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Application of DEA for selecting most efficient information system project with imprecise data

S. Nalchigar [a*] and S. M. Nasserzadeh [b]

[a] *University Pierre and Marie Curie BC 1694, place Jussieu 75252, Paris Cedex 05, France*;
[b] *Department of Information Technology Management, University of Tehran, Tehran, Iran*

Abstract. The selection of best Information System (IS) project from many competing proposals is a critical business activity which is very helpful to all organizations. While previous IS project selection methods are useful but have restricted application because they handle only cases with precise data. Indeed, these methods are based on precise data with less emphasis on imprecise data. This paper proposes a new integrated Data Envelopment Analysis (DEA) model which is able to identify most efficient IS project in presence of imprecise data. As an advantage, proposed model identifies most efficient IS project by solving only one Mixed Integer Linear Programming (MILP). Applicability of proposed method is indicated by using data set includes specifications of 8 competing projects in Iran Ministry of Commerce.

Keywords: Data envelopment analysis, Information system project selection, imprecise data.

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1. Introduction

Digital economy has converted Information Technology (IT) management to one of critical organizational positions. Today, IT managers have many responsibilities (data centers, staff management, telecommunication, servers, workstations, web sites, Information Systems (IS), user support, regulatory compliance, disaster recovery, etc.) and connect with almost all the departments (accounting, marketing, sales, distribution, etc.). In many organizations, they can have a direct influence on strategic direction of the company (Holtsnider & Jaffe, 2007). A critical aspect

*Corresponding author. Email: soroosh.nalchigar@etu.upmc.fr

of IT management is the decision whereby the best set of IS projects is selected from many competing proposals (Badri et al., 2001). According to Schniederjans and Santhanam (1993) an annual or quarterly managerial decision making activity that most IS managers have to perform is the selection of IS projects. Indeed, selecting the right IS project is a critical business activity that has been recognized and repeatedly emphasized by many researchers. The optimal selection process is a significant strategic resource allocation decision that can engage an organization in substantial long-term commitments (Santhanam & Kyparisis, 1995). In the literature, various decision techniques have been used to select IS projects. The decision can be accomplished using scoring, ranking, decision trees, game theoretic approach, the Delphi technique, Analytical Hierarchy Process (AHP), goal programming, AHP in conjunction with goal programming, dynamic programming, linear 0-1 programming (Badri, 2001). However, previously proposed selection methods deal with precise data settings with. In other words, these typically used methods do not consider real business environment conditions in which calculation of a precise numerical value for some criteria is difficult. Indeed, IS project selection takes place under an incomplete, vague (intangible), and uncertain information environment. For instance, some factors like "importance to user" are subjective and difficult to measure (Chen & Cheng, 2009). The current study attempts to overcome this shortcoming by proposing a new Data Envelopment Analysis (DEA) model which identifies most efficient IS project while considering imprecise data.

DEA introduced by Charnes, Cooper, and Rhodes (1978) and followed by Banker, Charnes, & Cooper (1984) is a non-parametric linear programming based technique for measuring the relative efficiency of a set of similar units, usually referred to as decision making units (DMUs). The original DEA models assume that inputs and outputs are measured by exact values on a ratio scale. Recently, Cooper et al. (1999) addressed the problem of imprecise data in DEA, in its general form. The term "imprecise data" reflects the situation where some of the input and output data are only known to lie within bounded intervals (interval numbers) while other data are known only up to an order (Despotis & Smirlis, 2002). The main contribution of this paper is to propose a new DEA model for finding most efficient IS project with imprecise data. Moreover, using this model, an innovative method is proposed for prioritizing IS projects by considering multiple criteria with imprecise data.

The rest of this paper is organized as follows: After investigating literature on IS project selection in Section 2, background DEA models are reviewed in section 3. Then, a new DEA model for finding most CCR-efficient DMU with imprecise data is proposed in Section 4. Section 5 shows applicability of proposed model on real case data of Iran Ministry of Commerce. The paper is closed with some concluding remark in section 6.

