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Fuzzy chance-constrained data envelopment analysis: a structured literature review, current trends, and future directions

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Abstract
Fuzzy data envelopment analysis (FDEA) is one of the most applicable approaches for performance assessment of peer decision making units under ambiguity which is evolving rapidly and gaining popularity under uncertain data envelopment analysis field. The goal of this paper is to review some FDEA models based on applied possibility, necessity, credibility, general fuzzy measures and chance-constrained programming to deal with data ambiguity. The study presents a comprehensive and structured literature review of fuzzy chance-constrained data envelopment analysis (FCCDEA) studies including 87 studies from 2000 to 2020. The main contributions of this research include the following details: (1) Review of fuzzy chance-constrained programming, (2) Survey of FCCDEA models based on different fuzzy measures, (3) Analysis of FCCDEA applications and features, (4) Classification of FCCDEA studies from modeling and uncertainty type viewpoints, (5) Bibliometric analysis of FCCDEA literature, and (6) Extraction of main research gaps and guidelines for future research directions.

Keywords Data envelopment analysis (DEA) · Fuzzy optimization · Fuzzy DEA (FDEA) · Chance-constrained programming (CCP) · Possibilistic programming · Fuzzy measure

1 Introduction

Performance appraisal is one of the most important decision-making issues in various areas of application and real-world problems. Data envelopment analysis (DEA) is a powerful and popular mathematical programming approach for

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performance measurement. DEA was presented by Charnes et al. (1978) for the first time and it is originated from Farrell's (1957) research for performance assessment of peer decision making units (DMUs) in the presence of multiple crisp inputs and outputs. However, for many real cases, most of the times, the observed values of inputs and/or outputs of DEA models are tainted by ambiguity (Hatami-Marbini et al., 2011). Data ambiguity can be the result of the absence or lack of knowledge about data, non-obtainable data, expert based information, linguistic terms, and unquantifiable data.

The conventional DEA models cannot be applied for performance evaluation and ranking DMUs in the presence of imprecise and vague data (Emrouznejad & Tavana, 2014). As a result, it is essential and important to develop DEA models for eliminating this issue, otherwise, the efficiency score and ranking of the DMUs may become unreliable and invalid (Peykani et al., 2020). Accordingly, in recent years, many researchers proposed variants of uncertain data envelopment analysis (UDEA) models by employing uncertain programming approaches.

Fuzzy chance-constrained data envelopment analysis (FCCDEA) is one of the popular and applicable approaches that can handle fuzzy data and linguistic terms. The FCCDEA approach is the result of the integration of DEA models, fuzzy mathematical programming (FMP) and chance-constrained programming (CCP). Given the importance and growing trend of FCCDEA field, in this paper, a comprehensive and structured literature review of fuzzy chance-constrained DEA researches is presented. The current study covers 87 studies of FCCDEA field from 2000 to 2020 and concludes with suggestions about the directions for further researches in this field. The main contributions of this literature review can be summarized as follows:

- The relations of fuzzy chance-constrained programming (FCCP) are introduced.
- FCCDEA modeling is explained based on different optimistic-pessimistic attitudes.
- Literature is classified according to the features and applications of FCCDEA studies.
- FCCDEA studies are categorized according to the type of uncertainty and FCCP approaches.
- Bibliometric analysis, beneficial statistical information and main research gaps are extracted.
- Future research directions are suggested through a comprehensive literature review.

The rest of this paper is organized as follows. The fundamentals and backgrounds of data envelopment analysis will be presented in Sect. 2. The background of fuzzy measures for measuring fuzzy events based on chance-constrained programming will be explained in Sect. 3. Fuzzy chance-constrained DEA modeling will be discussed in Sect. 4. Then, a comprehensive literature review of FCCDEA studies will be presented in Sect. 5. Finally, conclusions and some directions for future research are given in Sect. 6.

2 Data envelopment analysis (DEA)

Data envelopment analysis is one of the prominent non-parametric techniques for performance measurement, benchmarking and ranking of the peer DMUs. This technique is widely applied in many real-life problems and applications (Emrouznejad & Yang, 2018; Hosseinzadeh Lotfi et al., 2020). In term of modeling, the data envelopment analysis models are categorized according to four characteristics including (1) Projection Construction, (2) Model Form, (3) Model Orientation, and (4) Returns to Scale (RTS). The explanation of these characteristics is summarized as follows:

- *Projection Construction* The radial projection (RP) construction implies that the DEA optimizes all inputs or outputs of a DMU at a certain proportion. However, in the non-radial projection (NRP) construction, the DEA reduces inputs or increases outputs non-proportionally.
- *Form* The multiplier forms (M-F) and envelopment form (E-F) of conventional DEA models are modeled based on the concept of relative efficiency and production possibility set (PPS), respectively.
- *Orientation* DEA models are classified into the input-oriented, output-oriented, and non-oriented methods. In the input-oriented (I-O) models, the possible proportional reduction of inputs is fixed. In the output-oriented (O-O) models, the possible proportional increase in the outputs is considered, while the inputs are fixed. In the non-oriented (N-O) DEA models, the inputs are decreased and the outputs are increased, simultaneously.
- *Returns to Scale* RTS denotes the proportional changes in outputs per change in inputs, including constant returns to scale (CRS), variable returns to scale (VRS), non-increasing returns to scale (NIRS), and non-decreasing returns to scale (NDRS).

The graphical presentation of DEA characteristics classification is introduced in Fig. 1: Also, the orientation types, production possibility set, and efficient frontier (EF) under the different returns to scale assumptions are depicted in Fig. 2.

To get acquainted with DEA modeling, assume that there are n homogenous decision-making units $DMU_j (j = 1, ..., n)$ each consuming m inputs $x_{ij} (i = 1, ..., m)$ and producing s outputs $y_{rj} (r = 1, ..., s)$. Here, the subscript o refers to the DMU under consideration. Moreover, the non-negative weights $v_i (i = 1, ..., m)$ and $u_r (r = 1, ..., s)$ are assigned to inputs and outputs, respectively. Also, the free sign variable w allows the change of scale and non-negative variables $\lambda_j (j = 1, ..., n)$ are employed in production possibility set formulation.

After introducing the indices, parameters and decision variables that will be employed in DEA modeling, the basic and popular DEA models under different characteristics will be presented in the following. Charnes et al. (1978) proposed the first DEA model that based on the CRS assumption and called the CCR (*Charnes-Cooper-Rhodes*) model. The variants of CCR model are presented as follows:

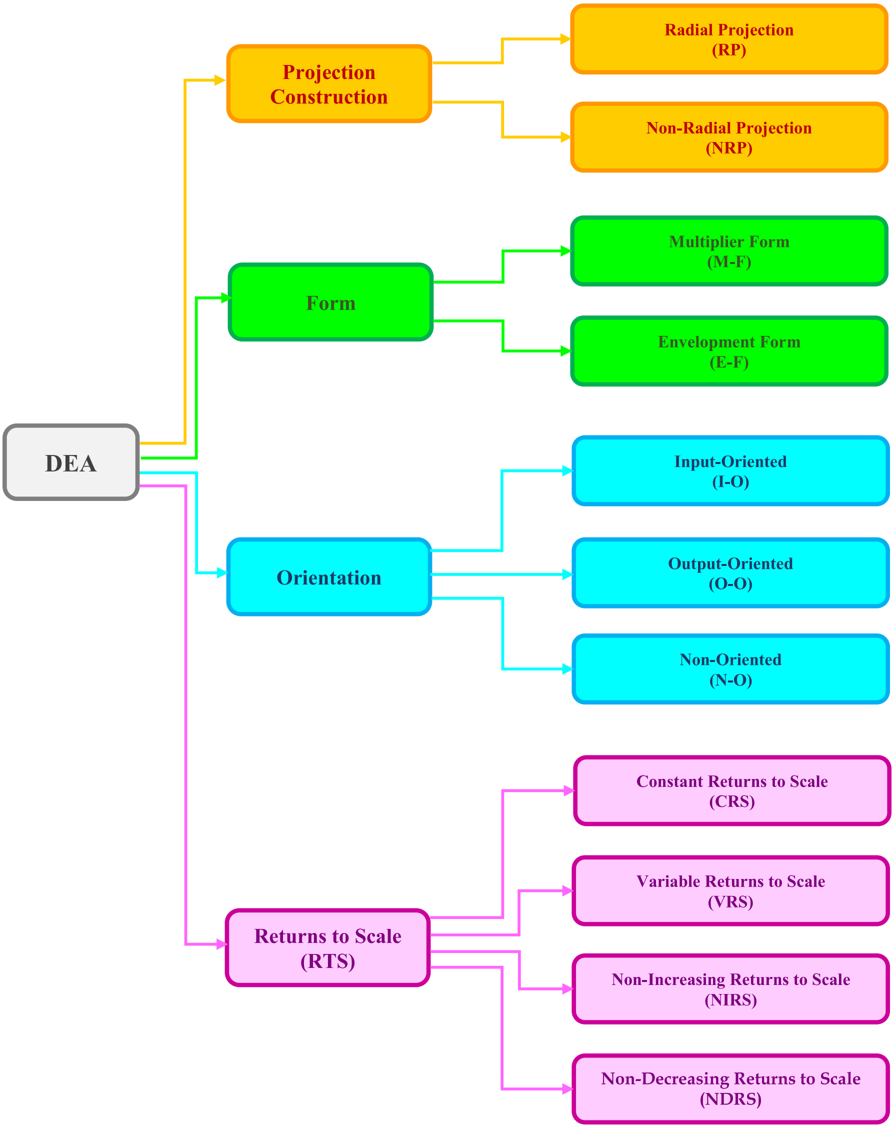


Fig. 1 Background of DEA modeling

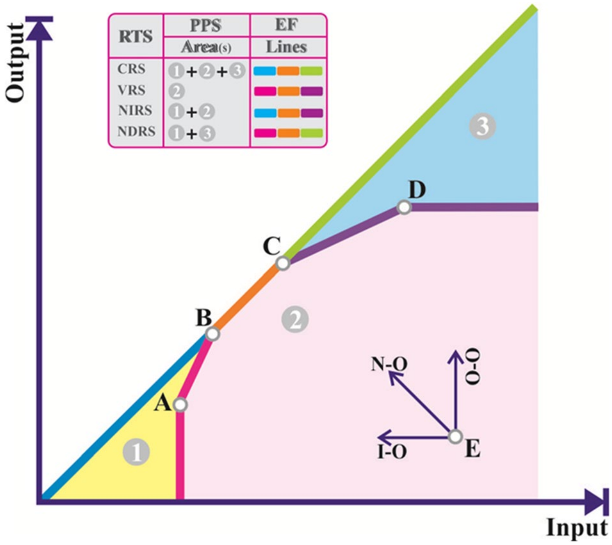


Fig. 2 PPS under different RTS assumptions and the orientation types

CCR (M-F & I-O)

$$\text{Max} \quad \sum_{r=1}^{s} y_{ro}u_r \tag{1}$$
$$\text{S.t.} \quad \sum_{i=1}^{m} x_{io}v_i = 1$$
$$\sum_{r=1}^{s} y_{rj}u_r - \sum_{i=1}^{m} x_{ij}v_i \le 0, \quad \forall j$$
$$v_i,\ u_r \ge 0, \quad \forall i, r$$

CCR (M-F & O-O)

$$\text{Min} \quad \sum_{i=1}^{m} x_{io}v_i \tag{2}$$
$$\text{S.t.} \quad \sum_{r=1}^{s} y_{ro}u_r = 1$$
$$\sum_{r=1}^{s} y_{rj}u_r - \sum_{i=1}^{m} x_{ij}v_i \le 0, \quad \forall j$$
$$v_i,\ u_r \ge 0, \quad \forall i, r$$

CCR (E-F & I-O)

$$\text{Min} \quad \Theta \tag{3}$$
$$\text{S.t.} \quad \sum_{j=1}^{n} \lambda_j x_{ij} \le \Theta x_{io}, \quad \forall i$$
$$\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{ro}, \quad \forall r$$
$$\lambda_j \ge 0, \quad \forall j$$

CCR (E-F & O-O)

$$\text{Max} \quad \Phi \tag{4}$$
$$\text{S.t.} \quad \sum_{j=1}^{n} \lambda_j x_{ij} \le x_{io}, \quad \forall i$$
$$\sum_{j=1}^{n} \lambda_j y_{rj} \ge \Phi y_{ro}, \quad \forall r$$
$$\lambda_j \ge 0, \quad \forall j$$

Then, Banker et al. (1984) developed CCR model based on the VRS assumption and called the BCC (*Banker-Charnes-Cooper*) model. The CCR and BCC models are radial projection constructs. The variants of BCC model are presented as follows:

BCC (M-F & I-O)

$$\begin{aligned} \text{Max} \quad & \sum_{r=1}^{s} y_{ro} u_r + w \\ \text{S.t.} \quad & \sum_{i=1}^{m} x_{io} v_i = 1 \\ & \sum_{r=1}^{s} y_{rj} u_r - \sum_{i=1}^{m} x_{ij} v_i + w \leq 0, \quad \forall j \\ & v_i, u_r \geq 0, \quad \forall i, r \end{aligned} \tag{5}$$

BCC (M-F & O-O)

$$\begin{aligned} \text{Min} \quad & \sum_{i=1}^{m} x_{io} v_i - w \\ \text{S.t.} \quad & \sum_{r=1}^{s} y_{ro} u_r = 1 \\ & \sum_{r=1}^{s} y_{rj} u_r - \sum_{i=1}^{m} x_{ij} v_i + w \leq 0, \quad \forall j \\ & v_i, u_r \geq 0, \quad \forall i, r \end{aligned} \tag{6}$$

BCC (E-F & I-O)

$$\begin{aligned} \text{Min} \quad & \Theta \\ \text{S.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} \leq \Theta x_{io}, \quad \forall i \\ & \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro}, \quad \forall r \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j \geq 0, \quad \forall j \end{aligned} \tag{7}$$

BCC (E-F & O-O)

$$\begin{aligned} \text{Max} \quad & \Phi \\ \text{S.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io}, \quad \forall i \\ & \sum_{j=1}^{n} \lambda_j y_{rj} \geq \Phi y_{ro}, \quad \forall r \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j \geq 0, \end{aligned} \tag{8}$$

Charnes et al., (1985b) proposed the non-radial DEA model by considering 3simultaneously both input minimization and output maximization and called the additive (ADD) model. The variants of ADD model are presented as follows:

ADD (M-F & CRS)

$$\begin{aligned} \text{Max} \quad & \sum_{r=1}^{s} y_{ro} u_r - \sum_{i=1}^{m} x_{io} v_i \\ \text{S.t.} \quad & \sum_{r=1}^{s} y_{rj} u_r - \sum_{i=1}^{m} x_{ij} v_i \leq 0, \quad \forall j \\ & u_r \geq 1, \quad \forall r \\ & v_i \geq 1, \quad \forall i \end{aligned} \tag{9}$$

ADD (M-F & VRS)

$$\begin{aligned} \text{Max} \quad & \sum_{r=1}^{s} y_{ro} u_r - \sum_{i=1}^{m} x_{io} v_i + w \\ \text{S.t.} \quad & \sum_{r=1}^{s} y_{rj} u_r - \sum_{i=1}^{m} x_{ij} v_i + w \leq 0, \quad \forall j \\ & u_r \geq 1, \quad \forall r \\ & v_i \geq 1, \quad \forall i \end{aligned} \tag{10}$$

ADD (E-F & CRS)

$$\begin{aligned} \text{Min} \quad & \sum_{i=1}^{m} \delta_i^- + \sum_{r=1}^{s} \delta_r^+ \\ \text{S.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + \delta_i^- = x_{io}, \quad \forall i \\ & \sum_{j=1}^{n} \lambda_j y_{rj} - \delta_r^+ = y_{ro}, \quad \forall r \\ & \lambda_j, \delta_i^-, \delta_r^+ \geq 0, \quad \forall j, r, i \end{aligned} \tag{11}$$

ADD (E-F & VRS)

$$\begin{aligned} \text{Min} \quad & \sum_{i=1}^{m} \delta_i^- + \sum_{r=1}^{s} \delta_r^+ \\ \text{S.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + \delta_i^- = x_{io}, \quad \forall i \\ & \sum_{j=1}^{n} \lambda_j y_{rj} - \delta_r^+ = y_{ro}, \quad \forall r \\ & \sum_{j=1}^{n} \lambda_j = 1 \\ & \lambda_j, \delta_i^-, \delta_r^+ \geq 0, \quad \forall j, r, i \end{aligned} \tag{12}$$

The multiplier and envelopment forms of conventional DEA are the dual linear programming problem to each other (Cooper et al., 2011).

