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Evaluation of information technology investment: a data envelopment analysis approach

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Abstract

The increasing use of information technology (IT) has resulted in a need for evaluating the productivity impacts of IT. The contemporary IT evaluation approach has focused on return on investment and return on management. IT investment has impacts on different stages of business operations. For example, in the banking industry, IT plays a key role in effectively generating (i) funds from the customer in the forms of deposits and then (ii) profits by using deposits as investment funds. Existing approaches based upon data envelopment analysis (DEA) only measure the IT efficiency or impact on one specific stage when a multi-stage business process is present. A detailed model is needed to characterize the impact of IT on each stage of the business operation. The current paper develops a DEA non-linear programming model to evaluate the impact of IT on multiple stages along with information on how to distribute the IT-related resources so that the efficiency is maximized. It is shown that this non-linear program can be treated as a parametric linear program. It is also shown that if there is only one intermediate measure, then the non-linear DEA model becomes a linear program. Our approach is illustrated with an example taken from previous studies.

Keywords: Information technology (IT); Data envelopment analysis (DEA); Efficiency; Performance

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1. Introduction

Information technology (IT) is reshaping the basics of business and customer service, operations, product and marketing strategies, and distribution are heavily, or sometimes even entirely, dependent on IT [1]. The increasing use of IT has resulted in a need for evaluating the productivity impacts of IT. As pointed out in Motiwalla and Khan [2], the contemporary IT evaluation approach has focused on return on investment and return on management and relied on quantitative assessment of IT costs, benefits, and risk during the systems development life cycle with very few post-implementation evaluation studies [3]. There are researches using economic models to study the relationships between IT investment and organizational performance of the firm (e.g., [4–9]). The impact of IT on performance has been studied within firms, industry, and individual information systems (e.g., [10,11]). Many studies have indicated that there were a variety of problems in evaluating IT's impact on firm performance. A number of studies on the "productivity paradox" [12] have found a positive relationship between IT investment and firm performance (e.g., [8,13,14]). The research at the industry level has yielded mixed results (e.g., [15–17]).

This is partly due to the fact that many factors affect firm performance and it is difficult to establish causality between IT investments and firm-level output performance [18]. Researchers have begun to use data envelopment analysis (DEA) as an alternative approach to evaluate the IT impact on firm performance, because DEA does not need a priori assumption on the functional form characterizing the relationships between IT investment and firm performance measures [19]. For example, Banker et al. [20] use DEA to study the operational efficiency gains from IT. Shafer and Byrd [21] propose a DEA framework for measuring the efficiency of organizational investments in IT.

In an effort to better model the IT impact on firm performance, Wang et al. [22] utilize DEA to study the marginal benefits of IT with respect to a two-stage process in firm-level banking industry. Although the two-stage DEA approach is developed to include the intermediate measures as a result of IT value-added activity, an overall efficient firm cannot guarantee 100% efficiency in each stage. In this regard, Chen and Zhu [23] develop a DEA-based model that identifies the efficient firms of a two-stage production process and measures the marginal benefits of IT on productivity based upon the identified two-stage best practice frontier. Note that the network DEA by Färe and Grosskopf [24] can also be applied in this type of two-stage process settings.

Although both models in Wang et al. [22] and Chen and Zhu [23] improve upon previous DEA-based studies, they do not fully characterize the IT impact on firm performance. For example, consider the scenario in Wang et al. [22] where the first stage is viewed as an IT-related value-added activity and deposit dollars as IT-produced intermediate measure, and in the second stage, banks use the deposit dollars as a source of funds to invest in securities and to provide loans, the IT and personnel support needed in the second stage are ignored. In other words, the two models consider the IT impact on firm performance with respect to the first stage only.

To correctly address the IT impact on firm performance, the current paper develops a model where IT support is considered in both stages of the scenario studied in Wang et al. [22] and Chen and Zhu [23]. This is achieved by decomposing the inputs of IT investment and others in the first stage into the second stage. The resulting model is a non-linear DEA program which can be solved as a parametric linear program. This new model not only evaluates the IT impact on both stages, but also provides an allocation of IT investment on the two stages. The results can help IT manager's decision making with respect to an effective IT budgeting and allocation.

