Dynamic Comprehensive Evaluation Using Semi-Partial Subtraction Set Pair Potential: Method and Application

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Abstract. Addressing the issue of absolute evaluation conclusions generated by dynamic comprehensive evaluation methods, this paper proposes a novel approach based on Semi-Partial Subtraction Set Pair Potential (SP-SSPP). Firstly, the method determines the grade intervals by calculating the grey relational degree between the ideal point of evaluation values and their geometric mean. Secondly, the evaluation values and grade intervals form a set pair system characterized by certain-uncertain relationships. The state and development trend of this set pair system are then analyzed using SP-SSPP to derive comprehensive evaluation values and rankings. The utilization of non-discrete grade intervals effectively avoids the "either-or" evaluation conclusions inherent in traditional comprehensive evaluation methods. This characteristic enables the method to effectively guide the evaluated entities towards sustained and substantial development. Finally, the validity of the proposed method is demonstrated through a case study.

Keywords: Grade Intervals; Connection Number; Semi-Partial Subtraction Set Pair Potential (SP-SSPP); Dynamic Comprehensive Evaluation.

1. Introduction

The essence of comprehensive evaluation lies in transforming disordered information into an ordered state and integrating multidimensional information [1]. While scholars hold diverse perspectives on the concept of comprehensive evaluation, a common understanding recognizes it as "a systematic, multidimensional assessment process applied to complex systems" [2-4]. As a typical system analysis tool, it generally comprises key elements such as the evaluation objective, subject, object, methodology, and results [5].

With the extension of evaluation cycles and the accumulation of data, comprehensive evaluation has evolved from analyzing static cross-sectional data towards assessing dynamic spatio-temporal panel data. The essence of dynamic evaluation involves introducing the time dimension into the static evaluation framework, utilizing time-series data processing to reveal the dynamic development process of the evaluated entities [6]. Academia has developed numerous dynamic evaluation methods. From the perspective of the comprehensive evaluation workflow, these methods can be categorized into two primary groups: dynamic weighting coefficient methods and temporal aggregation methods. Dynamic weighting methods determine indicator weights based on objective criteria such as indicator gain, trend evolution, and rate of change. Representative methods include the entropy method [7], grey relational analysis [8], quadratic weighting [9], horizontal and vertical scattering method [10], and orthogonal projection method [11]. Temporal Aggregation Methods focus on the dimensionality reduction of spatio-temporal panel data to provide an intuitive numerical basis for comparative superiority-inferiority analysis. Typical methods include the Ordered Weighted Averaging (OWA) operator [12], Induced Ordered Weighted Averaging (IOWA) operator [13], Time-Ordered Weighted Averaging (TOWA) operator [14], and Time-Ordered Weighted Geometric Averaging (TOWGA) operator [15].

At the application level, as a core branch of management science, comprehensive evaluation employs scientific quantification methods to measure the developmental state of entities in practical contexts. It provides objective and comprehensive foundations for decision-making, demonstrating extensive application value in fields such as economic management, environmental studies, and engineering [16-17]. Dynamic comprehensive evaluation enables the simultaneous measurement of both longitudinal temporal evolution and lateral spatial differentiation among evaluated entities, thereby furnishing temporally contextualized references for decision-making [18-20].

Current research in dynamic comprehensive evaluation primarily faces two challenges: (1) Uniform Grade Intervals: The reliance on a single, unified grade interval determined from all evaluation values across periods fails to fully characterize the state and developmental trends of evaluated entities at each specific time point. (2) Subjectively Defined Grades: The setting of grade thresholds often stems primarily from the evaluator's subjective intent, neglecting the inherent distribution characteristics of the indicator data.

