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CO-EVOLUTION EFFICACY OF PROJECT PORTFOLIO BASED ON STRATEGIC ORIENTATION

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Abstract. Multi-project management has been a trend of many large organizations' operations and a preferred organizational strategy in complex and dynamic environments. For an organization to achieve its strategy, it must integrate various projects into a project portfolio and implement coordinated management to make sure that these projects co-evolve in the direction of the overall strategy. As some elements in project portfolio (PP) cannot be quantified or determined accurately, a PP could be characterized as an uncertain and fuzzy problem where it is difficult to measure the co-evolution efficacy. To solve this difficulty, in this paper, we first propose a conceptual framework of Project Portfolio based on Strategic Orientation (PPSO) with quantitative indices and process of the co-evolution. A mathematical model based on Fuzzy Data Envelopment Analysis(FDEA) is built to measure the co-evolution efficacy of the PPSO, and provides a basis for optimal PPSO selection. The model is verified by a computational experiment based on actual data provided by a Chinese firm of HPM, a reputable Chinese project management consulting firm, which has also been officially certified by the International Project Management Association (IPMA). The results suggest that co-evolution efficacy is reasonably effective for selecting the optimal PPSO. To our knowledge, this study is the first time to apply the notion of co-evolution efficacy and fuzzy Data Envelopment Analysis to the PP domain, which enriches the theories of project management and strategic management. Also, this study makes an important contribution to integrating a group of projects into a PP under the strategic direction and helping an organization optimize its strategic management.

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1. Introduction

With the acceleration of globalization, project portfolio (PP) as an effective method to solve the multi-project problem has become more and more important during the past decades. Research literature reveals that PP focuses on investment and resource allocation decisions in order to align the entire portfolio with a strategy [18]. PP deals with the coordination and control of multiple projects pursuing the same strategic goals and competing for the same resources, whereby managers prioritize among projects to achieve strategic

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benefits [13,14,38]. Since projects provide products and services to satisfy market demand and enhance the core competitiveness of an enterprise, PP is considered to be the key to the implementation of business strategies [39] and has an important influence on the future competitive position of the enterprise [16]. Therefore, PP is of great significance to achieve long-term sustainable development of organizational strategies.

Many existing studies have been carried on the relationship between PP and organizational strategy. Hyvari [26] considers PP to be a holistic activity dependent on organizational strategy, and provides a close interconnection among enterprise strategy, projects and project portfolio. Sanchez [12] notes it was difficult but critical to develop key strategic PP performance indices for measuring the achievement of strategic objectives. Beringer [6] and Patanakul [43] argue that PP can reflect the realization of strategy as well as the development potential of an organization. In most research on PP, strategy is considered the most important objective that a PP should achieve. The process of achieving strategy using PP is also the co-evolution process of the PP in the strategic direction [3, 10, 21]. Many scholars consider the Resource Constrained project scheduling is very important to achieve objectives of the PP, while Project Scheduling Problem (RCPSP) is the standard model for project scheduling [5, 46]. As a result, various intelligent algorithms which solve the problems with multi-objectives and high complexity by simulating or revealing the laws or processes of natural phenomena have been designed to optimize the problem of project portfolio scheduling. For example, Sönke [28] considers the resource-constrained project scheduling problem with makespan minimization as the objective and proposes a new genetic algorithm approach to solve this problem. Vanhoucke [52] presents a new solution approach to solve the resource-constrained project scheduling problem in the presence of three types of logical constraints which can compete with the multi-mode algorithms when no logical constraints are taken into account to achieve. These papers provide a reference for solving the problem of project scheduling, make a great contribution to connecting project portfolio and organizational strategy, and provide a basis for decision making for managers to use when they implement portfolio management [8, 30, 40]. However, this RCPSP model cannot deal with all situations that occur in the real business world [2]. Consequently, many scholars have extended this model by simulation to build a more general model that optimizes project portfolio scheduling problems [25, 55] and achieve organizational strategy.

The conception of co-evolution is inherited from the ecology and used to describe the processes where two (or more) species reciprocally affect each other's evolution. So for example, an evolutionary change in the morphology of a plant, might affect the morphology of an herbivore that eats the plant, which in turn might affect the evolution of the plant, which might affect the evolution of the herbivore and so on. The co-evolution of species emphasizes the direction and indices during the evolution process, in the PP based on strategic orientation (PPSO), the co-evolution direction of the PP is the strategic direction, all project components that make up the project portfolio are interdependent and collaborative, that is, a change in the status of a project will affect the status of a project component that accompanies it directly or indirectly, and affect the degree of implementation of the strategy. So it is necessary to construct an index system to describe the evolutionary direction and reflect the co-evolution process in the PPSO. However, the phased indices are unclear and this may cause the problem that the co-evolution process of the PPSO cannot proceed in a planned way. Therefore, analyzing the PPSO co-evolution process has important practical significance emphasizing on the phased indices and seeking the balance between the achievement of the PP's own and organizational strategy. Moreover, it will further guide the generation of the optimal measure for the co-evolution efficacy. However, few studies have been done on this.

The purpose of the co-evolution of the PPSO is to achieve the strategy. The measurement of the co-evolution efficacy of the PPSO, which is used to evaluate the realization of the strategy and provide a basis for selecting the best PPSO, is another essential part to promote the sustainable development of organizational strategy. Many studies have been conducted on the methods of close correlation maintenance between PP and strategy, resources allocation across different projects and schedule optimization of the PP [9], making a great contribution to connecting PP and organizational strategy, and providing a basis for decision making when managers implement portfolio management [8,30,40]. However, only a few researchers have measured and evaluated the co-evolution efficacy of the PPSO [37], which may hinder managers from optimizing their PPSO. Therefore, it is necessary to investigate the co-evolution efficacy of the PPSO to realize organizational strategy optimally.

In this study, a conceptual framework of the PPSO with the quantitative indices and process of the co-evolution is proposed. A mathematical model based on the Fuzzy Data Envelopment Analysis (FDEA) is established for measuring the co-evolution efficacy of the PPSO. The proposed model is verified using a computational experiment based on an actual from an esteemed project management consulting firm in China.

This paper is structured as follows. Section 2 proposes a conceptual framework of the PPSO base on the classification of the quantitative indices and the division of the process accurately, and explains the meanings of each quantitative index. Section 3 builds a mathematical model for measuring the co-evolution efficacy of the PPSO base on the FDEA, and describes the parameters of this model are. Section 4 verifies the effectiveness and feasibility of the model using a computational experiment. Section 5 draws the conclusions.