3 Fuzzy chance-constrained programming (FCCP)

Zadeh (1978) suggested that in fuzzy linear programming, fuzzy coefficients can be viewed as fuzzy variables and constraints can be considered as fuzzy events (Inuiguchi et al., 1993). Accordingly, by integrating the chance-constrained programming (CCP) proposed by Charnes and Cooper (1959) and fuzzy measures such as possibility, necessity, credibility, and general, the chances of occurrence of fuzzy events can be measured. The goal of this section is to introduce the preliminaries, principles and relations of fuzzy chance-constrained programming (FCCP) approach under triangular and trapezoidal fuzzy variables.

The membership function of triangular fuzzy variable (TRFV) $\tilde{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$, $\alpha_1 < \alpha_2 < \alpha_3$ and trapezoidal fuzzy variable (TLFV) $\tilde{\beta} = (\beta_1, \beta_2, \beta_3, \beta_4)$, $\beta_1 < \beta_2 < \beta_3 < \beta_4$ are proposed in Eqs. (13) and (14), respectively:

TFV

$$\mu(x) = \begin{cases} \dfrac{x-\alpha_1}{\alpha_2-\alpha_1}, & \text{if } \alpha_1 \le x \le \alpha_2; \\ \dfrac{\alpha_3-x}{\alpha_3-\alpha_2}, & \text{if } \alpha_2 \le x \le \alpha_3; \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

$$\mu(x) = \begin{cases} \dfrac{x-\beta_1}{\beta_2-\beta_1}, & \text{if } \beta_1 \le x \le \beta_2; \\ 1, & \text{if } \beta_2 \le x \le \beta_3; \\ \dfrac{\beta_4-x}{\beta_4-\beta_3}, & \text{if } \beta_3 \le x \le \beta_4; \\ 0, & \text{otherwise.} \end{cases} \tag{14}$$

TRFV and TLFN are the most popular and applicable fuzzy number in fuzzy mathematical literature and they are special kind of *LR* fuzzy variable (Xu & Zhou, 2011). The membership function curve of TRFN and TLFN are shown in Fig. 3.

In the following of this section, by considering $\tilde{\alpha}$, $\tilde{\beta}$, and γ as a TRFN, TLFN, and crisp number, respectively, all relations will be introduced.

3.1 Possibility measure

Let the triple $(\Psi, \Omega(\Psi), Pos)$ be a possibility space where Ψ is the universe and non-empty set containing all possible events, $\Omega(\Psi)$ is the power set of Ψ, and *Pos* is a possibility measure (Zadeh, 1978). The properties of the possibility (*Pos*) measure are presented as follows:

- $Pos\{\emptyset\} = 0$, $Pos\{\Psi\} = 1$
- $\forall H \in \Omega(\Psi) \Rightarrow 0 \le Pos\{H\} \le 1$
- $Pos\{\cup_k H_k\} = Sup_k\left(Pos\{H_k\}\right)$

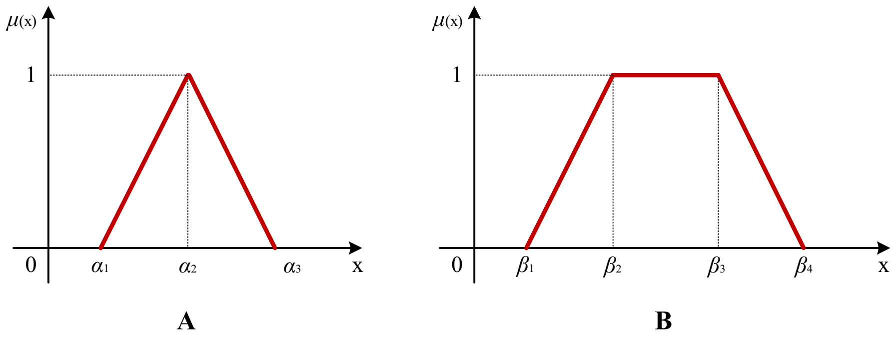


Fig. 3 The representation of fuzzy number. (A) Triangular membership function, (B) Trapezoidal membership function

- $\forall H, Q \in \Omega(\Psi), H \subseteq Q \Rightarrow Pos\{H\} \leq Pos\{Q\}$
- $\forall H, Q \in \Omega(\Psi) \Rightarrow Pos\{H \cup Q\} + Pos\{H \cap Q\} \leq Pos\{H\} + Pos\{Q\}$

The *Pos* measure of fuzzy events $\{\tilde{\alpha} \leq \gamma\}$, $\{\tilde{\alpha} \geq \gamma\}$, $\{\tilde{\beta} \leq \gamma\}$ and $\{\tilde{\beta} \geq \gamma\}$ are shown in Eqs. (15) to (18), respectively:

POS measure

$$Pos\{\tilde{\alpha} \leq \gamma\} = \begin{cases} 0, & if\ \alpha_1 \geq \gamma; \\ \frac{\gamma-\alpha_1}{\alpha_2-\alpha_1}, & if\ \alpha_1 \leq \gamma \leq \alpha_2; \\ 1, & if\ \alpha_2 \leq \gamma; \end{cases} \tag{15}$$

$$Pos\{\tilde{\alpha} \geq \gamma\} = \begin{cases} 1, & if\ \gamma \leq \alpha_2; \\ \frac{\alpha_3-\gamma}{\alpha_3-\alpha_2}, & if\ \alpha_2 \leq \gamma \leq \alpha_3; \\ 0, & if\ \alpha_3 \leq \gamma. \end{cases} \tag{16}$$

$$Pos\{\tilde{\beta} \leq \gamma\} = \begin{cases} 0, & if\ \beta_1 \geq \gamma; \\ \frac{\gamma-\beta_1}{\beta_2-\beta_1}, & if\ \beta_1 \leq \gamma \leq \beta_2; \\ 1, & if\ \beta_2 \leq \gamma; \end{cases} \tag{17}$$

$$Pos\{\tilde{\beta} \geq \gamma\} = \begin{cases} 1, & if\ \gamma \leq \beta_3; \\ \frac{\beta_4-\gamma}{\beta_4-\beta_3}, & if\ \beta_3 \leq \gamma \leq \beta_4; \\ 0, & if\ \beta_4 \leq \gamma. \end{cases} \tag{18}$$

According to the *Pos* measure and CCP, the deterministic counterparts and equivalent crisp ones of fuzzy chance constraints under desired confidence level ξ are presented in Eqs. (19) to (22) as follows:

POS measure

$$Pos\{\tilde{\alpha} \leq \gamma\} \geq \xi \Leftrightarrow (1-\xi)\,\alpha_1 + (\xi)\,\alpha_2 \leq \gamma \tag{19}$$

$$Pos\{\tilde{\alpha} \geq \gamma\} \geq \xi \Leftrightarrow (\xi)\,\alpha_2 + (1-\xi)\,\alpha_3 \geq \gamma \tag{20}$$

POS measure

$$Pos\{\tilde{\beta} \le \gamma\} \ge \xi \Leftrightarrow (1-\xi)\,\beta_1 + (\xi)\,\beta_2 \le \gamma \tag{21}$$

$$Pos\{\tilde{\beta} \ge \gamma\} \ge \xi \Leftrightarrow (\xi)\,\beta_3 + (1-\xi)\,\beta_4 \ge \gamma \tag{22}$$

The *Pos* measure indicates the most optimistic possibility occurrence level of fuzzy events. As a result, the *Pos* measure is applied in situations where the decision maker (DM) takes an optimistic viewpoint.

3.2 Necessity measure

The necessity measure of a fuzzy event $H \in \Omega(\Psi)$ is defined on $(\Psi, \Omega(\Psi), Pos)$ as $Nec\{H\} = 1 - Pos\{H^C\}$, where $\{H^C\}$ is the complement of $\{H\}$ (Dubois & Prade, 1978, 1988). The properties of the necessity (*Nec*) measure are presented as follows:

- $Nec\{\emptyset\} = 0,\ Nec\{\Psi\} = 1$
- $\forall H \in \Omega(\Psi) \Rightarrow 0 \le Nec\{H\} \le 1$
- $Nec\{\cap_k H_k\} = Inf_k\left(Nec\{H_k\}\right)$
- $\forall H, Q \in \Omega(\Psi), H \subseteq Q \Rightarrow Nec\{H\} \le Nec\{Q\}$
- $\forall H, Q \in \Omega(\Psi) \Rightarrow Nec\{H \cup Q\} + Nec\{H \cap Q\} \ge Nec\{H\} + Nec\{Q\}$
- $\forall H \in \Omega(\Psi), Pos\{H\} < 1 \Rightarrow Nec\{H\} = 0$
- $\forall H \in \Omega(\Psi), Nec\{H\} > 0 \Rightarrow Pos\{H\} = 1$

The *Nec* measure is the dual of *Pos* measure. The *Nec* measure of fuzzy events $\{\tilde{\alpha} \le \gamma\}, \{\tilde{\alpha} \ge \gamma\}, \{\tilde{\beta} \le \gamma\}$ and $\{\tilde{\beta} \ge \gamma\}$ are shown in Eqs. (23) to (26), respectively:

NEC measure

$$Nec\{\tilde{\alpha} \le \gamma\} = \begin{cases} 0, & if\ \gamma \le \alpha_2; \\ \frac{\gamma-\alpha_2}{\alpha_3-\alpha_2}, & if\ \alpha_2 \le \gamma \le \alpha_3; \\ 1, & if\ \alpha_3 \le \gamma. \end{cases} \tag{23}$$

$$Nec\{\tilde{\alpha} \ge \gamma\} = \begin{cases} 1, & if\ \alpha_1 \ge \gamma; \\ \frac{\alpha_2-\gamma}{\alpha_2-\alpha_1}, & if\ \alpha_1 \le \gamma \le \alpha_2; \\ 0, & if\ \alpha_2 \le \gamma; \end{cases} \tag{24}$$

$$Nec\{\tilde{\beta} \le \gamma\} = \begin{cases} 0, & if\ \gamma \le \beta_3; \\ \frac{\gamma-\beta_3}{\beta_4-\beta_3}, & if\ \beta_3 \le \gamma \le \beta_4; \\ 1, & if\ \beta_4 \le \gamma. \end{cases} \tag{25}$$

$$Nec\{\tilde{\beta} \ge \gamma\} = \begin{cases} 1, & if\ \beta_1 \ge \gamma; \\ \frac{\beta_2-\gamma}{\beta_2-\beta_1}, & if\ \beta_1 \le \gamma \le \beta_2; \\ 0, & if\ \beta_2 \le \gamma; \end{cases} \tag{26}$$

According to the *Nec* measure and CCP, the deterministic counterparts and equivalent crisp ones of fuzzy chance constraints under desired confidence level ξ are presented in Eqs. (27) to (30) as follows:

NEC measure	
$Nec\{\tilde{\alpha} \leq \gamma\} \geq \xi \Leftrightarrow (1-\xi)\,\alpha_2 + (\xi)\,\alpha_3 \leq \gamma$	(27)
$Nec\{\tilde{\alpha} \geq \gamma\} \geq \xi \Leftrightarrow (\xi)\,\alpha_1 + (1-\xi)\,\alpha_2 \geq \gamma$	(28)
$Nec\left\{\tilde{\beta} \leq \gamma\right\} \geq \xi \Leftrightarrow (1-\xi)\,\beta_3 + (\xi)\,\beta_4 \leq \gamma$	(29)
$Nec\left\{\tilde{\beta} \geq \gamma\right\} \geq \xi \Leftrightarrow (\xi)\,\beta_1 + (1-\xi)\,\beta_2 \geq \gamma$	(30)

According to the pessimistic viewpoint of the *Nec* measure, decision maker (DM) can be employed *Nec* measure instead of *Pos* measure in order to an allude risk (Xu & Zhou, 2011). It must be emphasized that *Pos* and *Nec* are two standards and well-known fuzzy measures that are wieldy applied in fuzzy chance-constrained programming models.

3.3 Credibility measure

The credibility measure of a fuzzy event $H \in \Omega(\Psi)$ is defined on $(\Psi, \Omega(\Psi), Pos)$ as $Cr\{H\} = 0.5\,(Pos\{H\} + Nec\{H\})$. In other words, credibility measure is the average of *Pos* and *Nec* measures (Liu & Liu, 2002). The properties of the credibility (*Cr*) measure are presented as follows:

- $Cr\left\{\emptyset\right\} = 0,\ Cr\{\Psi\} = 1$
- $\forall H \in \Omega(\Psi) \Rightarrow 0 \leq Cr\{H\} \leq 1$
- $\forall H \in \Omega(\Psi) \Rightarrow Cr\{H\} + Cr\left\{H^C\right\} = 1$
- $\forall H, Q \in \Omega(\Psi), H \subseteq Q \Rightarrow Cr\{H\} \leq Cr\{Q\}$
- $\forall H, Q \in \Omega(\Psi) \Rightarrow Cr\{H \cup Q\} \leq Cr\{H\} + Cr\{Q\}$
- $\forall H \in \Omega(\Psi) \Rightarrow Pos\{H\} \geq Cr\{H\} \geq Nec\{H\}$

It should be underlined that the *Cr* measure is self-dual and it capable to be supported a compromise attitude of the DM over both extremes (Liu & Liu, 2002). The *Cr* measure of fuzzy events $\{\tilde{\alpha} \leq \gamma\}$, $\{\tilde{\alpha} \geq \gamma\}$, $\left\{\tilde{\beta} \leq \gamma\right\}$ and $\left\{\tilde{\beta} \geq \gamma\right\}$ are shown in Eqs. (31) to (34), respectively:

CR measure

$$Cr\{\tilde{\alpha} \leq \gamma\} = \begin{cases} 0, & if\ \alpha_1 \geq \gamma; \\ \frac{\gamma-\alpha_1}{2\,(\alpha_2-\alpha_1)}, & if\ \alpha_1 \leq \gamma \leq \alpha_2 \\ \frac{\gamma+\alpha_3-2\alpha_2}{2\,(\alpha_3-\alpha_2)}, & if\ \alpha_2 \leq \gamma \leq \alpha_3; \\ 1, & if\ \alpha_3 \leq \gamma. \end{cases} \tag{31}$$

$$Cr\{\tilde{\alpha} \geq \gamma\} = \begin{cases} 1, & if\ \alpha_1 \geq \gamma; \\ \frac{2\alpha_2-\alpha_1-\gamma}{2\,(\alpha_2-\alpha_1)}, & if\ \alpha_1 \leq \gamma \leq \alpha_2; \\ \frac{\alpha_3-\gamma}{2\,(\alpha_3-\alpha_2)}, & if\ \alpha_2 \leq \gamma \leq \alpha_3; \\ 0, & if\ \alpha_3 \leq \gamma. \end{cases} \tag{32}$$

CR measure	
$Cr\{\tilde{\beta} \le \gamma\} = \begin{cases} 0, & if\ \beta_1 \ge \gamma; \\ \frac{\gamma-\beta_1}{2(\beta_2-\beta_1)}, & if\ \beta_1 \le \gamma \le \beta_2; \\ 0.5, & if\ \beta_2 \le \gamma \le \beta_3; \\ \frac{\gamma+\beta_4-2\beta_3}{2(\beta_4-\beta_3)} & if\ \beta_3 \le \gamma \le \beta_4; \\ 1, & if\ \beta_4 \le \gamma. \end{cases}$	(33)
$Cr\{\tilde{\beta} \ge \gamma\} = \begin{cases} 1, & if\ \beta_1 \ge \gamma; \\ \frac{2\beta_2-\beta_1-\gamma}{2(\beta_2-\beta_1)}, & if\ \beta_1 \le \gamma \le \beta_2; \\ 0.5, & if\ \beta_2 \le \gamma \le \beta_3; \\ \frac{\beta_4-\gamma}{2(\beta_4-\beta_3)}, & if\ \beta_3 \le \gamma \le \beta_4; \\ 0, & if\ \beta_4 \le \gamma. \end{cases}$	(34)

According to the *Cr* measure and CCP, the deterministic counterparts and equivalent crisp ones of fuzzy chance constraints under desired confidence level ξ are presented in Eqs. (35) to (38) as follows:

CR measure	
$Cr\{\tilde{\alpha} \le \gamma\} \ge \xi \Leftrightarrow \begin{cases} (1-2\xi)\alpha_1 + (2\xi)\alpha_2 \le \gamma, & if\ \xi \le 0.5; \\ (2-2\xi)\alpha_2 + (2\xi-1)\alpha_3 \le \gamma, & if\ \xi > 0.5. \end{cases}$	(35)
$Cr\{\tilde{\alpha} \ge \gamma\} \ge \xi \Leftrightarrow \begin{cases} (2\xi)\alpha_2 + (1-2\xi)\alpha_3 \ge \gamma, & if\ \xi \le 0.5; \\ (2\xi-1)\alpha_1 + (2-2\xi)\alpha_2 \ge \gamma, & if\ \xi > 0.5. \end{cases}$	(36)
$Cr\{\tilde{\beta} \le \gamma\} \ge \xi \Leftrightarrow \begin{cases} (1-2\xi)\beta_1 + (2\xi)\beta_2 \le \gamma, & if\ \xi \le 0.5; \\ (2-2\xi)\beta_3 + (2\xi-1)\beta_4 \le \gamma, & if\ \xi > 0.5. \end{cases}$	(37)
$Cr\{\tilde{\beta} \ge \gamma\} \ge \xi \Leftrightarrow \begin{cases} (2\xi)\beta_3 + (1-2\xi)\beta_4 \ge \gamma, & if\ \xi \le 0.5; \\ (2\xi-1)\beta_1 + (2-2\xi)\beta_2 \ge \gamma, & if\ \xi > 0.5. \end{cases}$	(38)

As it can be seen from Eqs. (35) to (38), for the confidence level ξ greater or less than 0.5, an equivalent crisp of fuzzy chance constraints based on *Cr* measure is different.