2. Literature Review

IS researchers have stressed the strategic importance of IS project selection and have suggested various methodologies for IS project selection. Schniederjans & Wilson (1991) used a hybrid approach of Analysis Hierarchical Process (AHP) and goal programming for IS project selection. Using a numerical example, they demonstrated that hybrid approaches have advantages from using these techniques separately. Schniederjans & Santhanam (1993) showed applicability of zero-one goal programming as a method for selection of IS projects. Santhanam & Kyparisis (1995) presented a multi-criteria decision model for IS project selection. The proposed model, explicitly consider interrelationships among candidate projects. Han et al. (1998) used Quality Function Deployment (QFD) as a technique for determination of IS development priority. The proposed method considers alignment between business strategy and IS. Shafer & Byrd (2000), using DEA, developed a framework for measuring efficiency of organization investment in information technology. Using data compiled for over 200 large organizations, they illustrated application of their framework. Lee & Kim (2001) considering interdependencies among criteria and candidate projects, suggested an integrated approach for interdependent IS project selection problems using Delphi, Analytic Network Process (ANP) concept and zero-one goal programming. Badri et al., (2001) developed a mixed 0-1 goal programming model for IS project selection in health service institutions, considering multiple factors. Wen et al., (2003) using DEA, proposed a model for evaluating e-commerce efficiency. The proposed model includes not only financial and operational measures, but also e-commerce specific measures such as information and system quality. They illustrated that DEA model can not only effectively reflect the relative efficiency of e-commerce firms, but also identify their potential efficiency problems. Sowlati et al., (2005) proposed a DEA model for prioritizing IS projects. Using the proposed model, each real project is compared to the set of defined projects and receives a score. Prioritization is based on this score. They believed that this is a significant advantage, because assessing the priority of a new added project would not affect the priority of already assessed ones. Kengpol & Touminen (2006) using ANP, Delphi and Maximize Agreement Heuristic (MAH), developed a framework for information technology evaluation. They showed the applicability of proposed framework for 5 logistics firms in Thailand. Wang & Yang (2007) proposed use of AHP and Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) as aids in making IS outsourcing decisions. They mentioned that weights determined by the AHP, are considered as complete subjective weights. They proposed using DEA as an objective method. Chen & Cheng (2009) presented a multiple-criteria decision-making method (MCDM) for selecting an information system project based on the fuzzy measure and the fuzzy integral. They described the subjective opinions of decision makers in linguistic terms expressed in trapezoidal fuzzy numbers. After aggregating the fuzzy ratings of all decision makers, they applied the vertex method to transform the aggregated fuzzy rating into a crisp value.

Investigation of previous studies shows that identifying best IS project in conditions with imprecise data has gained less attention. This paper tries to fill the gap by proposing a DEA model for identifying most efficient IS project with imprecise data.

3. DEA Models

Performance evaluation is an important task for a DMU to find its weaknesses so that subsequent improvements can be made. Since the pioneering work of Charnes et al. (1978), DEA has demonstrated to be an effective technique for measuring the relative efficiency of a set of DMUs which utilize the same inputs to produce the same outputs.

Assume that there are n DMUs, $(DMU_j : j = 1, 2, \ldots, n)$ which consume m inputs $(x_i : i = 1, 2, \ldots, m)$ to produce s outputs $(y_r : r = 1, 2, \ldots, s)$. The CCR input oriented (CCR-I) model evaluates the efficiency of DMU_o, DMU under consideration, by solving the following linear program:

$$
\begin{aligned}
\max\ & \sum_{r=1}^{s} u_r y_{rj} \\
\text{s.t.}\ & \sum_{i=1}^{m} w_i x_{io} = 1 \\
& \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} w_i x_{ij} \leqslant 0 \quad j = 1,2,\ldots,n \\
& w_i \geqslant \varepsilon \quad i = 1,2,\ldots,m \\
& u_r \geqslant \varepsilon \quad r = 1,2,\ldots,s
\end{aligned}
\tag{1}
$$

