.

5.1. Limitations and Future Research

Our conceptual framework and models do not address the creation of output and quality in the domain of e-services. For example, in e-services, the customer plays a key role during the service creation process. Also, the conceptual framework could be made richer by including the results from marketing research on the tradeoffs between price and quality. Developing a conceptual framework and model of e-business and embedding marketing results in the net revenue function represent opportunities for future research.

References

Apte, U. M., C. C. Reynolds. 1995. Quality management at Kentucky Fried Chicken. *Interfaces* **25**(3) 6–21.

Arthur, W. B. 1996. Increasing returns and the new world of business. *Harvard Business Review* **74**(4) 100–109.

Bairam, E. 1994. *Homogeneous and Nonhomogeneous Production Functions, Theory and Applications,* Avebury, Brookfield, Vermont.

Baldwin, J. 1997. Productivity and IT. *Capacity Management Review* **25**(3) 1–11.

Beatty, C. A. 1988. Tall tales and real results: Implementing a new technology for productivity. *Business Quarterly* **51**(3) 70–74.

Bowen, D., E. Lawler. 1992. The empowerment of service workers: What, why, how, and when. *Sloan Management Review,* Spring, 31–39.

Bradley, S. P., P. Ghemawat, S. Foley. 1996. *Wal-Mart Stores, Inc.,* Harvard Business School Case, Harvard Business School Publishing, Boston, Massachusetts.

Brandyberry, A., A. Rai, G. White. 1999. Intermediate performance impacts of advanced manufacturing technology systems: An empirical investigation. *Decision Sciences* **30**(4) 993–1020.

Brynjolfsson, E., L. Hitt. 1996. Paradox lost? Firm-level evidence on the returns to information systems spending. *Management Science* **42**(4) 541–558.

Chase, R. 1978. Where does the customer fit in a service operation? *Harvard Business Review* **56**(6) 137–142.

Chase, R., N. F. Aquilano, R. Jacobs. 2001. *Production and Operations Management,* 8th edition, Irwin, McGraw Hill, Boston, Massachusetts.

Chase, R. D. Garvin. 1989. The Service Factory. *Harvard Business Review* **67**(4) 61–69.

Chase. R., R. Hayes. 1991. Beefing up operation in service firms. *Sloan Management Review,* Fall, 15–26.

Chase, R., D. Stewart. 1996. The mall is my factory: Reflections of a service junkie. *Production and Operations Management*, Winter, 298–308.

Chiang, A. 1974. *Fundamental Methods of Mathematical Economics,* 2nd edition, McGraw-Hill, New York, New York.

Devaraj, S., R. Kohli. 2003. Performance impacts of information technology: Is usage the missing link. *Management Science* **49**(3) 273–289.

Dewan, S., K. L. Kraemer. 2000. Information technology and productivity: Evidence from country-level data. *Management Science* **46**(4) 548–562.

Dvorak, R. E., E. Holen, D. Mark, W. F. Meehan III. 1997. Six principles of higher performance IT. *McKinsey Quarterly* **3** 164–177.

Ebel, K. H., E. Ulrich. 1987. Some workplace effects of CAD and CAM. *International Labour Review* **126**(3) 351–370.

Fitzsimmons, J. A., M. J. Fitzsimmons. 2001. *Service Management: Operations, Strategy, and Information Technology,* 3rd edition, Irwin McGraw-Hill, Boston, Massachusetts.

Flynn, B., R. Schroeder, S. Sakakibara. 1995. The impact of quality management practices on performance and competitive advantage. *Decision Sciences* **26**(5) 659–691.

Froehle, C., A. V. Roth, R. Chase, C. Voss. 2000. Antecedents of new service development and effectiveness: An exploratory examination of strategic operations choices. *Journal of Service Research* **3**(1) 3–17.

Gaimon, C. 1997. Planning information technology-worker systems. *Management Science* **43**(9) 1308–1328.