2. Dynamic Comprehensive Evaluation Using SP-SSPP

Without loss of generality, in period t_k $(k=1,2,\cdots,N)$ the value of the evaluated object s_i with respect to the evaluation index x_j is denoted as $x_{ij}(t_k)$, where $i=1,2,\cdots,n; j=1,2,\cdots,m$. Assume that all indicators have undergone normalization processing and are all benefit-type indicators. The multi -period original evaluation value matrix is denoted as

$$\boldsymbol{X}=[x_{ij}(t_k)]_{n\times m}=\begin{pmatrix} x_{11}(t_1) & x_{12}(t_2) & \dots & x_{1m}(t_N) \\ x_{21}(t_1) & x_{22}(t_2) & \dots & x_{2m}(t_N) \\ \vdots & \vdots & \dots & \vdots \\ x_{n1}(t_1) & x_{n2}(t_2) & \dots & x_{nm}(t_N) \end{pmatrix}.$$

2.1 Indicator System

In dynamic comprehensive evaluation, using a unified grade interval determined from evaluation values across all periods fails to fully capture the state and developmental trends of values within individual periods. Therefore, this study establishes grade intervals based on the distribution characteristics of evaluation values within each specific period, objectively capturing their temporal states and evolutionary trajectories. Grey relational degree quantifies trend alignment between data sequences: A higher grey relational degree between evaluation values and the positive ideal point indicates closer proximity to optimal performance. A higher grey relational degree with the negative ideal point signifies closer alignment with suboptimal performance. A higher grey relational degree with the geometric mean reflects stronger convergence toward average performance (Conversely holds for lower relational degrees). The grade interval determination procedure comprises the following steps:

Step 1. Calculate grey relational degree coefficients for period evaluation values.

Let $u_{ij}^{+}(t_k)$, $u_{ij}^{-}(t_k)$ and $u^{*}_{ij}(t_k)$ respectively as the grey relational degree coefficients between the evaluation values of each evaluated object s_i in the same t_k period and the positive ideal point, negative ideal point, and geometric mean of that period. Compared with the arithmetic mean and median, the geometric mean is less affected by extreme values. The geometric mean of the evaluation values in the t_k period can reflect the overall numerical property of the evaluation values.

$$\begin{cases} u_{ij}^{+}(t_k)=\dfrac{\min\limits_{k}\min\limits_{i}\hat{x}_{ij}^{+}(t_k)+\rho\max\limits_{k}\max\limits_{i}\hat{x}_{ij}^{+}(t_k)}{\hat{x}_{ij}^{+}(t_k)+\rho\max\limits_{k}\max\limits_{i}\hat{x}_{ij}^{+}(t_k)} \\ u_{ij}^{-}(t_k)=\dfrac{\min\limits_{k}\min\limits_{i}\breve{x}_{ij}^{-}(t_k)+\rho\max\limits_{k}\max\limits_{i}\breve{x}_{ij}^{-}(t_k)}{\breve{x}_{ij}^{-}(t_k)+\rho\max\limits_{k}\max\limits_{i}\breve{x}_{ij}^{-}(t_k)} \\ u^{*}_{ij}(t_k)=\dfrac{\min\limits_{k}\min\limits_{i}\tilde{x}_{ij}^{*}(t_k)+\rho\max\limits_{k}\max\limits_{i}\tilde{x}_{ij}^{*}(t_k)}{\tilde{x}_{ij}^{*}(t_k)+\rho\max\limits_{k}\max\limits_{i}\tilde{x}_{ij}^{*}(t_k)} \end{cases} \quad (1)$$

where, $\widehat{x}_{ij}^{+}(t_k)=\left|x_{ij}(t_k)-x_{ij}^{+}(t_k)\right|$ is the absolute difference between the evaluation value in period t_k and the positive ideal point; $\breve{x}_{ij}^{-}(t_k)=\left|x_{ij}(t_k)-x_{ij}^{-}(t_k)\right|$ is the absolute difference between the evaluation value in period t_k and the negative ideal point; $\tilde{x}_{ij}^{*}(t_k)=\left|x_{ij}(t_k)-x_{ij}^{*}(t_k)\right|$ is the absolute difference between the evaluation value in period t_k and the geometric mean. $x_{ij}^{+}(t_k)$ 、 $x_{ij}^{-}(t_k)$ and $x_{ij}^{*}(t_k)$ are respectively the positive ideal point, negative ideal point, and geometric mean of each evaluation value in period t_k. The resolution coefficient can usually take ρ=0.5 [16].