3.4 General fuzzy measure

The general fuzzy measure of a fuzzy event $H \in \Omega(\Psi)$ is defined on $(\Psi, \Omega(\Psi), Pos)$ as $GF\{H\} = Nec\{H\} + (\dagger)(Pos\{H\} - Nec\{H\}) = (\dagger)Pos\{H\} + (1-\dagger)Nec\{H\}$ (Xu & Zhou, 2011, 2013). In other words, general fuzzy measure is equal to the convex combination of *Pos* and *Nec*. The properties of the general fuzzy (*GF*) measure are presented as follows:

- $GF\{\emptyset\} = 0,\ GF\{\Psi\} = 1$
- $\forall H \in \Omega(\Psi) \Rightarrow 0 \le GF\{H\} \le 1$
- $\forall H \in \Omega(\Psi), \dagger \le 0.5 \Rightarrow 0 \le GF\{H\} + GF\{H^C\} \le 1$
- $\forall H \in \Omega(\Psi), \dagger \ge 0.5 \Rightarrow 1 \le GF\{H\} + GF\{H^C\} \le 2$

- $\forall H, Q \in \Omega(\Psi), H \subseteq Q \Rightarrow GF\{H\} \leq GF\{Q\}$
- $\forall H, Q \in \Omega(\Psi), \dagger \geq 0.5 \Rightarrow GF\{H \cup Q\} \leq GF\{H\} + GF\{Q\}$
- $\forall H \in \Omega(\Psi) \Rightarrow Pos\{H\} \geq GF\{H\} \geq Nec\{H\}$

The *GF* measure $\dagger\,(0 \leq \dagger \leq 1)$ is the optimistic-pessimistic parameter to determine the attitude of a DM. The *GF* measure of fuzzy events $\{\tilde{\alpha} \leq \gamma\}$, $\{\tilde{\alpha} \geq \gamma\}$, $\left\{\tilde{\beta} \leq \gamma\right\}$ and $\left\{\tilde{\beta} \geq \gamma\right\}$ are shown in Eqs. (39) to (42), respectively:

GF measure

$$GF\{\tilde{\alpha} \leq \gamma\} = \begin{cases} 0, & if\ \alpha_1 \geq \gamma; \\ \dagger\left(\frac{\gamma-\alpha_1}{\alpha_2-\alpha_1}\right), & if\ \alpha_1 \leq \gamma \leq \alpha_2; \\ \dagger + (1-\dagger)\left(\frac{\gamma-\alpha_2}{\alpha_3-\alpha_2}\right), & if\ \alpha_2 \leq \gamma \leq \alpha_3; \\ 1, & if\ \alpha_3 \leq \gamma. \end{cases} \tag{39}$$

$$GF\{\tilde{\alpha} \geq \gamma\} = \begin{cases} 1, & if\ \alpha_1 \geq \gamma; \\ \dagger + (1-\dagger)\left(\frac{\alpha_2-\gamma}{\alpha_2-\alpha_1}\right), & if\ \alpha_1 \leq \gamma \leq \alpha_2; \\ \dagger\left(\frac{\alpha_3-\gamma}{\alpha_3-\alpha_2}\right), & if\ \alpha_2 \leq \gamma \leq \alpha_3; \\ 0, & if\ \alpha_3 \leq \gamma. \end{cases} \tag{40}$$

$$GF\left\{\tilde{\beta} \leq \gamma\right\} = \begin{cases} 0, & if\ \beta_1 \geq \gamma; \\ \dagger\left(\frac{\gamma-\beta_1}{\beta_2-\beta_1}\right), & if\ \beta_1 \leq \gamma \leq \beta_2; \\ \dagger, & if\ \beta_2 \leq \gamma \leq \beta_3; \\ \dagger + (1-\dagger)\left(\frac{\gamma-\beta_3}{\beta_4-\beta_3}\right), & if\ \beta_3 \leq \gamma \leq \beta_4; \\ 1, & if\ \beta_4 \leq \gamma. \end{cases} \tag{41}$$

$$GF\left\{\tilde{\beta} \geq \gamma\right\} = \begin{cases} 1, & if\ \beta_1 \geq \gamma; \\ \dagger + (1-\dagger)\left(\frac{\beta_2-\gamma}{\beta_2-\beta_1}\right), & if\ \beta_1 \leq \gamma \leq \beta_2; \\ \dagger, & if\ \beta_2 \leq \gamma \leq \beta_3; \\ \dagger\left(\frac{\beta_4-\gamma}{\beta_4-\beta_3}\right), & if\ \beta_3 \leq \gamma \leq \beta_4; \\ 0, & if\ \beta_4 \leq \gamma. \end{cases} \tag{42}$$

According to the *GF* measure and CCP, the deterministic counterparts and equivalent crisp ones of fuzzy chance constraints under desired confidence level ξ for both conditions of ξ greater or less than $\dagger$, are presented in Eqs. (43) to (46) as follows:

GF measure

$$GF\{\tilde{\alpha} \leq \gamma\} \geq \xi \Leftrightarrow \begin{cases} \left(\frac{\dagger-\xi}{\dagger}\right)\alpha_1 + \left(\frac{\xi}{\dagger}\right)\alpha_2 \leq \gamma, & if\ \xi \leq \dagger; \\ \left(\frac{1-\xi}{1-\dagger}\right)\alpha_2 + \left(\frac{\xi-\dagger}{1-\dagger}\right)\alpha_3 \leq \gamma, & if\ \xi > \dagger. \end{cases} \tag{43}$$

$$GF\{\tilde{\alpha} \geq \gamma\} \geq \xi \Leftrightarrow \begin{cases} \left(\frac{\xi}{\dagger}\right)\alpha_2 + \left(\frac{\dagger-\xi}{\dagger}\right)\alpha_3 \geq \gamma, & if\ \xi \leq \dagger; \\ \left(\frac{\xi-\dagger}{1-\dagger}\right)\alpha_1 + \left(\frac{1-\xi}{1-\dagger}\right)\alpha_2 \geq \gamma, & if\ \xi > \dagger. \end{cases} \tag{44}$$

GF measure

$$GF\{\tilde{\beta} \le \gamma\} \ge \xi \Leftrightarrow \begin{cases} \left(\frac{\dagger-\xi}{\dagger}\right)\beta_1 + \left(\frac{\xi}{\dagger}\right)\beta_2 \le \gamma, & \text{if } \xi \le \dagger; \\ \left(\frac{1-\xi}{1-\dagger}\right)\beta_3 + \left(\frac{\xi-\dagger}{1-\dagger}\right)\beta_4 \le \gamma, & \text{if } \xi > \dagger. \end{cases} \tag{45}$$

$$GF\{\tilde{\beta} \le \gamma\} \ge \xi \Leftrightarrow \begin{cases} \left(\frac{\xi}{\dagger}\right)\beta_3 + \left(\frac{\dagger-\xi}{\dagger}\right)\beta_4 \ge \gamma, & \text{if } \xi \le \dagger; \\ \left(\frac{\xi-\dagger}{1-\dagger}\right)\beta_1 + \left(\frac{1-\xi}{1-\dagger}\right)\beta_2 \ge \gamma, & \text{if } \xi > \dagger. \end{cases} \tag{46}$$

It should be noted that in special cases, if the † is set equal to 1, 0 and 0.5, the *GF* measure is converted to *Pos*, *Nec* and *Cr* measures, respectively (Xu & Zhou, 2013). The main characteristics of *Pos*, *Nec*, *Cr* and *GF* measures as well as FCCDEA models can be summarized in Fig. 4:

As it can be seen in Fig. 4, in the *GF* measure only by setting †, the desired attitude of DM can be achieved. As a result, in recent years, the popularity and applicability of *GF* measure is increasing among researchers and it is wieldy used in real-world problems under fuzzy environment.

4 Fuzzy chance-constrained data envelopment analysis (FCCDEA)

In this section, fuzzy chance-constrained DEA models are proposed which are based on possibility, necessity, credibility and general fuzzy approaches. It is noteworthy that the FCCDEA models will be presented based on the basic DEA model, i.e., CCR (M-F & I-O) model. Moreover, with respect to the generality of trapezoidal fuzzy number, data uncertainty is intended to be in all inputs and outputs under trapezoidal distribution $\tilde{x} = \left(x^{(1)}, x^{(2)}, x^{(3)}, x^{(4)}\right) x^{(1)} < x^{(2)} < x^{(3)} < x^{(4)}$ and $\tilde{y} = \left(y^{(1)}, y^{(2)}, y^{(3)}, y^{(4)}\right) y^{(1)} < y^{(2)} < y^{(3)} < y^{(4)}$. Accordingly, in the first step, to deal with the uncertainty of inputs and outputs, Model (1) is converted to Model (47) as follows:

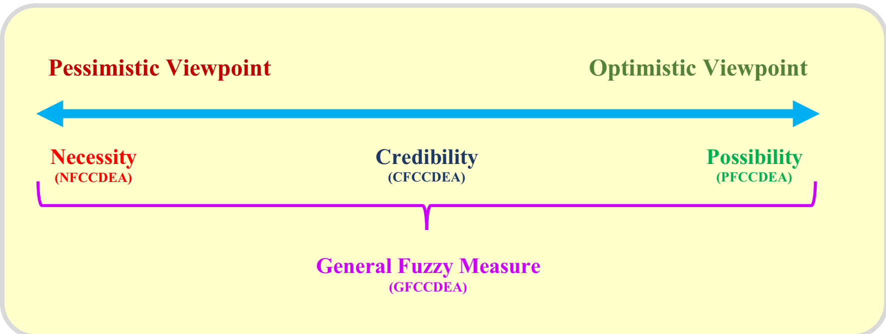


Fig. 4 The attitude of fuzzy measures

Uncertain DEA

$$\begin{aligned}
&\text{Max} \quad \Delta &(47)\\
&\text{S.t.} \quad \sum_{r=1}^{s} \tilde{y}_{ro} u_r \geq \Delta\\
&\sum_{i=1}^{m} \tilde{x}_{io} v_i \leq 1\\
&\sum_{r=1}^{s} \tilde{y}_{rj} u_r - \sum_{i=1}^{m} \tilde{x}_{ij} v_i \leq 0, \quad \forall j\\
&v_i,\ u_r \geq 0, \quad \forall i, r
\end{aligned}$$

The optimal solution of Model (47) is equal to Model (1) (for more details see Peykani et al., 2018a, b). Then, in the second step, in order to deal with uncertainty of fuzzy chance constraints in uncertain DEA model and convert them to their equivalent crisp values, suitable fuzzy measure and chance-constrained programming in form of FCCP can be used as follows:

FCCDEA

$$\begin{aligned}
&\text{Max} \quad \Delta &(48)\\
&\text{S.t.} \quad \underset{(Pos, Nec, Cr, GF)}{Measure} \left\{ \sum_{r=1}^{s} \tilde{y}_{ro} u_r \geq \Delta \right\} \geq \xi\\
&\underset{(Pos, Nec, Cr, GF)}{Measure} \left\{ \sum_{i=1}^{m} \tilde{x}_{io} v_i \leq 1 \right\} \geq \xi\\
&\underset{(Pos, Nec, Cr, GF)}{Measure} \left\{ \sum_{r=1}^{s} \tilde{y}_{rj} u_r - \sum_{i=1}^{m} \tilde{x}_{ij} v_i \leq 0 \right\} \geq \xi, \quad \forall j\\
&v_i,\ u_r \geq 0, \quad \forall i, r
\end{aligned}$$

4.1 Possibility-based FCCDEA (PFCCDEA)

According to the *Pos* approach and using Eqs. (21) and (22), the PFCCDEA model is proposed as Model (49):

PFCCDEA

$$\begin{aligned}
&\text{Max} \quad \Delta_{\text{POS}} &(49)\\
&\text{S.t.} \quad \sum_{r=1}^{s} \left((\xi) y_{ro}^{(3)} + (1-\xi) y_{ro}^{(4)}\right) u_r \geq \Delta_{\text{POS}}\\
&\sum_{i=1}^{m} \left((1-\xi) x_{io}^{(1)} + (\xi) x_{io}^{(2)}\right) v_i \leq 1\\
&\sum_{r=1}^{s} \left((1-\xi) y_{rj}^{(1)} + (\xi) y_{rj}^{(2)}\right) u_r - \sum_{i=1}^{m} \left((\xi) x_{ij}^{(3)} + (1-\xi) x_{ij}^{(4)}\right) v_i \leq 0, \quad \forall j\\
&v_i,\ u_r \geq 0, \quad \forall i, r
\end{aligned}$$

4.2 Necessity-based FCCDEA (NFCCDEA)

According to the *Nec* approach and using Eqs. (29) and (30), the NFCCDEA model is proposed as Model (50):

NFCCDEA

$$\text{Max} \quad \Delta_{\text{NEC}} \tag{50}$$

$$\text{S.t.} \quad \sum_{r=1}^{s} \left((\xi)y_{ro}^{(1)} + (1-\xi)y_{ro}^{(2)}\right)u_r \geq \Delta_{\text{NEC}}$$

$$\sum_{i=1}^{m} \left((1-\xi)x_{io}^{(3)} + (\xi)x_{io}^{(4)}\right)v_i \leq 1$$

$$\sum_{r=1}^{s} \left((1-\xi)y_{rj}^{(3)} + (\xi)y_{rj}^{(4)}\right)u_r - \sum_{i=1}^{m} \left((\xi)x_{ij}^{(1)} + (1-\xi)x_{ij}^{(2)}\right)v_i \leq 0, \quad \forall j$$

$$v_i, u_r \geq 0, \quad \forall i, r$$

4.3 Credibility-based FCCDEA (CFCCDEA)

According to the *Cr* approach and using Eqs. (37) and (38), the CFCCDEA model is proposed as Model (51). It is noteworthy that that in the *Cr* approach, an equivalent crisp of fuzzy chance constraints for the ξ greater or less than 0.5, is different. As a result, a binary variable Υ and a sufficient big number M are employed in Model (51), for the linearization of incompatible constraints.

