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Decision Support

Assessing the business values of information technology and e-commerce independently and jointly

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ABSTRACT

The purpose of this paper is to assess the business values of information technology (IT) and electronic commerce (EC) independently and simultaneously as measured by productive efficiency, in order to provide new insights into IT and EC investments and, consequently, lead to better decisions on IT and EC investments. The paper analyzes a panel data set at the country level based on the theory of production and its companions called the time-varying stochastic production frontier (SPF) approaches with the one-equation and two-equation models estimated by a two-step nonlinear maximum-likelihood method. The performance metric called productive efficiency is built in the research approaches. The empirical evidence strongly suggests that the presence of EC may strengthen or weaken IT value, and vice versa, which provide a good explanation for the disappearance or existence of the so-called productivity paradox, and that the paradox may exist in a country regardless of whether it is a developed or a developing country, inconsistent with conventional wisdom claiming that the paradox exists only in developing countries. The findings imply that it is imperative to carefully assess the values of IT and EC and, as such, prudent rather than blind IT and EC investing decisions are made, and that the values of IT and EC must be evaluated jointly rather than separately. The findings add significant contributions to the literature and serve as a catalytic agent in stimulating further comparative research in these important areas linking IT investments and EC developments when their business values are the major concern.

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1. Introduction

On the one hand, information technology (IT) and e-commerce (EC)[3] are an integrated part of production and operations management (POM)/information systems management (ISM) (Prasad & Babbar, 2000). By 1994, IT accounted for over 15.5 percent nonresidential fixed investments by the U.S. private sector; and from 1990 to 1994, IT investment increased at an annual rate of 7.4 percent, while the American economy grew at less than half that rate. On the other, the volume of EC for U.S. business transactions increased from $8 billion in 1996 to $327 billion by the year 2002 (*Digital Planet-The Global Economy 2004*); and the dollar amount spent on EC continues to increase rapidly through time. Especially, in recent years, we have witnessed that the activities of EC have gained their popularity. Accordingly, the business values of IT and EC should be a topic of burgeoning interest.

The literatures, however, clearly indicate that the business values of IT and EC have been assessed independently and separately (Brynjolfsson & Hitt, 1996; Chen & Lin, 2009; Chou, Shao, & Lin, 2012; Dewan & Kraemer, 2000; Kao & Hwang, 2010; Lee, 2010; Lin, 2009, 2013, Chap. 3; Lin & Chiang, 2011; Lin & Chuang, 2013; Lin, Chuang, & Choi, 2010; Lin & Shao, 2000; Ramanathan, Ramanathan, & Hsia, 2012) rather than jointly and simultaneously, with the work by Zhu (2004) being an exception. But the study concerns only the positive interaction effect (the complementarity phenomenon) and undermines the possible negative interaction effect (the substitutability phenomenon) between IT infrastructure and EC capability. Thus, the study leaves a gap to be bridged; and the gap reveals a critically important research problem to be resolved, that is, the values of IT and EC should be evaluated simultaneously rather than separately. When IT and EC are invested simultaneously, the presence of IT may enhance (reduce) EC value, hence, complementarity

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[3] IT and EC differ in concepts and properties as depicted by Fig. 1. The figure is self-explanatory and, as such, no further explanations are given to keep the length of the article under control.

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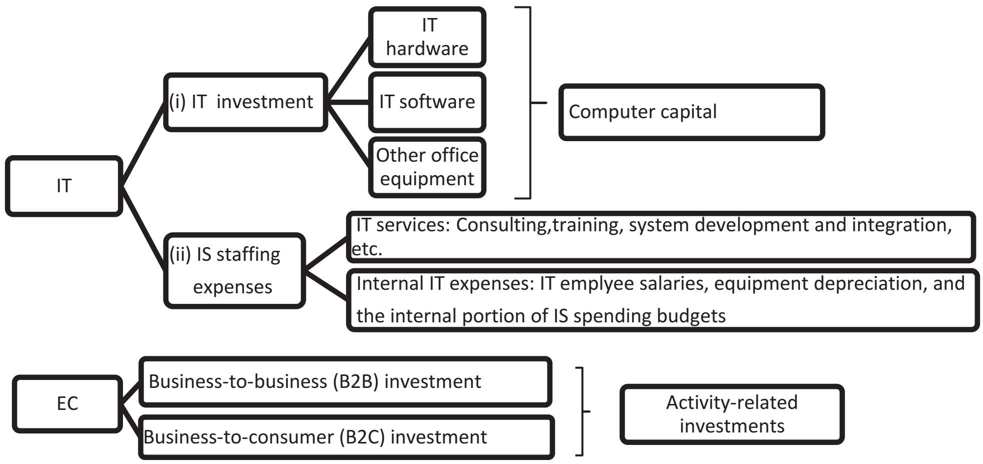

Fig. 1. Definitions of IT and EC: Components of IT and EC. *Notes*: [a]The literature has used (i) and (ii) of IT to construct IT capital based on Eq. (8). [b]The data sources have used spending and investment(s) interchangeably. [c]IT investment that emphasizes dollar amounts is a flow concept, but it also can be transformed into computer capital (IT hardware and software and other office equipment) which emphasizes physical units and is a stock concept. This is possibly a main source of confusion between the concepts of flow and stock.

(substitutability), and vice versa. We, therefore, argue that the joint presence of IT and EC may lead to both the complementarity and substitutability relationships between IT and EC in the value-generating process and that the values of IT and EC must be assessed jointly rather than independently.

Here, precisely defined, the substitutability (complementarity) phenomenon means that a reduction (an enhancement) of IT value arises when IT investment produces smaller (greater) gains in the presence of EC than by itself, and vice versa. Thus, IT and EC, when invested simultaneously, may interact with each other, to reduce or enhance their business values and, consequently, assessing them separately may lead to over-estimating or under-estimating the values of IT and EC. Moreover, the substitutability and complementarity relationships between IT and EC may provide an explanation on the existence and disappearance of the productivity paradox. Virtually all previous research has neglected the potential of the substitutability and complementarity relationships between IT and EC in evaluating their business values when IT and EC are present jointly.

On the basis of the theory of production (Bakos & Kemerer, 1992; Beattie & Taylor, 1985; Chen & Lin, 2009), the present study proposes to assess the business values of EC and IT independently and jointly, with evidence from country-level data. Our methodology of research is the traditional one-equation and generalized two-equation time-varying stochastic production frontier (SPF) approaches derived from the theory of production; and the performance measure is the so-called productive (technical) efficiency that is built in the time-varying SPF approaches. The method of research allows us to analyze our empirical results not only *collectively* based simply on the signs and statistical significance of the coefficient estimates, but also *individually* by undertaking a highly comprehensive comparison of individual firms or countries (as used in this study). Furthermore, the SPF methodology suggests that there are two sources of productive (technical) (in)efficiency, implying that there are two ways to treat IT capital in the value-creating or production process in two cases: IT capital is treated as an observed (actual) output-influencing variable along with EC (Case 1) and is treated as a production factor along with ordinary capital and ordinary labor impacting the maximum (desired) output (Case 2) (see Section 3.4 for more details).

Especially, there are no country-level studies on IT and EC values that have ever applied the generalized (or two-equation) time-varying SPF incorporating the Box–Tidwell (BT) transformation (Box and Tidwell, 1962) as used in this research. Employing the SPF specified by BT, fitted into a panel data set, we are able to claim that when EC and IT are present simultaneously, they do not necessarily become more powerful in creating greater value than by themselves alone, hence, the notions of substitutability and complementarity.

According to Lin (2009) and Melville, Kraemer, and Gurbarani (2004), there have been too much emphasis on the U.S. firms and lack of cross-country research on the values of IT and EC and, consequently, knowledge accumulation concerning IT value at the country level has been inhibited and poor. Thus, there are prominent reasons (Lin, 2009; Prasad & Babbar, 2000; Rosenzweig, 1994) for the need to undertake a country-level study such as this research.

The study would provide the clues or answers to such open questions as: (i) As IT and EC are present jointly, does the presence of IT weaken (strengthen) EC value larger than what the presence of EC does to IT value? (ii) Based on the theory of production and the SPF approaches derived from the theory, is the classical regression analysis approach or the nonparametric DEA (e.g., Shao & Lin, 2002) used in previous research appropriate? (iii) Realizing the need to differentiate the collective analytical method from the individual analytical method, are the conclusions drawn based only on the former method convincing or misleading (Lin, 2009)? (iv) Is it true that the productivity paradox is absent from the group of (advanced and newly) developed countries but remains in the group of developing countries (Dewan & Kraemer, 2000)? (v) Does IT contribute to technical efficiency more than EC when IT and EC appear separately or jointly?

The remainder of this paper is divided into six sections as follows. Section 2 is devoted to a literature review. Section 3 describes the production theory, the one-equation and generalized (two-equation) time-varying SPF approaches, the six research models, the performance metrics derived from the theory, seven research hypotheses, and the method of estimation, where, the two-step nonlinear maximum-likelihood (2SNML) method of estimation is explained. Section 4 defines the variables involved, describes the country-level panel data used, and reports the empirical results obtained, followed by Section 5 in which the likelihood ratio (LR), specification error, and nonparametric Wilcoxon signed-ranks tests are conducted; the empirical results are analyzed in great details; major findings are summarized; and the decision-making components are identified. Finally, Section 6 concludes with some remarks and proposals for future research.

2. Literature review

The studies on IT and EC in the literature may be classified into two groups. One group focuses on usage (adoption) of IT and EC, and was less concerned with their performance assessment. The other group has paid attention to the issue of the assessment of IT and EC values. The studies focusing on IT and EC usage include: EC in supply chain dynamics (Disney, Naim, & Potter, 2004); in operations management (Gunasekaran et al., 2002); in supply chain management (Swaminathan & Tayur, 2003); EC adoption in U.S. small and medium enterprises (Grandon & Pearson, 2004); technology adoption under uncertainty (Ulu & Smith, 2009); and the like.