Step 2. Calculate the grey relational degree of evaluation values.

$$\begin{cases} l_{ij}^{+}(t_k)=\dfrac{1}{n}\sum\limits_{i=1}^{n}u_{ij}^{+}(t_k) \\ l_{ij}^{-}(t_k)=\dfrac{1}{n}\sum\limits_{i=1}^{n}u_{ij}^{-}(t_k) \\ l_{ij}^{*}(t_k)=\dfrac{1}{n}\sum\limits_{i=1}^{n}u_{ij}^{*}(t_k) \end{cases} \tag{2}$$

in the formula, $l_{ij}^{+}(t_k)$, $l_{ij}^{-}(t_k)$ and $l_{ij}^{*}(t_k)$ are respectively the grey relational degrees between the evaluation values in period t_k and the positive ideal point, negative ideal point, and geometric mean of that period.

Step 3. Determination of grade intervals for periods.

$$\begin{cases} a_{ij}^{+}(t_k)=\partial+x_{ij}^{+}(t_k)l_{ij}^{+}(t_k) \\ a_{ij}^{-}(t_k)=\partial+x_{ij}^{*}(t_k)l_{ij}^{*}(t_k) \end{cases} \tag{3}$$

in the formula, $a_{ij}^{+}(t_k)$ and $a_{ij}^{-}(t_k)$ represent the upper and lower limits of the grade interval in period t_k respectively. $\partial=\ln k, k=2,3\cdots N$, where ∂ is the grade interval correction coefficient. ∂ is a monotonically increasing function: as k increases, ∂ rises with a decelerating growth rate, matching the idea of guiding the evaluated object to "develop steadily and grow moderately".

The upper and lower limits of the grade interval are determined by the proximity of the evaluation values in period t_k to the positive ideal point and the geometric mean. The closer the overall evaluation value is to the ideal point, the larger the upper and lower limit values of the grade interval; the closer the overall evaluation value is to the geometric mean, the smaller the upper and lower limit values of the grade interval. To reflect the differentiated guidance ideology, the value range of the grade interval is $[x_{ij}^{+}(t_k),u_{ij}^{-}(t_k)l_{ij}^{-}(t_k)]$. If $a_{ij}^{+}(t_k)>x_{ij}^{+}(t_k)$ and $a_{ij}^{-}(t_k)<u_{ij}^{-}(t_k)l_{ij}^{-}(t_k)$, the grade interval envelops all evaluation values, exerting no guiding effect on all evaluated objects.

2.2 Determination of Incentive Quantity

To thoroughly characterize the relationship between evaluation values and grade intervals, this study employs Semi-Partial Subtraction Set Pair Potential (SP-SSPP) theory to dynamically adjust the cross-sectional performance of evaluated objects. The evaluation values and longitudinal grade intervals form a set pair system. Through calculating the ternary connection number of this system, we analyze the identity, discrepancy, and contrary aspects of evaluation values relative to grade intervals. The computational procedure is as follows:

Step 1. Calculation of Evaluation Value Connection

The lower and upper limits of the grade interval can partition the evaluation values in period t_k into three evaluation grade intervals: $[a_{ij0}(t_k),a_{ij}^{-}(t_k)]$, $[a_{ij}^{-}(t_k),a_{ij}^{+}(t_k)]$ and $[a_{ij}^{+}(t_k),a_{ij3}(t_k)]$, with

$i = 1,2,\cdots,n$ and $j = 1,2,\cdots,m$. Here $a_{ij0}(t_k)$ can be taken as three times the geometric mean value for reference.