Gaimon, C., K. Napoleon. 2000. Information technology-worker systems in structured and unstructured environments. In New Service Development: Creating Memorable Experiences, J. Fitzsimmons and M. Fitzsimmons (eds.), Sage Publications, Inc., California, 183–215.

Gatewood, R., H. Field. 1994. *Human Resource Selection,* Dryden Press, Ft. Worth, Texas.

Hendricks, K., V. Singhal. 1997. Does implementing a TQM program improve operating performance. *Management Science* **43**(9) 1258–1274.

Herzberger, M. 1998. Personal communications. January.

Huete, L. A., V. Roth. 1998. The industrialization and span of retail banks' delivery systems. *International Journal of Operations and Production Management* **8**(3) 46–66.

Hoffman, T. 1997. Feds link IT, productivity, but hard evidence is lacking. *Computerworld* **31**(34) 1–2.

Kohli, R., S. Devaraj. 2003. Measuring information technology payoff: A meta-analysis of structural variables in firm-level empirical research. *Information Systems Research* **14**(2) 127–145.

McAfee, A. 2002. The impact of enterprise information technology adoption on operational performance: An empirical investigation. *Production and Operations Management* **11**(1) 33–53.

Metters, R., K. King-Metters, M. Pullman. 2003. *Successful Service Operations Management,* Thompson South-Western, Mason, Ohio.

Milgrom, P., J. Roberts. 1990. The economics of modern manufacturing: technology, strategy, and organization. *American Economic Review* **80**(3) 511–528.

Mukhopadhyay, T., S. Rajiv, K. Srinivasan. 1997. Information technology impact on process output and quality. *Management Science* **43**(12) 1645–1659.

Napoleon, K. 1997. *Improvement in Productivity and Quality from Information Technology-Worker Systems,* Ph.D. Dissertation. Georgia Institute of Technology, Atlanta, Georgia.

Napoleon, K., C. Gaimon. 2004. A Framework to Analyze IT-Worker Systems in Services, Working Paper, University of Georgia, Terry College of Business.

Roth, A., W. E. Jackson. 1995. Strategic determinants of service quality and performance: Evidence from the banking industry. *Management Science* **41**(11) 1720–1733.

Schmenner, R. 1986. How can businesses survive and prosper? *Sloan Management Review,* Spring, 21–32.

Seligman, D. 1997. Brains in the office. *Fortune, January* **13** 38.

Simon, H. 1977. *The New Science of Management Decisions.* Prentice Hall, Prentice Hall, New Jersey.

Simons, R. L., H. A. Weston. 1999. *Nordstrom: Dissention in the Ranks.* Harvard Business School Case, Harvard Business School Publishing, Boston, Massachusetts.

Stewart, D., R. Chase. 1999. The impact of human error on delivering service quality. *Production and Operations Management*, Fall, 240–263.

Stiroh, K. J. 2001. Investing in information technology: Productivity payoffs for U.S Industry. *Current Issues in Economics and Finance* **7**(6) 1–6.

Stohr, E. A., B. R. Konsynski. 1992. *Information Systems and Design Processes,* IEEE Computer Society Press, California.

Stross, R. E. 1996. Microsoft's big advantage-hiring only the supersmart. *Fortune, November* **25** 159–162.

Sulek, J., A. Maruchek 1992. A study of the impact of an integrated information technology on the time utilization of information workers. *Decision Sciences* **23**(5) 1174–1198.

Teal, T. 1991. Service Comes First: An Interview with USAA's Robert F. McDermott. *Harvard Business Review,* September–October: 117–127.

Thatcher, M., J. Oliver. 2001. The impact of technology investments on a firm's production efficiency, product quality, and productivity. *Journal of Management Information Systems* **18**(2) 17–45.

Zuboff, S. 1988. *In the Age of the Smart Machine: The Future of Work and Power,* Basic Books, Inc., New York, New York.