The group of the studies placing emphasis on the issue of assessment is composed of EC or IT impacts and validation (Cao & Dowlatshahi, 2005; Disney et al., 2004; Romero & Rodriquez, 2010); EC and market value of firms (Disney et al., 2004; Li, Wu, & Lai, 2013; Ramanathan et al., 2012); IT value and its impact on the firm's product quality (Kohli & Grover, 2008; Thatcher & Oliver, 2001); IT, operational performance, and productivity (Melville, Gurbarani, & Kraemer, 2007; Melville et al., 2004); IT, output, and quality in services (Napoleon & Gaimon, 2004); IT and organizational performance (Melville et al., 2004); EC, efficiency, and profit margin (Romero & Rodriquez, 2010); activity-based justification of IT investment (Peacock & Tanniru, 2005); IT and productivity (Brynjolfsson & Hitt, 1996; Chen & Lin, 2009; Collier, Johnson, & Ruggier, 2011; Dewan & Kraemer, 2000; Lee, 2006, 2010; Lin, 2009, 2013, Chap. 3; Lin & Chiang, 2011; Lin & Chuang, 2013; Lin et al., 2010; Lin & Kao, 2014; Melville et al., 2007; Thatcher & Oliver, 2001); IT value, stochastic production frontiers, and productive (technical) efficiency (Chen & Lin, 2009; Lin, 2009, 2013, Chap. 3; Lin & Chiang, 2011; Lin & Chuang, 2013; Lin & Shao, 2000; Shu & Lee, 2003); IT value, the partial adjustment valuation approaches, and performance index (ratio) (Lin et al., 2010; Lin & Kao, 2014); the complementarity relationship between IT infrastructure and EC capability (Zhu, 2004); and the complementarity and substitutability relationships between IT and national characteristics (Chen & Lin, 2009; Lin & Chiang, 2011).

The literature review reveals a research problem of vital importance to be resolved as far as the business values of IT and EC are concerned. That is, as stated earlier, the values of IT and EC must be assessed jointly or simultaneously rather than separately or independently, amid the fact that IT investment and EC activities have rapidly increased in recent years. The literature review also clearly indicates that this research is unique and we find no other research work has been devoted to the topic as this study. Thus, this study provides new insights into IT and EC investment decisions by looking into the complementary and/or substitutive interactions between these two types of spending at the country level.

The methodologies applied in previous research on the relationship between IT or EC investments and performance differs substantially (Lin & Kao, 2014): (a) a multitude of previous studies (e.g., Collier et al. (2011), Dewan and Kraemer (2000), and Kao and Hwang (2010)) have applied the traditional regression analysis; (b) some others (e.g., Bădin, Daraio, and Simar (2012), Kao (2012), and Fethi and Pasiouras (2010)) have relied on data envelopment analysis (DEA); (c) a group of authors (e.g., Lin and Shao (2000, 2006), Lin (2009), Lee (2006, 2010), and Lin and Chuang (2013)) have used the traditional (one-equation) time-varying stochastic production frontier (SPF) approach to assess IT value; (d) Chen and Lin (2009) have proposed the generalized (two-equation) time-varying SPF approach; (e) subsequently, Lin et al. (2010) and Lin and Kao (2014) have, respectively, developed the one-equation and two-equation partial adjustment valuation (PAV) approaches; (f) some authors (e.g., Tohidi, Razaryan, & Tohidnia, 2012) have applied the Malmquist (1953) index incorporating DEA); and (g), finally, still some authors have applied the Malmquist index incorporating the one-equation SPF approach (e.g., Chou et al., 2012) or the two-equation SPF method (e.g., Lin, 2013, Chap. 3). Nonetheless, all these different approaches focus exclusively on IT value, independent of EC value.

As far as the performance metrics are concerned, the metrics used to measure IT value or benefits also differ from different authors: productivity was used by Giraleas, Emrouznejad, and Thanassoulis (2012), Shao and Shu (2004), etc.; productive efficiency by Chen and Lin (2009), Collier et al. (2011), Lee (2006, 2010), Lee, Palekar, and Qualls (2011), Lin (2009), Lin and Chiang (2011), Lin and Chuang (2013), Lin and Shao (2000, 2006), etc.; operational efficiency by Kao (2012), Krüger (2012), etc.; Malmquist total factor productivity by Chou et al. (2012), Lin (2013, Chap. 3), Tohidi et al. (2012), etc.; and such like.

3. Theory, research approaches, research models, performance measures and hypotheses

The methodology used in this study is the parametric time-varying stochastic production frontier (SPF) approaches. The SPF approaches are appropriate for this research as the methodology (i) is built on the well-established theory of production; thereby it has a sound theoretical foundation; (ii) enables the development of the one-equation and two-equation research models that allow us to achieve the objective of assessing the values of IT and EC separately and jointly; (iii) provides a proper built-in measure of performance called technical (productive) efficiency; thereby there is no need to find performance metrics from outside the research models; and (iv) permits us to analyze the empirical results *collectively and individually*.

3.1. The theory of production

This research is based on the theory of production (Bakos & Kemerer, 1992; Beattie & Taylor, 1985; Chen & Lin, 2009; Lin, 2009; Lin & Shao, 2000, 2006) that is characterized by three notable elements: (i) A production process in which a production unit utilizes different resources (inputs) to produce tangible goods or intangible services called actual or observed outputs; (ii) A production frontier that defines the relationship between inputs and outputs and specifies the maximum (desired or ideal) output level realizable from a given combination of inputs, where the maximum output and the actual (observed) output are connected by a production function denoted in symbol by $Y_{jt} \le f(\boldsymbol{X}_{jt}; \boldsymbol{\beta})$, where Y_{jt} is the actual output produced by production unit j (country j in this research) at time t, $\boldsymbol{X}_{jt}$ is a vector of inputs, $\boldsymbol{\beta}$ is a vector of unknown coefficients, and $f(\boldsymbol{X}_{jt}; \boldsymbol{\beta})$ represents the maximum output which in reality must be greater than or equal to the actual output Y_{jt}; and (iii) The technical (or productive) inefficiency (u_{jt}) which is the difference between the maximum and the actual output, denoted by $u_{jt} = f(\boldsymbol{X}_{jt}; \boldsymbol{\beta}) - Y_{jt}$ or

$$Y_{jt} = f(\boldsymbol{X}_{jt}; \boldsymbol{\beta}) - u_{jt}, \quad j = 1, \dots, n \text{ and } t = 1, \dots, T \tag{1}$$

where u_{jt} is random, must be non-negative technologically and, hence, is assumed to be one-sided (or half-) normally distributed according to $|N(0, \sigma_u^2)|$ (Aigner, Lovell, & Schmidt, 1977; Jondrow, Lovell, Materov, & Schmidt, 1982; Lovell, 1993; Schmidt & Lin, 1984). Thus, the production unit either operates on the frontier (if it is technically or productively efficient, i.e., $u_{jt} = 0$) or below the frontier (if it is technically or productively inefficient, i.e., $u_{jt} > 0$).

3.2. The traditional time-varying SPF approach: one-equation models

Adding the traditional random error (v_{jt}) to the right-hand side of Eq. (1) yields the one-equation time-varying SPF approach described by (Aigner et al., 1977; Lin, 2009)

$$Y_{jt} = f(\boldsymbol{X}_{jt}; \boldsymbol{\beta}) - u_{jt} + v_{jt}, \quad j = 1, \dots, n \text{ and } t = 1, \dots, T \tag{2}$$

where the radom error is assumed to be distributed as $N(0, \sigma_v^2)$, $\boldsymbol{X}_{jt} = (K_{jt}, L_{jt})$ without IT capital and $\boldsymbol{X}_{jt} = (K_{jt}, L_{jt}, I_{jt})$ in the presence of IT capital, with $K_{jt}, L_{jt},$ and I_{jt} denoting ordinary (non-IT) capital, ordinary labor, and IT capital, respectively. Thus, the frontier approach, Eq. (2), involves a composite error $\varepsilon_{jt} = -u_{jt} + v_{jt}$.

3.3. The generalized time-varying SPF approach: two-equation models

Technical inefficiency u_{it} in the one-equation model (2) may be affected by various controllable factors. To account for this (e.g., to identify the sources of the technical inefficiency), the two-equation (generalized) time-varying SPF approach is called for (Chen & Lin, 2009); and first applied by Lin and Chuang (2013):

$$Y_{jt} = f(\boldsymbol{X}_{jt}; \boldsymbol{\beta}) - u_{jt} + v_{jt}, \tag{3}$$

$$u_{jt} = g\left(\boldsymbol{Z}_{jt}; \boldsymbol{\alpha}\right) + w_{jt}, \tag{4}$$

where u_{jt} is constituted by two components, namely, the deterministic component, $g(\boldsymbol{Z}_{jt}; \boldsymbol{\alpha})$, subject to (determined by) the influence of $\boldsymbol{Z}_{jt}$ and the one-sided (half-) normally distributed random component, w_{jt}, where $\boldsymbol{Z}_{jt}$ is a vector which represents a broad set of country-specific characteristics and macroeconomic factors common to all countries considered, observable and/or unobservable, that cause and explain the differences in technical (in)efficiency across countries. In applied research, the vector may include the time variable (t) to serve as the proxy of general economic conditions or technological progress, national characteristics, industry concentration and dynamism (Melville et al., 2007), firm-level determinants (e.g., return on assets), and the like.

Like $\boldsymbol{\beta}$, $\boldsymbol{\alpha}$ is a vector of unknown coefficients. The two-equation framework constituted by Eqs. (3) and (4) is referred to as the generalized time-varying SPF approach with a stochastic and dynamic inefficiency and represents a significant departure from the traditional one-equation time-varying SPF approach (Eq. (2)).