When $a_{ij}^{+}(t_k) < x_{ij}(t_k) \le a_{ij3}(t_k)$, the connection number $v_{ijr}(t_k)$ is:

$$\begin{cases} v_{ij1}(t_k) = 1 \\ v_{ij2}(t_k) = 1 - 2(x_{ij}(t_k) - a_{ij}^{+}(t_k)) / (a_{ij3}(t_k) - a_{ij}^{+}(t_k)) \\ v_{ij3}(t_k) = -1 \end{cases} \quad (4)$$

When $a_{ij}^{-}(t_k) < x_{ij}(t_k) \le a_{ij}^{+}(t_k)$, the connection number $v_{ijr}(t_k)$ is:

$$\begin{cases} v_{ij1}(t_k) = 1 - 2(a_{ij}^{+}(t_k) - x_{ij}(t_k)) / (a_{ij}^{+}(t_k) - a_{ij}^{-}(t_k)) \\ v_{ij2}(t_k) = 1 \\ v_{ij3}(t_k) = 1 - 2(x_{ij}(t_k) - a_{ij}^{+}(t_k)) / (a_{ij}^{+}(t_k) - a_{ij}^{-}(t_k)) \end{cases} \quad (5)$$

When $a_{ij0}(t_k) < x_{ij}(t_k) \le a_{ij}^{-}(t_k)$, the connection number $v_{ijr}(t_k)$ is:

$$\begin{cases} v_{ij1}(t_k) = -1 \\ v_{ij2}(t_k) = 1 - 2(a_{ij}^{-}(t_k) - x_{ij}(t_k)) / (a_{ij}^{-}(t_k) - x_{ij}(t_k)) \\ v_{ij3}(t_k) = 1 \end{cases} \quad (6)$$

in the formula, the range of the connection coefficient $v_{ijr}(t_k)$ is [-1,1]. Its value is taken as 1 or -1, or a value between them, depending on whether the evaluation value falls into the same interval, adjacent interval, or separated interval of the evaluation grade. $v_{ijr}(t_k)$ quantitatively describes the degree of relationship within the set pair system and can serve as a difference function for the variable fuzzy relationship regarding the proximity degree between the evaluation value and the evaluation grade. The corresponding relative membership degree is:

$$\mu_{ijr}^{*}(t_k) = 0.5 + 0.5 v_{ijr}(t_k), i = 1,2,\cdots,n; k = 1,2,\cdots,N; r = 1,2,3 \quad (7)$$

Normalize the above formula to obtain the connection coefficient component $\mu_{ijr}(t_k)$ for the evaluation grade. This component reflects the degree of identity, difference, and opposition relationships within the set pair system between the evaluation value and the grade interval. The numerical differences among these three (identity, difference, and opposition) express, to a certain extent, the relative development trend between the evaluation value and the grade interval in the set pair system. Among them, $\mu_{ij1}(t_k)$ represents the identity degree, $\mu_{ij2}(t_k)$ the difference degree, and $\mu_{ij3}(t_k)$ the opposition degree. The identity degree and opposition degree denote relatively definite fuzzy relationships, while the difference degree represents a relatively uncertain fuzzy relationship.

$$\mu_{ijr}(t_k) = \mu_{ijr}^{*}(t_k) / \sum_{r=1}^{3} \mu_{ijr}^{*}(t_k) \quad (8)$$

The evaluation value connection coefficient $\mu_{ijr}(t_k)$ is composed of the connection coefficient components $v_{ij}(t_k)$, as follows:

$$v_{ij}(t_k) = \mu_{ij1}(t_k) + \mu_{ij2}(t_k) I + \mu_{ij3}(t_k) J \quad (9)$$

where, $\mu_{ij1}(t_k) + \mu_{ij2}(t_k) + \mu_{ij3}(t_k) = 1$ and all are non-negative real numbers; the difference degree coefficient $I \in [-1,1]$,and the opposition degree coefficient $J = -1$ .When $a_{ij}^{+}(t_k) < x_{ij}(t_k) \le a_{ij3}(t_k)$, $I = 0.5$;When $a_{ij}^{-}(t_k) < x_{ij}(t_k) \le a_{ij}^{+}(t_k)$, $I = 0$;When $a_{ij0}(t_k) < x_{ij}(t_k) \le a_{ij}^{-}(t_k)$, $I = -0.5$. According to different values of *I*, the evaluation values in period t_k are horizontally differentiated in grades.