2. Conceptual framework of the PPSO

The co-evolution of the PP is a dynamic process in which all project components cooperate and compete with each other in accordance with strategic requirements. Building a scientific and effective PP is challengeable for any enterprise, since many unpredictable factors influence on it. In addition, Using merely qualitative indices to measure the co-evolution efficacy is insufficient, and measurements supported by the quantitative indices need to be employed first.

Business strategy exerts a profound influence on the PPSO management and its success [5]. In order to measure the cooperation relationship between PP and strategy, business indices are generalized into six categories: customer satisfaction, strategic goals advantage, organizational growth, technical superiority target formation, risk avoidance capability and social reputation [11, 17]. These indices can help measure the scale of realization of strategic objectives, but they cannot reflect co-evolution efficacy of the PPSO. Therefore, it is important to identify the quantitative indices before measuring the co-evolution efficacy of a PPSO. Based on existing research [4, 24, 31] and PMBOK [44], a framework is built with quantitative indices and process of co-evolution of the PPSO, which is shown in Figure 1.

The definition and the Source of indices in Figure 1 are shown in Table 1.

Here, I_α^j is the α-th $(1 \le \alpha \le 7)$ input index of project $(1 \le j \le n)$, T_β^j is the $\beta th\,(1 \le \beta \le 2)$ transitional index of project $j\,(1 \le j \le n)$, shown as Figure 1, the influence factors are categorized as seven indices: profitability I_1^1 is a traditional evaluation index that measures the viability of the project component [13]. Function achievement I_2^1 reflects the completion of specific goals set artificially. It indicates the project's purposes, such as developing new business and new markets, or increasing the market share in the case of loss [45, 51]. Resource fitness I_3^1 is a classical problem in the PP, and it can ensure that the resource adapter helpful in optimizing the structure of the PP and enhances the efficacy of project implementation [22]. The utilization rationality of organizational capacity I_4^1 is a measurement index that evaluates the utilization of the limited capacity supported by the organization. Without this support, the project cannot be implemented successfully [33]. Different projects contribute different functions to realize the strategy, and the strategic weight of project components I_5^1 demonstrates the contribution and importance of the components to organizational strategy; it is for determining the project's priority [7]. Project management maturity I_6^1 is the index for assessing the level of organizational project management that has an important significance for enterprise project management practice. Ensuring the project starts at the right time is very important for the PPSO operation success. The value of the Start Timeliness I_7^1 reflects the boundary of the PP scheduling.

Here the indices values are input into a single project, and transferred into two transitional indices. Those present the evolution efficacy of each project including the achievement of its own strategy T_1^1 and the contribution to organizational strategy T_2^1. The two indices are optimized and the co-evolution efficacy of the PPSO is calculated.

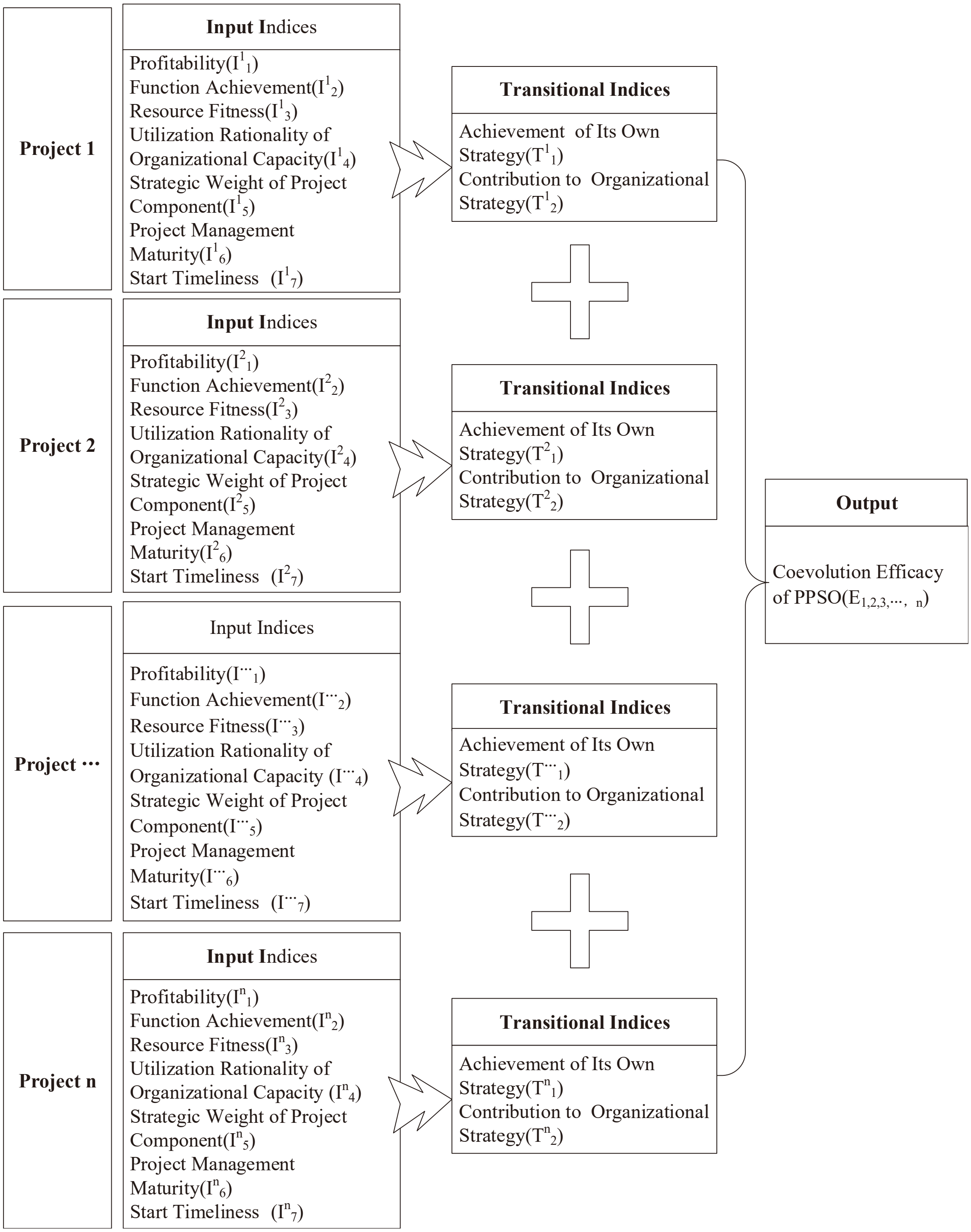

Figure 1. Conceptual framework of the PPSO.

Table 1. The definition and the Source of indices.