where x_{ij} and y_{rj} (all nonnegative) are the inputs and outputs of the DMU_j, w_i and u_r are the input and output weights (also referred to as multipliers). x_{io} and y_{ro} are the inputs and outputs of DMU_o. Also, ε is non-Archimedean infinitesimal value for forestalling weights to be equal to zero. The CCR-I model must be run n times, once for each unit, to get the relative efficiency of all DMUs. The envelopment in CCR is constant returns to scale meaning that a proportional increase in inputs results in a proportionate increase in outputs. Banker, Charnes and Cooper (1984) developed the BCC model to estimate the pure technical efficiency of decision making units with reference to the efficient frontier. It also identifies whether a DMU is operating in increasing, decreasing or constant returns to scale. So CCR models are a specific type of BCC models. New applications with more variables and more complicated models are being introduced (Emrouznejad et al., 2007). In many applications of DEA, finding the most efficient DMU is desirable. Amin & Toloo (2007) proposed an integrated model for finding most efficient DMU, as follows:

$$
\begin{aligned}
M^* = \min\ & M \\
\text{s.t.}\ & M - d_j \geqslant 0 \quad j = 1,2,\ldots,n \\
& \sum_{i=1}^{m} w_i x_{ij} \leqslant 1 \quad j = 1,2,\ldots,n \\
& \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} w_i x_{ij} + d_j - \beta_j = 0 \quad j = 1,2,\ldots,n \\
& \sum_{j=1}^{n} d_j = n - 1 \\
& 0 \leqslant \beta_j \leqslant 1, \quad d_j \in \{0,1\} \quad j = 1,2,\ldots,n \\
& w_i \geqslant \varepsilon \quad i = 1,2,\ldots,m \\
& u_r \geqslant \varepsilon \quad r = 1,2,\ldots,s
\end{aligned}
\tag{2}
$$

where d_j as a binary variable represents the deviation variable of DMU_j. β_j is considered in the Model (2) because of discrete nature of d_j and M represents maximum inefficiency which should be minimized. DMU_j is most efficient if and only if $d_j = 0$.

First constraint implies that M is equal to maximum inefficiency. Second constraint shows input-oriented nature of the Model (2). Third constraint causes efficiency of all units to be less than 1. The last one implies among all the DMUs for only most efficient unit, say DMU_p, which has $d_p^* = 0$ in any optimal solution. In addition, to determine the non-Archimedean epsilon, Amin & Toloo (2007) developed an epsilon model.

It should be noted that Model (2) is based on CCR model and identify most CCR-efficient DMU. Indeed, Model (2) is not applicable for situations in which DMUs operating in variable return to scale. To overcome this drawback, Toloo &

Nalchigar (2009) proposed an integrated model which is able to find most BCC-efficient DMU. These DEA models are applicable in situations in which data of DMUs is precise. In the next section, a new DEA model is proposed which is able to find most efficient DMU while considering imprecise data.

4. Proposed Model

Cooper et al. (1999) and Kim et al. (1999) discussed that some of the outputs and inputs are imprecise data in the forms of bounded data, ordinal data, and ratio bounded data as follows: Bounded data

$$\underline{y}_{rj} \leqslant y_{rj} \leqslant \bar{y}_{rj} \quad and \quad \underline{x}_{ij} \leqslant x_{ij} \leqslant \bar{x}_{ij} \quad for \quad r \in BO, i \in BI \tag{3}$$

where $\underline{y}_{rj}$ and $_{ij}$ are the lower bands and $\bar{y}_{rj}$ and $\bar{x}_{ij}$ are the upper bounds, and BO and BI represent the associated sets containing bounded outputs bounded inputs, respectively. Weak ordinal data

$$y_{rj} \leqslant y_{rk} \quad and \quad x_{ij} \leqslant x_{ik} \quad for \quad j \neq k,\ r \in DO, i \in DI$$