Step 2. Calculate the semi-deviation subtraction set pair potential of the evaluation value.

$$V_{ij}(t_k)=[a+ab/(a+b)]-[c+bc/(b+c)] \tag{10}$$

in the formula, $V_{ij}(t_k)$ represents the semi-deviation subtraction set pair potential, with a value range of [−1,1]. It reflects the development state and trend of the evaluation value relative to the grade interval. Here, $a=\mu_{ij1}(t_k)$, $b=\mu_{ij2}(t_k)$, $c=\mu_{ij3}(t_k)$.

Step 3. Calculate the Incentive Volume.

Implement incentive control over the development trend of evaluation values within the set pair system, expressed by the following formula:

$$V_{ij}^*(t_k)=\varepsilon(V_{ij}(t_k)-V_{ij}(t_{k-1})), k=2,3,\cdots,N \tag{11}$$

where, $V_{ij}^*(t_k)$ denotes the horizontal incentive quantity of the evaluation value at time t_k , and $V_{ij}(t_k)-V_{ij}(t_{k-1})$ represents the gain amplitude of the set pair potential relative to the previous period. $V_{ij}^*(t_k)$ incentivizes the development trend of the evaluation value based on this gain amplitude. The incentive coefficient ε is defined as $\varepsilon=1+1/\ln(1+1/n)^n, n=2,3,\cdots,N$. ε is a monotonically increasing function, growing as *n* increases, though its growth rate decelerates with larger *n*. This function's intrinsic characteristics match the trend incentive control concept for evaluated objects, reflecting the aim of guiding them toward "stable development with moderate growth". Formula (11) thus realizes incentive guidance for the development trends of evaluated objects.

The incentive amount is jointly determined by both the gain amplitude of the set pair potential and its hierarchical development trend. When the set pair potential stays within the same level as the previous period, ε=1, so $V_{ij}^*(t_k)$ directly serves as the gain amplitude to incentivize or penalize the set pair potential. If the set pair potential level rises or falls, *n* in the ε function is assigned based on the number of layers increased or decreased, achieving incentive control. Specific values are detailed in Table 1.

Table 1. Specific Values of Incentive Volume

Set Pair Potential Development Trend	Incentive/Penalty Level	Value
No change	No incentive	ε=1
Increase/Decrease by 1 layer	Level 1 Incentive/Penalty	*n*=2
Increase/Decrease by 2 layers	Level 2 Incentive/Penalty	*n*=3
Increase/Decrease by 3 layers	Level 3 Incentive/Penalty	*n*=4
Increase/Decrease by 4 layers	Level 4 Incentive/Penalty	*n*=3

The total correction value $V_{ij}^{\oplus}(t_k)$, for the grade interval of the evaluated object s_i within the time period $[t_1,t_k]$ is obtained by summing the connection coefficients $v_{ij}(t_k)$ (which describe the status of the evaluation value in each period) and the horizontal incentive quantities $V_{ij}^*(t_k)$ (which characterize the development trend) across all periods.

$$V_{ij}^{\oplus}(t_k)=\sum_{i=1}^{n}\sum_{k=1}^{N}v_{ij}(t_k)+\sum_{i=1}^{n}\sum_{k=1}^{N}V_{ij}^*(t_k) \tag{12}$$

3. Aggregation of Dynamic Comprehensive Evaluation Values

The comprehensive evaluation value S_i for the evaluated object at time t_k is constructed by integrating the evaluation values and incentive adjustments across all periods, formulated as:

$$S_i = \sum_{j=1}^{m}\sum_{k=1}^{N} x_{ij}(t_k) + V_{ij}^{\oplus}(t_k) \qquad (13)$$

The application steps of the interval incentive control model are summarized as follows:

Step 1 Evaluators provide corresponding raw evaluation values based on the actual situation of the evaluated objects, and perform type normalization and dimensionless processing on the raw data.