Indices		Definition	Source
Input indices	Profitability	The state or condition of yielding a financial profit or gain.	[31] [32] [33]
	Function achievement	The function of the project itselfi ncluding the development of the market, improve competitiveness, win social honor and so on	[21][28][31] [33] [34]
	Resource fitness	Rational allocation of limited resources	[4] [31] [36][37]
	Utilization rationality of organizational capacity	Rational use of the limited organizational capacity	[24] [30] [31] [36] [37] [38]
	Strategic weight of project components	The importance of the projects to strategy	[15] [24] [27] [30] [39]
	Project management maturity	The progressive development of an enterprise-wide project management approach, methodology, strategy, and decision-making process.	[31] [34] [35] [36]
	Value of the Start Timeliness	The suitability of the project start time	[32] [33] [34]
Transitional indices	Achievement ofi ts own strategy	The realization degree of the project's own strategy	[15] [21] [24] [27] [28] [30] [31] [33] [34] [39] [40]
	Contribution to organizational strategy	Contribution the project makes for the realization of strategy	[24] [30] [31] [37]

3. Quantitative model of Co-evolution efficacy of the PPSO

There are many evaluation methods examining the portfolio efficacy [23, 49, 50]; however, most are used for measuring the efficacy of financial portfolios, rather than the PPSO management. As some of the measuring indices of the PPSO cannot be quantified or determined precisely, traditional measuring methods cannot adapt to the vagueness and uncertain of measured indices. Fuzzy Data Envelopment Analysis (FDEA) is an operational method used to study economic production boundaries. And it is highly suitable to solve uncertain problems.

Thus, a mathematical model based on the FDEA is proposed in this section for measuring the co-evolution efficacy of the PPSO.

3.1. Fuzzy set

Fuzzy DEA is the combination of fuzzy and DEA theories which is used to account for subjective input and output values, so it is necessary to recall some basic definitions on fuzzy sets theory [57] needed for the paper before constructing the model of co-evolution efficacy of the PPSO.

Definition 3.1. let X be a classical set of objects, whose elements are denoted generically by x, A fuzzy set $\tilde{\sigma}$ in X is a set of ordered pairs: $\tilde{\sigma} = \{(x, \mu_{\tilde{\sigma}}(x) \mid x \in X)\}$, where $\mu_{\tilde{\sigma}}(x)$ is membership function of x in $\tilde{\sigma}$ that $\mu_{\tilde{\sigma}}\colon x \to [0,1]$.

Definition 3.2. The $\alpha{-}level{-}set$ of a fuzzy set $\tilde{\sigma}$ is a crisp subset of X and is denoted by $\tilde{\sigma}_\alpha = \{x \in X \mid \mu_{\tilde{\sigma}}(x)\}$.

Definition 3.3. A fuzzy set $\tilde{\sigma}$ of set X is convex if $\mu_{\tilde{\sigma}}(\lambda x_1 + (1-\lambda)x_2) \geq \min\{\mu_{\tilde{\sigma}}(x_1), \mu_{\tilde{\sigma}}(x_2)\}, x_1, x_2 \in X, \lambda \in [0,1]$.

Definition 3.4. A fuzzy set $\tilde{\sigma}$ of set X is normal if and only if $sup_x \mu_{\tilde{\sigma}}(x) = 1$, that is, the supremum of $\mu_{\tilde{\sigma}}(x)$ over X is unity, a fuzzy number $\tilde{\sigma}$ is a normal and convex fuzzy set $\tilde{\sigma}$ of the real line R.

Definition 3.5. If $\tilde{x}^g_{qi}$ and $\tilde{y}^h_{ti}$ are triangular fuzzy numbers; that is $\tilde{x}^g_{qi} = (\underline{x}^g_{qi}, x^g_{qi}, \overline{x}^g_{qi})$ and $\tilde{y}^h_{ti} = \left(\underline{y}^h_{ti}, y^h_{ti}, \overline{y}^h_{ti}\right)$, the value of $\tilde{x}^g_{qi}$ and $\tilde{y}^h_{ti}$ are determined as follows [20]:

Very Bad (VB) : $(0, 0, 0.1)$, *Bad (B)* : $(0, 0.1, 0.3)$,

Middle Lower(ML) : $(0.1, 0.3, 0.5)$, *Middle Upper (MU)* : $(0.5, 0.7, 0.9)$,

Good (G) : $(0.7, 0.9, 1)$, *Very Good (VG)* : $(0.9, 0.9, 1)$.

Definition 3.6. If $\tilde{L_1}$ and $\tilde{L_2}$ are triangular fuzzy numbers, $\tilde{L_1} = (l_1, m_1, b_1)$ and $\tilde{L_2} = (l_2, m_2, b_2)$, the operational laws are shown as follows [42,56]:

$$\tilde{L_1} + \tilde{L_2} = (l_1 + l_2, m_1 + m_2, b_1 + b_2) \tag{3.1}$$

$$\tilde{L_1} \cdot \tilde{L_2} = (l_1 l_2, m_1 m_2, b_1 b_2) \tag{3.2}$$

$$\rho \cdot \tilde{L_1} = (\rho l_1, \rho m_1, \rho b_1) \tag{3.3}$$

$$\tilde{L_1} / \tilde{L_2} = (l_1/l_2, m_1/m_2, b_1/b_2) \tag{3.4}$$

$$\text{If } (l_1 \leq l_2, m_1 \leq m_2, b_1 \leq b_2), \text{ the } \tilde{L_1} \leq \tilde{L_2}. \tag{3.5}$$

3.2. Model design

Assuming k kinds of PPSO implementations as decision-making units $DMU_i i = 1, 2, 3, \ldots, k$; 1 kind of index is input and m kinds of indices are output in order to achieve the effectiveness of valid measurement. Assuming the input of decision-making units DMU_i ($i = 1, 2, 3, \ldots, k$) is the input vector of project g, $\tilde{X}^g_i = (\tilde{x}^g_{1i}, \tilde{x}^g_{2i}, \ldots, \tilde{x}^g_{li})$, $g = 1, 2, 3, \ldots, n$, the output of DMU_i is the output vector of project h, $\tilde{Y}^h_i = \left(\tilde{y}^h_{1i}, \tilde{y}^h_{2i}, \ldots, \tilde{y}^h_{li}\right)$, $h = 1, 2, 3, \ldots, n$. It is convenient to obtain a model for measuring the relative co-evolution efficacy of project g to h (E_h^g) in a PPSO [32,34,54]:

$$\min \quad \left\{E_h^g - \varepsilon \cdot \left(\sum_{q=1}^{l} S_q^- + \sum_{q=1}^{l} S_q^+\right)\right\} \tag{3.6}$$