3.4. Two sources of technical (in)efficiency: Case 1 and Case 2

Eq. (1) or, equivalently, $u_{jt} = f(\cdot) - Y_{jt}$, indicates that there are only two ways to change u_{jt}. One way is technological, determined by $f(\cdot)$ which in turn is determined by its functional form and the inputs entering $f(\cdot)$. This means that the determinants of u_{it} in the technological aspect are the functional form (e.g., BT) and inputs substitution and complement among the production factors entering $f(\cdot)$. The other way to shift u_{jt} is to identify the factors that influence observed output Y_{jt}. These may include EC (to be considered in this research) and performance variables such as return on assets and cost of goods sold, national characteristics, and firm or industry characteristics as identified in Chen and Lin (2009), Lin and Chiang (2011), Melville et al. (2007), Zhu (2004). The relation, $u_{jt} = f(\cdot) - Y_{jt}$, also implies that an increase (a decrease) in Y_{jt} means to reduce (increase) u_{jt}.

These two ways represent two major sources of technical (in)efficiency. On the technological side, the functional form of $f(\cdot)$ must be specified. To this end, we use the Box–Tidwell (BT) transformation (Box & Tidwell, 1962, see Appendix A) which includes the Cobb–Douglas (CD) production function and the Box–Cox (BC) transformation (Box & Cox, 1964) as special cases and, therefore, BT is more generalized than CD and BC. The production inputs to enter $f(\cdot)$ are ordinary (non-IT) capital (K_{jt}), ordinary labor (L_{jt}), and IT capital (I_{jt}).

On the output side lies the factors that can change the observed (actual) output Y_{jt}; and EC (denoted by E_{jt} for country j at time t) is considered as one national characteristic that plays such an important role on this side. I_{jt} is another characteristic that plays the same role as E_{jt}. Therefore, the two major sources of technical (in)efficiency imply that there are two ways to treat I_{jt} in the value-creating or production process. First, I_{jt} is used as an observed (actual) output-affecting variable along with E_{jt} (Case 1). Then, in Case 1, the two-equation-two-factor model is called for and both I_{jt} and E_{jt} enter the second equation rather than the first equation in the two-equation-two-factor model, with $\boldsymbol{X}_{jt} = (K_{jt}, L_{jt})$ and $\boldsymbol{Z}_{jt} = (I_{jt}, E_{jt})$. Second, I_{jt} is employed as an input along with K_{jt} and L_{jt} impacting the maximum (desired) output; that is, as a desired output-influencing factor (Case 2). Then, in Case 2, the two-equation-three-factor model is needed, and I_{jt} enters the first equation rather than the second equation in the two-equation-three-factor model, with $\boldsymbol{X}_{jt} = (K_{jt}, L_{jt}, I_{jt})$ and $\boldsymbol{Z}_{it} = (E_{jt})$. Accordingly, as stated above, the generalized (two-equation) time-varying SPF (consisting of Eqs. (3) and (4)) differs significantly from the traditional (one-equation) SPF approach (Eq. (2)).

Distinguishing between Cases 1 and 2 and between the one- and two-equation approaches are based on the differing characteristics of I_{jt} and E_{jt} and theoretical foundations. Moreover, the modeling strategies of Cases 1 and 2 and the one- and two-equation settings are theoretically sound and practically useful. This is because they serve as methodological instruments to assess the business values of EC and IT separately and jointly, and because they provide the avenues to achieve the purpose of comparing the differences in the values of EC and IT resulting from assessing EC and IT independently and simultaneously. Furthermore, the identification of Cases 1 and 2 is justified by the same theory, the research approaches, and the research models. It has an important managerial implication for IT-investment decision making, that is, it provides an alternative choice of IT investment: investing IT in the way directed by Case 1 (i.e., IT investment made to change the inefficiency) or investing IT in the direction dictated by Case 2 (i.e., IT investment made to change the desired output via the production process), using the performance as measured by productive efficiency. More importantly, the validity of the identification of Cases 1 and 2 is further supported by (i) the tests of our research hypotheses (Section 3.9 and Table 8); (ii) the likelihood ratio (LR) test (Section 5.1 and Table 6); (iii) the specification error tests (Section 5.2); and (iv) the Wilcoxon signed-ranks test (Section 5.3 and Table 7).

3.5. Two one-equation research models

Eq. (2) implies two one-equation research models designated as Model 1 and Model 2:

Model 1 (base of Cases 1 and 2): The one-equation-two-factor model without IT and EC given by

$$Y_{jt} = f\left(K_{jt}, L_{jt}; \boldsymbol{\beta}\right) - u_{jt} + v_{jt}, j = 1, \ldots, n \text{ and } t = 1, \ldots, T$$

This is the traditional one-equation-two-factor model of the parametric time-varying SPF approach (Aigner et al., 1977; Lee & Schmidt, 1993; Lin, 2009; Lin & Shao, 2000, 2006) in which IT capital has been ignored.

Model 2 (base of Case 2): The one-equation-three-factor model with IT but without EC

$$Y_{jt} = f\left(K_{jt}, L_{jt}, I_{jt}; \boldsymbol{\beta}\right) - u_{jt} + v_{jt}, j = 1, \ldots, n;\ t = 1, \ldots, T$$

3.6. Four two-equation research models

The discussions presented in the preceding Sections 3.3 and 3.4 lead to four two-equation research models given by:

Model 3: The two-equation-two-factor model with I_{jt} appearing in the second equation (Case 1)

$$Y_{jt} = f(K_{jt}, L_{jt}; \boldsymbol{\beta}) + v_{jt} - u_{jt}$$

$$u_{jt} = g(I_{jt}; \boldsymbol{\alpha}) + w_{jt}, \quad j = 1, \ldots, n;\ t = 1, \ldots, T$$

Model 4: The two-equation-two-factor model with E_{jt} entering the second equation (Case 1)

$$Y_{jt} = f(K_{jt}, L_{jt}; \boldsymbol{\beta}) + v_{jt} - u_{jt}$$

$$u_{jt} = g(E_{jt}; \boldsymbol{\alpha}) + w_{jt}$$

Model 5: The two-equation-two-factor model with I_{jt} and E_{jt} appearing in the second equation (Case 1)

$$Y_{jt} = f(K_{jt}, L_{jt}; \boldsymbol{\beta}) + v_{jt} - u_{jt}$$

$$u_{jt} = g(E_{jt}, I_{jt}; \boldsymbol{\alpha}) + w_{jt}$$

Model 6:The two-equation-three-factor model with E_{jt} appearing in the second equation (Case 2)

$$Y_{jt} = f(K_{jt}, L_{jt}, I_{jt}; \boldsymbol{\beta}) + v_{jt} - u_{jt}$$

$$u_{jt} = g(E_{jt}; \boldsymbol{\alpha}) + w_{jt}, \quad j = 1, \ldots, n; \ t = 1, \ldots, m.$$

3.7. Technical (in)efficiency and the average technical efficiency of the country

Based on Eq. (2) or Eqs. (3) and (4), we can transform technical (productive) inefficiency (u_{jt}) into technical (productive) efficiency (TE_{jt}) (Aigner et al., 1977; Chen & Lin, 2009; Jondrow et al., 1982; Lin, 2009; Lin & Shao, 2000; Lovell, 1993) given by

$$\mathrm{TE}_{jt} = e^{-u_{jt}} = \exp\,(-u_{jt}) \tag{5}$$

for country j at time t. The u_{jt} lies in the interval $[0, \infty]$ and the $\mathrm{TE}_{jt} \in [0, 1]$, implying that u_{jt} and TE_{jt} have one-to-one correspondence. Thus, there are two limiting cases: when u_{jt} tends to 0 (no inefficiency), TE_{jt} tends to 1 (the maximum efficiency); and as u_{jt} tends to infinite (the highest inefficiency), TE_{jt} tends to zero (no efficiency). In principle, the smaller (larger) u_{jt} is, the higher (smaller) TE_{jt} will be. As suggested by Aigner et al. (1977), Jondrow et al. (1982), Lin (2009), Lin and Shao (2000), and Lovell (1993), TE_{jt} is an appropriate measure of the business values of IT and EC. One important theoretical reason is that since the SPF approach is the companion of the theory of production and the TE_{jt} metric is the companion of the SPF approach, there is no need to search for other performance measures, such as business profitability and consumer surplus (Hitt & Brynjolfsson, 1996); inventory turnover, return on assets and cost of goods sold (Zhu, 2004); etc., all from outside the research methods used. In addition, there are prominent practical reasons (Lin & Shao, 2000) for TE_{jt}: (i) it is a built-in metric, (ii) it is more useful than previously used measures from the organization's perspective, and (iii) it belongs to the domain of economic analysis and, therefore, is closely related to, but different from, productivity and effectiveness.

In order to compare and rank the performance of IT and EC for individual countries under study, we can use the average technical efficiency of country j (ATE_j) defined as

$$\mathrm{ATE}_j = \sum_t \mathrm{TE}_{jt}/T, \quad j = 1, \ldots, n \tag{6}$$

Finally, the overall performance can be measured by the overall technical efficiency (ATE) given by

$$\mathrm{ATE} = \sum_j \sum_t \mathrm{TE}_{jt}/nT. \tag{7}$$

3.8. Specifications of the production function f(•)

The maximum (ideal) output represented by the production function $f(\bullet)$ in the SPF models is specified by BT (see Appendix A). Different values of transformation parameters λ and θ mean different functional specifications of the desired output. Mathematically and conceptually, as λ^* tends to be equal to θ^*, BT collapses to BC, i.e., BC becomes a special case of BT; and as λ^* and θ^* tend to zero, the limit of BT is CD. Thus, the deployment of BT that includes BC and CD as special cases can be justified conceptually and mathematically. In other words, if $\lambda^* \neq \theta^*$, BC is not valid; and if both λ^* and θ^* do not tend to zero, CD is not valid. Because these mathematical conditions are not empirically confirmed by the data (see Tables 2 and 3 for the values of λ^* and θ^*), it suffices to work with BT rather than others.