Step 2 Use Formulas (1)-(4) to calculate the grade intervals.

Step 3 Construct a set pair system with evaluation values and grade intervals, and calculate the evaluation value connection coefficients through Formulas (5)-(9).

Step 4 Calculate the semi-deviation subtraction set pair potential of the set pair system between evaluation values and grade intervals using Formula (10), and compute the incentive volume using Formulas (11) and (12).

Step 5 Calculate the dynamic comprehensive evaluation value using Formula (13) and sort them.

4. Application Example

This paper cites the case study in Reference [8] to validate the effectiveness of the interval incentive control model, evaluating the performance appraisals of enterprise employees over the past six years.

Using Step 2, the upper and lower limits of vertical and horizontal incentive control intervals are calculated, as shown in Table 2.

Table 2. Values of Grade Intervals

	t_1	t_2	t_3	t_4	t_5	t_6
Upper limit	6.170	6.333	5.556	6.325	5.745	6.716
Upper limit	2.568	3.603	3.312	3.479	3.084	3.087

As shown in Table 2, the upper and lower limits of the grade intervals do not increase monotonically with time. This is because the interval boundaries are primarily determined by the objective attributes of evaluation values, with moderate corrections applied.

Using Step 3, connection numbers are calculated for the set pair system formed by evaluation values and incentive control intervals. Then, Step 4 is employed to compute the incentive volume for the set pair system between evaluation values and grade intervals, as shown in Tables 3.

Table 3. Incentive Volumes for Semi-deviation Subtraction Set Pair Potential

	t_1	t_2	t_3	t_4	t_5	t_6
s_1	0.81	0.73	0.75	-0.27	-2.69	-1.00
s_2	0.78	0.82	0.86	0.41	1.84	0.72
s_3	0.80	0.19	-2.05	-0.66	1.04	-0.36
s_4	0.48	-3.88	2.69	-3.19	3.78	-3.73
s_5	0.77	0.87	0.72	0.83	0.74	0.83
s_6	0.80	0.69	-1.81	3.76	-3.29	3.61
s_7	-0.79	-0.71	0.21	-0.15	1.26	-0.26
s_8	0.31	-0.61	2.36	0.77	0.83	0.79
s_9	-0.85	-0.74	2.03	0.81	0.85	0.79
s_{10}	-0.49	0.51	-2.08	0.63	-1.37	2.77

Using Step 6, the dynamic comprehensive evaluation values are calculated and ranked, as shown in Table 4.

Table 4. Incentive Volumes for Semi-deviation Subtraction Set Pair Potential

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
Dynamic Comprehensive	33.10	59.57	28.79	20.82	55.53	43.79	24.14	45.06	35.54	23.50

Evaluation Value										
Ranking in This Paper	6	1	7	10	2	4	8	3	5	9
One-dimensional Clustering Ranking	6	1	7	9	2	4	8	3	5	10

The proposed method provides nuanced characterization of evaluation value states and developmental trends through grade-interval-based analysis. As evidenced in Table 4, minor discrepancies exist between our method's ranking and clustering results. This arises because s_4 exhibits more pronounced sharp fluctuations (rapid ascent followed by abrupt decline) during the evaluation period than s_{10}, incurring greater penalty in our assessment framework.

5. Conclusion

This paper proposes an interval-incentive dynamic comprehensive evaluation method based on semi-partial subtraction set pair potential (SP-SSPP). The principal innovations are:(1) Objective grade interval determination: Grade intervals are derived from intrinsic value attributes of evaluation data;(2) Set pair system construction: Evaluation values and grade intervals form coupled systems for deep information mining. This methodology demonstrates broad applicability in management practice domains including enterprise development assessment, employee performance evaluation, and cadre promotion systems.

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