$$\text{s.t.} \quad \sum_{i=1}^{k} \omega_i \cdot \tilde{x}_{qi}^g + S_q^- = E_h^g \cdot \tilde{x}_{qi_0}^g,\ (q = 1,2,3,\ldots,l) \tag{3.7}$$

$$\sum_{i=1}^{k} \omega_i \cdot \tilde{Y}_{ti}^h - S_q^+ = \tilde{Y}_{ti_0}^h,\ (t = 1,2,3,\ldots,m) \tag{3.8}$$

$$S_q^-, S_q^+ \geq 0 \tag{3.9}$$

$$\omega_i \geq 0, (i = 1,2,3,\ldots,k) \tag{3.10}$$

$$\sum\nolimits_{i=1}^{k} \omega_i = 1. \tag{3.11}$$

Here, equation (3.6) refers to the cross-fuzzy DEA model where ε is infinitesimal, $\varepsilon = 1 * 10^{-7}$, and S_q^- and S_q^+ are slack variables, where $s^- = \left(s_1^-, s_2^-, \ldots, s_l^-\right)$ and $s^+ = \left(s_1^+, s_2^+, \ldots, s_m^+\right)$; ω_i is the weights of the DMU_i; if $\tilde{x}_{qi}^g$ or $\tilde{y}_{ti}^h$ is a certain index, the $\tilde{x}_{qi}^g = \left(x_{qi}^g, x_{qi}^g, x_{qi}^g\right)$ or $\tilde{y}_{qi}^g = \left(y_{ti}^h, y_{ti}^h, y_{ti}^h\right)$. Assuming the $\alpha - level - set$ of triangular fuzzy numbers $\tilde{x}_{qi}^g$ and $\tilde{y}_{ti}^h$ are determined according to equations (3.12) and (3.13) [20]:

$$\left[\left(\tilde{x}_{qi}^g\right)_{\alpha_1}, \left(\tilde{x}_{qi}^g\right)_{\alpha_2}\right] = \left[\left(\frac{\alpha}{2} \cdot \overline{x}_{qi}^g + \left(1 - \frac{\alpha}{2}\right) \cdot \underline{x}_{qi}^g\right), \left(\frac{\alpha}{2} \cdot \underline{x}_{qi}^g + \left(1 - \frac{\alpha}{2}\right) \cdot \overline{x}_{qi}^g\right)\right] \tag{3.12}$$

$$\left[\left(\tilde{y}_{ti}^h\right)_{\alpha_1}, \left(\tilde{y}_{ti}^h\right)_{\alpha_2}\right] = \left[\left(\frac{\alpha}{2} \cdot \overline{y}_{ti}^h + \left(1 - \frac{\alpha}{2}\right) \cdot y_{ti}^h\right), \left(\frac{\alpha}{2} \cdot \underline{y}_{ti}^h + \left(1 - \frac{\alpha}{2}\right) \cdot \overline{y}_{ti}^h\right)\right] \tag{3.13}$$

Based on equations (3.12) and (3.13), equations (3.6)$-$(11) are converted into a cross-efficiency CCR model:

$$\min \quad \left\{E_h^g - \varepsilon \cdot \left(\sum_{q=1}^{l} \left(S_{1q}^- + S_{2q}^-\right) + \sum_{t=1}^{m} \left(S_{1t}^+ + S_{2t}^+\right)\right)\right\} \tag{3.14}$$

$$\text{s.t.} \quad \sum_{i=1}^{k} \omega_i \cdot \left(\tilde{x}_{qi}^g\right)_{\alpha_1} + S_{1q}^- = E_h^g \cdot \left(\tilde{x}_{qi_0}^g\right)_{\alpha_1}, (q = 1,2,3,\ldots,l) \tag{3.15}$$

$$\sum_{i=1}^{k} \omega_i \cdot \left(\tilde{x}_{qi}^g\right)_{\alpha_2} + S_{2q}^- = E_h^g \cdot \left(\tilde{x}_{qi_0}^g\right)_{\alpha_2}, (q = 1,2,3,\ldots,l) \tag{3.16}$$

$$\sum_{i=1}^{k} \omega_i \cdot \left(\tilde{y}_{ti}^h\right)_{\alpha_1} - S_{1t}^+ = \left(\tilde{y}_{ti_0}^h\right)_{\alpha_1},\ (t = 1,2,3,\ldots,m) \tag{3.17}$$

$$\sum_{i=1}^{k} \omega_i \cdot \left(\tilde{y}_{ti}^h\right)_{\alpha_2} - S_{1t}^+ = \left(\tilde{y}_{ti_0}^h\right)_{\alpha_2},\ (t = 1,2,3,\ldots,m) \tag{3.18}$$

$$S_{1q}^- S_{2q}^-, S_{1q}^+, S_{2q}^+ \geq 0 \tag{3.19}$$

$$\sum_{i=1}^{k} \omega_i = 1, \omega_i \geq 0, (i = 1,2,3,\ldots,k) \tag{3.20}$$

Equations (3.14)$-$(3.19) constitute a linear planning problem concerning the parameter α. From this CCR model, it can be concluded that: if $S_{1q}^- = 0, S_{2q}^- = 0, S_{1q}^+ = 0$ and $S_{2q}^+ = 0$, the DMU_{i_0} is valid. Many valid values of DMU have been employed in practical application, while those valid DMU values cannot be evaluated further. Therefore, it is necessary to modify and improve this CCR model into a cross-efficiency $ICCR$ model, shown as equations (3.16)−(3.22) [29,35]:

$$\min \quad \left\{ E_h^g - \varepsilon \cdot \left(\sum_{q=1}^{l} \left(S_{1q}^- + S_{2q}^- \right) + \sum_{t=1}^{m} \left(S_{1t}^+ + S_{2t}^+ \right) \right) \right\} \tag{3.21}$$

$$\text{s.t.} \quad \sum_{i=1, i \neq i_0}^{k} \omega_i \cdot \left(\tilde{x}_{qi}^g \right)_{\alpha_1} + S_{1q}^- = E_h^g \cdot \left(\tilde{x}_{qi_0}^g \right)_{\alpha_1}, \ (q = 1, 2, 3, \ldots, l) \tag{3.22}$$

$$\sum_{i=1, i \neq i_0}^{k} \omega_i \cdot \left(\tilde{x}_{qi}^g \right)_{\alpha_2} + S_{2q}^- = E_h^g \cdot \left(\tilde{x}_{qi_0}^g \right)_{\alpha_2}, \ (q = 1, 2, 3, \ldots, l) \tag{3.23}$$

$$\sum_{i=1, i \neq i_0}^{k} \omega_i \cdot \left(\tilde{y}_{ti}^h \right)_{\alpha_1} - S_{1t}^+ = \left(\tilde{y}_{ti_0}^h \right)_{\alpha_1}, \ (t = 1, 2, 3, \ldots, m) \tag{3.24}$$

$$\sum_{i=1, i \neq i_0}^{k} \omega_i \cdot \left(\tilde{y}_{ti}^h \right)_{\alpha_2} - S_{1t}^+ = \left(\tilde{y}_{ti_0}^h \right)_{\alpha_2}, \ (t = 1, 2, 3, \ldots, m) \tag{3.25}$$

$$S_{1q}^-, S_{2q}^-, S_{1q}^+, S_{2q}^+ \geq 0 \tag{3.26}$$

$$\sum\nolimits_{i=1}^{k} \omega_i = 1, \omega_{_i} \geq 0, (i = 1, 2, 3, \ldots, k) \tag{3.27}$$