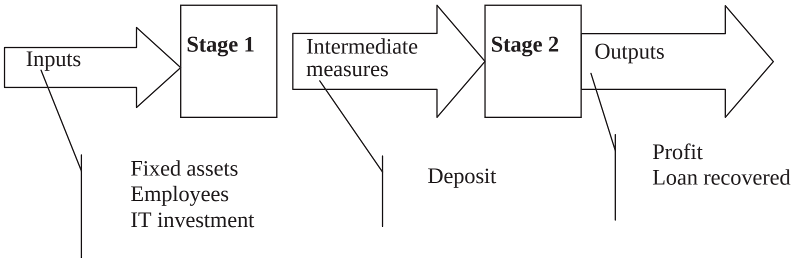


Fig. 1. Two-stage process.

The remainder of the paper is organized as follows. The next section briefly introduces DEA under the context of the scenario studied in Wang et al. [22] and Chen and Zhu [23]. The new non-linear DEA model and related efficiency measures are then developed. We show that if there is only one intermediate measure, then the non-linear DEA model is equivalent to a linear program. The new approach is then illustrated by a set of firms from the banking industry. Concluding remarks are provided in the last section.

2. Data envelopment analysis

DEA is a mathematical programming approach that evaluates the relative efficiency of peer units with respect to multiple performance measures [25,26]. In DEA, the units under evaluation (e.g., banks) are called decision making units (DMUs) and the performance measures are grouped into inputs and outputs. DEA is particularly useful when the relationships among the input and output measures are unknown.

Consider Fig. 1 where a bank's operation is viewed as a two-stage process. In the first stage, the banks use fixed assets, number of employees, and IT investment as inputs to generate deposit dollars as an IT-produced intermediate measure. In the second stage, banks use the deposit dollars as a source of funds to invest in securities and to provide loans. Profit and fraction of loans recovered are used as two outputs in the second stage. For simplicity, our modeling process is based upon the inputs and outputs in Fig. 1, although it can be generalized into cases with any multiple inputs and outputs.

The DEA inputs in this case are (i) fixed assets (denoted as F), (ii) IT budget (denoted as I), and (iii) employees (denoted as E). Also, profit (denoted as P) and fraction of loan recovered (denoted as R) are treated as DEA outputs. Suppose we have n DMUs or observations with respect to the inputs and outputs given in Fig. 1. There are two possible ways to treat the intermediate measure—loan (denoted as D) when the standard DEA model, e.g., CCR model is used.[1]

One is to treat the loan (denoted as D) as an output in the following CCR model when DMU_0 is under evaluation

$$
\begin{aligned}
\text{Max} \quad & \frac{U_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix} + U_D D_0}{V_F F_0 + V_I I_0 + V_E E_0}, \\
\text{s.t.} \quad & \frac{U_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} + U_D D_j}{V_F F_j + V_I I_j + V_E E_j} \leqslant 1, \quad j = 1, \ldots, n, \\
& V_F, V_I, V_E, U_D, U_L^T \geqslant 0,
\end{aligned} \tag{1}
$$

[1] See Wang et al. [22] for detailed discussion on these DEA measures.

where (i) V_F, V_I, and V_E represent weights on inputs of fixed assets, IT budget and employee, respectively; (ii) U_L^T is a weight vector for the two outputs of profits and fraction of loan recovered; (iii) U_D represents the weight associated with loan output.

The other is to ignore the loan in the following CCR model, i.e., the intermediate(s) is excluded in performance evaluation.

$$\begin{aligned} \text{Max} \quad & \frac{U_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}}{V_F F_0 + V_I I_0 + V_E E_0}, \\ \text{s.t.} \quad & \frac{U_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix}}{V_F F_j + V_I I_j + V_E E_j} \leqslant 1, \quad j = 1, \ldots, n. \\ & V_F, V_I, V_E, U_L^T \geqslant 0, \end{aligned} \tag{2}$$

As demonstrated in Chen and Zhu [23], both DEA models (1) and (2) do not correctly characterize the two-stage process described in Fig. 1. The IT impact is only explicitly studied for the first stage. In the current paper, we develop a new DEA-based approach that explicitly models the IT impact on both stages.

3. New model

Fig. 1 represents a simplified two-stage bank operation process. In fact, fixed assets, IT budget and employees are directly associated with each stage. Both stages need IT and personnel support. To better reflect the two-stage process, we suppose (i) fixed assets (F) is divided into two parts αF and $(1-\alpha)F\,(\alpha \leqslant 1)$, (ii) IT budget ($I$) is divided into two parts βI and $(1-\beta)I\,(\beta \leqslant 1)$ for deposit and loan stage, respectively and (iii) employees (E) are divided into two parts γE and $(1-\gamma)E$ $(\gamma \leqslant 1)$ for deposit and loan, respectively.