Empirically, the choice of BT is also verified by our specification error tests including the Wald (Coelli, 1995; Lin, 2009), Lagrangian multiplier (LM) (Lee, 1983; Lin, 2009; Schmidt & Lin, 1984), LR (Coelli, 1995; Lin, 2009), and Hausman and Wu tests (Greene, 2012; Hausman, 1978; Wu, 1973), as presented in Section 5.2. The tests show that BT, including CD and BC as special cases, is the best choice.

3.9. Research hypotheses

Our methodology of research (the one-equation and two equation time-varying SPF approaches) and the two sources of technical (in)efficiency implied by the research methodology enable us to test seven relevant hypotheses.

Because of the controversies (Brynjolfsson & Hitt, 1996; Chen & Lin, 2009; Chou et al., 2012; Dewan & Kraemer, 2000; Hitt & Brynjolfsson, 1996; Lin, 2009, 2013, Chap. 3; Lin & Chiang, 2011; Lin & Chuang, 2013; Lin et al., 2010; Lin & Kao, 2014; Lin & Shao, 2000) surrounding the so-called productivity paradox (PP), [4] we would like to test two hypotheses, H1 and H2, when IT and EC are assessed separately (independently). The theory underlying H1 and H2 is the theory of production. Consider Case 2 in H1 first. The theory requires that the marginal output of an input is positive, meaning $\partial f(\cdot)/\partial I_{jt} > 0$ which also means that the theory requires that the sign of the coefficient of I_{jt} [5] be positive. Then, it follows from the one-equation-three-factor model (Model 2) or from the first-equation of three factors in the two-equation model (Model 6) that an increase in I_{jt} is expected to increase the desired output $f(\cdot)$ and, as a result, the inefficiency, $u_{jt} = f(\cdot) - Y_{jt}$, would decrease or, equivalently, $-u_{jt} = -f(\cdot) + Y_{jt}$ would increase, holding the actual output Y_{jt} unchanged. Thus, mathematically and normally, it follows from Eq. (5) that an increase in $-u_{jt}$ implies that $\mathrm{TE}_{jt} = e^{-u_{jt}}$ would increase. Therefore, the theory of production applied to the one-equation-three-factor model (Model 2) and the first equation of three factors in the two-equation model (Model 6) leads to Case 2 in H1. Now, consider Case 1 in H1, referring to Models 3 and 5. The theory requires that $\partial u/\partial I_{jt} = \partial g/\partial I_{jt} > 0$ or $\partial(-u)/\partial I_{jt} = \partial(-g)/\partial I_{jt} < 0$, where g is defined in Eq. (4). Then, it follows that an increase in I_{jt} is expected to increase the actual output Y_{jt} and, consequently, $-u_{jt} = -f(\cdot) + Y_{jt}$ would increase, holding the desired output $f(\cdot)$ constant. Again, transforming this into TE_{jt} using Eq. (5) suggests that $\mathrm{TE}_{jt} = e^{-u_{jt}}$ would increase and, therefore, the same theory leads to Case 1 in H1. By the same inference, the theory applied to Models 4 and 6 for Case 2 in H2 and to Models 4 and 5 for Case 1 in H2 also leads to H2. Thus, we can hypothesize H1 and H2 as follows:

H1. IT has a positive impact on technical efficiency, regardless of if it is treated as an observed output-influencing factor (Case 1) or as a production factor, i.e., an ideal output-influencing factor (Case 2).

H2. EC has a positive impact on technical efficiency in Cases 1 and 2 as well.

Second, the above empirical discussions and theoretical justifications can also be applied to the situation in which EC and IT are evaluated jointly to determine whether or not the impact of IT on actual output is greater than that of EC, as measured by technical efficiency. In other words, the third hypothesis that explores and compares the performance of IT and EC as measured by technical efficiency follows

[4] The PP is a phenomenon that was coined in the late 1980s to describe the issue of the apparent lack of "productivity" improvements that are expected to occur as a result of IT investment at the firm level and the country level as well (Brynjolfsson & Hitt, 1996; Lin & Shao, 2006).

[5] Refer to Table 1 for the symbols of the variables concerned.

immediately from the same empirical and theoretical grounds for H1 and H2:

H3. The impact of IT on technical efficiency is greater than that of EC, when both IT and EC are assessed jointly and are treated as observed (actual) output-affecting factors (Case 1). (This hypothesis is not applicable to Case 2).

Third, since in Zhu (2004), the complementarity (instead of substitutability) phenomenon is confirmed uniformly across different regression equations, using a set of firm-level cross-sectional data of one single industry, it is instructive to show whether such firm evidence is still attainable in "an international generalization" pursued by this study using different methodology and performance measure, and using country-level panel data. In fact, both the complementarity and substitutability phenomena are observed across six different national characteristics when the CES (constant elasticity of substitution) frontier (Chen & Lin, 2009; Lin & Chuang, 2013) is deployed. Thus, we are concerned with the justification of the substitutability phenomenon, in addition to the complementarity phenomenon confirmed empirically by Zhu (2004).

One important justification for substitutability (complementarity) to take place is that IT investment and EC investments in a decision-making unit (the firm at both the macroeconomic and microeconomic levels, with the country being just the observed statistical unit at the macroeconomic level) shift disproportionally (proportionally) or in opposite (same) directions. There are other good reasons for substitutability (complementarity). These include (i) overinvestment in IT but underinvestment in EC, underinvestment in IT but overinvestment in EC, (ii) lack (follow-up) of organizational changes accompanying the IT investment (Brynjolfsson & Hitt, 1996; Hitt & Brynjolfsson, 1996) and EC investments, and (iii) mismanagement (prudent management) of IT investment and EC investments in the joint presence of IT and EC. Thus, either the complementarity or the substitutability phenomenon could take place in the decision-making unit engaging in IT investment and EC activities. These justifications lead to the fourth and fifth hypotheses:

H4. The complementarity phenomenon prevails (i.e., the substitutability phenomenon is rejected) when both IT and EC are treated as actual (observed) output-influencing factors (Case 1).

H5. The joint presence of EC and IT creates the complementarity phenomenon (i.e., rejecting the substitutability phenomenon) when IT is considered as a production input, i.e., an expected (ideal) output-impacting factor (Case 2).

Fourth, it has been theorized that the value of IT increases with advancement of the country's economic growth (or as the degree of industrialization is higher) (Jorgenson, 2003; Solow, 1987). Thus, one important question to ask is: Do the advanced developed or industrialized countries (the so-called G7) perform better than other groups of countries in terms of the values of IT and EC measured by technical efficiencies? The theory leads to the following hypothesis aiming at testing the theory and answering the question:

H6. Collectively, the group of G7 countries outperforms the other groups (newly developed and developing) considered in our sample regardless of whether IT is treated as an input (Case 2) or not (Case 1).

Fifth, explanations of the well-known "productivity paradox" associated with IT have been a central issue in the arena of IT investment. At the country level, Dewan and Kraemer (2000) have hypothesized that the productivity paradox exists only in developing economies but it is absent in developed countries. In contrast, some country-level studies (Chen & Lin, 2009; Lin, 2009; Lin & Chiang, 2011; Lin et al., 2010; Lin & Kao, 2014) have provided strong evidence suggesting that the paradox may exist in a nation no matter if it is developed or developing. The conclusion of Dewan and Kraemer (2000), based on the results obtained from their regression models fitted into subsample (group) data, was obviously drawn from the collective, rather than individual, analytical method. Nevertheless, the contradictory conclusions offer justifications of testing one final hypothesis, H7.

H7 could be attributed to more theoretical reasoning than the above justifications all based on prior empirical work. First, the hypothesis may be attributed to the impacts of various macroeconomic variables from different sectors of an economy, including the unexpected shocks of foreign exchange and interest rates from the financial sector, the country stock return index from the real sector, and the balances of trade from the external sector. Second, different countries face differing economic conditions and exercise distinct economic policies (e.g., IT and EC investments, fiscal and monetary). Third (final), one important explanation for H7 is possibly that some countries have more efficiently used their IT capital in the production process, while other countries have less efficiently used it. Nonetheless, the driving forces may be political, social, economic, and cultural reasons and H7 is relevant to a highly heterogeneous context of countries in the sample. As further suggested by these country differences that may cause the productivity paradox to remain in individual countries, we would like to test H7 described by

H7. The productivity paradox may exist in a country regardless of whether it is an advanced developed, a newly developed, or a developing country.

3.10. Method of estimation

All six research models were estimated by the two-step nonlinear maximum-likelihood (2SNML) procedure provided by the LIMDEP statistical software. The task of estimation is carried out in two steps (Greene, 2012; Jondrow et al., 1982; Lin, 2009; Lin & Shao, 2000). In *Step 1*, the ordinary least squares (OLS) estimates are obtained and then these estimates serve as the initial values of the 2SNML estimation in *Step 2*. However, if the OLS residuals are negatively skewed, referred to as wrong skewness, then the estimation process is called off and no estimates are obtainable because, under this situation, Waldman (1982) has been able to prove that the 2SNML estimates are simply the OLS estimates. Otherwise, the residuals are calculated by the formula, $E[\, u_{jt} | (v_{jt} - u_{jt})]$ according to Jondrow et al. (1982). The 2SNML method is a panel-data procedure.