CFCCDEA

$$\text{Max} \quad \Delta_{\text{CR}} \tag{51}$$

$$\text{S.t.} \quad \sum_{r=1}^{s} \left((2\xi)y_{ro}^{(3)} + (1-2\xi)y_{ro}^{(4)}\right)u_r \geq \Delta_{\text{CR}} - \text{M}\Upsilon$$

$$\sum_{r=1}^{s} \left((2\xi-1)y_{ro}^{(1)} + (2-2\xi)y_{ro}^{(2)}\right)u_r \geq \Delta_{\text{CR}} - \text{M}(1-\Upsilon)$$

$$\sum_{i=1}^{m} \left((1-2\xi)x_{io}^{(1)} + (2\xi)x_{io}^{(2)}\right)v_i \leq 1 + \text{M}\,\Upsilon$$

$$\sum_{i=1}^{m} \left((2-2\xi)x_{io}^{(3)} + (2\xi-1)x_{io}^{(4)}\right)v_i \leq 1 + \text{M}\,(1-\Upsilon)$$

$$\sum_{r=1}^{s} \left((1-2\xi)y_{rj}^{(1)} + (2\xi)y_{rj}^{(2)}\right)u_r - \sum_{i=1}^{m} \left((2\xi)x_{ij}^{(3)} + (1-2\xi)x_{ij}^{(4)}\right)v_i \leq \text{M}\Upsilon, \quad \forall j$$

$$\sum_{r=1}^{s} \left((2-2\xi)y_{rj}^{(3)} + (2\xi-1)y_{rj}^{(4)}\right)u_r - \sum_{i=1}^{m} \left((2\xi-1)x_{ij}^{(1)} + (2-2\xi)x_{ij}^{(2)}\right)v_i \leq \text{M}\,(1-\Upsilon), \quad \forall j$$

$$\xi \leq 0.5 + \text{M}\,\Upsilon$$

$$\xi > 0.5 - \text{M}\,(1-\Upsilon)$$

$$\Upsilon \in \{0, 1\}$$

$$v_i, u_r \geq 0, \quad \forall i, r$$

4.4 General fuzzy-based FCCDEA (GFCCDEA)

According to the *GF* approach and using Eqs. (45) and (46), the GFCCDEA model is proposed as Model (52):

GFCCDEA

$$
\begin{aligned}
&\text{Max} \quad \Delta_{GF} && (52)\\
&\text{S.t.} \quad \sum_{r=1}^{s}\left(\left(\tfrac{\xi}{\dagger}\right)y_{ro}^{(3)} + \left(\tfrac{\dagger-\xi}{\dagger}\right)y_{ro}^{(4)}\right)u_r \geq \Delta_{GF} - \mathrm{M}\,\Upsilon\\
&\sum_{r=1}^{s}\left(\left(\tfrac{\xi-\dagger}{1-\dagger}\right)y_{ro}^{(1)} + \left(\tfrac{1-\xi}{1-\dagger}\right)y_{ro}^{(2)}\right)u_r \geq \Delta_{GF} - \mathrm{M}\,(1-\Upsilon)\\
&\sum_{i=1}^{m}\left(\left(\tfrac{\dagger-\xi}{\dagger}\right)x_{io}^{(1)} + \left(\tfrac{\xi}{\dagger}\right)x_{io}^{(2)}\right)v_i \leq 1 + \mathrm{M}\,\Upsilon\\
&\sum_{i=1}^{m}\left(\left(\tfrac{1-\xi}{1-\dagger}\right)x_{io}^{(3)} + \left(\tfrac{\xi-\dagger}{1-\dagger}\right)x_{io}^{(4)}\right)v_i \leq 1 + \mathrm{M}\,(1-\Upsilon)\\
&\sum_{r=1}^{s}\left(\left(\tfrac{\dagger-\xi}{\dagger}\right)y_{rj}^{(1)} + \left(\tfrac{\xi}{\dagger}\right)y_{rj}^{(2)}\right)u_r - \sum_{i=1}^{m}\left(\left(\tfrac{\xi}{\dagger}\right)x_{ij}^{(3)} + \left(\tfrac{\dagger-\xi}{\dagger}\right)x_{ij}^{(4)}\right)v_i \leq \mathrm{M}\,\Upsilon, \quad \forall j\\
&\sum_{r=1}^{s}\left(\left(\tfrac{1-\xi}{1-\dagger}\right)y_{rj}^{(3)} + \left(\tfrac{\xi-\dagger}{1-\dagger}\right)y_{rj}^{(4)}\right)u_r - \sum_{i=1}^{m}\left(\left(\tfrac{\xi-\dagger}{1-\dagger}\right)x_{ij}^{(1)} + \left(\tfrac{1-\xi}{1-\dagger}\right)x_{ij}^{(2)}\right)v_i \leq \mathrm{M}\,(1-\Upsilon), \quad \forall j\\
&\xi \leq \dagger + \mathrm{M}\,\Upsilon\\
&\xi > \dagger - \mathrm{M}\,(1-\Upsilon)\\
&\Upsilon \in \{0,1\}\\
&v_i,\ u_r \geq 0, \quad \forall i, r
\end{aligned}
$$

Similar to CFCCDEA model, by applying a binary variable Υ and a sufficient big number M, the linearization of incompatible constraints for the ξ greater or less $\dagger$ than are made in Model (52). In the GFCCDEA model only by setting $\dagger$, the desired attitude of DM can be achieved. In special cases, if the optimistic-pessimistic parameter $\dagger$ is set equal to 1, 0 and 0.5, GFCCDEA model can be converted to PFCCDEA, NFCCDEA, and CFCCDEA models, respectively (for more detail see Peykani et al., 2019a, b, c). Also, for the optimistic-pessimistic parameter $\dagger$, efficiency scores of DMUs decrease while the confidence level ξ increases. Additionally, as shown in Fig. 4, by increasing optimistic-pessimistic parameter $\dagger$, the attitudes of DM are changed from pessimistic to optimistic viewpoint in order to measure the chances of occurrence of fuzzy events.

The efficiency scores of DMUs under crisp (certain) data are less than or equal to one. But in uncertain DEA especially FCCDEA model, this relation may be violated. As a result, by calculating the efficiency scores of DMUs for the same optimistic-pessimistic attitude, the DMUs can be classified under FCCDEA approach as follows:

- A DMU is ultra-efficient (Θ^{++}) if its efficiency scores Δ^* for all confidence levels ξ are greater than or equal to one.
- A DMU is marginal-efficient (Θ^{+}) if its efficiency scores Δ^* for some of confidence levels ξ are greater than or equal to one.

- A DMU is inefficient (Θ^-) if its efficiency scores Δ^* for all confidence levels ξ are less than one.

At the end of this section, it is worthwhile to mention that fuzzy chance-constrained DEA models can be presented based on other basic DEA models and characteristics in a similar manner.

5 A Structured literature review of fuzzy chance-constrained DEA

In this section, a comprehensive and structured literature review of FCCDEA studies will be presented. Accordingly, a systematic and comprehensive search is done in different database including Web of Science (WoS), Scopus, and Google Scholar as well as popular publishers such as Elsevier, Springer, Wiley-Blackwell, Taylor & Francis, Sage, Wolters Kluwer, Emerald, Inderscience, and IEEE.

The search strategy of the paper is illustrated in Fig. 5. According to the Fig. 5, the aforementioned keywords were searched in "Title, Abstract, Keywords" of documents belonging to WoS, Scopus, and Google Scholar databases. Then, duplicate documents are eliminated and grey literature is excluded. Finally, 87 relevant researches were found in FCCDEA literature from 2000 to 2020.

5.1 Bibliometric analysis of FCCDEA literature

In the first step, the bibliometric information of fuzzy chance-constrained DEA Literature is presented in Table 1. It should be noted that in this section, the research code of each FCCDEA study is employed for reference in all tables.

The statistical information of fuzzy chance-constrained DEA studies including the quantity of researches per year, the growing trend of FCCDEA field, and distribution of publication type, are presented in Fig. 6:

According to the Fig. 6, the FCCDEA studies have increased rapidly in the last decade and the growing trend is expected for literature of FCCDEA in the future. In order to examine the place of the FCCDEA field among journals, the most influential journals in the fuzzy chance-constrained DEA literature are introduced in Table 2:

As it can be seen in Table 2, numerous articles of FCCDEA literature have been published in top-tier journals, which this point indicates on the importance, applicability, and attractiveness of this area.

At the end of bibliometric analysis, statistics based on top contributing affiliations in FCCDEA literature is introduced. Accordingly, Fig. 7 presents the most influential countries/territories as well as organizations/institutions along-with their number of FCCDEA publications:

According to the Fig. 7, top 5 contributing countries in FCCDEA area are Iran, China, USA, Thailand, and Canada, respectively. Also, top 5 contributing university in FCCDEA field are Islamic Azad University (IAU), Iran University of Science and

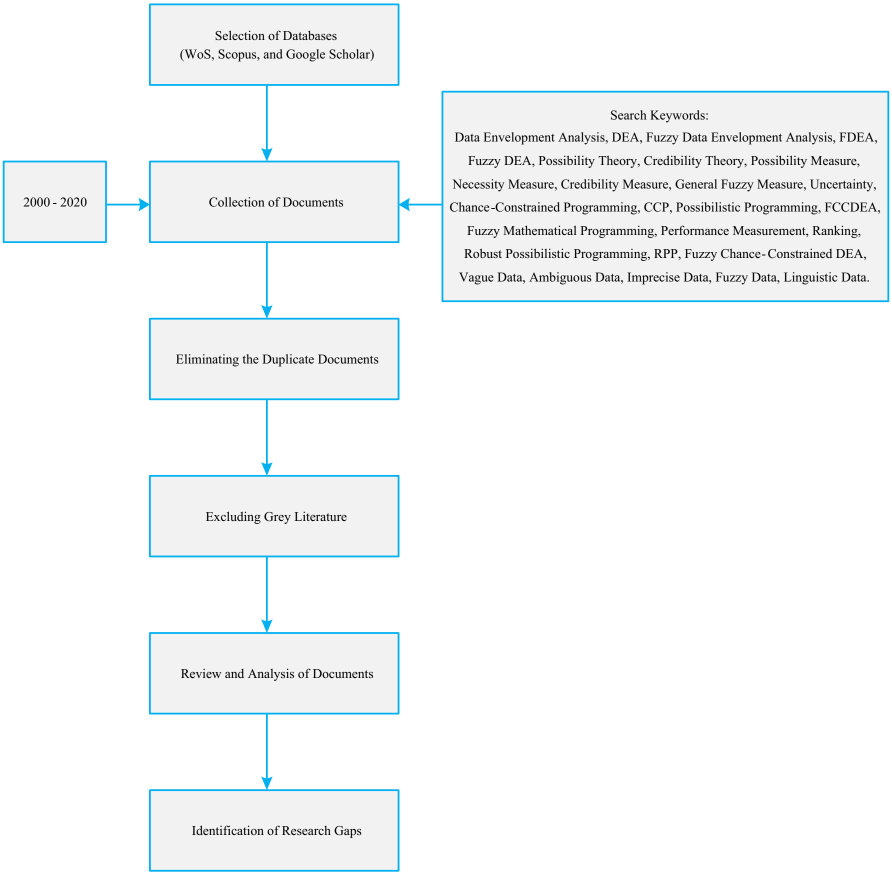


Fig. 5 Research methodology and search strategy

Technology (IUST), Hebei University, La Salle University, and Beihang University, respectively.

5.2 A Survey of features and applications of FCCDEA researches

In the second step, all 87 fuzzy chance-constrained DEA studies are examined according to their perspectives, number of DMUs, number of inputs and outputs, uncertainty type of data, the research objective, the research feature, and the research application which the results are introduced in Table 3:

As is seen in Table 3, most of the research applies fuzzy chance-constrained DEA approach in real-world application and this point demonstrates the applicability of FCCDEA field. The analysis of applications in FCCDEA literature indicated that most researches address assessments in the fields of banking (9 researches), health care (7 researches), supply chain (7 researches), and financial market (5 researches) in order to performance measurement of DMUs under uncertainty environment.

Table 1 The fuzzy chance-constrained DEA studies

Research code	References	Publication	Publication type
FCCDEA 01	Guo et al. (2000)	IEEE transactions on systems, man, and cybernetics: systems	JP
FCCDEA 02	Lertworasirikul (2002)	North Carolina State University	PT
FCCDEA 03	Lertworasirikul et al. (2002a)	Joint conference on information sciences	CP
FCCDEA 04	Lertworasirikul et al. (2002b)	Bellman continuum	CP
FCCDEA 05	Lertworasirikul et al. (2003a)	Fuzzy sets and systems	JP
FCCDEA 06	Lertworasirikul et al. (2003b)	Fuzzy optimization and decision making	JP
FCCDEA 07	Garcia et al. (2005)	Progress in nuclear energy	JP
FCCDEA 08	Ramezanzadeh et al. (2005)	Iranian journal of fuzzy systems	JP
FCCDEA 09	Punyangarm et al. (2006)	Asia pacific industrial engineering and management systems conference	CP
FCCDEA 10	Wu et al. (2006)	Applied mathematics and computation	JP
FCCDEA 11	Jiang and Yang (2007)	International journal of business and management	JP
FCCDEA 12	Meng and Liu (2007)	International conference on fuzzy systems and knowledge discovery	CP
FCCDEA 13	Wen and You (2007)	Technical report	TR
FCCDEA 14	Nedeljković and Drenovac (2008)	PosTel	JP
FCCDEA 15	Punyangarm et al. (2008)	Thailand statistician	JP
FCCDEA 16	Qin and Liu (2008)	International conference on machine learning and cybernetics	CP
FCCDEA 17	Qin et al. (2009)	International symposium on neural networks	BC
FCCDEA 18	Wen and Li (2009)	Journal of computational and applied mathematics	JP
FCCDEA 19	Dai et al. (2010)	International conference in swarm intelligence	CP
FCCDEA 20	Ketsarapong and Punyangarm (2010)	Industrial engineering and management systems	JP
FCCDEA 21	Khodabakhshi et al. (2010)	Applied mathematical modelling	JP
FCCDEA 22	Khodabakhshi and Kheirollahi (2010)	International conference of fuzzy information and engineering	CP
FCCDEA 23	Lin (2010)	Computers & industrial engineering	JP
FCCDEA 24	Punyangarm (2010)	Conference proceedings	CP
FCCDEA 25	Wen et al. (2010)	Computers and mathematics with applications	JP
FCCDEA 26	Hosseinzadeh Lotfi et al. (2011)	African journal of business management	JP

Table 1 (continued)

Research code	References	Publication	Publication type
FCCDEA 27	Meng et al. (2011)	International conference on fuzzy systems and knowledge discovery	CP
FCCDEA 28	Qin et al. (2011)	Expert systems with applications	JP
FCCDEA 29	Wen et al. (2011a)	Fuzzy optimization and decision making	JP
FCCDEA 30	Wen et al. (2011b)	Information-an international interdisciplinary journal	JP
FCCDEA 31	Zuojun et al. (2011)	Procedia engineering	JP
FCCDEA 32	Nedeljković and Drenovac (2012)	International journal for traffic and transport engineering	JP
FCCDEA 33	Tavana et al. (2013)	Expert systems with applications	JP
FCCDEA 34	Zhao and Yue (2012)	Procedia computer science	JP
FCCDEA 35	Bai-Qing et al. (2013)	International conference on management science and engineering	CP
FCCDEA 36	Payan and Shariff (2013)	Journal of uncertain systems	JP
FCCDEA 37	Tavana et al. (2013)	Knowledge-based systems	JP
FCCDEA 38	Wen et al. (2013)	Information	JP
FCCDEA 39	Agarwal (2014)	International conference on soft computing for problem solving	CP
FCCDEA 40	Kheirollahi (2014)	National conference on data envelopment analysis	CP
FCCDEA 41	Meng (2014)	Expert systems with applications	JP
FCCDEA 42	Paryab et al. (2014)	Journal of intelligent & fuzzy systems	JP
FCCDEA 43	Shiraz et al. (2014a)	Expert systems with applications	JP
FCCDEA 44	Shiraz et al. (2014b)	International journal of data analysis techniques and strategies	JP
FCCDEA 45	Azadi et al. (2015)	Computers and operations research	JP
FCCDEA 46	Fasanghari et al. (2015)	Applied soft computing	JP
FCCDEA 47	Feng et al. (2015)	Journal of uncertain systems	JP
FCCDEA 48	Paryab et al. (2015)	International journal of data mining, modelling and management	JP
FCCDEA 49	Payan (2015)	Journal of intelligent & fuzzy systems	JP
FCCDEA 50	Wen (2015)	Uncertain data Envelopment analysis	BC

Table 1 (continued)

Research code	References	Publication	Publication type
FCCDEA 51	Zerafat Angiz et al. (2015)	Computers and industrial engineering	JP
FCCDEA 52	Nasseri et al. (2016)	International journal of applied decision sciences	JP
FCCDEA 53	Yaghoubi et al. (2016)	Journal of optimization in industrial engineering	JP
FCCDEA 54	Zhou et al. (2016)	Applied soft computing	JP
FCCDEA 55	Agarwal (2017)	International journal of business and systems research	JP
FCCDEA 56	Kheirollahi et al. (2017)	Croatian operational research review	JP
FCCDEA 57	Ruiz and Sirvent (2017)	Fuzzy optimization and decision making	JP
FCCDEA 58	Tlig and Ben Hamed (2017)	Journal of data envelopment analysis and decision science	JP
FCCDEA 59	Yousefi et al. (2017)	Journal of cleaner production	JP
FCCDEA 60	Zhou et al. (2017)	International conference on management science and engineering management	CP
FCCDEA 61	Ahmadvand and Pishvaee (2018)	Health care management science	JP
FCCDEA 62	Izadikhah and Khoshroo (2018)	RAIRO-operations research	JP
FCCDEA 63	Kumar et al. (2018)	Quality, IT and business operations	BC
FCCDEA 64	Nasseri et al. (2018)	International journal of fuzzy systems	JP
FCCDEA 65	Peykani and Mohammadi (2018)	International Conference on intelligent decision science	CP
FCCDEA 66	Peykani et al. (2018a)	RAIRO-operations research	JP
FCCDEA 67	Peykani et al. (2018b)	International journal of hospital research	JP
FCCDEA 68	Sabouhi et al. (2018)	Computers and industrial engineering	JP
FCCDEA 69	Wardana et al. (2018)	International journal of industrial and systems engineering	JP
FCCDEA 70	Zhou et al. (2018)	Journal of cleaner production	JP
FCCDEA 71	Amini et al. (2019)	Decision science letters	JP
FCCDEA 72	Ebrahimnejad et al. (2019a)	RAIRO-operations research	JP
FCCDEA 73	Ebrahimnejad et al. (2019b)	International journal of information technology and decision making	JP
FCCDEA 74	Gholizadeh and Fazlollahtabar (2019)	International journal of mathematical, engineering and management sciences	JP