Or to simplify the presentation,

$$y_{r1} \leqslant y_{r2} \leqslant \ldots \leqslant y_{rk} \leqslant \ldots \leqslant y_{rn} \quad (r \in DO), \tag{4}$$

$$x_{i1} \leqslant x_{i2} \leqslant \ldots \leqslant x_{ik} \leqslant \ldots \leqslant x_{in} \quad (i \in DI) \tag{5}$$

where DO and DI represent the associated sets containing weak ordinal outputs and inputs, respectively. Strong ordinal data

$$y_{r1} < y_{r2} < \cdots < y_{rk} < \cdots < y_{rn} \quad (r \in SO), \tag{6}$$

$$x_{i1} < x_{i2} < \cdots < x_{ik} < \cdots < x_{in} \quad (i \in SI) \tag{7}$$

where SO and SI represent the associated sets containing strong ordinal outputs and inputs, respectively.

Ratio bounded data

$$L_{ij} \leqslant \frac{y_{rj}}{y_{rj_o}} \leqslant U_{rj} \qquad (j \neq j_o)(r \in RO) \tag{8}$$

$$G_{ij} \leqslant \frac{x_{rj}}{x_{ij_o}} \leqslant H_{ij} \qquad (j \neq j_o)(i \in RI) \tag{9}$$

where L_{rj} and G_{ij} represent the lower bounds, and U_{rj} and H_{ij} represent the upper bounds. RO and RI represent the associated sets containing ratio bounded outputs and inputs, respectively.

By adding Eqs. (3)-(9) added to Model (2), there will be

$$
\begin{aligned}
M^* = \min\ & M \\
\text{s.t.}\ & M - d_j \geqslant 0 && j = 1,2,\dots,n \\
& \sum_{i=1}^{m} w_i x_{ij} \leqslant 1 && j = 1,2,\dots,n \\
& \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} w_i x_{ij} + d_j - \beta_j = 0 && j = 1,2,\dots,n \\
& \sum_{j=1}^{n} d_j = n - 1 \\
& 0 \leqslant \beta_j \leqslant 1, \quad d_j \in \{0,1\} && j = 1,2,\dots,n \\
& (x_{ij}) \in \Theta_i^- \\
& (y_{rj}) \in \Theta_r^+ \\
& w_i \geqslant \varepsilon && i = 1,2,\dots,m \\
& u_r \geqslant \varepsilon && r = 1,2,\dots,s
\end{aligned}
\tag{10}
$$

where $(x_{ij}) \in \Theta_i^-$ and $(y_{rj}) \in \Theta_r^+$ represent any or all of Eqs. (3)-(9).

Clearly, Model (10) is nonlinear and non-convex, because some of the outputs and inputs become unknown decision variables. Since Model (10) is nonlinear and non-convex, consequently local optimum is produced and global optimum may remains unknown.

To convert Model (10) into the linear program (LP), some approaches exist in literature. For instance, Despotis and Smirlis (2002) proposed a generalized model which is capable to handle both interval and ordinal data. Their approach is to transform a non-linear DEA model to a linear programming equivalent, on the basis of the original data set, by applying transformations only on the variables. In addition, Zhu (2003) developed a simple approach by defining

$$
\begin{aligned}
X_{ij} &= w_i x_{ij} && \forall i, j \\
Y_{rj} &= u_r y_{rj} && \forall r, j
\end{aligned}
\tag{11}
$$

In this paper, by adopting Zhu's approach, Model (10) is converted to Model (12) which is a MILP.

$$
\begin{aligned}
M^* = \min\ & M \\
\text{s.t.}\ & M - d_j \geqslant 0 && j = 1,2,\dots,n \\
& \sum_{i=1}^{m} X_{ij} \leqslant 1 && j = 1,2,\dots,n \\
& \sum_{r=1}^{s} Y_{rj} - \sum_{i=1}^{m} X_{ij} + d_j - \beta_j = 0 && j = 1,2,\dots,n \\
& \sum_{j=1}^{n} d_j = n - 1 \\
& 0 \leqslant \beta_j \leqslant 1, \quad d_j \in \{0,1\} && j = 1,2,\dots,n \\
& (X_{ij}) \in \tilde{D}_i^- \\
& (Y_{rj}) \in \tilde{D}_r^+ \\
& X_{ij} \geqslant \varepsilon^* && \forall i, j \\
& Y_{rj} \geqslant \varepsilon^* && \forall r, j
\end{aligned}
\tag{12}
$$

where Θ_i^- and Θ_r^+ are replaced by $\tilde{D}_i^-$ and $\tilde{D}_r^+$ with:

- Bounded data: $\underline{y}_{rj} u_r \leqslant Y_{rj} \leqslant \bar{y}_{rj} u_r,\ \underline{x}_{ij} w_i \leqslant X_{ij} \leqslant \bar{x}_{ij} wi$
- Ordinal dara: $Y_{rj} \leqslant Y_{rk},\ X_{ij} \leqslant X_{ik}\ \forall j \neq k$ for some r, k

- ratio bounded data: $L_{rj} \leqslant \frac{Y_{rj}}{Y_{rj_o}} \leqslant U_{rj}$ and $G_{ij} \leqslant \frac{X_{ij}}{X_{ij_o}} \leqslant H_{ij} \quad (j \neq j_o)$
- Cardinal data: $Y_{rj} = \hat{y}_{rj} u_r$ and $X_{ij} = \hat{x}_{ij}$, where $\hat{y}_{rj}$ and $\hat{x}_{ij}$ represent cardinal data.

Indeed Model (12) is extended version of Amin & Toloo's model. Hence, the following LP, which is extended version of Amin & Toloo (2007) epsilon model, is proposed to determine the non-Archimedean epsilon:

$$
\begin{aligned}
\varepsilon^* = \max\ & \varepsilon \\
\text{s.t.}\ & \sum_{i=1}^{m} X_{ij} \leqslant 1 && j = 1, 2, \ldots, n \\
& \sum_{r=1}^{s} Y_{rj} - \sum_{i=1}^{m} X_{ij} \leqslant 0 && j = 1, 2, \ldots, n \\
& (X_{ij}) \in \tilde{D}_i^- \\
& (Y_{rj}) \in \tilde{D}_r^+ \\
& X_{ij} - \varepsilon \geqslant && \forall i, j \\
& Y_{rj} - \varepsilon \geqslant && \forall r, j
\end{aligned}
\tag{13}
$$

As mentioned in section (3), the model which was proposed by Amin & Toloo (2007) is based on CCR model and evaluates DMUs in constant return to scale. Hence, Model (12) is not applicable for situations in which DMUs, in presence of cardinal and ordinal data, operating in variable return to scale. By extending previous work of Toloo & Nalchigar (2008), Appendix A proposes a model which is able to find most BCC-efficient DMU in existence of imprecise data.

5. Application of Proposed Model

The manager of IS department at Iran Ministry of Commerce used to perform personally the task of selecting IS projects. The manager had to depend on experience and intuition. From an operational aspect, selecting the best project among large number of projects was difficult to do in order to the lack of a formal process and a clearly defined and transparent way for decision making. It was necessary to choose a model that could be used as an objective method for selecting right IS project. DEA was suggested as the best solution which could model the complexity of choosing projects and show that the decisions so made are fair and equitable. To choose the best IS project from a set of projects that are in competition for limited resources, different criteria, which may be qualitative in nature, must be included in the evaluation. First, IS department of Iran Ministry of Commerce employed a team include several specialists on the field of IS and software engineering. These specialists were asked to develop a set of criteria which capture all aspects of IS projects and to estimate them for each project. It is notable that data of software cost, training cost and support cost values were obtained from proposals and potential risk, time reduction, system accuracy and improvement management capabilities were subjectively scored by specialist. Because of difficulties in measurement of precise numerical value for potential risk and improvement management capabilities, these data are in ordinal and interval format. Table (1) shows estimations of inputs and outputs obtained by specialist.