4. Variables, data and results

4.1. Variables, countries, and data sources

The variables and data sources needed for our SPF models are summarized and explained in Table 1. In particular, IT capital (I_{jt}) is constructed as IT stock equal to

$$I_{jt} = \text{Computer capital plus } 3 \times \text{IS staffing expenses} \tag{8}$$

(Brynjolfsson & Hitt, 1996; Hitt & Brynjolfsson, 1996; Lin, 2009; Lin & Shao, 2000), where 3 is usually called the multiplier applied to each and every year of the time period to construct the I_{jt} series. The multiplier of three used to calculate I_{jt} is the assumed service life of the asset created by IS labor and is commonly used in the literature. The multiplier does not affect the sample size at all. We have conducted sensitivity analyses by allowing the multiplier to shift from 1 to 7 and reached the same conclusion. The dependent variable Y_{it} is represented by the value-added created by the input factors and, therefore, it is measured by the gross domestic product (GDP) of the country.

The country-level data on IT and EC were collected over the time period from 1999 to 2003 for 18 countries. The only source of the country-level data of IT and EC is *Digital Planet–The Global Information Economy*, published by the World Information Technology and

Table 1
Variables, definitions, and data sources.

Variable	Definition	Data source
Capital	Ordinary or non-IT capital + IT stock	(i) The Yearbook of a country
Labor	Ordinary or non-IT labor + IS staffing expenses, measured by the cost of employee	(ii) The United Nations Common Database
IT investment	IT hardware + IT software + other office equipment (Fig. 1)	(iii) The Statistical Department of a country
IS (information system) staffing expenses	The expenses of IT services + Internal IT expenses (Fig. 1)	(iv) The OECD Database
K_{jt} = ordinary or non-IT capital	Capital – IT stock	(v) Digital Planet 2002 – The Global Information Technology, published by the WITSA
L_{jt} = ordinary or non-IT labor	Labor – IS staffing expenses	(vi) Digital Planet 2004 – The Global Information Technology, published by the WITSA
I_{jt} = IT capital (stock)	Obtained by applying Eq. (8)	
E_{jt} = electronic commerce investments	B2B investment + B2C investment (Fig. 1)	
Y_{jt}	Gross domestic product (GDP)	

Notes: [a]Unites: US 2000 $M. [b]The WITSA stands for the World Information Technology and Services Alliance. The WITSA has used the data provided by the International Data Corporation.

Table 2
Estimated results of the stochastic production frontier models: Case 1 (collective analysis).

Model	Coefficient estimate of					ATE	R^2	λ^*	θ^*	LLF
	Constant	ln K	ln L	ln I	ln E					
1	10.2510**	0.1341**	0.0808**	–	–	0.58572	0.9455	0.172	0.055	−42.30
3	5.3219**	0.0928**	0.0557**	0.7203**	–	0.67279	0.9837	0.170	0.055	−94.66
4	−20.3660$^{\Delta}$	0.2929**	0.1462**	–	2.5873**	0.65200	0.9773	0.179	0.109	−107.53
5	4.8441**	0.0928**	0.0555**	0.6346**	0.0878**	0.67745	0.9841	0.170	0.055	−90.90

Notes: [a]$**$ denotes significant at the 1 percent level, $*$ at the 5 percent level, and Δ at the 10 percent level. [b]LLF stands for the value of the log likelihood function from the 2SNML method of estimation. [c]λ^* and θ^* are the optimal transformation parameters associated with BT (Appendix A).

Table 3
Estimated results of the stochastic production frontier models: Case 2 (collective analysis).

Model	Coefficient estimate of					ATE	R^2	λ^*	θ^*	LLF
	Constant	ln K	ln L	ln I	ln E					
1	10.251**	0.1341**	0.0808**	–	–	0.58572	0.9455	0.172	0.055	−42.301
2	6.9001**	0.2925**	0.1882**	0.2461**	–	0.50671	0.9874	0.150	0.110	−48.024
6	4.3559**	0.2929**	0.1846**	0.2105**	0.2300**	0.51843	0.9882	0.150	0.110	−96.447

Service Alliance. Though the data on IT are available for virtually all the countries in the globe, the data availability for EC was limited to the period from1999 to 2003 only. With the 18 countries selected in the sample, we were able to collect a panel data set of 90 observations which almost doubles the minimum requirement of 50 observations (Box, Jenkins, & Reinsel, 1994). It is fairly large in view of the fact that in the international context, data are difficult to come by. Especially, EC data at the international level are much more limited than IT data. As such, the data set is precious, enabling the investigation of this original and unique research of critical importance.

The 18 chosen countries are: Canada (CN), France (FR), Germany (GM), Italy (IL), Japan (JP), the United Kingdom (UK), the United States (US), China (CH), South Korea (SK), Singapore (SG), Austria (AS), Belgium (BG), Denmark (DM), the Netherlands (NL), Norway (NW), Spain (SP), Sweden (SD), and Switzerland (SL).[6] The 18 countries were classified into G7, N10, and D1.[7] The selection of the countries follows these criteria: (i) their economic status and importance, (ii) significant investment on IT (e.g., the top 10 nations per capita IT investment in 2001 were SL, JP, US, DM, SD, NW, NL, UK, SP, and HK, with SL topping the list) as well as significant investments on EC (e.g., US is the world's biggest EC marketplace, followed by JP; and CH, TW, SK, and FR are some forefront competitors), and (iii) their per capita gross domestic product according to *the 2002 Digital Access Indices* released by International Telecommunication Union, Geneva, on November 19, 2003, (http://www.itu.int/ITU-D/ict/dai/).

The select countries are mainly leading IT-EC economies. According to *Digital Planets* (2002 and 2004), even though the leading IT-EC economies may change slightly from year to year, their collective dominance of the world IT-EC marketplace remains unchanged.

In order to account for changes in general economic conditions, exchange rates, national accounting standards, and other relevant factors, the data on various variables must be transformed into a common basis. Here, the data were transformed into U.S. dollars and the transformed data were then deflated by the U.S. consumer price index (CPI). The CPI is the most popularly used aggregate price statistic in the United States. It is perhaps the most widely known and cited measure of change in general economic conditions. Thus, all the data used were denoted in terms of "2000 U.S. million dollars."

4.2. Results

Tables 2 and 3 report estimated results for Cases 1 and 2, respectively. Included in these tables are the overall average technical efficiency (ATE), the coefficient of determination (R^2), and the two optimal transformation parameters (λ^* and θ^*) of BT. Virtually, all estimated coefficients are highly significant and bear the expected signs. R^2's are very high, ranging from 0.9455 to 0.9882. The optimal transformation parameters are positive; and neither the condition (λ^* tends to be equal to θ^*) for BC to be valid is met nor the condition (both λ^* and θ^* tend to 0) for CD to be valid is satisfied. Tables 2 and 3

[6] Australia, Hong Kong, and Taiwan were forced to drop off due to wrong skewness (w.s.) arising in the estimation process.

[7] See note a right below Table 4.

Table 4
Comparisons of the ATE_j's of individual countries: Case 1 (individual analysis).

Country	Model 1		Model 3		Model 4		Model 5	
	ATE_j	Rank	ATE_j	Rank	ATE_j	Rank	ATE_j	Rank
CN	0.78055	4	0.85420	5	0.65308	10	0.83789	5
FR	0.78297	3	0.77373	8	0.70246	1	0.82062	7
GM	0.79402	2	0.88457	2	0.70017	2	0.89421	2
IL	0.56359	12	0.80325	7	0.65210	11	0.80166	8
JP	0.39416	17	0.37909	18	0.58562	18	0.37350	18
UK	0.82182	1	0.88411	3	0.68544	3	0.88376	3
US	0.61987	7	0.55145	14	0.68186	4	0.54524	14
AVG/G7	0.67957		0.73291		0.66582		0.73670	
SK	0.56818	10	0.85698	4	0.63976	12	0.83955	4
SG	0.50366	14	0.61371	10	0.62337	15	0.58543	12
AS	0.58014	9	0.68835	9	0.65584	8	0.69376	9
BG	0.56780	11	0.60137	11	0.67369	6	0.63573	10
DM	0.43882	16	0.41489	16	0.62460	14	0.42545	16
NL	0.53276	13	0.48902	15	0.63678	13	0.50651	15
NW	0.65036	6	0.83005	6	0.67055	7	0.82647	6
SP	0.60616	8	0.93852	1	0.67693	5	0.93956	1
SD	0.67010	5	0.56455	13	0.65542	9	0.57977	13
SL	0.48322	15	0.39999	17	0.62063	16	0.41293	17
AVG/N10	0.56012		0.63974		0.64776		0.64452	
CH	0.18474	18	0.58229	12	0.59682	17	0.59206	11
AVG/D1	0.18474		0.58229		0.59682		0.59206	

Notes: [a]We have now classified the 18 countries under study into two groups according to the 5-year (1999–2003) average 2008 gross national income (GNI) per capita, calculated using the World Bank Atlas method, namely, developed countries with high income \$11,906 or more; and developing countries with middle income \$976–\$11,905. The group of developed countries with high income is further divided into two subgroups: the advanced developed or industrialized countries = G7: CN, FR, GM, IL, JP, UK, and US; and the newly developed or emerging economies = N10: SK, SG, AS, BG, DM, NL, NW, SP, SD, and SL. The group of developing countries with middle income is composed of two subgroups: the developing countries with lower-middle income (\$976–\$3,855): only CH = D1 in the sample; and the developing countries with upper-middle income (\$3856–\$11,905): none in our sample.
[b]AVG/G7 stands for the average efficiency of the group of the G7 countries, AVG/N10 for the average efficiency of the group of 10 newly developed or emerging countries in the sample, and CH is the only developing country.
[c]The group results were obtained based on the whole sample rather than the subsamples.

Table 5
Comparisons of the ATE_j's of individual countries: Case 2 (individual analysis).