Table 1 (continued)

Research code	References	Publication	Publication type
FCCDEA 75	Ji et al. (2019a)	Journal of the operational research society	JP
FCCDEA 76	Ji et al. (2019b)	Health care management science	JP
FCCDEA 77	Mehrasa and Behzadi (2019)	Soft computing	JP
FCCDEA 78	Nasseri and Khatir (2019)	Journal of intelligent and fuzzy systems	JP
FCCDEA 79	Nosrat et al. (2019)	Journal of intelligent and fuzzy systems	JP
FCCDEA 80	Peykani et al. (2019a)	Expert systems with applications	JP
FCCDEA 81	Peykani et al. (2019b)	Advances in mathematical finance and applications	JP
FCCDEA 82	Peykani et al. (2019c)	Conference on data envelopment analysis	CP
FCCDEA 83	Seyed Esmaeili et al. (2019)	Conference on data envelopment analysis	CP
FCCDEA 84	Roghaee et al. (2020)	International journal of management and decision making	JP
FCCDEA 85	Shiraz et al. (2020)	Soft computing	JP
FCCDEA 86	Wang et al. (2020)	Conference on system science and engineering	CP
FCCDEA 87	Wardana et al. (2020)	Cogent engineering	JP

JP Journal Paper, *CP* Conference Paper, *BC* Book Chapter, *PT* Ph.D. Thesis, *TR* Technical Report

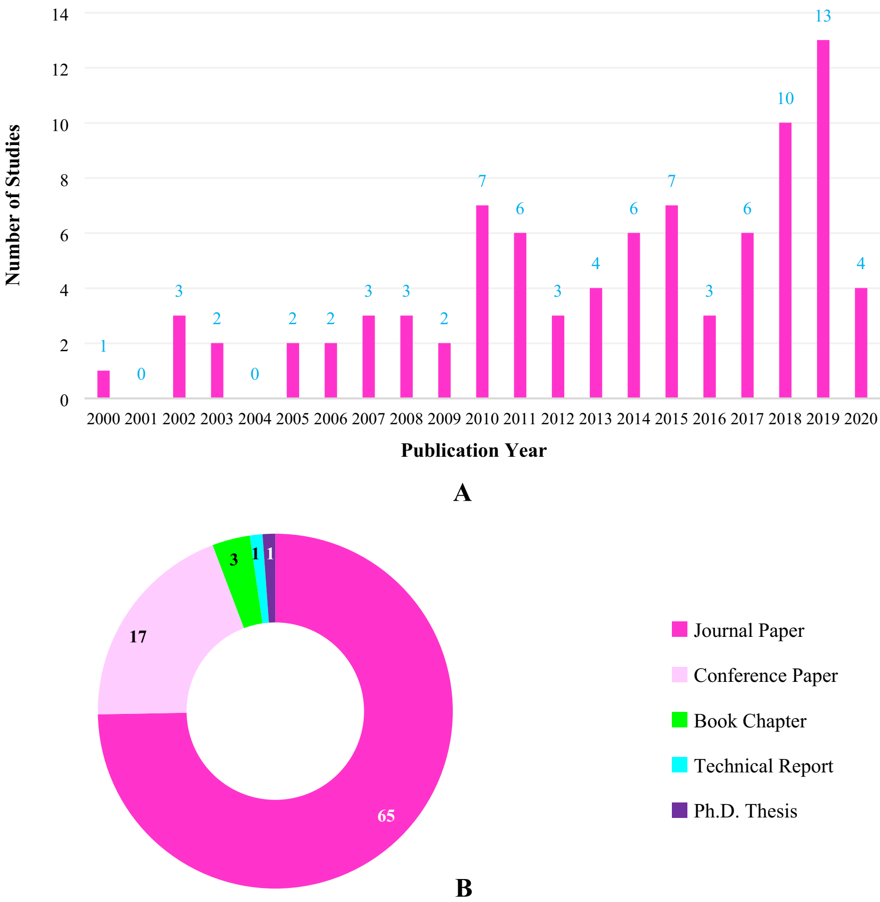


Fig. 6 Bibliometric Information of FCCDEA Literature (A) Distribution of Studies per Year, (B) Distribution of Publication Type

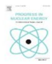
Moreover Fig. 8 shows the frequency analysis of data uncertainty type in FCCDEA literature:

It should be explained that the application of mixed uncertainty to demonstrate an uncertain parameter is becoming more and more popular among researchers.

5.3 Analysis of FCCDEA studies in terms of modeling

In the third step, fuzzy chance-constrained DEA studies are classified according to the type of FCCDEA models including basic DEA model, projection construction, form, orientation, RTS, the uncertain data, fuzzy measures, hybrid uncertain programming approaches and class of proposed FCCDEA model which are reported in Table 4. Moreover, the statistical information of FCCDEA models is presented in Fig. 9:

Table 2 The top publishing journals contributing to the FCCDEA literature

Journal (Number of Papers)		Journal (Number of Papers)	
	Expert Systems with Applications (**5**)		Computers & Operations Research (**1**)
	Journal of Intelligent & Fuzzy Systems (**4**)		Computers and Mathematics with Applications (**1**)
	Computers & Industrial Engineering (**3**)		Fuzzy Sets and Systems (**1**)
	Fuzzy Optimization and Decision Making (**3**)		IEEE Transactions on Systems, Man, and Cybernetics: Systems (**1**)
	RAIRO-Operations Research (**3**)		International Journal of Fuzzy Systems (**1**)
	Applied Soft Computing (**2**)		International Journal of Information Technology & Decision Making (**1**)
	Health Care Management Science (**2**)		Iranian Journal of Fuzzy Systems (**1**)
	Journal of Cleaner Production (**2**)		Journal of Computational and Applied Mathematics (**1**)
	Soft Computing (**2**)		Journal of the Operational Research Society (**1**)
	Applied Mathematical Modelling (**1**)		Knowledge-Based Systems (**1**)
	Applied Mathematics and Computation (**1**)		Progress in Nuclear Energy (**1**)

As can be seenin Table 4 and Fig. 9, most studies presented fuzzy chance-constrained DEA model based on input-oriented multiplier CCR (M-F & I-O) model. Also, the most commonly used uncertain measures in FCCDEA literature are possibility and credibility, respectively.

6 Conclusions and future research directions

The integration of data envelopment analysis method and fuzzy chance-constrained programming in context of FCCDEA, is one of the applicable and effective approach that wieldy employed for performance measurement of DMUs under data ambiguity. Accordingly, this paper introduced a comprehensive literature review of fuzzy chance-constrained DEA. Moreover, all FCCDEA studies are analyzed and classified according to several aspects and factors such as bibliometric information, the features and objectives of the FCCDEA model, real-world

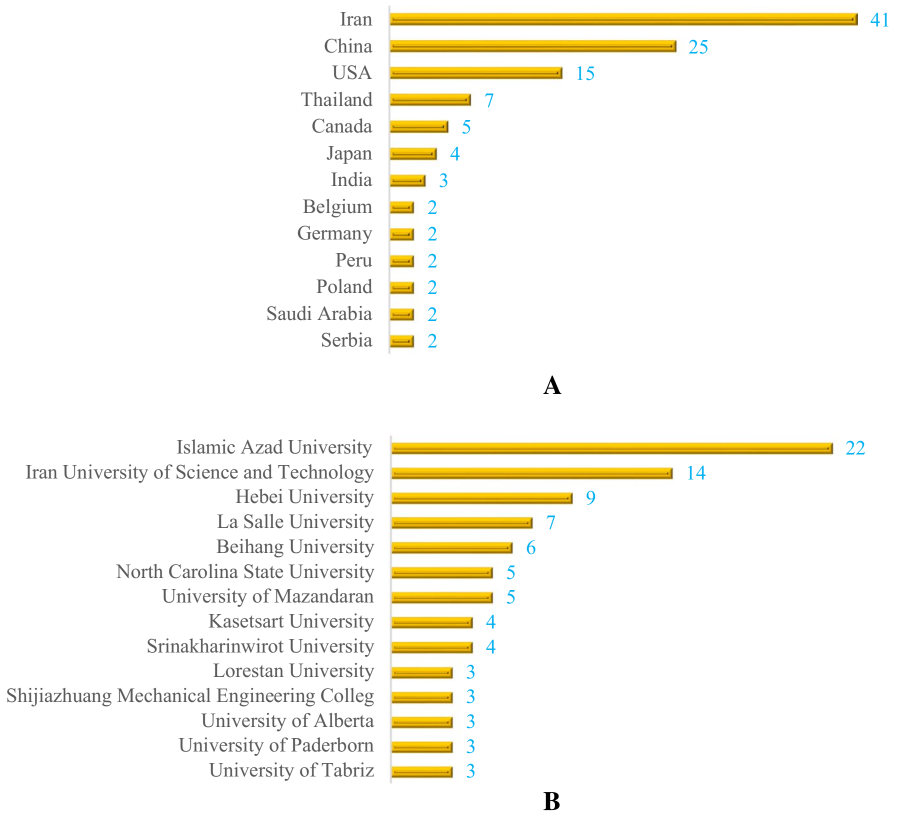


Fig. 7 Top contributing affiliations in FCCDEA literature. (A) Countries/Territories, (B) Organizations/ Institutions

application and case study, basic DEA model, characteristics of DEA modeling, type of uncertainty, and uncertain measures.

Now, pursuant to the classification, observations, and discussions of previous sections, the research fronts in FCCDEA field will be proposed to guide future researches. The following areas are suggested for future researches:

- *Adjustable Fuzzy Data Envelopment Analysis (AFDEA)* Presenting FCCDEA approach based on general fuzzy measure for handling all attitudes of DM only by setting an adjustable optimistic-pessimistic parameter (for more details see Xu & Zhou, 2011, 2013; Peykani et al., 2019a, b, c).
- *Fuzzy Network Data Envelopment Analysis (FNDEA)* Proposing fuzzy network chance-constrained DEA approach for performance assessment and ranking of homogeneous DMUs with network structure such as two-stage, series, parallel, and mixed (for more details seeKao & Hwang, 2008; Chen et al., 2009; Kao, 2014, 2017; Peykani et al., 2021).

Table 3 The features, objectives, and applications of FCCDEA studies

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 01	✓	✓		✓	5	1	4	✓					Ranking	Unity input	ACM system
FCCDEA 02	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 03	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 04	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 05	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 06	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 07		✓		✓	13			✓					Ranking	FMEA/linguistic variable	AFW system

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 08	✓		✓		4	2	1			✓			Performance evaluation		
FCCDEA 09	✓									✓			Performance evaluation		
FCCDEA 10		✓		✓	808	7	6	✓					Performance evaluation	Linguistic variable	Cross-region bank branches
FCCDEA 11	✓		✓					✓					Performance evaluation		
FCCDEA 12	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 13	✓		✓					✓					Performance evaluation		

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 14		✓		✓				✓					Performance evaluation		Post offices
FCCDEA 15	✓		✓		4	4	1			✓			Performance evaluation	MOP	
FCCDEA 16	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 17	✓		✓		8	5	3		✓				Performance evaluation		
FCCDEA 18	✓		✓		5	2	2	✓					Ranking	FS/GA	
FCCDEA 19	✓		✓		5	2	2	✓					Performance evaluation	EV	
FCCDEA 20	✓	✓	✓	✓				✓					Ranking	AHP/FMEA/dummy input	Production of liquid medicine

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 21	✓		✓		3	1	1	✓					Estimating returns to Scale	Stochastic DEA	
FCCDEA 22	✓							✓					Measuring congestion		
FCCDEA 23	✓	✓		✓	8		3	✓					Ranking	ANP	Personnel Selection
FCCDEA 24	✓												Ranking	AHP/dummy input	
FCCDEA 25	✓		✓		5	2	2	✓		✓			Ranking	FS/GA	
FCCDEA 26	✓	✓	✓		5	2	2	✓					Performance evaluation/ ranking	MOP	
				✓	38	3	2								Electricity distribution companies

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 27	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 28	✓		✓		5	4	4		✓				Performance evaluation	EV/reduction methods/parametric programming	
FCCDEA 29	✓		✓		5	2	2	✓					Sensitivity and stability analysis		
FCCDEA 30	✓		✓					✓					Ranking		
FCCDEA 31	✓	✓		✓	4	2	2	✓					Performance evaluation	MTP	Engineering project comparison and selection
FCCDEA 32		✓		✓	5	2	1	✓					Performance evaluation		Post offices

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 33	✓	✓		✓	40	4	2			✓			Performance evaluation		BRAC
FCCDEA 34	✓	✓		✓	32			✓					Performance evaluation	Multi-subsystem model	Mutual funds management company
FCCDEA 35	✓	✓		✓	16			✓					Performance evaluation	Two-stage structure	Commercial bank
FCCDEA 36	✓	✓	✓		4	2	2	✓					Measuring productivity changes		
				✓	19	2	2								Social security organizations

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 37	✓	✓	✓		5	2	2				✓		Performance evaluation	Fuzzy threshold level	
					10	2	1								
				✓	30	2	2								SCM
FCCDEA 38	✓		✓					✓					Ranking	Hurwicz criterion	
FCCDEA 39	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 40	✓		✓		7	1	1			✓			Measuring congestion		
FCCDEA 41	✓		✓		5	2	2	✓					Performance evaluation	Approximation method/PSO/NN/GA	
FCCDEA 42	✓	✓	✓		8	3	2		✓				Performance evaluation	Bifuzzy variable	

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
				✓	15	2	2								Supply chain problem/hypothetical company
FCCDEA 43	✓		✓		5	2	2					✓	Performance evaluation	Rough set theory/EV	
FCCDEA 44	✓		✓		5	2	2	✓					Performance evaluation		
FCCDEA 45	✓	✓		✓	26	4	2	✓					Performance evaluation		SSCM/SSS
FCCDEA 46	✓	✓		✓	12			✓					Performance evaluation	GDMM/P-robustness technique	EASA

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 47	✓		✓		5	2	2	✓					Performance evaluation	EV/approximation approach/ NN/SA	
FCCDEA 48	✓		✓		10	2	2	✓					Measuring cost efficiency	Convex and non-convex approaches	
FCCDEA 49	✓	✓	✓		5	2	2	✓					Ranking		
				✓	16	3	2								Chief executive officers of public banks and thrifts

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 50	✓		✓		5	2	2	✓					Performance evaluation/ranking/sensitivity and stability analysis	Ranking criterions/ FS/GA	
					8	2	2								
FCCDEA 51	✓	✓	✓		6	2	2	✓					Extracting relationship	Non-discretionary variables	
				✓	10	3	2								Commercial bank branches
FCCDEA 52	✓	✓		✓	20	3	2			✓			Performance evaluation		Insurance industry

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 53	✓	✓		✓	5	3	2				✓		Performance evaluation	Monte carlo simulation/GA	Gas stations
FCCDEA 54	✓	✓		✓	15	4	2		✓				Performance evaluation/ranking		Sustainable supplier evaluation
FCCDEA 55	✓		✓		5	2	2	✓					Measuring scale efficiency		
FCCDEA 56	✓	✓	✓		7	1	1	✓					Measuring congestion		
					5	2	2								
				✓	16	4	2								Hospital
FCCDEA 57	✓	✓	✓		5	2	2	✓					Ranking	Alternative secondary goals	
					10	2	2								

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
				✓	12	2	4								FMS
FCCDEA 58	✓	✓		✓	14	4	3	✓					Performance evaluation		Commercial banks
FCCDEA 59	✓	✓		✓	18			✓					Performance evaluation/ranking	Goal programming (GP)/likert scale	Sustainable supply chains
FCCDEA 60	✓	✓		✓	16			✓					Performance evaluation	Two-stage structure/undesirable outputs	Commercial banks
FCCDEA 61	✓	✓		✓	97	3	1	✓					Performance evaluation/ranking	Undesirable inputs	Kidney allocation problem
FCCDEA 62	✓	✓		✓	22	4	1	✓					Ranking	Integer programming/undesirable output	Barley production farms