Comparison between the cross-efficiency CCR model and the cross-efficiency $ICCR$ model reveals that the $ICCR$ model excludes the DMU_{i_0}. Upon comparing the cross-efficiency CCR model against the linear portfolios of other DMU when measuring the DMU_{i_0}, we find that the valid DMU values may increase their investment proportionally but still maintain their relative validity. In the $ICCR$ model, the maximum proportional value of the DMU that increases the investment proportionally but still maintains the relative validity is defined as the "validity" of this DMU. This value is used to evaluate the validity of this DMU and reorder all other DMU values [29].

When the results of the $ICCR$ model in the form of the portfolio is obtained by taking the average value of the transitional indices for projects g and h, and the indices of project f are used as the input parameters to calculate the relative co-evolution efficacy of project f to projects g and h; which is E_{fgh}. Co-evolution efficacy can be calculated in the similar way when more projects exist in the PPSO.

3.3. Quantitative model of Co-evolution efficacy of the PPSO

As stated by the "Cask Effect", capacity of a cask is relying on the shortest wood chip. Similarly, the co-evolution efficacy of the PPSO is determined by the minimum value of the relative co-evolution efficacy. Quantitative model of the PPSO co-evolution efficacy is built for the following different situations.

Situation 3.1. *If the PPSO is composed of* 2 *projects: g and h, the co-evolution efficacy of this PPSO is denoted as E_{gh}, this quantitative model can be illustrated as equation* (3.28):

$$E_{gh} = \min \left\{ E_h^g, E_g^h \right\} / \max \left\{ E_h^g, E_g^h \right\} \tag{3.28}$$

Situation 3.2. *If the PPSO is composed of* 3 *projects: fg and h, the co-evolution efficacy of this PPSO is denoted as E_{fgh}, this quantitative model can be illustrated as equation* (3.29):

$$E_{fgh} = \frac{\min \left\{ E_{gh}^f \cdot E_{gh}, E_{fh}^g \cdot E_{fh}, E_{fg}^h \cdot E_{fg} \right\}}{\max \left\{ E_{gh}^f \cdot E_{gh}, E_{fh}^g \cdot E_{fh}, E_{fg}^h \cdot E_{fg} \right\}} \tag{3.29}$$

Table 2. Values of input and transitional indices for project A.

Sequence / Project / Index		$n = A$				
		First	Second	Third	Forth	Fifth
Input index	I_1^n	(0.52, 0.71, 0.93)	(0.47, 0.73, 0.88)	(0.33, 0.56, 0.72)	(0.04, 0.15, 0.38)	(0.23, 0.45, 0.67)
	I_2^n	(0.12, 0.18, 0.21)	(0.72, 0.95, 1)	(0.23, 0.45, 0.67)	(0.37, 0.79, 0.82)	(0.75, 0.85, 1)
	I_3^n	(0.52, 0.73, 0.94)	(0.38, 0.51, 0.76)	(0.11, 0.35, 0.59)	(0.12, 0.35, 0.56)	(0.13, 0.35, 0.77)
	I_4^n	(0.43, 0.55, 0.77)	(0.32, 0.56, 0.78)	(0.12, 0.32, 0.52)	(0.07, 0.11, 0.32)	(0.37, 0.54, 0.69)
	I_5^n	(0.17, 0.36, 0.58)	(0.89, 0.92, 1)	(0.65, 0.74, 0.96)	(0.12, 0.33, 0.58)	(0.54, 0.73, 0.92)
	I_6^n	(0.54, 0.78, 0.89)	(0.45, 0.67, 0.92)	(0.35, 0.57, 0.89)	(0.77, 0.83, 0.94)	(0.71, 0.92, 0.98)
	I_7^n	(0.33, 0.52, 0.71)	(0.72, 0.81, 0.92)	(0, 0.15, 0.32)	(0.71, 0.89, 0.94)	(0.56, 0.72, 0.9)
Trans-tional index	T_1^n	(0.32, 0.42, 0.53)	(0.54, 0.71, 0.83)	(0.37, 0.42, 0.57)	(0.35, 0.52, 0.75)	(0.33, 0.54, 0.82)
	T_2^n	(0.52, 0.67, 0.88)	(0.45, 0.78, 0.91)	(0.11, 0.32, 0.54)	(0.73, 0.86, 0.91)	(0.45, 0.72, 0.93)

Situation 3.3. *If the number of projects in the PPSO is r ($r \geq 3$), the equation* (3.24) *can be generalized as equation* (3.30):

$$E_{1,2,3,\ldots,r} = \frac{\min\left\{E_{23}^{1} \cdot E_{23}, \ldots, E_{(r-2)(r-1)}^{r} \cdot E_{(r-2)(r-1)}\right\}}{\max\left\{E_{23}^{1} \cdot E_{23}, \ldots, E_{(r-2)(r-1)}^{r} \cdot E_{(r-2)(r-1)}\right\}} \tag{3.30}$$

As the parameters in equations (3.6)−(27) are triangular fuzzy numbers, the relative co-evolution efficiency of the PPSO could be calculated according to Definition 1–5 and equations (3.1)−(3.5). Based on the equations (3.23)−(3.30), the PPSO co-evolution efficacy can be measured with more than two projects.

4. Computational experiment and results

A computational experiment is conducted based on a database provided by HPM, a reputable Chinese project management consulting firm, which has also been officially certified by the International Project Management Association. In our experiment, there are $2^n - 1 - n$ portfolios if the number of projects to be implemented is n. For example, if the number of projects is 3, 4 or 5, the numbers of the possible portfolios are 4, 11 and 26 respectively. Here, 4 projects $ABCD$ from a same company are selected from the database of the HPM, and every project has been executed 5 times. These 4 projects belongs to different categories, that is (A, B, C, D) = (*EPC, PPP, Characteristic town, Engineering Infrastructure*), EPC project includes the process of engineer, procure and construct, it is the traditional business of this company and focus in the area of engineering construction, PPP (Public-Private-Partnership) consulting project is a new project model which the Chinese government continuously encouraged to boost the economic revenues, and the task of this company is to build the structure; the Characteristic town project is a comprehensive construction project, in this project this company provides advisory services to the government as a decision-making consultants instead of participates in the construction of the project. Engineering Infrastructure is the main business of this company which is also focus in the area of engineering construction.