Country	Model 1		Model 2		Model 6	
	ATE_j	Rank	ATE_j	Rank	ATE_j	Rank
CN	0.78055	4	0.77593	4	0.72136	5
FR	0.78297	3	0.60365	8	0.70021	6
GM	0.79402	2	0.79456	3	0.82180	2
IL	0.56359	12	0.64460	7	0.64379	8
JP	0.39416	17	0.17444	17	0.17652	18
UK	0.82182	1	0.80025	2	0.79158	3
US	0.61987	7	0.38874	11	0.43224	12
AVG/G7	0.67957		0.59745		0.61250	
SK	0.56818	10	0.70180	6	0.66353	7
SG	0.50366	14	0.47182	10	0.43242	11
AS	0.58014	9	0.50518	9	0.52305	9
BG	0.56780	11	0.37771	12	0.44103	10
DM	0.43882	16	0.18468	16	0.20219	16
NL	0.53276	13	0.23179	15	0.25422	15
NW	0.65036	6	0.75327	5	0.74988	4
SP	0.60616	8	0.88811	1	0.88516	1
SD	0.67010	5	0.36906	13	0.39372	13
SL	0.48322	15	0.16550	18	0.18027	17
AVG/N10	0.56012		0.46489		0.47255	
CH	0.18474	18	0.28964	14	0.31883	14
AVG/D1	0.18474		0.28464		0.31883	

Notes: [a]The Model 1 column in this table and the Model 1 column in Table 4 are identical.
[b]The group results are obtained based on the whole sample rather than the subsamples.

Table 6
The likelihood ratio (LR) test.

Model	The observed value of the LR test statistic	The critical value at the 5 percent level	Conclusion
1 vs. 2	11.45	3.84	H_1
1 vs. 3	104.72	7.81	H_1
1 vs. 4	130.46	7.81	H_1
1 vs. 5	97.20	9.49	H_1
1 vs. 6	108.29	9.49	H_1
2 vs. 3	93.28	9.49	H_1
2 vs. 4	119.01	9.49	H_1
2 vs. 5	85.75	11.07	H_1
2 vs. 6	96.85	7.81	H_1
5 vs. 4	33.25	3.84	H_1
5 vs. 6	11.09	5.99	H_1
6 vs. 4	22.76	3.84	H_1

Table 7
Wilcoxon signed-ranks test results (based on individual TE_{jt}'s).

Model	W^+	W^-	$W*$	$\lvert Z*\rvert$	Conclusion
Model 3 vs. Model 1	3534	561	561	5.98	H_1
Model 3 vs. Model 4	3486	609	609	5.78	H_1
Model 3 vs. Model 5	859	3236	859	4.78	H_1
Model 4 vs. Model 5	703	3392	703	5.41	H_1
Model 3 vs. Model 1	3675	420	420	6.55	H_1
Model 6 vs. Model 2	2974	1121	1121	3.73	H_1

enable us to conduct a *collective* analysis as commonly practiced in the literature.

From Tables 2 and 3, we are able to establish Tables 4 and 5 which present the average technical efficiencies (ATE_j's) of individual countries and their rankings. On the basis of Tables 4 and 5, an *individual* analysis becomes possible. As mentioned earlier, the individual countries appearing in these tables are divided into three groups, namely, G7, N10, and D1. It is repeatedly emphasized that the group results are based on the estimates obtained from the entire sample rather than the group subsamples as did in, for instance, Dewan and Kraemer (2000), and that Tables 4 and 5 enable us to engage in a comprehensive comparison of the business values of IT and EC in terms of ATE_j across individual countries and different models.

Finally, Tables 6 and 7 show conclusions of the LR test and the Wilcoxon signed-ranks test, respectively; and Table 8 offers a summary of the hypothesis test conclusions, based on our analyses and findings, for a quick and easy reference.

5. Analyses and findings

5.1. The likelihood ratio test to evaluate model parameter magnitude differences

Since the second step of the 2SNML process of estimation has supplied the maximum-likelihood values, we, therefore, can use these values to undertake LR test (Coelli, 1995; Godfrey, 1998; Greene, 2012; Johnson & Wichern, 2002; Kmenta, 1986; Lin, 2009). We are interested in testing the following hypothesis composed of the null hypothesis, H_0: model parameter magnitude differences do not exist vs. the alternative hypothesis, H_1: model parameter magnitude differences exist. In other words, we want to determine whether the differences in the parameters associated with any two models differ significantly from zero. The test statistic (Coelli, 1995; Greene, 2012; Lin, 2009) is given by

$$LR = -2\left[\log(L_0) - \log(L_1)\right] \tag{9}$$

which is usually assumed to be asymptotically distributed as a chi-square random variable with degrees of freedom (k) equal to the number of restrictions involved, where $\log(L_0)$ and $\log(L_1)$ are the log-likelihood values under H_0 and under H_1, respectively.

Table 8
A summary of the test conclusions: major findings.

Hypothesis	Case 1	Case 2
H1	Collectively, not rejected, Individually, rejected for 7 or not rejected for 11 countries	Collectively, rejected based on ATE, but not rejected based on signs, Individually, rejected for 12 or not rejected for 6 countries
H2	Collectively, not rejected, Individually, rejected for 5 or not rejected for13 countries	Collectively, not rejected, Individually, not applicable
H3	Collectively, not rejected, Individually, rejected for 9 or not rejected for 9 countries	Not applicable
H4	Collectively, not rejected, Individually, rejected for 8 or not rejected for a significant majority of 10 countries	Not applicable
H5	Not applicable	Collectively, not rejected, Individually, rejected for 7 or not rejected for a significant majority of 11 countries
H6	Not rejected	Not rejected
H7	Collectively, not applicable, Individually, not rejected	Collectively, not applicable, Individually, not rejected

Godfrey (1998) and Greene (2012) have defined log (L_0) and log (L_1) as the log-likelihood values with and without restrictions on the parameters to be estimated, respectively. Normally, log (L_0) cannot be larger than log (L_1).

The test results are presented in Table 6. One can observe from Table 6 that the conclusions for all the pairs of research models at the 5 percent level of significance are H_1, meaning that H_1 is not rejected, which in turn suggests that the model parameter magnitudes are different from model to model. The conclusion further justifies the identification of Cases 1 and 2 on which the six SPF research models are based. The parametric LR test differs from the nonparametric Wilcoxon signed-ranks test (Kvanli et al., 2000; Lin, 2009) in that the former focuses on the parameter differences associated with, while the latter on the differences in technical efficiencies calculated from, any two models. Both tests are based on the same 2SNML method.

5.2. Specification error tests on the identification assumptions of the SPF approaches

Two major assumptions underlying the SPF methods are (i) the presence of the random inefficiency variable (u_{jt}) and (ii) the normal and half-normal assumptions imposed on v_{jt} and u_{jt}, respectively. Thus, it is instructive to test if these two assumptions are met, thereby determining whether our six SPF models exist.

The first key specification error test is directed to testing for the existence (absence) of the SPF approaches, i.e., the existence of the inefficiency effect represented by u_{jt}, since the validity of the SPF approaches lie in the one-sided random error. Under the half-normal assumption, the null hypothesis is H_0: $\sigma_u^2 = 0$ against the alternative hypothesis H_1: $\sigma_u^2 > 0$ (Coelli, 1995; Schmidt & Lin, 1984) or, equivalently, H_0: $\lambda = 0$ against H_1: $\lambda > 0$ (Coelli, 1995), where $\lambda = \sigma_u/\sigma_v$. The test statistic is called the Wald statistic or $Z = \hat{\lambda}/s(\hat{\lambda}) \sim N(0, 1)$ (Coelli, 1995), where $\hat{\lambda}$ is the 2SNML estimate of λ and $s(\hat{\lambda})$ is the estimated standard error of $\hat{\lambda}$. The calculated values of the test statistic for our Models 1–6 are, respectively, 2.79, 3.58, 4.01, 4.67, 5.95, and 8.90 which are all greater than the critical values of 1.645 and 2.326 at the 5 percent and 1 percent levels, strongly suggesting that the null hypothesis of no inefficiency effect is rejected and that the presence of u_{jt} and the choice of the BT production frontier are justified statistically, i.e., confirmed by the data. Applying the LM test (Schmidt & Lin, 1984) and the LR test (Coelli, 1995), we have reached the same conclusion.

The second key specification error test must be the testing for the half-normal distribution assumption imposed on the random inefficiency error (u_{jt}). To do this, Lee (1983) has developed a LM test on the hypothesis composed of H_0: u_{jt} is half-normal distributed against H_1: u_{jt} is not. The LM test statistic is shown to follow the χ^2 distribution with three degrees of freedom under H_0. The observed values of the test statistic for our six research models are 6.40, 5.81, 5.12, 4.79, 4.09, and 3.83 which are all less than the critical values of 7.81 and 11.34 at the 5 percent and 1 percent levels of significance, again strongly suggesting that the half-normal distribution is not misspecified. The LR test proposed by Coelli (1995) has reached the same conclusion.

Moreover, the Hausman and Wu tests (Greene, 2012) were undertaken to conclude that the exogeneity of the independent variables involved is not an assumption of major concern. The SPF methodology accounts for the interlinked and confounding issues. The Granger–Sims causality test (Greene, 2012) was performed to observe that IT and EC are not confounding. In the two-equation SPF system, IT and EC are interlinked by the two equations and, therefore, they impact the country's performance through different channels: IT influences the desired output via the first equation, whereas EC impacts the actual (observed) output through the second equation.

The test conclusions combined represent a piece of empirical evidence implying that the specifications of our six research models are valid. In other words, the specification error tests have established the validity and reliability of our research models and, hence, the identification of Cases 1 and 2.

5.3. The nonparametric Wilcoxon signed-ranks test

Here, we conduct the nonparametric Wilcoxon signed-ranks test (Kvanli et al., 2000; Lin, 2009). The test can be applied to determine whether the differences in the technical efficiencies across countries and through time, relative to the individual ATE_j's shown in Tables 4 and 5, for any two different models differ significantly from zero (H_1) or not (H_0). The test conclusions are reported in Table 7. Based on the test results, we are able to conclude, with a 99 percent confidence, that the differences in the technical efficiencies for any pair of the six models are indeed significantly different from zero.