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 63	✓	✓		✓	5	2	2	✓					Ranking	GA	Selection of optimal software reliability growth models
FCCDEA 64	✓	✓		✓	20	2	3			✓			Performance evaluation	Undesirable output	Banking industry
FCCDEA 65	✓	✓		✓	10			✓					Performance evaluation	Two-stage structure	Investment companies
FCCDEA 66	✓	✓	✓		5	2	2	✓					Performance evaluation/ranking	RPP	
FCCDEA 67	✓	✓		✓	10	4	3	✓					Measuring productivity changes	Linguistic variable	Hospital

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 68	✓	✓		✓	9			✓					Performance evaluation		Supplier selection and resilient supply chain design
FCCDEA 69	✓	✓		✓	6	8	6	✓					Performance evaluation/ranking		Welding process selection for storage tank
FCCDEA 70	✓	✓		✓	10				✓				Performance evaluation	Two-stage structure	Industrial production and environmental management system
FCCDEA 71	✓	✓		✓	31	5	3	✓					Performance evaluation		Road safety

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 72	✓	✓	✓		4	2	1			✓			Performance Evaluation/ranking		NATO enlargement problem
					4	2	1								
				✓	18	2	2								
FCCDEA 73	✓	✓	✓		4	2	1			✓			Performance evaluation/ranking		Banking industry
				✓	25	3	2								
FCCDEA 74	✓	✓		✓	24			✓					Performance evaluation	Fuzzy neural network/RPP	Production control process
FCCDEA 75	✓	✓	✓		10	3	2	✓					Performance evaluation/ranking	Interactive fuzzy variables/Choquet Integral	
				✓	14	3	4								Hospital

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 76	✓	✓		✓	30	2	1	✓					Classification	DEA classification machine/PLDA	Healthcare management
FCCDEA 77	✓		✓		25	3	5				✓		Performance evaluation		
FCCDEA 78	✓	✓		✓	31					✓			Performance evaluation/ranking	Two-stage structure/undesirable output	Banking industry
FCCDEA 79	✓	✓		✓	24			✓					Performance evaluation/sensitivity and stability analysis	Two-stage structure	Non-life insurance companies

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 80	✓	✓	✓		5	2	2	✓					Performance evaluation/ranking	Adjustable approach	
				✓	38	3	3								Hospitals
FCCDEA 81	✓	✓		✓	18	3	3	✓					Performance evaluation/ranking	Negative data	Stock exchange
FCCDEA 82	✓	✓		✓	12	3	3	✓					Performance evaluation/ranking	Negative data	Stock exchange
FCCDEA 83	✓	✓	✓		5	1	1	✓					Measuring productivity changes		

Table 3 (continued)

Research code	Research perspective		Implementation type		Implementation information			Data uncertainty type					Research description		
	Theoretical	Application	Numerical example	Case study	Number of DMUs	Number of inputs	Number of outputs	FT-I	FT-II	FURA	RAFU	FURO	Research objective	Research feature	Research application
FCCDEA 84	✓	✓		✓	16			✓					Performance evaluation/ranking	Three-stage structure	Electricity companies
FCCDEA 85	✓	✓		✓	24	1	1				✓		Performance evaluation/ranking		Stock exchange
FCCDEA 86		✓		✓	20	2	3	✓					Performance evaluation/ranking	Undesirable outputs	Green supplier evaluation
FCCDEA 87	✓	✓	✓		7	8	2	✓					Performance evaluation	GDMM/P-robustness technique	Welding process selection

FT-I Fuzzy Type-I, *FT-II* Fuzzy Type-II, *FURA* Fuzzy Random, *RAFU* Random Fuzzy, *FURO* Fuzzy Rough, *ACM* Agent-Clients Evaluation, *FMEA* Failure Mode and Effect Analysis, *AFW* Auxiliary Feed Water, *MOP* MultI-Objective Programming, *EV* Expected Value, *GA* Genetic Algorithm, *AHP* Analytical Hierarchy Process, *ANP* Analytic Network Process, *FS* Fuzzy Simulation, *MTP* Multi-Target Programming, *BRAC* Base Realignment and Closure, *SCM* Supply Chain Management, *PSO* Particle Swarm Optimization, *NN* Neural Network, *SSCM* Sustainable Supply Chain Management, *SSS* Sustainable Supplier Selection, *GDMM* Group Decision Making Method, *EASA* Enterprise Architecture Scenario Analysis, *SA* Simulated Annealing, *FMS* Flexible Manufacturing System, *GP* Goal Programming, *RPP* Robust Possibilistic Programming, *PLDA* Piecewise-Linear Discriminant Analysis

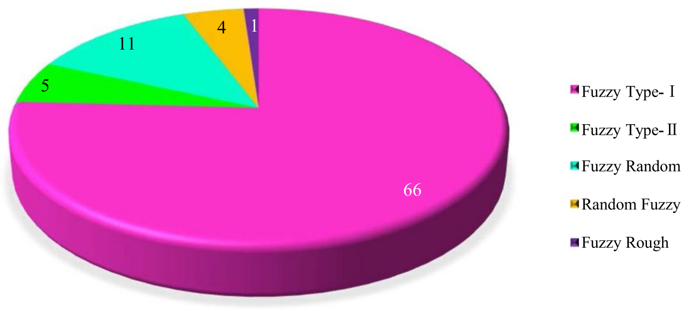


Fig. 8 Distribution of data uncertainty type

- *Robust Possibilistic Data Envelopment Analysis (RPDEA)* Extending FCCDEA models based on robust possibilistic programming to endogenously adjust the confidence level of each fuzzy chance constraints (for more details see Pishvaee et al., 2012; Pishvaee & Khalaf, 2016; Peykani et al., 2018a, b).
- *Z-Number Data Envelopment Analysis (ZNDEA)* Introducing fuzzy chance-constrained DEA approach based on Z-number instead of classical fuzzy number in order to improve reliability of uncertain data (for more details see Zadeh, 2011; Azadeh & Kokabi, 2016; Mohtashami & Ghiasvand, 2020).
- *Fuzzy Dynamic Data Envelopment Analysis (FDDEA)* Dynamic efficiency evaluation of DMUs under fuzzy panel data using dynamic data envelopment analysis (DDEA), Malmquist productivity index (MPI), and window data envelopment analysis (WDEA) approaches (for more details see Färe & Grosskopf, 1992; Charnes et al., 1985a; Mariz et al., 2018).

In addition to the above suggestions, FCCDEA models can be proposed in the presence of negative data, undesirable factor, non-discretionary factor, dual-role factor. Finally, the most valuable suggestion and direction for future researches would be to employ existing or extended fuzzy chance-constrained DEA models in real-world problems and applications.

Table 4 The classification of FCCDEA models

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 01	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 02	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 03	✓																		✓		✓	
FCCDEA 04	✓																		✓		✓	
FCCDEA 05	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 06		✓																	✓		✓	
		✓																	✓			✓
FCCDEA 07	✓																		✓		✓	
FCCDEA 08	✓																		✓			✓
FCCDEA 09	✓																		✓			✓
FCCDEA 10	✓																		✓		✓	
	✓																		✓			✓
		✓																	✓		✓	
		✓																	✓			✓
FCCDEA 11	✓																		✓		✓	
FCCDEA 12	✓																		✓		✓	

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 13	✓																		✓		✓	
FCCDEA 14	✓																		✓		✓	
FCCDEA 15	✓																		✓			✓
FCCDEA 16														✓					✓		✓	
														✓					✓		✓	
														✓					✓		✓	
														✓					✓		✓	
FCCDEA 17	✓																		✓		✓	
FCCDEA 18	✓																		✓		✓	
FCCDEA 19	✓																		✓		✓	
FCCDEA 20	✓																	✓	✓		✓	
	✓																	✓	✓			✓
FCCDEA 21			✓																	✓		✓
FCCDEA 22							✓													✓		✓
FCCDEA 23	✓																		✓		✓	
FCCDEA 24	✓																	✓	✓		✓	
	✓																	✓	✓			✓

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 25	✓																		✓		✓	
FCCDEA 26	✓																		✓		✓	
FCCDEA 27	✓																		✓		✓	
FCCDEA 28	✓																		✓		✓	
FCCDEA 29			✓																	✓		✓
FCCDEA 30			✓																	✓		✓
FCCDEA 31	✓																	✓	✓		✓	
FCCDEA 32	✓																		✓		✓	
FCCDEA 33	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 34																		✓	✓		✓	
FCCDEA 35																✓			✓		✓	
FCCDEA 36									✓										✓			✓
FCCDEA 37	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓			✓

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
	✓																		✓			✓
FCCDEA 38			✓																	✓		✓
FCCDEA 39				✓																✓		✓
FCCDEA 40							✓													✓		✓
							✓													✓		✓
							✓													✓		✓
FCCDEA 41	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 42	✓																		✓		✓	
FCCDEA 43	✓																		✓		✓	
FCCDEA 44												✓							✓		✓	
												✓							✓		✓	
												✓							✓		✓	
												✓							✓		✓	
FCCDEA 45					✓															✓	✓	
FCCDEA 46																		✓	✓		✓	
FCCDEA 47	✓																		✓		✓	
	✓																		✓		✓	

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 48								✓											✓		✓	
								✓				✓							✓		✓	
								✓				✓							✓		✓	
								✓				✓							✓		✓	
								✓				✓							✓		✓	
FCCDEA 49						✓													✓		✓	
FCCDEA 50			✓																	✓		✓
			✓																	✓		✓
	✓																		✓		✓	
							✓													✓		✓
FCCDEA 51	✓																		✓			✓
FCCDEA 52	✓																		✓		✓	
FCCDEA 53															✓			✓	✓		✓	
FCCDEA 54					✓												✓	✓		✓	✓	
FCCDEA 55		✓																	✓		✓	
FCCDEA 56							✓													✓		✓
FCCDEA 57											✓								✓		✓	
FCCDEA 58	✓																		✓		✓	

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 59																✓		✓		✓		✓
FCCDEA 60																✓			✓		✓	
																✓			✓		✓	
FCCDEA 61						✓													✓		✓	
FCCDEA 62					✓					✓								✓		✓		✓
FCCDEA 63	✓																		✓		✓	
FCCDEA 64	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 65																✓			✓			✓
																✓			✓			✓
																✓			✓			✓
																✓			✓			✓
FCCDEA 66	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
	✓																		✓		✓	
FCCDEA 67									✓										✓			✓

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 68	✓																		✓			✓
FCCDEA 69	✓																		✓		✓	
FCCDEA 70																✓	✓		✓			✓
FCCDEA 71		✓																	✓			✓
FCCDEA 72	✓																	✓	✓		✓	
FCCDEA 73	✓																	✓	✓			✓
FCCDEA 74	✓																		✓			✓
FCCDEA 75	✓																		✓		✓	
											✓								✓		✓	
FCCDEA 76	✓																	✓	✓		✓	
FCCDEA 77	✓																	✓	✓		✓	
	✓																	✓	✓		✓	
FCCDEA 78																✓			✓		✓	
FCCDEA 79																✓			✓			✓
				✓												✓			✓			✓
FCCDEA 80	✓																		✓		✓	

Table 4 (continued)

Research code	Basic model																		Model type		Model form	
	CCR	BCC	ADD	SBM	ERM	CSWDEA	CDEA	COEDEA	MPI	SEDEA	CREDEA	FDH	RDM	GDEA	DDEA	NDEA	MODEA	EDEA	RP	NRP	M-F	E-F
FCCDEA 81													✓							✓	✓	
													✓							✓		✓
FCCDEA 82													✓							✓	✓	
FCCDEA 83									✓										✓			✓
FCCDEA 84																✓			✓		✓	
FCCDEA 85	✓																		✓			✓
	✓																		✓			✓
	✓																		✓			✓
FCCDEA 86	✓																		✓		✓	
FCCDEA 87	✓																		✓		✓	

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
FCCDEA 01	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓		✓							✓		
FCCDEA 02	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓		✓							✓		
FCCDEA 03	✓			✓				✓	✓	✓								✓		
FCCDEA 04	✓			✓				✓	✓	✓								✓		

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
FCCDEA 05	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓		✓							✓		
FCCDEA 06	✓						✓	✓	✓	✓								✓		
	✓						✓	✓	✓	✓								✓		
FCCDEA 07	✓			✓				✓	✓	✓								✓		
FCCDEA 08	✓			✓				✓	✓					✓	✓					✓
FCCDEA 09	✓			✓				✓	✓					✓	✓					✓
FCCDEA 10	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓	✓								✓		
	✓						✓	✓	✓	✓								✓		
	✓						✓	✓	✓	✓								✓		
FCCDEA 11	✓			✓				✓	✓			✓						✓		
FCCDEA 12	✓			✓				✓	✓			✓						✓		
FCCDEA 13	✓			✓				✓	✓			✓						✓		
FCCDEA 14	✓			✓				✓	✓			✓						✓		
FCCDEA 15	✓			✓				✓	✓	✓				✓	✓			✓		
FCCDEA 16	✓			✓				✓	✓			✓						✓		
	✓				✓			✓	✓			✓						✓		
	✓					✓		✓	✓			✓						✓		
	✓						✓	✓	✓			✓						✓		
FCCDEA 17	✓			✓				✓	✓			✓						✓		
FCCDEA 18	✓			✓				✓	✓			✓						✓		
FCCDEA 19			✓	✓				✓	✓			✓							✓	

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
FCCDEA 20	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓	✓								✓		
FCCDEA 21			✓				✓	✓	✓	✓								✓		
FCCDEA 22		✓					✓	✓	✓	✓								✓		
FCCDEA 23		✓		✓					✓	✓								✓		
FCCDEA 24	✓			✓				✓	✓	✓				✓	✓			✓		
	✓			✓				✓	✓	✓				✓	✓			✓		
FCCDEA 25	✓			✓				✓	✓			✓						✓		
FCCDEA 26	✓			✓				✓	✓			✓						✓		
FCCDEA 27	✓			✓				✓	✓			✓						✓		
FCCDEA 28	✓			✓				✓	✓			✓								✓
FCCDEA 29			✓				✓	✓	✓			✓						✓		
FCCDEA 30			✓				✓	✓	✓			✓						✓		
FCCDEA 31	✓			✓				✓	✓	✓								✓		
FCCDEA 32	✓			✓				✓	✓	✓								✓		
FCCDEA 33	✓			✓				✓	✓	✓				✓	✓			✓		
	✓			✓				✓	✓		✓			✓	✓			✓		
	✓			✓				✓	✓			✓		✓	✓			✓		
FCCDEA 34	✓			✓				✓	✓	✓								✓		
FCCDEA 35	✓			✓				✓	✓	✓								✓		
FCCDEA 36	✓			✓				✓	✓			✓						✓		
FCCDEA 37	✓			✓				✓	✓	✓				✓	✓					✓
	✓			✓				✓	✓		✓			✓	✓					✓

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
	✓			✓				✓	✓	✓				✓	✓					✓
	✓			✓				✓	✓		✓			✓	✓					✓
FCCDEA 38			✓				✓	✓	✓			✓						✓		
FCCDEA 39	✓			✓				✓	✓	✓								✓		
FCCDEA 40		✓					✓	✓	✓	✓				✓	✓			✓		
		✓					✓	✓	✓		✓			✓	✓			✓		
		✓					✓	✓	✓			✓		✓	✓			✓		
FCCDEA 41			✓	✓				✓	✓			✓						✓		
			✓	✓				✓	✓			✓							✓	
FCCDEA 42	✓			✓				✓	✓	✓								✓		
FCCDEA 43	✓			✓				✓	✓	✓							✓	✓		
FCCDEA 44	✓			✓				✓	✓	✓								✓		
	✓				✓			✓	✓	✓								✓		
	✓					✓		✓	✓	✓								✓		
	✓						✓	✓	✓	✓								✓		
FCCDEA 45			✓	✓				✓	✓	✓								✓		
FCCDEA 46	✓			✓				✓	✓			✓				✓		✓		
FCCDEA 47	✓			✓				✓	✓			✓							✓	
		✓		✓				✓	✓			✓							✓	
FCCDEA 48	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓	✓								✓		
	✓				✓			✓	✓	✓								✓		
	✓					✓		✓	✓	✓								✓		