In company's strategic Planning, we can obtain the comprehensive strategic target of co-evolution, it is an integrated value, we remark it as 1 after normalized, then we can get the value of the input and transitional indices by inviting peer experts to score them according to the contribution to the achievement of strategic objectives according to Definition 5, The values of input and transitional indices are shown in Tables 2–5.

Table 3. Values of input and transitional indices for project B.

Sequence \ Project / Index		$n = B$				
		First	Second	Third	Forth	Fifth
Input index	I_1^n	(0.32, 0.54, 0.71)	(0.11, 0.33, 0.62)	(0.23, 0.45, 0.67)	(0.14, 0.43, 0.59)	(0.79, 0.89, 0.96)
	I_2^n	(0.67, 0.92, 1)	(0.09, 0.32, 0.43)	(0.37, 0.65, 0.74)	(0.11, 0.23, 0.53)	(0.52, 0.71, 0.93)
	I_3^n	(0.36, 0.52, 0.74)	(0.16, 0.39, 0.57)	(0.55, 0.72, 0.92)	(0.76, 0.93, 1)	(0.54, 0.73, 0.97)
	I_4^n	(0.91, 0.91, 1)	(0.65, 0.72, 0.89)	(0.06, 0.14, 0.38)	(0.77, 0.82, 0.93)	(0.72, 0.92, 1)
	I_5^n	(0.15, 0.23, 0.33)	(0.71, 0.93, 1)	(0.32, 0.56, 0.73)	(0.16, 0.39, 0.53)	(0.31, 0.45, 0.72)
	I_6^n	(0.58, 0.72, 0.49)	(0.38, 0.56, 0.27)	(0.17, 0.32, 0.55)	(0.08, 0.15, 0.36)	(0.33, 0.54, 0.71)
	I_7^n	(0.36, 0.54, 0.76)	(0.34, 0.51, 0.73)	(0.11, 0.34, 0.56)	(0.32, 0.58, 0.72)	(0.72, 0.83, 0.93)
Transtional index	T_1^n	(0.34, 0.55, 0.64)	(0.23, 0.43, 0.58)	(0.36, 0.76, 0.87)	(0.32, 0.47, 0.84)	(0.45, 0.53, 0.75)
	T_2^n	(0.12, 0.33, 0.52)	(0.32, 0.55, 0.78)	(0.12, 0.31, 0.56)	(0.32, 0.56, 0.72)	(0.53, 0.76, 0.92)

Table 4. Values of input and transitional indices for project C.

Sequence \ Project / Index		$n = C$				
		First	Second	Third	Forth	Fifth
Input index	I_1^n	(0.57, 0.79, 0.84)	(0.12, 0.38, 0.54)	(0.12, 0.34, 0.52)	(0.91, 0.91, 1)	(0.12, 0.34, 0.56)
	I_2^n	(0.13, 0.32, 0.56)	(0.13, 0.34, 0.52)	(0.56, 0.73, 0.91)	(0.13, 0.32, 0.54)	(0.13, 0.23, 0.34)
	I_3^n	(0, 0.12, 0.33)	(0.11, 0.32, 0.54)	(0.72, 0.91, 1)	(0.53, 0.74, 0.92)	(0.71, 0.83, 0.98)
	I_4^n	(0.27, 0.49, 0.73)	(0.52, 0.74, 0.89)	(0.12, 0.31, 0.52)	(0.67, 0.79, 0.84)	(0.14, 0.33, 0.56)
	I_5^n	(0.12, 0.33, 0.54)	(0.71, 0.83, 0.92)	(0.52, 0.73, 0.91)	(0.16, 0.39, 0.52)	(0.53, 0.72, 0.94)
	I_6^n	(0.71, 0.92, 1)	(0.45, 0.72, 0.96)	(0.21, 0.33, 0.51)	(0, 0.12, 0.35)	(0.31, 0.56, 0.74)
	I_7^n	(0.36, 0.52, 0.76)	(0.32, 0.59, 0.78)	(0.13, 0.32, 0.58)	(0.32, 0.54, 0.72)	(0.74, 0.93, 1)
Trans-tional index	T_1^n	(0.64, 0.64, 0.64)	(0.54, 0.61, 0.73)	(0.35, 0.35, 0.35)	(0.47, 0.52, 0.63)	(0.65, 0.65, 0.65)
	T_2^n	(0.31, 0.52, 0.78)	(0.71, 0.84, 0.93)	(0.32, 0.56, 0.72)	(0.12, 0.33, 0.55)	(0.52, 0.73, 0.96)

In the tables, the values are triangular fuzzy numbers which are uncertain, α is a constant determined by the decision maker based on actual data [52], which is 0.75 here. The values of triangular fuzzy numbers $\tilde{x}_{qi}^{g}$ and $\tilde{y}_{ti}^{h}$ are calculated according to equations (3.12) and (3.13), as shown in Tables 6–7:

A MATLAB program on platform of R2012b is developed to calculate the relative co-evolution efficacies among different projects [41,58]. Based on equations (3.28)−(3.30), the co-evolution efficacies of the 11 PPSOs comprised by project A, B, C and D are calculated shown in Table 8.

The values of the $PPSO$ co-evolution efficacy constituted by projects A and B, E_{AB} are $0.715, 0.323, .545, 0.913$ and 0.664. For the same $PPSO$, the co-evolution efficacy in different times is different, since many identified factors affect the implementation of the $PPSO$. Therefore, average value of results is used as the co-evolution efficacy in order to reduce the influence of these factors. In Table 8, we found that the value of the PPSO co-evolution efficacy comprised by project A and D ($PPSO_{AD}$) equal to 0.732 which is the maximum. It means when the company selects $PPSO$, the $PPSO_{AD}$ will be the best solution. The second best is the $PPSO_{AB}$ with its' co-evolution efficacy of 0.632. Comparing with the $PPSO_{AD}$ and $PPSO_{AB}$, the value of co-evolution efficacy of $PPSO_{AD}$ is 0.1 higher than $PPSO_{AB}$, which represents the $PPSO_{AD}$ will

TABLE 5. Values of input and transitional indices for project D.