5.4. Methods of analysis

The analyses of the estimated results will be pursued, using two apparently distinct methods. One method analyzes the business values of IT and EC *collectively*, applied to Tables 2 and 3. The other method ranks and compares the contributions of IT and EC to technical efficiencies *individually*, applied to Tables 4, 5, and 8. The first method is a common practice (e.g., Brynjolfsson & Hitt, 1996; Dewan & Kraemer, 2000; Hitt & Brynjolfsson, 1996; Lee, 2006; Lin & Shao, 2000, 2006; Zhu, 2004), used to explore IT or EC value based on the signs and statistical significance of the coefficient of the IT or EC variable, the overall ATE measure, and R^2. The second method is a logical continuation of the collective method and represents a significant departure from the traditional analytical practice (Chen & Lin, 2009; Lin, 2009). It uses the ATE_j of individual country j and allows for a comparative analysis of individual countries across different models and countries.

5.5. Assessing the values of IT and EC independently and jointly: Case 1

Collectively, we can readily observe from Table 2 several interesting points that are stated as follows. First, both IT and EC have positive impacts on the output and, hence, the technical efficiency, based on the positive signs of the coefficients of the IT and EC variables.

Second, the independent or joint presence of IT and EC leads to the increase in the overall average technical efficiency (ATE). For example, when BT was employed, the ATE was 0.67279 (Model 3) and 0.6520 (Model 4) if IT and EC were present alone, respectively; and 0.67745 (Model 5) if IT and EC were present jointly, in comparison with 0.58572 (Model 1) if both IT and EC were absent from the value-creating process. A better way to compare these contributions is to transform the numerical values into percentages. For instance, the change in ATE from 0.67279 to 0.67745 means an increase of 0.69 percent [8] in ATE if IT and EC were assessed jointly instead of evaluating IT alone; similarly, the change in ATE from 0.6520 to 0.67745 implies a rise of 3.9 percent in ATE if IT and EC were assessed jointly instead of evaluating EC alone; and the change from 0.58572 to 0.67745 means an increase of 16.17 percent in ATE if both IT and EC were present (Model 5) in comparison with the situation where both IT and EC were absent (Model 1). All the evidence suggests that the first parts of H1 and H2 are not rejected and that collectively, the productivity paradox does not exist in the sample of the countries considered. As a consequence, the collective empirical country-level evidence supports the claim at the firm level that the IT paradox has disappeared since the 1990s (Brynjolfsson & Hitt, 1996; Lin & Shao, 2000, 2006; Shu & Lee, 2003). We now can also claim that the empirical evidence suggests that collectively, the EC paradox does not exist either.

Third, however, the contribution (0.67279) of IT to ATE was larger than that (0.65200) of EC, but was smaller than that (0.67745) if both IT and EC appeared jointly. Thus, both H3 and H4 are not rejected, implying that the complementarity phenomenon prevails. The explanations are possibly that IT overwhelmingly dominates EC and, therefore, IT is more powerful than EC in making a larger impact on ATE than its counterpart (EC) does (i.e., the own impact of IT on ATE is larger than the own impact of EC on ATE), and that the interaction effects of IT and EC create the complementarity phenomenon. This conclusion supports the finding of Zhu (2004) who has confirmed that collectively, at the firm level, the complementarity relationship between IT infrastructure and EC capacity in the retail industry prevails.

The SPF approaches make it possible for us to apply the individual analytical method. To do this, we now turn to Table 4 for Case 1 in which IT, like EC, is treated as one of the sources of the productive (in)efficiency impacted by changing the observed (actual) output.

Individually, a comparison of the ATE_j's from Model 3 with those from Model 1 leads to the conclusion that the first part of H1 for Case 1 is either rejected for seven countries (e.g., for FR, 0.77373 from Model 3 in the presence of IT vs. 0.78297 from Model 1 in the absence of IT) or not rejected for eleven countries (CN, GM, IL, UK, SK, SG, AS, BG, NW, SP, and CH). Similarly, upon comparing the ATE_j's from Model 4 and those from Model 1, we can conclude that the first part of H2 for Case 1 is also either rejected for five countries (e.g., CN and SD) or not rejected for thirteen countries (e.g., IL and BG). Moreover, the results reported in Table 4 also clearly indicate that H3 and H4 are either rejected or not rejected and that H7 is not rejected. We can observe from Table 4 that the ATE_j's of 0.41489 (for DM), 0.48902 (NL), 0.56455(SD), 0.39999(SL), 0.77373 (FR), 0.37909 (JP), and 0.55145 (US) with IT alone (Table 3) were smaller than their counterparts (0.43882, 0.53276, 0.67010, 0.48322, 0.78297, 0.39416, and 0.61987, respectively) without IT (Table 1), implying that the productivity paradox appears in these countries (advanced developed and newly developed), i.e., H7 is not rejected. The explanation is simply that, as mentioned before, countries such as US and JP have suffered from nearly saturated IT and EC markets and their IT investment and EC investments have shifted disproportionally (especially, overinvestment in IT); on the contrary, countries like CH (developing), SK (newly developed), etc. have enjoyed year-to-year investment gains in both IT and EC. In particular, there are the driving forces from social, economic, and cultural perspectives to explain the noticeable IT-efficiency gain of China (Lin, 2009).

To determine if H4 is rejected or not, we compare the ATE_j's from Models 5 and 3. The ATE_j's of 0.77373 (for FR), 0.88457 (GM), 0.68835 (AS), 0.60137 (BG), 0.41489 (DM), 0.48902 (NL), 0.93852 (SP), 0.56455 (SD), 0.39999 (SL), and 0.58229 (CH) with IT (from Model 3) were smaller than their counterparts (0.82062, 0.89421, 0.69376, 0.63573, 0.42545, 0.50651, 0.93956, 0.57977, 0.41293, and 0.59206, respectively) in the joint presence of IT and EC (Model 5), suggesting that the complementarity phenomenon prevails in these nations (developing, advanced developed, or newly developed), that is, H4 is not rejected for 10 countries.

In contrast, 0.85420 (for CN), 0.80325 (IL), 0.37909(JP), 0.88411 (UK), 0.55145 (US), 0.85698 (SK), 0.6137 (SG), and 0.83005 (NW), recorded higher ATE_j's when IT appeared alone than those, (0.83789, 0.80166, 0.37350, 0.88376, 0.54524, 0.83955, 0.58543, and 0.82647, respectively) when IT and EC were present jointly, indicating that the substitutability phenomenon prevails in these countries (advanced or newly developed), i.e., H4 is rejected for 8 countries.

Generally speaking, the complementarity phenomenon is inspired by the balanced growth of IT and EC, accompanied by management changes in order to properly manage IT and EC investments. Consequently, the enhanced interaction effects on technical efficiencies lead to the phenomenon of complementarity. On the contrary, the substitutability phenomenon is mainly caused by the disproportional investments in IT and EC and mismanagement that severely weaken the interaction effects on the technical efficiency.

By comparing the ATE_j's from Models 1, 3, 4, and 5 in Table 4, we further observe that for nine countries (CN, FR, GM, IL, UK, SK, AS, NW, and SP), the impact of IT is greater than EC (i.e., H3 is not rejected), while for other nine countries, the impact of IT is smaller than EC (i.e., H3 is rejected). Thus, the empirical evidence does not support conventional wisdom (Dewan & Kraemer, 2000) which claims that the productivity paradox is an unpleasant outcome in developing economies only since it has disappeared in developed countries. The evidence bears an important implication that assessing the value of IT and that of EC separately may lead to seriously understating or overstating the actual contributions of IT and EC.

Next, from Table 4, we cannot reject the second part of H6 for Case 1, meaning that the G7 countries as a group outperform the group of newly developed countries, and the developing country D1 = CH in the sample, across different models, suggesting that IT value is enhanced with advancement of industrialization. The conclusion reached for H6 is evidenced by the group averages of ATE_j as shown in Table 4: AVG/G7 vs. AVG/N10 vs. AVG/D1 = 0.73291 vs. 0.63974 vs. 0.58229 when IT stands alone (Model 3); 0.66582 vs. 0.64776 vs. 0.59682 as EC appears by itself (Model 4); and 0.73670 vs. 0.644452 vs. 0.59206 when IT and EC are present simultaneously. Thus, the evidence implies that the degrees of industrialization or the levels of economic development in G7, N10, and D1 make a significant difference in the group averages of the ATE_j's. Consequently, H6 is supported by the data.

Finally, in Model 1 with the absence of IT and EC, UK wins the first spot and CH = D1 ranks last. In Model 5 with the joint presence of IT and EC, the biggest winner is SP and the biggest loser is JP. Moreover, when IT and EC are present jointly, the winners are GM and UK in the G7 group and SP and SK in the N10 group, while the losers include JP and US in the G7 group and SL, DM, and NL in the N10 group.

[8] (0.67745 − 0.67279)/0.67279 = 0.69 percent and so on.