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
	✓						✓	✓	✓	✓								✓		
FCCDEA 49			✓	✓				✓	✓			✓						✓		
FCCDEA 50			✓				✓	✓	✓	✓								✓		
			✓				✓	✓	✓			✓						✓		
	✓			✓				✓	✓			✓						✓		
			✓				✓	✓	✓			✓						✓		
FCCDEA 51	✓			✓				✓		✓								✓		
FCCDEA 52	✓			✓				✓	✓					✓	✓			✓		
FCCDEA 53			✓	✓				✓	✓					✓	✓					✓
FCCDEA 54			✓	✓				✓	✓			✓							✓	
FCCDEA 55	✓						✓	✓	✓			✓						✓		
FCCDEA 56		✓					✓	✓	✓	✓								✓		
FCCDEA 57	✓			✓				✓	✓	✓								✓		
FCCDEA 58	✓			✓				✓	✓	✓								✓		
FCCDEA 59	✓			✓				✓	✓	✓								✓		
FCCDEA 60	✓			✓				✓	✓	✓								✓		
	✓						✓	✓	✓	✓								✓		
FCCDEA 61			✓	✓				✓	✓			✓						✓		
FCCDEA 62			✓	✓				✓	✓	✓								✓		
FCCDEA 63	✓			✓				✓	✓			✓						✓		
FCCDEA 64	✓			✓				✓	✓	✓				✓	✓					✓
	✓			✓				✓	✓		✓			✓	✓					✓
	✓			✓				✓	✓			✓		✓	✓					✓

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
FCCDEA 65			✓	✓				✓	✓	✓									✓	
			✓		✓			✓	✓	✓									✓	
			✓			✓		✓	✓	✓									✓	
			✓				✓	✓	✓	✓									✓	
FCCDEA 66	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓		✓							✓		
	✓			✓				✓	✓			✓						✓		
	✓			✓				✓	✓	✓						✓		✓		
	✓			✓				✓	✓		✓					✓		✓		
	✓			✓				✓	✓			✓				✓		✓		
FCCDEA 67	✓			✓				✓	✓		✓							✓		
FCCDEA 68	✓			✓				✓	✓		✓							✓		
FCCDEA 69	✓			✓				✓	✓			✓						✓		
FCCDEA 70	✓			✓				✓	✓			✓							✓	
FCCDEA 71	✓						✓	✓	✓			✓						✓		
FCCDEA 72	✓			✓				✓	✓	✓				✓	✓			✓		
FCCDEA 73	✓			✓				✓	✓					✓	✓			✓		
FCCDEA 74	✓			✓				✓	✓			✓				✓			✓	
FCCDEA 75	✓			✓				✓	✓	✓								✓		
	✓			✓				✓	✓	✓								✓		
FCCDEA 76	✓			✓				✓	✓	✓								✓		
FCCDEA 77	✓			✓				✓	✓	✓				✓	✓					✓
	✓			✓				✓	✓		✓			✓	✓					✓

Table 4 (continued)

Research code	Model orientation			Model RTS				Uncertain data		Uncertain measure					Hybrid uncertain programming approach			FCCDEA model class		
	I-O	O-O	N-O	CRS	NIRS	NDRS	VRS	Inputs	Outputs	POS	NEC	CR	GF	PR	Stochastic	Robust	Rough	LP	FP	NLP
FCCDEA 78	✓			✓				✓	✓	✓				✓	✓			✓		
FCCDEA 79	✓			✓				✓	✓			✓						✓		
	✓			✓				✓	✓			✓						✓		
FCCDEA 80	✓			✓				✓	✓				✓					✓		
FCCDEA 81			✓				✓	✓	✓	✓								✓		
			✓				✓	✓	✓	✓								✓		
FCCDEA 82			✓				✓	✓	✓		✓							✓		
FCCDEA 83	✓			✓				✓	✓	✓								✓		
FCCDEA 84	✓			✓				✓	✓		✓							✓		
FCCDEA 85	✓			✓				✓	✓	✓				✓	✓					✓
	✓			✓				✓	✓		✓			✓	✓					✓
	✓			✓				✓	✓			✓		✓	✓					✓
FCCDEA 86	✓			✓				✓	✓				✓					✓		
FCCDEA 87	✓			✓				✓	✓			✓				✓		✓		

CCR Charnes-Cooper-Rhodes, *BCC* Banker-Charnes-Cooper, *ADD* Additive, *SBM* Slack Based Model, *ERM* Enhanced Russell Measure, *CSWDEA* Common Set of Weights Data Envelopment Analysis, *CDEA* Congestion Data Envelopment Analysis, *COEDEA* Cost Efficiency Data Envelopment Analysis, *MPI* Malmquist Productivity Index, *SEDEA* Supper Efficiency Data Envelopment Analysis, *CREDEA* Cross Efficiency Data Envelopment Analysis, *FDH* Free Disposal Hull, *RDM* Range Directional Measure, *DDEA* Dynamic Data Envelopment Analysis, *NDEA* Network Data Envelopment Analysis, *MODEA* MultI-Objective Data Envelopment Analysis, *EDEA* Extended Data Envelopment Analysis, *RP* Radial Projection, *NRP* Non-Radial Projection, *M-F* Multiplier Form, *E-F* Envelopment Form, *I-O* Input Oriented, *O-O* Output Oriented, *N-O* Non Oriented, *RTS* Return to Scale, *CRS* Constant Return to Scale, *NIRS* Non Increasing Return to Scale, *NDRS* Non Decreasing Return to Scale, *VRS* Variable Return to Scale, *POS* Possibility, *NEC* Necessity, *CR* Credibility, *GF* General Fuzzy, *PR* Probability, *LP* Linear Programming, *FP* Fractional Programming, *NLP* Non-Linear Programming

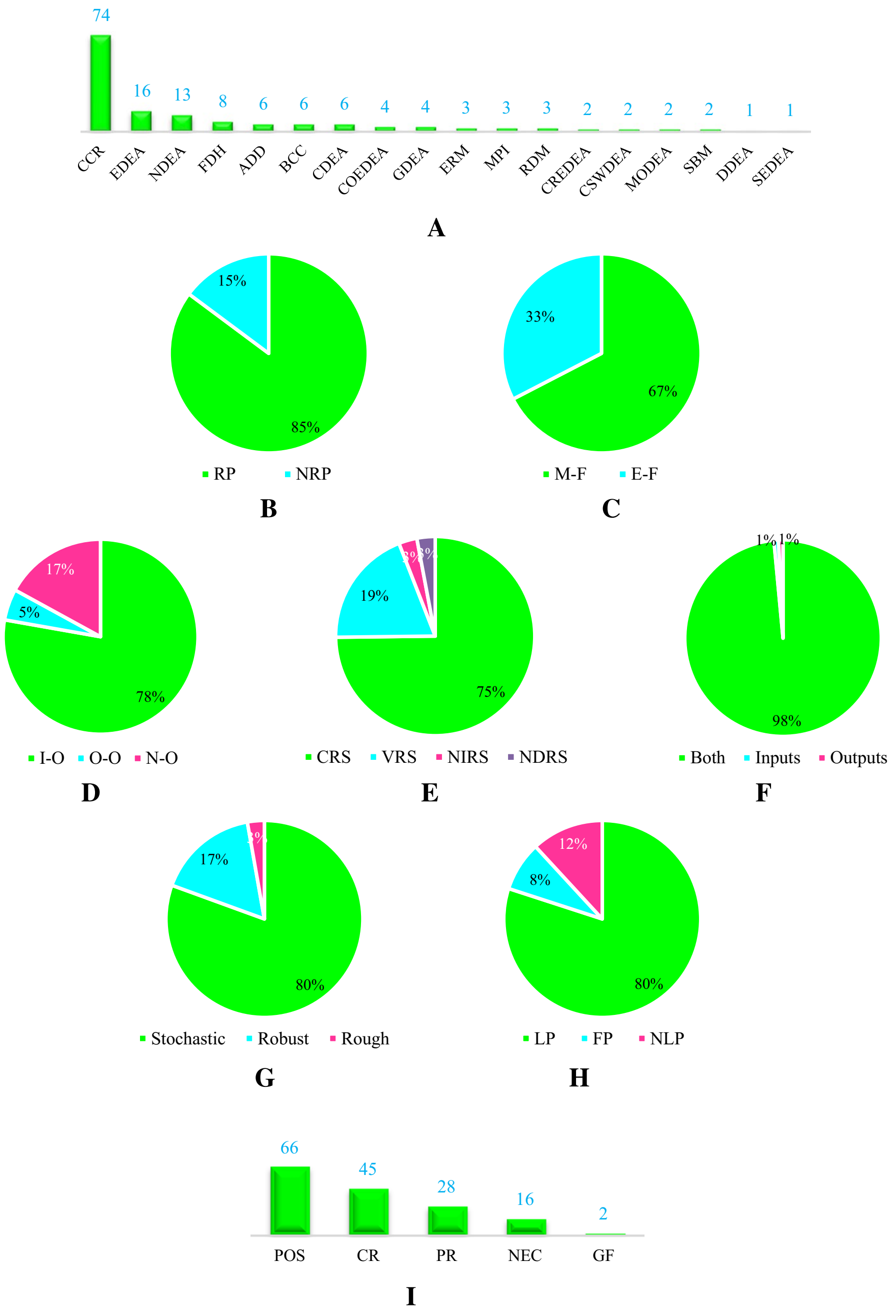


Fig. 9 Statistical information of RDEA models. (A) Basic model, (B) Model type, (C) Model form, (D) Model orientation, (E) Model return to scale, (F) Uncertain data, (G) Hybrid uncertain programming approach, (H) FCCDEA model class, (I) Uncertain measure

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References

Agarwal, S. (2014). Fuzzy slack based measure of data envelopment analysis: A possibility approach. In: *The 3rd international conference on soft computing for problem solving* (pp. 733–740). New Delhi:Springer.

Agarwal, S. (2017). Scale efficiency with fuzzy data. *International Journal of Business and Systems Research, 11*(1–2), 152–162.

Ahmadvand, S., & Pishvaee, M. S. (2018). An Efficient method for kidney allocation problem: A credibility-based fuzzy common weights data envelopment analysis approach. *Health Care Management Science, 21*(4), 587–603.

Amini, M., Dabbagh, R., & Omrani, H. (2019). A fuzzy data envelopment analysis based on credibility theory for estimating road safety. *Decision Science Letters, 8*(3), 275–284.

Azadeh, A., & Kokabi, R. (2016). Z-number DEA: A new possibilistic DEA in the context of Z-numbers. *Advanced Engineering Informatics, 30*(3), 604–617.

Azadi, M., Jafarian, M., Farzipoor Saen, R., & Mirhedayatian, S. M. (2015). A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context. *Computers and Operations Research, 54*, 274–285.

Bai-Qing, S., Yue, Q., & Shan, X. (2013). Improvement of relational two-stage DEA model under fuzzy chance constraints. In: *The 20th international conference on management science and engineering*, (pp. 306–313). IEEE.

Banker, R. D., Charnes, A., & Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Management Science, 30*(9), 1078–1092.

Charnes, A., Clark, C. T., Cooper, W. W., & Golany, B. (1985a). A development study of data envelopment analysis in measuring the effect of maintenance units in the US Air Force. *Annals of Operations Research, 2*, 95–112.

Charnes, A., & Cooper, W. W. (1959). Chance-constrained programming. *Management Science, 6*(1), 73–79.

Charnes, A., Cooper, W. W., Golany, B., Seiford, L., & Stutz, J. (1985b). Foundations of data envelopment analysis for pareto-koopmans efficient empirical production functions. *Journal of Econometrics, 30*(1–2), 91–107.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research, 2*(6), 429–444.

Chen, Y., Cook, W. D., Li, N., & Zhu, J. (2009). Additive efficiency decomposition in two-stage DEA. *European Journal of Operational Research, 196*(3), 1170–1176.

Cooper, W. W., Seiford, L. M., & Zhu, J. (2011). *Handbook on Data Envelopment Analysis. International Series in Operations Research & Management Science*, (Vol. 71). Boston, MA: Springer.

Dai, X., Liu, Y., & Qin, R. (2010). Modeling fuzzy data envelopment analysis with expectation criterion. In: *International conference in swarm intelligence* (pp. 9–16). Berlin, Heidelberg:Springer.

Dubois, D., & Prade, H. (1978). Operations on fuzzy numbers. *International Journal of Systems Science, 9*(6), 613–626.

Dubois, D., & Prade, H. (1988). *Possibility theory: An approach to computerized processing of uncertainty*. Plenum.

Ebrahimnejad, A., Nasseri, S. H., & Gholami, O. (2019a). Fuzzy stochastic data envelopment analysis with application to NATO enlargement problem. *RAIRO-Operations Research, 53*(2), 705–721.

Ebrahimnejad, A., Tavana, M., Nasseri, S. H., & Gholami, O. (2019b). A new method for solving dual DEA problems with fuzzy stochastic data. *International Journal of Information Technology and Decision Making, 18*(01), 147–170.

Emrouznejad, A., & Tavana, M. (2014). *Performance measurement with fuzzy data envelopment analysis*. Springer.

Emrouznejad, A., & Yang, G. L. (2018). A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. *Socio-Economic Planning Sciences, 61*(1), 4–8.

Färe, R., & Grosskopf, S. (1992). Malmquist productivity indexes and fisher ideal indexes. *The Economic Journal, 102*(410), 158–160.

Farrell, M. J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society. Series A (general), 120*(3), 253–290.

Fasanghari, M., Amalnick, M. S., Anvari, R. T., & Razmi, J. (2015). A novel credibility-based group decision making method for enterprise architecture scenario analysis using data envelopment analysis. *Applied Soft Computing, 32*, 347–368.

Feng, X. Q., Meng, M. Q., & Liu, Y. K. (2015). Modeling credibilistic data envelopment analysis under fuzzy input and output data. *Journal of Uncertain Systems, 9*, 230–240.

Garcia, P. A. A., Schirru, R., & eMelo, P. F. F. (2005). A fuzzy data envelopment analysis approach for FMEA. *Progress in Nuclear Energy, 46*(3–4), 359–373.

Gholizadeh, H., & Fazlollahtabar, H. (2019). Production control process using integrated robust data envelopment analysis and fuzzy neural network. *International Journal of Mathematical, Engineering and Management Sciences, 4*(3), 580–590.

Guo, P., Tanaka, H., & Inuiguchi, M. (2000). Self-organizing fuzzy aggregation models to rank the objects with multiple attributes. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 30*(5), 573–580.

Hatami-Marbini, A., Emrouznejad, A., & Tavana, M. (2011). A taxonomy and review of the fuzzy data envelopment analysis literature: two decades in the making. *European Journal of Operational Research, 214*(3), 457–472.

Hosseinzadeh Loti, F., Jahanshahloo, G. R., Khodabakhshi, M., & Moradi, F. (2011). A fuzzy chance constraint multi objective programming method in data envelopment analysis. *African Journal of Business Management, 5*(33), 12873–12881.

Hosseinzadeh Lotfi, F., Ebrahimnejad, A., Vaez-Ghasemi, M., & Moghaddas, Z. (2020). Fuzzy data envelopment analysis models with R codes. In: *Data envelopment analysis with R.* Studies in fuzziness and soft computing (vol 386, pp. 163–236). Cham: Springer.

Inuiguchi, M., Ichihashi, H., & Kume, Y. (1993). Modality constrained programming problems: A unified approach to fuzzy mathematical programming problems in the setting of possibility theory. *Information Sciences, 67*(1–2), 93–126.

Izadikhah, M., & Khoshroo, A. (2018). Energy management in crop production using a novel fuzzy data envelopment analysis model. *RAIRO-Operations Research, 52*(2), 595–617.

Ji, A. B., Chen, H., Qiao, Y., & Pang, J. (2019a). Data envelopment analysis with interactive fuzzy variables. *Journal of the Operational Research Society, 70*(9), 1502–1510.

Ji, A. B., Qiao, Y., & Liu, C. (2019b). Fuzzy DEA-based classifier and its applications in healthcare management. *Health Care Management Science, 22*(3), 560–568.

Jiang, N., & Yang, Y. (2007). A fuzzy chance-constrained DEA model based on Cr measure. *International Journal of Business and Management, 2*(2), 17–21.

Kao, C. (2014). Network data envelopment analysis: a review. *European Journal of Operational Research, 239*(1), 1–16.

Kao, C. (2017). *Network data envelopment analysis: Foundations and extensions*. Springer.

Kao, C., & Hwang, S. N. (2008). Efficiency decomposition in two-stage data envelopment analysis: An application to non-life insurance companies in Taiwan. *European Journal of Operational Research, 185*(1), 418–429.

Ketsarapong, S., & Punyangarm, V. (2010). An application of fuzzy data envelopment analytical hierarchy process for reducing defects in the production of liquid medicine. *Industrial Engineering and Management Systems, 9*(3), 251–261.