Sequence \ Project / Index		$n = D$				
		First	Second	Third	Forth	Fifth
Input index	I_1^n	(0.35, 0.79, 0.92)	(0.11, 0.53, 0.75)	(0.18, 0.43, 0.56)	(0.69, 0.88, 0.92)	(0.21, 0.43, 0.62)
	I_2^n	(0.21, 0.43, 0.65)	(0.21, 0.33, 0.55)	(0.45, 0.57, 0.79)	(0.16, 0.32, 0.55)	(0, 0, 0.1)
	I_3^n	(0.33, 0.51, 0.73)	(0.41, 0.63, 0.75)	(0.67, 0.79, 0.82)	(0.45, 0.57, 0.69)	(0.57, 0.69, 1)
	I_4^n	(0.57, 0.69, 0.84)	(0.54, 0.73, 0.89)	(0.16, 0.35, 0.51)	(0.67, 0.79, 0.82)	(0.12, 0.32, 0.54)
	I_5^n	(0.09, 0.23, 0.56)	(0.73, 0.92, 1)	(0.52, 0.72, 0.92)	(0.14, 0.32, 0.53)	(0.35, 0.73, 0.96)
	I_6^n	(0.67, 0.79, 0.81)	(0.35, 0.67, 0.89)	(0.13, 0.46, 0.11)	(0.24, 0.41, 0.63)	(0.42, 0.55, 0.67)
	I_7^n	(0.23, 0.45, 0.73)	(0.53, 0.75, 0.87)	(0.19, 0.33, 0.52)	(0.33, 0.52, 0.72)	(0.57, 0.87, 0.92)
Trans-tional index	T_1^n	(0.23, 0.42, 0.68)	(0.72, 0.72, 0.72)	(0.53, 0.62, 0.18)	(0.64, 0.64, 0.64)	(0.62, 0.81, 0.88)
	T_2^n	(0.33, 0.51, 0.72)	(0.88, 0.91, 1)	(0.32, 0.56, 0.72)	(0.14, 0.33, 0.57)	(0.51, 0.73, 0.94)

TABLE 6. Values of $\alpha - level - set$ for project A and B.

Sequence \ Project / Index		$n = A$									
		First		Second		Third		Forth		Fifth	
		α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2
Input index	I_1^n	0.33	0.78	0.62	0.73	0.48	0.57	0.17	0.25	0.40	0.51
	I_2^n	0.08	0.18	0.83	0.90	0.40	0.51	0.54	0.65	0.84	0.91
	I_3^n	0.33	0.78	0.52	0.62	0.29	0.41	0.29	0.40	0.37	0.53
	I_4^n	0.27	0.64	0.49	0.61	0.27	0.37	0.16	0.23	0.49	0.57
	I_5^n	0.11	0.43	0.93	0.96	0.77	0.84	0.29	0.41	0.68	0.78
	I_6^n	0.34	0.76	0.63	0.74	0.55	0.69	0.83	0.88	0.81	0.88
	I_7^n	0.21	0.57	0.80	0.85	0.12	0.20	0.80	0.85	0.69	0.77
Trans-tional index	T_1^n	0.20	0.45	0.65	0.72	0.45	0.50	0.50	0.60	0.51	0.64
	T_2^n	0.33	0.75	0.62	0.74	0.27	0.38	0.80	0.84	0.63	0.75
Sequence \ Index / Project		$n = B$									
		First		Second		Third		Forth		Fifth	
		α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2
Input index	I_1^n	0.20	0.56	0.30	0.43	0.40	0.51	0.31	0.42	0.85	0.90
	I_2^n	0.42	0.88	0.22	0.30	0.51	0.60	0.27	0.37	0.67	0.78
	I_3^n	0.23	0.60	0.31	0.42	0.69	0.78	0.85	0.91	0.70	0.81
	I_4^n	0.57	0.97	0.74	0.80	0.18	0.26	0.83	0.87	0.83	0.90
	I_5^n	0.09	0.26	0.82	0.89	0.47	0.58	0.30	0.39	0.46	0.57
	I_6^n	0.36	0.52	0.34	0.31	0.31	0.41	0.19	0.26	0.47	0.57
	I_7^n	0.23	0.61	0.49	0.58	0.28	0.39	0.47	0.57	0.80	0.85
Trans-tional index	T_1^n	0.21	0.53	0.36	0.45	0.55	0.68	0.52	0.65	0.56	0.64
	T_2^n	0.08	0.37	0.49	0.61	0.29	0.40	0.47	0.57	0.68	0.77

achieve 15.8% more the strategic objectives than $PPSO_{AB}$ when they are in the same management environment. This phenomenon is consistent with the actual as *project A (EPC project)* and *project D (Engineering Infrastructureproject)* are both focus in the area of engineering construction , the personnel, equipment and resources and other elements of them can be shared, once the these elements are released, they can be reused by the desired project immediately and promote the effective implementation of another project. However, *project*

TABLE 7. Values of $\alpha - level - set$ for projects C and D.

Sequence \ Project / Index		$n=C$									
		First		Second		Third		Forth		Fifth	
		α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2
Input index	I_1^n	0.36	0.74	0.28	0.38	0.27	0.37	0.94	0.97	0.29	0.40
	I_2^n	0.80	0.40	0.28	0.37	0.69	0.78	0.28	0.39	0.21	0.26
	I_3^n	0.00	0.21	0.27	0.38	0.83	0.90	0.68	0.77	0.81	0.88
	I_4^n	0.17	0.56	0.66	0.75	0.27	0.37	0.73	0.78	0.30	0.40
	I_5^n	0.08	0.38	0.79	0.84	0.67	0.76	0.30	0.39	0.68	0.79
	I_6^n	0.44	0.89	0.64	0.77	0.32	0.40	0.13	0.22	0.47	0.58
	I_7^n	0.23	0.61	0.49	0.61	0.30	0.41	0.47	0.57	0.84	0.90
Trans-tional index	T_1^n	0.40	0.64	0.61	0.66	0.35	0.35	0.53	0.57	0.65	0.65
	T_2^n	0.19	0.60	0.79	0.85	0.47	0.57	0.28	0.39	0.69	0.80

Sequence \ Index / Project		$n=D$									
		First		Second		Third		Forth		Fifth	
		α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2	α_1	α_2
Input index	I_1^n	0.22	0.71	0.35	0.51	0.32	0.42	0.78	0.83	0.36	0.47
	I_2^n	0.13	0.49	0.34	0.42	0.58	0.66	0.31	0.40	0.04	0.06
	I_3^n	0.21	0.58	0.54	0.62	0.73	0.76	0.54	0.60	0.73	0.84
	I_4^n	0.36	0.74	0.67	0.76	0.29	0.38	0.73	0.76	0.28	0.38
	I_5^n	0.06	0.38	0.83	0.90	0.67	0.77	0.29	0.38	0.58	0.73
	I_6^n	0.42	0.76	0.55	0.69	0.12	0.12	0.39	0.48	0.51	0.58
	I_7^n	0.14	0.54	0.66	0.74	0.31	0.40	0.48	0.57	0.70	0.79
Trans-tional index	T_1^n	0.14	0.51	0.72	0.72	0.40	0.31	0.64	0.64	0.72	0.78
	T_2^n	0.21	0.57	0.93	0.96	0.47	0.57	0.30	0.41	0.67	0.78

TABLE 8. Co-evolution Efficacy of 11 PPSOS comprised by project A, B, C and D.