In this section, applicability of proposed model is illustrated. Inputs and outputs

Table 1. Estimation of criteria values for IS projects

IS Project (DMU)	Inputs				Outputs		
	Software Cost (x_{1j})	Training Cost (x_{2j})	Support Cost (x_{3j})	Potential *Risk*^{2} (x_{4j})	Time Reduction (y_{1j})	System Accuracy (y_{2j})	Improvement managment capabilities (y_{3j})
1	3500	12	24	6	5	5	$[1,15]$
2	455	45	0.83	2	23	5	$[7,20]$
3	695	69	1.5	1	14	5	$[1,15]$
4	513	14	122	4	16	5	$[8,15]$
5	3510	351	16.8	3	23	5	$[5,10]$
6	3725	30	100	7	14	5	$[1,5]$
7	4000	40	50	5	10	5	$[1,5]$
8	2500	250	30	8	13	5	$[4,12]$

[a] Ranking such that $8 \equiv$ highest rank, ..., $1 \equiv$ lowest rank ($x_{48} > x_{46} > \cdots > x_{43}$).

of IS projects are as follows:

$$
\begin{array}{ll}
\Theta_1^- = \{x_{11} = 3500, x_{12} = 455, x_{13} = 695, \ldots, x_{18} = 2500\} & \text{(Cardinal data)} \\
\Theta_2^- = \{x_{21} = 12, x_{22} = 45, x_{23} = 69, \ldots, x_{28} = 250\} & \text{(Cardinal data)} \\
\Theta_3^- = \{x_{31} = 24, x_{32} = 0.83, x_{33} = 1.5, \ldots, x_{38} = 30\} & \text{(Cardinal data)} \\
\Theta_4^- = \{x_{48} > x_{46} > \cdots > x_{43}\} & \text{(Ordinal data)} \\
\Theta_1^+ = \{y_{11} = 5, y_{12} = 23, y_{13} = 14, \ldots, y_{18} = 13\} & \text{(Cardinal data)} \\
\Theta_2^+ = \{y_{21} = 5, y_{22} = 5, y_{23} = 5, \ldots, y_{28} = 5\} & \text{(Cardinal data)} \\
\Theta_3^+ = \{1 \leqslant y_{31} \leqslant 15, 7 \leqslant y_{32} \leqslant 20, 1 \leqslant y_{33} \leqslant 15, \ldots, 4 \leqslant y_{38} \leqslant 12\} & \text{(Interval data)}
\end{array}
$$

According to Zhu's approach,

$$
\begin{array}{l}
\tilde{D}_1^- = \{X_{11} = 3500w_1, X_{12} = 455w_1, X_{13} = 695w_1, \ldots, X_{18} = 216w_1\} \\
\tilde{D}_2^- = \{X_{21} = 12w_2, X_{22} = 45w_2, X_{23} = 69w_2, \ldots, X_{28} = 250w_2\} \\
\tilde{D}_3^- = \{X_{31} = 24w_3, X_{32} = 0.83w_3, X_{33} = 1.5w_3, \ldots, X_{38} = 300w_3\} \\
\tilde{D}_4^- = \{X_{48} > X_{46} > \cdots > X_{43}\} \\
\tilde{D}_1^+ = \{Y_{11} = 5\mu_1, Y_{12} = 23\mu_1, Y_{13} = 14\mu_1, \ldots, Y_{18} = 13\mu_1\} \\
\tilde{D}_2^+ = \{Y_{21} = 5\mu_2, Y_{22} = 5\mu_2, Y_{23} = 5\mu_2, \ldots, Y_{28} = 5\mu_2\} \\
\tilde{D}_3^+ = \{\mu_3 \geqslant Y_{31} \geqslant 15\mu_3, 7\mu_3 \geqslant Y_{32} \geqslant 20\mu_3, \mu_3 \geqslant Y_{33} \geqslant 15\mu_3, \ldots, 4\mu_3 \geqslant Y_{38} \geqslant 12\mu_3\}
\end{array}
$$

Using these equations and solving Model (14) for data presented in Table (1), (with considering suitable value for epsilon, equal to 0.0067)DMU_2 is easily identified as most CCR-efficient IS project ($d_2^* = 0, d_{j\neq 2}^* = 1$).The detailed results of proposed model are presented in Table (2).