Kheirollahi, H. (2014). Fuzzy stochastic congestion model for data envelopment analysis. In: *The 6th national conference on data envelopment analysis, Iran*.

Kheirollahi, H., Hessari, P., Charles, V., & Chawshini, R. (2017). An input relaxation model for evaluating congestion in fuzzy DEA. *Croatian Operational Research Review, 8*(2), 391–408.

Khodabakhshi, M., Gholami, Y., & Kheirollahi, H. (2010). An additive model approach for estimating returns to scale in imprecise data envelopment analysis. *Applied Mathematical Modelling, 34*(5), 1247–1257.

Khodabakhshi. M, & Kheirollahi. H. (2010). An input relaxation measure of congestion in fuzzy data envelopment analysis: a possibility approach. In: *The 4th international conference of fuzzy information and engineering, Iran*.

Kumar, V., Singh, V. B., Garg, A., & Kumar, G. (2018). Selection of optimal software reliability growth models: A fuzzy DEA ranking approach. In: *Quality, IT and business operations*. Springer proceedings in business and economics (pp. 347–357). Singapore: Springer.

Lertworasirikul, S. (2002). *Fuzzy Data Envelopment Analysis (DEA)*. Ph.D. Dissertation, Department of Industrial Engineering, North Carolina State University.

Lertworasirikul, S., Fang, S. C., Joines, J. A., & Nuttle, H. L. W. (2002a). A possibility approach to fuzzy data envelopment analysis. *Joint Conference on Information Sciences, 6*, 176–179.

Lertworasirikul, S., Fang, S. C., Joines, J. A., & Nuttle, H. L. W. (2003a). Fuzzy data envelopment analysis (DEA): a possibility approach. *Fuzzy Sets and Systems, 139*(2), 379–394.

Lertworasirikul, S., Fang, S. C., Nuttle, H. L. W., & Joines, J. A. (2002). Fuzzy data envelopment analysis. *The 9th bellman continuum*, *342*, Beijing

Lertworasirikul, S., Fang, S. C., Nuttle, H. L. W., & Joines, J. A. (2003b). Fuzzy BCC model for data envelopment analysis. *Fuzzy Optimization and Decision Making, 2*(4), 337–358.

Lin, H. T. (2010). Personnel selection using analytic network process and fuzzy data envelopment analysis approaches. *Computers and Industrial Engineering, 59*(4), 937–944.

Liu, B., & Liu, Y. K. (2002). Expected value of fuzzy variable and fuzzy expected value models. *IEEE Transactions on Fuzzy Systems, 10*(4), 445–450.

Mariz, F. B., Almeida, M. R., & Aloise, D. (2018). A review of dynamic data envelopment analysis: State of the art and applications. *International Transactions in Operational Research, 25*(2), 469–505.

Mehrasa, B., & Behzadi, M. H. (2019). Chance-constrained random fuzzy CCR model in presence of skew-normal distribution. *Soft Computing, 23*(4), 1297–1308.

Meng, M. (2014). A hybrid particle swarm optimization algorithm for satisficing data envelopment analysis under fuzzy chance constraints. *Expert Systems with Applications, 41*(4), 2074–2082.

Meng, M., & Liu, Y. (2007). Fuzzy data envelopment analysis with credibility constraints. In: *The 4th international conference on fuzzy systems and knowledge discovery, 1* (pp. 149–153). IEEE.

Meng, M., Yuan, G., & Huang, J. (2011). Satisficing data envelopment analysis model with credibility constraints. In: *The 8th international conference on fuzzy systems and knowledge discovery, 2* (pp. 703–707). IEEE.

Mohtashami, A., & Ghiasvand, B. M. (2020). Z-ERM DEA integrated approach for evaluation of banks and financial institutes in stock exchange. *Expert Systems with Applications, 147*, 113218.

Nasseri, S. H., Ebrahimnejad, A., & Gholami, O. (2016). Fuzzy stochastic input-oriented primal data envelopment analysis models with application to insurance industry. *International Journal of Applied Decision Sciences, 9*(3), 259–282.

Nasseri, S. H., Ebrahimnejad, A., & Gholami, O. (2018). Fuzzy stochastic data envelopment analysis with undesirable outputs and its application to banking industry. *International Journal of Fuzzy Systems, 20*(2), 534–548.

Nasseri, S. H., & Khatir, M. A. (2019). Fuzzy stochastic undesirable two-stage data envelopment analysis models with application to banking industry. *Journal of Intelligent and Fuzzy Systems, 37*(5), 7047–7057.

Nedeljković, R., & Drenovac, D. (2008). *Fuzzy data envelopment analysis application in postal traffic* (pp. 47–56). PosTel.

Nedeljković, R. R., & Drenovac, D. (2012). Efficiency measurement of delivery post offices using fuzzy data envelopment analysis (possibility approach). *International Journal for Traffic and Transport Engineering, 2*(1), 22–29.

Nosrat, A., Sanei, M., Payan, A., Hosseinzadeh Lotfi, F., & Razavyan, S. (2019). Using credibility theory to evaluate the fuzzy two-stage DEA; sensitivity and stability analysis. *Journal of Intelligent and Fuzzy Systems, 37*(4), 5777–5796.

Paryab, K., Shiraz, R. K., Jalalzadeh, L., & Fukuyama, H. (2014). Imprecise data envelopment analysis model with bifuzzy variables. *Journal of Intelligent and Fuzzy Systems, 27*(1), 37–48.

Paryab, K., Tavana, M., & Shiraz, R. K. (2015). Convex and non-convex approaches for cost efficiency models with fuzzy data. *International Journal of Data Mining, Modelling and Management, 7*(3), 213–238.

Payan, A. (2015). Common set of weights approach in fuzzy DEA with an application. *Journal of Intelligent and Fuzzy Systems, 29*(1), 187–194.

Payan, A., & Shariff, M. (2013). Scrutiny Malmquist productivity index on fuzzy data by credibility theory with an application to social security organizations. *Journal of Uncertain Systems, 7*(1), 36–49.

Peykani, P., & Mohammadi, E. (2018). Fuzzy network data envelopment analysis: A possibility approach. In: *The 3th international conference on intelligent decision science, Iran.*

Peykani, P., Mohammadi, E., & Emrouznejad, A. (2021). An adjustable fuzzy chance-constrained network DEA approach with application to ranking investment firms. *Expert Systems with Applications, 166*, 113938.

Peykani, P., Mohammadi, E., Emrouznejad, A., Pishvaee, M. S., & Rostamy-Malkhalifeh, M. (2019a). Fuzzy data envelopment analysis: An adjustable approach. *Expert Systems with Applications, 136*, 439–452.

Peykani, P., Mohammadi, E., Farzipoor Saen, R., Sadjadi, S. J., & Rostamy-Malkhalifeh, M. (2020). Data envelopment analysis and robust optimization: A review. *Expert Systems, 37*(4), e12534.

Peykani, P., Mohammadi, E., Pishvaee, M. S., Rostamy-Malkhalifeh, M., & Jabbarzadeh, A. (2018a). A novel fuzzy data envelopment analysis based on robust possibilistic programming: Possibility necessity and credibility-based approaches. *RAIRO-Operations Research, 52*(4–5), 1445–1463.

Peykani, P., Mohammadi, E., Rostamy-Malkhalifeh, M., & Hosseinzadeh Lotfi, F. (2019b). Fuzzy data envelopment analysis approach for ranking of stocks with an application to Tehran stock exchange. *Advances in Mathematical Finance and Applications, 4*(1), 31–43.

Peykani, P., Seyed Esmaeili, F. S., Rostamy-Malkhalifeh, M., & Hosseinzadeh Lotfi, F. (2018b). Measuring productivity changes of hospitals in Tehran: The fuzzy Malmquist productivity index. *International Journal of Hospital Research, 7*(3), 1–17.

Peykani. P, Seyed Esmaeili. F.S, Rostamy-Malkhalifeh. M, Hosseinzadeh Lotfi. F, & Tehrani. R. (2019). Fuzzy range directional measure: The pessimistic approach, In: *The 11th national conference on data envelopment analysis, Iran*.

Pishvaee, M. S., & Khalaf, M. F. (2016). Novel robust fuzzy mathematical programming methods. *Applied Mathematical Modelling, 40*(1), 407–418.

Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2012). Robust possibilistic programming for socially responsible supply chain network design: A new approach. *Fuzzy Sets and Systems, 206*, 1–20.

Punyangarm, V. (2010). Possibility approach for solve the data envelopment analytical hierarchy process (DEAHP) with fuzzy judgment scales. In: *Conference Proceedings*.

Punyangarm, V., Yanpirat, P., Charnsethikul, P., & Lertworasirikul, S. (2006). A credibility approach for fuzzy stochastic data envelopment analysis (FSDEA). In: *The 7th Asia pacific industrial engineering and management systems conference, Thailand.*

Punyangarm, V., Yanpirat, P., Charnsethikul, P., & Lertworasirikul, S. (2008). A case of constant returns to scale in fuzzy stochastic data envelopment analysis: Chance-constrained programming and possibility approach. *Thailand Statistician, 6*(1), 75–90.

Qin, R., & Liu, Y. K. (2008). A Credibility method to fuzzy generalized data envelopment analysis. In: *International conference on machine learning and cybernetics, 2* (pp. 1052–1058), IEEE.

Qin, R., Liu, Y., & Liu, Z. Q. (2011). Modeling fuzzy data envelopment analysis by parametric programming method. *Expert Systems with Applications, 38*(7), 8648–8663.

Qin, R., Liu, Y., Liu, Z., & Wang, G. (2009). Modeling fuzzy DEA with type-2 fuzzy variable coefficients. In: *International symposium on neural networks*, (pp. 25–34). Berlin, Heidelberg: Springer.

Ramezanzadeh, S., Memariani, M., & Saati, S. (2005). Data envelopment analysis with fuzzy random inputs and outputs: A chance-constrained programming approach. *Iranian Journal of Fuzzy Systems, 2*(2), 21–29.

Roghaee, N., Mohammadi, E., & Varzgani, N. (2020). Performance evaluation and ranking of electricity companies using fuzzy network data envelopment analysis: A case study of Iranian regional electricity organisations. *International Journal of Management and Decision Making, 19*(4), 450–472.

Ruiz, J. L., & Sirvent, I. (2017). Fuzzy cross-efficiency evaluation: A possibility approach. *Fuzzy Optimization and Decision Making, 16*(1), 111–126.

Sabouhi, F., Pishvaee, M. S., & Jabalameli, M. S. (2018). Resilient supply chain design under operational and disruption risks considering quantity discount: A case study of pharmaceutical supply chain. *Computers and Industrial Engineering, 126*, 657–672.

Seyed Esmaeili, F. S., Rostamy-Malkhalifeh, M., & Hosseinzadeh Lotfi, F. (2019). The possibilistic Malmquist productivity index with fuzzy data. In: *The 11th national conference on data envelopment Analysis, Iran*.

Shiraz, R. K., Charles, V., & Jalalzadeh, L. (2014a). Fuzzy rough DEA model: A possibility and expected value approaches. *Expert Systems with Applications, 41*(2), 434–444.

Shiraz, R. K., Tavana, M., & Fukuyama, H. (2020). A random-fuzzy portfolio selection DEA Model using value-at-risk and conditional value-at-risk. *Soft Computing, 24*, 17167–17186.

Shiraz, R. K., Tavana, M., & Paryab, K. (2014b). Fuzzy free disposal hull models under possibility and credibility measures. *International Journal of Data Analysis Techniques and Strategies, 6*(3), 286–306.

Tavana, M., Shiraz, R. K., Hatami-Marbini, A., Agrell, P. J., & Paryab, K. (2012). Fuzzy stochastic data envelopment analysis with application to Base Realignment and Closure (BRAC). *Expert Systems with Applications, 39*(15), 12247–12259.

Tavana, M., Shiraz, R. K., Hatami-Marbini, A., Agrell, P. J., & Paryab, K. (2013). Chance-constrained DEA models with random fuzzy inputs and outputs. *Knowledge-Based Systems, 52*, 32–52.

Tlig, H., & Ben Hamed, A. (2017). Assessing the efficiency of commercial Tunisian Banks using fuzzy data envelopment analysis. *Journal of Data Envelopment Analysis and Decision Science, 2017*(2), 14–27.

Wang, H., Dong, M., & Wang, L. (2020). A new fuzzy DEA model for green supplier evaluation considering undesirable outputs. In: *International conference on system science and engineering* (pp. 1–6). IEEE.

Wardana, R. W., Masudin, I., & Restuputri, D. P. (2020). A novel group decision-making method by P-robust fuzzy DEA credibility constraint for welding process selection. *Cogent Engineering, 7*(1), 1728057.

Wardana, R. W., Warinsiriruk, E., & Joy-A-Ka, S. (2018). Welding process selection for storage tank by integrated data envelopment analysis and fuzzy credibility constrained programming approach. *International Journal of Industrial and Systems Engineering, 12*(10), 986–990.

Wen, M. (2015). Fuzzy DEA. In: *Uncertain data envelopment analysis*. Uncertainty and operations research (pp. 83–116). Berlin, Heidelberg: Springer.

Wen, M., Guo, L., & Kang, R. (2013). A new ranking method to fuzzy data envelopment analysis using Hurwicz criterion. *Information, 16*(2), 847–853.

Wen, M., & Li, H. (2009). Fuzzy data envelopment analysis (DEA): Model and ranking method. *Journal of Computational and Applied Mathematics, 223*(2), 872–878.

Wen, M., Qin, Z., & Kang, R. (2011a). Sensitivity and stability analysis in fuzzy data envelopment analysis. *Fuzzy Optimization and Decision Making, 10*(1), 1–10.

Wen, M., & You, C., (2007). A fuzzy Data Envelopment Analysis (DEA) model with credibility measure. *Technical Report*.

Wen, M., You, C., & Kang, R. (2010). A new ranking method to fuzzy data envelopment analysis. *Computers and Mathematics with Applications, 59*(11), 3398–3404.

Wen, M., Zhou, D., & Lv, C. (2011b). A fuzzy Data Envelopment Analysis (dea) model with credibility measure. *Information-an International Interdisciplinary Journal, 14*(6), 1947–1958.

Wu, D. D., Yang, Z., & Liang, L. (2006). Efficiency analysis of cross-region bank branches using fuzzy data envelopment analysis. *Applied Mathematics and Computation, 181*(1), 271–281.

Xu, J., & Zhou, X. (2011). *Fuzzy-like multiple objective decision making*. Springer.

Xu, J., & Zhou, X. (2013). Approximation based fuzzy multI-Objective models with expected objectives and chance constraints: application to earth-rock work allocation. *Information Sciences, 238*, 75–95.

Yaghoubi, A., Amiri, M., & Safi Samghabadi, A. (2016). A new dynamic random fuzzy DEA model to predict performance of decision making units. *Journal of Optimization in Industrial Engineering, 9*(20), 75–90.

Yousefi, S., Soltani, R., Farzipoor Saen, R., & Pishvaee, M. S. (2017). A Robust fuzzy possibilistic programming for a new network GP-DEA Model to evaluate sustainable supply chains. *Journal of Cleaner Production, 166*, 537–549.

Zadeh, L. A. (1978). Fuzzy sets as a basis for a theory of possibility. *Fuzzy Sets and Systems, 1*(1), 3–28.

Zadeh, L. A. (2011). A Note on Z-numbers. *Information Sciences, 181*(14), 2923–2932.

Zerafat Angiz, M., Mustafa, A., Ghadiri, M., & Tajaddini, A. (2015). Relationship between efficiency in the traditional data envelopment analysis and possibility sets. *Computers and Industrial Engineering, 81*, 140–146.

Zhao, X., & Yue, W. (2012). A multi-subsystem fuzzy DEA model with its application in mutual funds management companies' competence evaluation. *Procedia Computer Science, 1*(1), 2469–2478.

Zhou, X., Luo, R., Lev, B., & Tu, Y. (2017). Two-stage fuzzy DEA models with undesirable outputs for banking system. In: *International conference on management science and engineering management* (pp. 1604–1615). Cham: Springer.

Zhou, X., Pedrycz, W., Kuang, Y., & Zhang, Z. (2016). Type-2 fuzzy multI-Objective DEA model: an application to sustainable supplier evaluation. *Applied Soft Computing, 46*, 424–440.

Zhou, X., Xu, Z., Yao, L., Tu, Y., Lev, B., & Pedrycz, W. (2018). A novel data envelopment analysis model for evaluating industrial production and environmental management system. *Journal of Cleaner Production, 170*, 773–788.
Zuojun, P., Yuhong, C., & Lei, S. (2011). Applied research on improved fuzzy chance-constrained model in engineering project comparison and selection. *Procedia Engineering, 12*, 184–190.

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