Note that deposits (denoted as D) is the output of the first stage and is one of the inputs for the second stage. We now have (i) αF, βI and γE as the inputs for the first stage, (ii) $(1-\alpha)F$, $(1-\beta)I$, $(1-\gamma)E$ and D as the inputs for the second stage, and (iii) P (profit) and R (fraction of loan recovered) as the outputs for second stage (see Fig. 2).

Consider the following model:

$$\begin{aligned} \text{Max} \quad & \frac{1}{2}\left[\frac{U_D D_0}{V_F \alpha F_0 + V_I \beta I_0 + V_E \gamma E_0} + \frac{U_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}}{V_F(1-\alpha)F_0 + V_I(1-\beta)I_0 + V_E(1-\gamma)E_0 + U_D D_0}\right], \\ \text{s.t.} \quad & \frac{U_D D_j}{V_F \alpha F_j + V_I \beta I_j + V_E \gamma E_j} \leqslant 1, \\ & \frac{U_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix}}{V_F(1-\alpha)F_j + V_I(1-\beta)I_j + V_E(1-\gamma)E_j + U_D D_j} \leqslant 1, \\ & 1 \geqslant \alpha, \beta, \gamma \geqslant 0, \\ & V_F, V_I, V_E, U_D, U_L^T \geqslant 0. \end{aligned} \tag{3}$$

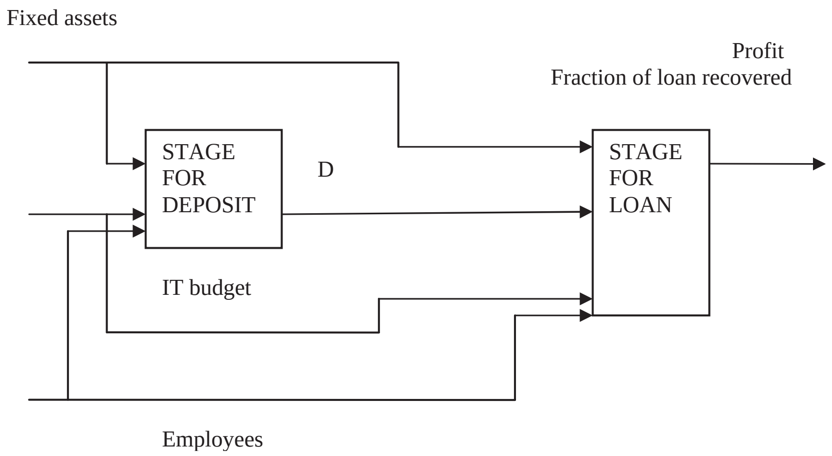


Fig. 2. Inputs and outputs.

Model (3) unifies two CCR models via maximizing the average CCR ratios of stage 1,

$$\frac{U_D D_0}{V_F \alpha F_0 + V_I \beta I_0 + V_E \gamma E_0}$$

and stage 2,

$$\frac{U_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}}{V_F(1-\alpha)F_0 + V_I(1-\beta)I_0 + V_E(1-\gamma)E_0 + U_D D_0}$$

and using a same set of input and output weights for the two stages presented in Fig. 2. We should note that one can use a preference weighting structure in the weighted Russell measure to develop the objective function (see, e.g., [19,27]).

Model (3) is a non-linear fractional program. We next convert model (3) so that it can be solved using linear programming technique. Let

$$t_D = \frac{1}{V_F \alpha F_0 + V_I \beta I_0 + V_E \gamma E_0},$$

$$\omega_{DF} = t_D V_F, \quad \omega_{DI} = t_D V_I, \quad \omega_{DE} = t_D V_E, \quad \mu_D = t_D U_D,$$

$$t_L = \frac{1}{V_F(1-\alpha)F_0 + V_I(1-\beta)I_0 + V_E(1-\gamma)E_0 + U_D D_0}, \quad \omega_{LF} = t_L V_F, \quad \omega_{LI} = t_L V_I,$$

$$\omega_{LE} = t_L V_E, \quad c_L = t_L U_D, \quad \mu_L^T = t_L U_L^T.$$

Note that

$$\frac{\omega_{LF}}{\omega_{DF}} = \frac{\omega_{LI}}{\omega_{DI}} = \frac{\omega_{LE}}{\omega_{DE}} = \frac{c_L}{\mu_D} = \frac{t_L}{t_D} = k.$$