5.6. Assessing the values of IT and EC independently and jointly: Case 2

We now refer to Tables 3 and 5 for Case 2 where I_{jt}, like K_{jt} and L_{jt}, is employed as a production factor. The typical explanations given for the findings in Case 1 may apply to Case 2. Collectively, Table 3 indicates that both IT and EC have positive impacts upon the technical efficiency. However, the lone presence of IT and the joint appearance of IT and EC worsen the ATE (0.50671 from Model 2 and 0.51843 from Model 6 less than 0.58572 from Model 1 in their absence). Again, we can compare these contributions by transforming the numerical figures into percentages. The change in ATE from 0.58572 to 0.50671 means a decrease of 13.49 percent [9] in ATE if IT was assessed alone, compared to the situation where both IT and EC were absent; the change in ATE from 0.58572 to 0.51843 means a decrease of 11.49 percent in ATE if both IT and EC were evaluated jointly, in comparison with the situation in which both IT and EC were absent; and the change in ATE from 0.50671 to 0.51843 implies an increase of 2.31 percent in ATE if both IT and EC were assessed jointly instead of evaluating IT alone. The empirical evidence suggests that the second part of H1 for Case 2 is not rejected based on the positive signs of the coefficients of IT and EC; and it is rejected, based on the ATE. The evidence also suggests that collectively, the productivity paradox does not exist in our sample of the countries studied and that the second part of H2 is not rejected. Moreover, the contribution (0.50671) of IT alone to the ATE is smaller than its counterpart (0.51843) under the situation in which both IT and EC appear simultaneously. This empirical evidence suggests that H5 is not rejected, implying that collectively, the joint appearance of IT and EC does create the complementarity phenomenon.

Individually, the second part of H1 is either rejected for twelve countries (e.g., for SD, 0.36906 smaller than 0.67010 from Table 5) or not rejected for six countries (e.g., for SK, 0.70180 greater than 0.56818 from Table 5).

In Case 2, as in Case 1, the results presented in Table 5 indicate that H5 is either rejected or not rejected and that H7 is not rejected. To explain, we can observe from Table 5 the following points of interest. First, the ATE_j's (Model 2) of 0.47182 (for SG), 0.50518 (AS), 0.37771 (BG), 0.18468 (DM), 0.23179 (NL), 0.36906 (SD), 0.16550 (SL), 0.77593 (CN), 0.60365 (FR), 0.17444 (JP), 0.80025 (UK), and 0.38874 (US) with IT only were less than their counterparts (Model 1) (0.50366, 0.58014, 0.56780, 0.43882, 0.53276, 0.67010, 0.48322, 0.78055, 0.78297, 0.39416, 0.82182, and 0.61987, respectively) without IT, suggesting that the productivity paradox prevails in these countries (advanced and newly developed), i.e., H7 is not rejected and, again, conventional wisdom claiming that the paradox exists only in developing economies is not confirmed by the data. Instead, the conclusion here clearly suggests that the paradox may exist in a country regardless of whether it is a developing or a developed country.

Second, the ATE_j's (Model 2) of 0.28964 (for CH), 0.50518 (AS), 0.37771 (BG), 0.18468 (DM), 0.23179 (NL), 0.36906 (SD), 0.16550 (SL), 0.60365 (FR), 0.79456 (GM), 0.17444 (JP), and 0.38874 (US) with IT alone were less than their counterparts (Model 6) (0.31883, 0.52305, 0.44103, 0.20219, 0.25422, 0.39372, 0.18027, 0.70021, 0.82180, 0.17652, and 0.43224, respectively) in the joint appearance of IT and EC, indicating that the appearance of EC along with IT does enhance IT value, hence, the complementarity relationship between IT and EC, that is, H5 is not rejected for eleven (61 percent), a significant majority of countries, and is rejected for other seven (39 percent) nations, implying that assessing the value of IT and that of EC separately may lead to seriously under-estimating or over-estimating the effects of IT and EC upon the ATE_j.

Third, it is noticed from Table 5 that the AVG/G7 is greater than the AVG/N10 and the AVG/D1 uniformly across differing models, strongly suggesting that the first part of H6 is not rejected empirically. This again implies that the group of G7 countries outperforms the groups of N10 and D1.

Finally, in the absence of both IT and EC (Model 1), UK again wins the first spot and CH ranks lowest in terms of their efficiency performance. With both IT and EC being present jointly (Model 6), the three biggest winners are SP, GM, and UK; and the three biggest losers are JP, SL, and DM. Overall, in Case 2, just as in Case 1, the winners are GM and UK in the G7 group and SP and NW in the N10 group, whereas the losers are JP and US in the G7 group and SL, DM, and NL in the N10 group. To sum up, for the G7 peers, the rankings of Cases 1 and 2 in the joint presence of IT and EC are exactly identical: GM ranked highest overall in efficiency performance, followed by UK, CN, FR, IL, US, and JP. For the N10 group, the rankings of Cases 1 and 2 in the joint presence of IT and EC are also exactly the same in these countries: SP (the highest), AS, BG, SD, NL, DM, and, SL (the lowest).

5.7. A summary of the test findings

Table 8 summarizes the test conclusions for an easy and quick reference. Specifically, H1–H6 are collectively conclusive in Cases 1 and 2; H1, H2, and H4 are individually confirmed for a significant majority of countries in Case 1 (where H2 is not applicable individually in Case 2); H3 is mixed in Case 1 (where H3 and H4 are not applicable collectively and individually in Case 2); H5 is individually confirmed for a significant majority of countries in Case 2 (H5 is not applicable in Case 1); and H7 is not rejected.

One point to be emphasized is that both the complementarity and substitutability phenomena are possible consequences led by the interactions between IT and EC. Hence, the values of IT and EC must be assessed jointly rather than separately. Another point that deserves our attention is that the conclusions reached by the *collective* method of analysis differ overwhelmingly from or actually conflict with those of the *individual* analytical method.

5.8. The decision-making components

Though the present study considers the country as the level of analysis, it has some obvious decision-making components. These include, but are not limited to, the following: decision-making on (i) dividing the investments between IT and EC, two different types of investments (Fig. 1), using the assessed values of IT and EC as a criterion, (ii) whether to assess the values of IT and EC separately or jointly, (iii) choosing between the one-equation SPF approach and the two-equation SPF approach, and (iv) selecting a most appropriate production frontier, e.g., between BT if the substitution and complement relationships among K_{jt}, L_{jt}, I_{jt} are neglected (Lin, 2009, 2013, Chap. 3; Lin & Chiang, 2011; Lin et al., 2010; Lin & Kao, 2014; Lin & Shao, 2000, 2006) and CES (Chen & Lin, 2009; Lin & Chuang, 2013) if the relationships among the three inputs are a major concern. The country-level research is important (in view of the fact that the economy is increasingly globalized (Lin, 2009; Rosenzweig, 1994) but has been poorly accumulated (Lin, 2009; Melville et al., 2004).

6. Concluding remarks and proposals for future research

The IT and EC investments have increased substantially over time. Since investments in IT and EC are costly, their business values have become the management's primary concern. In the literature, however, their values have been dealt with as two independent or separate issues. This tends to neglect the possibilities of enhancing and offsetting impacts of IT and EC on their values in the value-creation process, thereby leading to seriously over- or under-estimating their values. We have considered this issue of assessing the values of IT and EC jointly rather than separately as a critically important research question.

[9] (0.50671 − 0.58572)/0.58572 = −13.49 percent and so on.

To pursue such a research problem, this paper has attempted to bridge the gap by linking EC and IT in the two-equation time-varying SPF models and assessing their values separately and jointly as well. In theory, this research is based on the theory of production. In the front of methodology, we used the time-varying SPF approaches rather than the traditional regression approach. The SPF approaches have a built-in performance measure called technical (or productive) efficiency. In the estimation front, we applied the 2SNML, rather than the classical OLS method. Empirically, we have tested seven relevant hypotheses and analyzed the 2SNML estimates in two distinct methods, *collectively and individually*. Our empirical findings add new contributions to the literature and should stimulate and induce a body of comparative studies that links IT and EC together in an effort to correctly assess their business values separately and jointly. All in all, it is emphasized that the substitutability or complementarity phenomenon may exist in a country, developing or developed. As a final remark, we would like to put emphasis on the originality of the contents proposed in the paper.

Finally, we offer four proposals of further research issues. The first proposal suggests considering investments in IT and communications technology (CT) along with EC when the EC data needed become available. The second one has to do with a firm-level study concerning the application of the SPF approaches to evaluating the performance of a country's (e.g., US) manufacturing and service firms in the presence of IT and EC, again when the EC data needed are available. In the third extension, we propose to investigate the impacts of the substitution and complement relationships among K_{jt}, L_{jt}, and I_{jt} and the firm characteristics (e.g., vertical integration and growth option) and industry characteristics (e.g., industry dynamism and concentration by deploying the CES production function. Finally, the fourth proposal concerns the application of the partial adjustment valuation (PAV) approaches to assessing the values of IT and EC separately and simultaneously; and it is interesting to compare the PAV results with their SPF counterparts.

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Appendix A. BT specification

The three-factor stochastic frontier of the BT transformation (Lin, 2009, 2013, Chap. 3; Lin & Kao, 2014; Lin & Shao, 2000, 2006) can be specified as

$$\frac{Y_{jt}^{\lambda}-1}{\lambda} = \beta_0 + \beta_1\left(\frac{K_{jt}^{\theta}-1}{\theta}\right) + \beta_2\left(\frac{L_{jt}^{\theta}-1}{\theta}\right) + \beta_3\left(\frac{I_{jt}^{\theta}-1}{\theta}\right) - u_{jt+}v_{jt}, j = 1, \ldots, n; t = 1, \ldots, T \tag{A1}$$

The transformation parameters are calculated using the maximum likelihood method. The maximum likelihood value, $L_{\max}(\lambda, \theta)$, is calculated for different values of the pair of λ and θ based on the following equation:

$$L_{\max}(\lambda, \theta) = -\left(\frac{nT}{2}\right)\ln\left(\frac{\text{SSE}}{nT}\right) + (\lambda - 1)\sum_{j,t}\ln(Y_{jt}) + (\theta - 1)\sum_{j,t}\ln(Y_{jt}), \tag{A2}$$

Then, the optimal parameters (λ^* and θ^*) that maximize (A2) are used to transform the data on both sides of Eq. (A1). (The two-factor function can be obtained by simply omitting I_{jt} from the three-factor function.)

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