Table 2. Results of propose model

Variable	Optimum Value
d_j^*	$d_4^* = 0, d_{j\neq 4}^* = 1$
w_1^*	0.0002
w_2^*	0.0006
w_3^*	0.0002
w_4^*	0.0325
u_1^*	0.0157
u_2^*	0.0110
u_3^*	0.0002

So is most efficient IS project and is proposed to allocate resource. Using the proposed method, IS department at Iran Ministry of Commerce is able to identify most efficient IS objectively. In comparison with the conventional weighted score model and the AHP model some of the clear benefits of the proposed model are:

- The model finds most efficient IS project objectively and there is no need for determining weights and pair-wise comparison for all criteria and projects.
- IT manager could find most efficient IS by solving only one LP, so it is computationally efficient.

6. Conclusion

Selecting best IS projects is a critical aspect of IT management and has been recognized and repeatedly emphasized by many researchers. Indeed, the optimal selection process is a significant strategic resource allocation decision that can engage an organization in substantial long-term commitments. Although there are numerous methods for IS project selection, prior researches have ignored the presence of imprecise data. Therefore, this paper developed upon the work conducted on IS project selection considering the cases in which data of projects are imprecise. This paper proposed a new DEA model which identifies most efficient IS project by solving only one MILP. Moreover, using this model, an innovative method for ranking IS projects with imprecise data proposed. As an advantage, this method it is complex enough to handle cases with imprecise data well and accurately and yet simple enough to be understood by the IT managers' community. Finally, applicability of proposed method illustrated in real case of Iran Ministry of Commerce.

Appendix A.

Toloo & Nalchigar (2009) developed Model (15) as a new integrated model for finding the most BCC-efficient DMU.

$$
\begin{aligned}
M^* = \min\ & M \\
\text{s.t.}\ & M - d_j \geqslant 0 && j = 1, 2, \ldots, n \\
& \sum_{i=1}^{m} w_i x_{ij} \leqslant 1 && j = 1, 2, \ldots, n \\
& \sum_{r=1}^{s} u_r y_{rj} - u_o - \sum_{i=1}^{m} w_i x_{ij} + d_j - \beta_j = 0 && j = 1, 2, \ldots, n \\
& \sum_{j=1}^{n} d_j = n - 1 \\
& 0 \leqslant \beta_j \leqslant 1, d_j \in \{0, 1\} && j = 1, 2, \ldots, n \\
& M, u_o \quad free \\
& (w_i) \geqslant \varepsilon^* \\
& (u_r) \geqslant \varepsilon^*
\end{aligned}
\tag{A1}
$$

Model (A1) is computationally efficient and also has wider range of application than models which find most CCR-efficient DMU (Model (2)), because is capable for situation in which return to scale is variable. By incorporating Eqs. (3)-(9) to Model (A1), and converting non-linear model to a LP (based on Zhu (2003)'s approach), there will be:

$$
\begin{aligned}
M^* = \min\ & M \\
\text{s.t.}\ & M - d_j \geqslant 0 && j = 1, 2, \ldots, n \\
& \sum_{i=1}^{m} X_{ij} \leqslant 1 && j = 1, 2, \ldots, n \\
& \sum_{r=1}^{s} Y_{rj} - u_o - \sum_{i=1}^{m} X_{ij} + d_j - \beta_j = 0 && j = 1, 2, \ldots, n \\
& \sum_{j=1}^{n} d_j = n - 1 \\
& 0 \leqslant \beta_j \leqslant 1, d_j \in \{0, 1\} && j = 1, 2, \ldots, n \\
& (X_{ij}) \in \tilde{D}_i^- \\
& (Y_{rj}) \in \tilde{D}_r^+ \\
& X_{ij} \geqslant \varepsilon^* && \forall i, j \\
& Y_{rj} \geqslant \varepsilon^* && \forall r, j \\
& M, u_o \quad \text{free}
\end{aligned}
\tag{A2}
$$

Model (A2) finds most BCC-efficient DMU in presence of both cardinal and ordinal data. Similar to Model (12), this model could be used for ranking DMUs which operate in variable return to scale.

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