Thus, model (3) can be transformed into model (4) as follows:

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right],\\
\text{s.t.}\quad & \omega_{DF}\alpha F_j + \omega_{DI}\beta I_j + \omega_{DE}\gamma E_j - \mu_D D_j \geqslant 0,\\
& \omega_{DF}\alpha F_0 + \omega_{DI}\beta I_0 + \omega_{DE}\gamma E_0 = 1,\\
& \omega_{DF}(1-\alpha)F_j + \omega_{DI}(1-\beta)I_j + \omega_{DE}(1-\gamma)E_j + \mu_D D_j - \frac{1}{k}\mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0,\\
& \omega_{DF}(1-\alpha)F_0 + \omega_{DI}(1-\beta)I_0 + \omega_{DE}(1-\gamma)E_0 + \mu_D D_0 = \frac{1}{k},\\
& 1 \geqslant \alpha, \beta, \gamma \geqslant 0,\\
& \omega_{DF}, \omega_{DI}, \omega_{DE}, \omega_{LF}, \omega_{LI}, \omega_{LE}, \mu_D, k, \mu_L^T \geqslant 0,
\end{aligned} \tag{4}$$

Next, let $\omega'_{DF} = \alpha\omega_{DF}$, $\omega'_{DI} = \beta\omega_{DI}$, $\omega'_{DE} = \gamma\omega_{DE}$, and note $\omega_{DF}\alpha F_0 + \omega_{DI}\beta I_0 + \omega_{DE}\gamma E_0 = 1$. We have

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right],\\
\text{s.t.}\quad & \omega'_{DF} F_j + \omega'_{DI} I_j + \omega'_{DE} E_j - \mu_D D_j \geqslant 0,\\
& \omega'_{DF} F_0 + \omega'_{DI} I_0 + \omega'_{DE} E_0 = 1,\\
& (\omega_{DF} - \omega'_{DF})F_j + (\omega_{DI} - \omega'_{DI})I_j + (\omega_{DE} - \omega'_{DE})E_j + \mu_D D_j - \frac{1}{k}\mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0,\\
& \omega_{DF} F_0 + \omega_{DI} I_0 + \omega_{DE} E_0 + \mu_D D_0 = 1 + \frac{1}{k},\\
& \omega_{DF} - \omega'_{DF} \geqslant 0,\\
& \omega_{DI} - \omega'_{DI} \geqslant 0,\\
& \omega_{DE} - \omega'_{DE} \geqslant 0,\\
& \omega_{DF}, \omega_{DI}, \omega_{DE}, \omega'_{DF}, \omega'_{DI}, \omega'_{DE}\mu_D, k, \mu_L^T \geqslant 0, \quad j = 1, 2, \ldots, n,
\end{aligned} \tag{5}$$

where

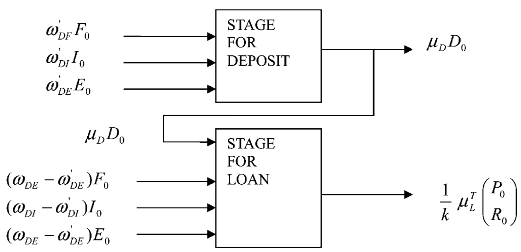
$$\alpha = \frac{\omega'_{DF}}{\omega_{DF}}, \quad \beta = \frac{\omega'_{DI}}{\omega_{DI}}, \quad \gamma = \frac{\omega'_{DE}}{\omega_{DE}}$$

or the following model (6) if let $k' = \frac{1}{k}$:

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right],\\
\text{s.t.}\quad & \omega'_{DF} F_j + \omega'_{DI} I_j + \omega'_{DE} E_j - \mu_D D_j \geqslant 0,\\
& \omega'_{DF} F_0 + \omega'_{DI} I_0 + \omega'_{DE} E_0 = 1,\\
& (\omega_{DF} - \omega'_{DF})F_j + (\omega_{DI} - \omega'_{DI})I_j + (\omega_{DE} - \omega'_{DE})E_j + \mu_D D_j - k'\mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0,\\
& \omega_{DF} F_0 + \omega_{DI} I_0 + \omega_{DE} E_0 + \mu_D D_0 - k' = 1,\\
& \omega_{DF} - \omega'_{DF} \geqslant 0,\\
& \omega_{DI} - \omega'_{DI} \geqslant 0,\\
& \omega_{DE} - \omega'_{DE} \geqslant 0,\\
& \omega_{DF}, \omega_{DI}, \omega_{DE}, \omega'_{DF}, \omega'_{DI}, \omega'_{DE}\mu_D, k', \mu_L^T \geqslant 0, \quad j = 1, 2, \ldots, n.
\end{aligned} \tag{6}$$