Sequence \ Project / Index	Co-evolution Efficacy of Project Portfolio-based Organizational Strategy $(E1, 2, 3, \ldots, n)$					
	First	Second	Third	Forth	Fifth	Average Value
$\mathbf{E}_{(\mathbf{AB})}$	0.715	0.323	0.545	0.913	0.664	0.632
$\mathbf{E}_{(\mathbf{AC})}$	0.0001	0.535	0.381	0.530	0.714	0.432
$\mathbf{E}_{(\mathbf{AD})}$	0.663	0.932	0.998	0.896	0.172	0.732
$\mathbf{E}_{(\mathbf{BC})}$	0.016	0.555	0.817	0.605	0.490	0.497
$\mathbf{E}_{(\mathbf{BD})}$	0.948	0.258	0.577	0.970	0.112	0.573
$\mathbf{E}_{(\mathbf{CD})}$	0.000	0.489	0.354	0.455	0.256	0.311
$\mathbf{E}_{(\mathbf{ABC})}$	0.005	0.443	0.340	0.305	0.436	0.306
$\mathbf{E}_{(\mathbf{ABD})}$	0.472	0.124	0.843	0.673	0.028	0.428
$\mathbf{E}_{(\mathbf{ACD})}$	0.177	0.327	0.763	0.328	0.419	0.403
$\mathbf{E}_{(\mathbf{BCD})}$	0.007	0.363	0.320	0.278	0.054	0.204
$\mathbf{E}_{(\mathbf{ABCD})}$	0.001	0.236	0.112	0.206	0.009	0.113

B is a PPP project, the personnel, equipment and resources and other elements could not be shared very well, so co-evolution efficacy of $PPSO_{AB}$ is lower than $PPSO_{AD}$.

In Table 8, the $PPSO_{AD}$ is the most optimal if the company wants to select the best one in all $PPSOs$ or a $PPSO$ composed of 2 projects. However, the best option should be $PPSO_{ABD}$ rather than $PPSO_{AD}$ if the number of projects in the PPSO is limited to more than 2. When managers make decision on the PPSO they should take the actual situation into account and the best portfolio is relative.

The value of the co-evolution efficacy of the PPSO that includes all projects is 0.113 and this is also the final co-evolution efficacy that the company realizes in the real life. If we select the $PPSO_{AD}$ according to this proposed approach, the value of the PPSO co-evolution efficacy is 0.732, the realization of strategic objectives in co-evolution aspect will be increased by 62.1% compared with $PPSO_{ABCD}$, which means there are dramatic benefits could be achieved by following this model. The reason for the co-evolution efficacy of the $PPSO_{ABCD}$ is much lower than that of other PPSOs is the negative synergistic effect [24] that exists among different kinds of projects and this negative synergistic effect will reduce co-evolution efficacy of the PPSO, which requires us to take the synergistic effect among different projects into account when making the PP decisions.

5. Conclusion

Many firms manage various projects in complex and dynamic environments. Therefore, they need to implement coordinated management to make sure that these projects co-evolve in the direction of the overall strategy. In other words, they need to manage Project Portfolio based on Strategic Orientation (PPSO). In this paper, we build a conceptual framework of the $PPSO$ including the quantitative indices and process of the co-evolution and a quantitative model to capture the real complexity of the modern business environment. In the conceptual framework, we categorized the influence factors into seven indices: profitability, function achievement, resource fitness, utilization rationality of organizational capacity, strategic weight of project components, project management maturity, start timeliness. The scope of this system covers the traditional evaluation objectives and measures the contribution of the project component to organizational strategy, as well as the importance of each component.

The system evaluates projects to determine how they contribute dynamically to the achievement of the organizational strategy. In the system, the co-evolution efficacy of the PPSO is taken as the final output, and reflects the level of fitness of the PP for achieving the overall strategy. It is complicated to measure the fitness of a PPSO, as some indices cannot be quantified or determined precisely. As DEA is pertinent to solve such uncertain problems, the traditional DEA is transformed into an FDEA approach and a model is built for measuring the co-evolution efficacy of a PPSO. The FDEA model modifies and improves the CCR model into a cross-efficiency $ICCR$ model to measure the relative co-evolution efficacy of different projects. Then, a model is proposed to solve the problem of measuring the co-evolution efficacy of the PPSO. With rising complexity of the environment, the benefits of co-evolution become even larger. This study contributes to the literature on and project portfolio management in several ways.

This study proposes a conceptual framework of the PPSO offering a deeper understanding of the elements and process of co-evolution of the PPSO. The quantitative indices and process of co-evolution of the PPSO show the mechanism by which input and transitional indices affect the co-evolution efficacy of the PPSO and, consequently, the result of project portfolio selection.

This study also establishes a quantitative model to measure the co-evolution efficacy of the PPSO based on the theory of FDEA. Our results from a comprehensive computational experiment suggest that co-evolution efficacy is reasonably effective for selecting the optimal PPSO. To our knowledge, this is the first time to apply the notion of co-evolution efficacy and the FDEA to the research area on, which enriches the theories of project management and strategic management and makes an important contribution to integrating a group of projects into a PP under the strategic direction and helping an organization optimize its strategic management. This model is further verified by a computational experiment from a real database of a reputable Chinese project management firm. Our results of this experiment show that the co-evolution efficacy can be measured by the quantitative model and provide a basis for selecting the best PPSO. Practitioners may benefit most from applying the finding that the co-evolution efficacy must be considered in an integrated fashion to achieve the optimal strategic objectives.

There are also some limitations in this study. First, systematic deficiencies of the indices may be induced by the negative synergistic relationship between indices having not been taken into account. Second, the quantitative model of co-evolution efficacy of the PPSO base on the FDEA has been built in this study. However, the corresponding algorithm to solve this problem has not been proposed, which may cause the sensitive analysis of parameters and the hidden factors insufficient. Third, the effectiveness and feasibility of this proposed model can be verified by a computational experiment. However, the implemented projects are only for the problem of co-evolution hence the results of the computational experiment may not be generalizable. These limitations would be addressed in future research.

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