Models (5) or (6) is a nonlinear program. However, note that, e.g., model (6) only contains one nonlinear item $k'\mu_L^T(P_j, R_j)$. Therefore, it is not difficult to obtain the global optimal solution. In fact, note that $\omega_{DF}F_0 + \omega_{DI}I_0 + \omega_{DE}E_0 + \mu_D D_0 = 1 + 1/k = 1 + k'$. Since $\omega_{DF}F_0 + \omega_{DI}I_0 + \omega_{DE}E_0 \geqslant \omega'_{DF}F_0 + \omega'_{DI}I_0 + \omega'_{DE}E_0 = 1$, we have $\mu_D D_0 \leqslant k'$ (or $0 < k \leqslant (1/\mu_D D_0)$). Therefore, in computation, we treat k' (or k) as a parameter. As a result, models (5) or (6) can be treated as a linear program.

We next develop efficiency measures for the two stages. Based upon model (4), Fig. 2 can be modified as follows:



Deposit stage's efficiency can be characterized as $\mu_D D_0$ (note that $\omega'_{DF}F_0 + \omega'_{DI}I_0 + \omega'_{DE}E_0 = 1$), and loan stage's efficiency

$$\frac{1}{k}\mu_L^T\begin{pmatrix}P_0\\R_0\end{pmatrix}\bigg/\frac{1}{k} = \mu_L^T\begin{pmatrix}P_0\\R_0\end{pmatrix}$$

(note that $(\omega_{DF} - \omega'_{DF})F_0 + (\omega_{DI} - \omega'_{DI})I_0 + (\omega_{DE} - \omega'_{DE})E_0 + \mu_D D_0 = 1/k$). Thus, the average efficiency of the two-stage process can be defined as

$$\frac{1}{2}\left[\mu_D D_0 + \mu_L^T\begin{pmatrix}P_0\\R_0\end{pmatrix}\right].$$

Finally, we have a set of optimized

$$\alpha = \frac{\omega'_{DF}}{\omega_{DF}}, \quad \beta = \frac{\omega'_{DI}}{\omega_{DI}}, \quad \gamma = \frac{\omega'_{DE}}{\omega_{DE}}.$$

I.e., we have information on how to distribute the resources so that IT-related efficiency is maximized.

4. Special case

When there is only one intermediate measure as shown in Fig. 2, model (3) can be converted into a linear program directly. In fact, model (3) is equivalent to the following model:

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right], \\
\text{s.t.}\quad & \omega_{DF}\alpha F_j + \omega_{DI}\beta I_j + \omega_{DE}\gamma E_j - \mu_D D_j \geqslant 0, \\
& \omega_{DF}\alpha F_0 + \omega_{DI}\beta I_0 + \omega_{DE}\gamma E_0 = 1, \\
& \omega_{LF}(1-\alpha) F_j + \omega_{LI}(1-\beta) I_j + \omega_{LE}(1-\gamma) E_j + c_L D_j - \mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0, \\
& \omega_{LF}(1-\alpha) F_0 + \omega_{LI}(1-\beta) I_0 + \omega_{LE}(1-\gamma) E_0 + c_L D_0 = 1, \\
& 1 \geqslant \alpha, \beta, \gamma \geqslant 0, \\
& \omega_{DF}, \omega_{DI}, \omega_{DE}, \omega_{LF}, \omega_{LI}, \omega_{LE}, \mu_D, c_L, \mu_L^T \geqslant 0.
\end{aligned} \tag{7}$$

Let $\omega'_{DF} = \alpha\omega_{DF}$, $\omega'_{DI} = \beta\omega_{DI}$, $\omega'_{DE} = \gamma\omega_{DE}$ and $\omega'_{LF} = (1-\alpha)\omega_{LF}$, $\omega'_{LI} = (1-\beta)\omega_{LI}$, $\omega'_{LE} = (1-\gamma)\omega_{LE}$, we have

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right], \\
\text{s.t.}\quad & \omega'_{DF} F_j + \omega'_{DI} I_j + \omega'_{DE} E_j - \mu_D D_j \geqslant 0, \\
& \omega'_{DF} F_0 + \omega'_{DI} I_0 + \omega'_{DE} E_0 = 1, \\
& \omega'_{LF} F_j + \omega'_{LI} I_j + \omega'_{LE} E_j + c_L D_j - \mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0, \\
& \omega'_{LF} F_0 + \omega'_{LI} I_0 + \omega'_{LE} E_0 + c_L D_0 = 1, \\
& \omega'_{LF}, \omega'_{LI}, \omega'_{LE}, \omega'_{DF}, \omega'_{DI}, \omega'_{DE}, \mu_D, c_L, \mu_L^T \geqslant 0, \quad j = 1, 2, \ldots, n.
\end{aligned} \tag{8}$$

Model (8) is equivalent to the following model (9) which is a linear program:

$$\begin{aligned}
\text{Max}\quad & \frac{1}{2}\left[\mu_D D_0 + \mu_L^T \begin{pmatrix} P_0 \\ R_0 \end{pmatrix}\right], \\
\text{s.t.}\quad & \frac{c_L}{\mu_D}\omega'_{DF} F_j + \frac{c_L}{\mu_D}\omega'_{DI} I_j + \frac{c_L}{\mu_D}\omega'_{DE} E_j - c_L D_j \geqslant 0, \\
& \frac{c_L}{\mu_D}\omega'_{DF} F_0 + \frac{c_L}{\mu_D}\omega'_{DI} I_0 + \frac{c_L}{\mu_D}\omega'_{DE} E_0 = \frac{c_L}{\mu_D}, \\
& \omega'_{LF} F_j + \omega'_{LI} I_j + \omega'_{LE} E_j + c_L D_j - \mu_L^T \begin{pmatrix} P_j \\ R_j \end{pmatrix} \geqslant 0, \\
& \omega'_{LF} F_0 + \omega'_{LI} I_0 + \omega'_{LE} E_0 + c_L D_0 = 1, \\
& \omega'_{LF}, \omega'_{LI}, \omega'_{LE}, \omega'_{DF}, \omega'_{DI}, \omega'_{DE}, \mu_D, c_L, \mu_L^T \geqslant 0, \quad j = 1, 2, \ldots, n.
\end{aligned} \tag{9}$$

Table 1
Data

Bank	Fixed assets ($ billion)	IT budget ($ billion)	# of employees (thousand)	Deposits ($ billion)	Profit ($ billion)	Fraction of loans recovered
1	0.713	0.15	13.3	14.478	0.232	0.986
2	1.071	0.17	16.9	19.502	0.34	0.986
3	1.224	0.235	24	20.952	0.363	0.986
4	0.363	0.211	15.6	13.902	0.211	0.982
5	0.409	0.133	18.485	15.206	0.237	0.984
6	5.846	0.497	56.42	81.186	1.103	0.955
7	0.918	0.06	56.42	81.186	1.103	0.986
8	1.235	0.071	12	11.441	0.199	0.985
9	18.12	1.5	89.51	124.072	1.858	0.972
10	1.821	0.12	19.8	17.425	0.274	0.983
11	1.915	0.12	19.8	17.425	0.274	0.983
12	0.874	0.05	13.1	14.342	0.177	0.985
13	6.918	0.37	12.5	32.491	0.648	0.945
14	4.432	0.44	41.9	47.653	0.639	0.979
15	4.504	0.431	41.1	52.63	0.741	0.981
16	1.241	0.11	14.4	17.493	0.243	0.988
17	0.45	0.053	7.6	9.512	0.067	0.98
18	5.892	0.345	15.5	42.469	1.002	0.948
19	0.973	0.128	12.6	18.987	0.243	0.985
20	0.444	0.055	5.9	7.546	0.153	0.987
21	0.508	0.057	5.7	7.595	0.123	0.987
22	0.37	0.098	14.1	16.906	0.233	0.981
23	0.395	0.104	14.6	17.264	0.263	0.983
24	2.68	0.206	19.6	36.43	0.601	0.982
25	0.781	0.067	10.5	11.581	0.12	0.987
26	0.872	0.1	12.1	22.207	0.248	0.972
27	1.757	0.0106	12.7	20.67	0.253	0.988

5. Illustration

We consider the numerical example presented in Table 1 taken from Wang et al. [22]. Table 2 reports the results from our new non-linear model (6).[2] The second column reports the average efficiency for the two-stage process. The third and fourth columns report the efficiency scores for the deposit and loan stages, respectively. Table 2 also shows the values of α, β, and γ. The last column reports the value of k.

Only three firms are efficient in both stages. Our DEA results indicate that IT investment, assets and employee should be allocated to one specific stage only. This seems unreasonable and is due to the fact that the only criterion used in our new model is maximizing the average CCR ratio of the two stages. The results can be corrected by imposing some constraints on α, β, and γ so that each stage gets a fair share.

[2] Our linear model (9) yields the same results.

Table 2
New model results

Bank No.	Average efficiency	Deposit efficiency	Loan efficiency	α	β	γ	k
1	0.743	0.639	0.847	0.379	0	1	0.995
2	0.767	0.651	0.884	0.379	0	1	0.937
3	0.687	0.518	0.857	0.379	0	1	1.149
4	0.799	0.599	1	0.239	0	1	1.049
5	0.772	0.556	0.988	0.239	0	1	1.120
6	0.723	0.760	0.686	0.309	0.385	0.999	0.839
7	1	1	1	0.722	0	1	0.929
8	0.714	0.535	0.894	1	0.263	1	1.119
9	0.630	0.625	0.635	1	0	1	1.6
10	0.625	0.496	0.755	1	0.263	1	1.156
11	0.625	0.495	0.755	1	0.263	1	1.160
12	0.773	0.669	0.877	0.003	0.003	1	0.017
13	0.931	0.949	0.912	0	0	0.019	0.019
14	0.603	0.588	0.618	0.558	0	1	1.399
15	0.658	0.658	0.658	0.558	0	1	1.266
16	0.682	0.665	0.699	0.975	0.264	1	0.897
17	0.859	0.718	1	0.150	0	1	0.125
18	1	1	1	1	0	1	1
19	0.770	0.814	0.726	0.005	0	0.018	0.013
20	0.847	0.693	1	1	0	0.999	1.441
21	0.853	0.707	1	1	0	0.869	1.195
22	0.897	0.794	1	0.098	0	1	0.497
23	0.890	0.780	1	0.378	0	0.999	1.011
24	0.912	0.930	0.893	0.003	1	0.024	0.017
25	0.693	0.627	0.758	0.997	0.126	1	0.589
26	0.895	1	0.789	0.001	1	0.003	0.003
27	1	1	1	1	0.244	0.999	0.942

Finally, Table 3 presents a comparison of several DEA-based approaches. The second column reports the efficiency from the new model. The third and fourth columns report the CCR efficiency of models (1) and (2). The last column reports the results from Chen and Zhu [23].

6. Conclusions

Despite significant amount of research effort in evaluating the productivity payoffs from IT investment, it has been recognized that we need a more inclusive and comprehensive approach that considers broader economic and strategic IT impacts on productivity [8]. The current study provides a set of new tools for addressing such IT impact on productivity. The objective of this paper is to develop new models for evaluating IT impacts on firm performance when intermediate measures are present. To simplify the model presentation, we use a scenario from a previous study, although the model works under any two-stage process. We should point out that although it is assumed that inputs to the first stage are decomposed, the model can be easily modified to situations where only some of the input measures are decomposed.

Table 3
Efficiency comparison

Bank No.	Our model	CCR (1)	CCR (2)	Chen-Zhu
1	0.743	0.763	0.737	0.737
2	0.767	0.803	0.803	0.832
3	0.687	0.642	0.642	0.655
4	0.799	1	1	1
5	0.772	0.913	0.913	0.998
6	0.723	0.763	0.644	0.712
7	1	1	1	1
8	0.714	0.683	0.629	0.683
9	0.630	0.625	0.487	1
10	0.625	0.560	0.536	0.536
11	0.625	0.556	0.533	0.533
12	0.773	0.882	0.878	0.880
13	0.931	1	0.913	0.920
14	0.603	0.592	0.500	0.526
15	0.658	0.670	0.581	0.677
16	0.682	0.724	0.623	1
17	0.859	1	1	1
18	1	1	1	1
19	0.770	0.862	0.726	0.726
20	0.847	1	1	1
21	0.853	1	1	1
22	0.897	1	1	1
23	0.890	1	1	1
24	0.912	0.955	0.893	1
25	0.693	0.786	0.742	0.749
26	0.895	1	0.790	0.790
27	1	1	1	1

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References

[1] Keen PCW. Shaping the future. Boston: Harvard Business School Press; 1991.
[2] Motiwalla L, Khan MR. Financial impact of e-business initiatives in the retail industry. Journal of Electronic Commerce in Organization 2002;1(1):55–73.
[3] Kumar K. Post-implementation evaluation of computer based IS: current practices. Communications of ACM 1990;33: 203–12.
[4] Kivijärvi H, Saarinen T. Investment in information systems and the financial performance of the firm. Information & Management 1995;28:143–63.
[5] Bryd T, Marshall T. Relating information technology investment to organizational performance: a causal model analysis. Omega 1997;25:43–56.

[6] Li M, Ye R. Information technology and firm performance: linking with environmental, strategic and managerial contexts. Information & Management 1999;35:43–51.
[7] Farbey B, Land F, Targett D. Moving IS evaluation forward: learning themes and research issues. Journal of Strategic Information Systems 1999;8:189–207.
[8] Brynjolfsson E, Hitt LM. Beyond the productivity paradox. Communications of the ACM 1998;41(8):49–56.
[9] Rai A, Patnayakuni R, Patnayakuni N. Technology investment and business performance. Communications of the ACM 1997;40(7):89–97.
[10] Bakos JY, Kemerer CF. Recent applications of economic theory in information technology research. Decision Support Systems 1992;8:365–86.
[11] Kauffman RJ, Weill P. An evaluative framework for research on the performance effects of information technology investment. In: Proceedings of the 10th international conference on information systems. Boston, MA, December 1989, p. 377–88.
[12] Brynjolfsson E. The productivity paradox of information technology. Communications of the ACM 1993;36:67–77.
[13] Brynjolfsson E, Hitt LM. Paradox lost? firm-level evidence on the returns to information systems spending. Management Science 1996;42:541–58.
[14] Lichtenberg FR. The output contributions of computer equipment and personnel: a firm-level analysis. Economic Innovations and New Technology 1995;3:201–17.
[15] Berndt ER, Morrison CJ. High-tech capital formation and economic performance in US manufacturing industries: an exploratory analysis. Journal of Econometrics 1995;33:7–29.
[16] Cron W, Sobol M. The relationship between computerization and performance: a strategy for maximizing economic benefits of computerization. Information and Management 1983;6:171–81.
[17] Harris SE, Katz JL. Organizational performance and information technology investment intensity in the insurance industry. Organization Science 1991;2:263–95.
[18] Im KS, Dow KE, Grover V. Research report: a reexamination of IT investment and the market value of the firm—an event study methodology. Information Systems Research 2001;12(1):103–17.
[19] Zhu J. Quantitative models for performance evaluation and benchmarking: data envelopment analysis with spreadsheets. Boston: Kluwer Academic Publishers; 2002.
[20] Banker RD, Kauffman RJ, Morey RC. Measuring gains in operational efficiency from information technology: a study of the positran deployment at Hardee's Inc. Journal of Management Information Systems 1990;7(2):29–54.
[21] Shafer SM, Byrd TA. A framework for measuring the efficiency of organizational investments in information technology using envelopment analysis. Omega 2000;28:125–41.
[22] Wang CH, Gopal R, Zionts S. Use of data envelopment analysis in assessing information technology impact on firm performance. Annals of Operations Research 1997;73:191–213.
[23] Chen Y, Zhu J. Measuring information technology's indirect impact on firm performance. Information Technology & Management Journal 2004;5(1–2):9–22.
[24] Färe R, Grosskopf S. Network DEA. Socio-Economic Planning Sciences 2000;34:35–49.
[25] Charnes A, Cooper WW, Rhodes E. Measuring the efficiency of decision making units. European Journal of Operational Research 1978;2:429–44.
[26] Cooper WW, Seiford LM, Zhu J. Data envelopment analysis. In: Cooper WW, Seiford LM, Zhu J, editors. Handbook on data envelopment analysis, chapter 1. Boston: Kluwer Academic Publishers; 2004. p. 1–39.
[27] Ruggiero J, Bretschneider. The weighted Russell measure of technical efficiency. European Journal of Operational Research 1998;108(2):438–51.