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A Rough Set-Cloud Model Approach for Digital Twin-Enabled Natural Heritage Protection Evaluation: A Case Study of Huanglong Scenic Area, China

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Abstract

While digital twin technology has emerged as a promising tool for natural heritage conservation, few studies have put forward systematic evaluation frameworks specifically designed for assessing the operational effectiveness of such platforms. Building on existing research, this paper introduces a hybrid evaluation methodology that combines rough set theory with cloud modeling techniques to measure the performance of digital twin platforms in heritage protection contexts. To address the complexity of multi-dimensional evaluation systems with intricate interrelationships among indicators, we employ rough set theory grounded in conditional information entropy to filter out redundant metrics and compute objective weight values. The cloud model component translates qualitative assessments provided by domain experts into quantitative evaluation clouds through forward and backward cloud generation algorithms, while a thickness-based iterative scoring process helps converge divergent expert opinions toward consensus. By weighting each indicator cloud according to its importance, a comprehensive evaluation cloud can be synthesized. We test the proposed method using data from Huanglong Scenic Area, a UNESCO World Natural Heritage site in southwestern China where an integrated digital twin platform-incorporating multi-source data fusion capabilities and real-time monitoring systems for conservation management-has been deployed and running for several years. Our findings indicate that this approach not only successfully pinpoints key performance indicators but also overcomes the difficulties associated with converting qualitative judgments into quantitative measures, while offering intuitive three-dimensional visualizations of evaluation results. The evaluation framework presented in this study provides a practical, replicable model for assessing digital technology implementations in protected area management settings.

Keywords

Digital Twin; Rough Set; Cloud Model; Natural Heritage; Huanglong Scenic Area; Smart Conservation.

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1. Introduction

Natural World Heritage sites constitute some of humanity's most valuable and irreplaceable ecological treasures, but in recent decades they have come under growing pressure from multiple directions-rising global temperatures, expanding tourism footprints, and more frequent extreme weather events all pose significant risks to these fragile ecosystems[1]. Digital twin technology uses real-world data to create a mirror image in the computer virtual world, which provides innovative ideas for digital heritage protection [2,3]. However, there are still many shortcomings in the existing research on the evaluation of digital twin systems in natural heritage sites.

There are three major challenges in the evaluation of the digital twin system of natural heritage sites. First of all, the index system consists of multiple indicators, such as data quality, system performance and protection effectiveness. There is a complex interdependence between these indicators at the same time, which makes the evaluation difficult. Secondly, there are a number of qualitative indicators in the index system, which need to be converted into quantitative indicators for evaluation to proceed smoothly. However, how to accurately convert the qualitative evaluation given by experts into quantitative indicators is a difficult problem. Third, traditional evaluation methods often ignore the inconsistency of experts' opinions, but minority views may be correct, which will affect the accuracy of the evaluation.

In order to solve the above problems, this paper proposes an evaluation method that combines rough set and cloud model theory. Rough set theory, introduced by Pawlak [4], effectively handles uncertain and incomplete information through attribute reduction and has been successfully applied to infrastructure project evaluation[5–8]. The cloud model, proposed by Li et al. [9], enables bidirectional transformation between qualitative concepts and quantitative data, accommodating both fuzziness and randomness in human cognition[10–12].

The proposed approach is validated through a case study of Huanglong Scenic Area, a UNESCO World Natural Heritage site in Sichuan Province, China. The "Smart Huanglong" project has established a comprehensive digital twin platform that integrates multi-source data (e.g., satellite imagery, UAV LiDAR, and IoT sensors) to support real-time monitoring of geological hazards, forest fires, and water quality[13,14]. This platform provides a representative testbed for validating the proposed evaluation approach.

The remainder of this paper is organized as follows. Section 2 presents the rough set-cloud model methodology. Section 3 describes the evaluation index system. Section 4 reports the case study results. Section 5 discusses the implications and concludes the paper.

2. Methodology

2.1. Rough Set Theory with Conditional Information Entropy

Rough set theory, introduced by Pawlak [4], is a mathematical approach for handling uncertainty and imprecision in data analysis. An information system is defined as a quadruple $S=\left(U, A, V, f\right)$, where U is a non-empty finite set of objects (the universe), A is a non-empty finite set of attributes, $V=U_{a\in A}V_a$ with V_a being the value domain of attribute a, and $f: U\times A\rightarrow V$ is an information function assigning values to each object-attribute pair [5].

For a decision table $S=(U, C\bigcup D, V, f)$, where C is the set of condition attributes and D is the decision attribute, the conditional information entropy of D relative to C is defined as[6,7]:

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$$I(D|C)=\sum_{i=1}^{m}\frac{|C_i|^2}{|U|^2}\sum_{j=1}^{k}\frac{|D_j\cap C_i|}{|C_i|}\left(1-\frac{D_j\cap C_i}{C_i}\right) \tag{1}$$

where $U/C=\{C_1,C_2,\dots,C_m\}$ and $U/D=\{D_1,D_2,\dots,D_k\}$ are the partitions of U induced by C and D, respectively.
The significance of a condition attribute $c\in C$ is calculated as:

$$Sig(c)=I(D|C-\{c\})-I(D|C) \tag{2}$$

The weight of condition attribute c is then determined by[7]:

$$W(c)=\frac{Sig(c)+I(D|\{c\})}{\sum_{a\in C}\{Sig(a)+I(D|\{a\})\}} \tag{3}$$

This weighting scheme combines both the individual importance of an attribute $I(D|\{c\})$ and its significance within the full attribute set $Sig(c)$, ensuring comprehensive and objective weight determination[6,8].

2.2. Cloud Model

The cloud model, proposed by Li et al.[9], enables the transformation between qualitative concepts and quantitative data. It is characterized by three numerical features: expectation *Ex*, entropy *En*, and hyper-entropy *He*[10,11].

Forward Cloud Generator: Transforms a qualitative concept (*Ex*,*En*,*He*) into quantitative cloud drops [12]:

1) Generate a normally distributed random number En' with mean *En* and standard deviation *He*.
2) Generate a normally distributed random number x with mean Ex and standard deviation En′.
3) Compute membership degree $y=e^{-\frac{(x-Ex)^2}{2(En')^2}}$.
4) The pair (x,y) constitutes a cloud drop.

Backward Cloud Generator: Recovers the numerical features (*Ex*,*En*,*He*) from a set of cloud drops [11].

Comprehensive Cloud: For indicator evaluation clouds *Si* and weight clouds *Wi*, the comprehensive evaluation cloud is synthesized as:

$$A=\sum_{i=1}^{n}S_iW_i\Big/\sum_{i=1}^{n}W_i \tag{4}$$

Thickness-Based Iterative Scoring: When the evaluation cloud exhibits excessive thickness and dispersion, indicating significant expert disagreement, the results are fed back to the expert panel for discussion and re-evaluation. This iterative process continues until satisfactory cloud thickness is achieved, thereby ensuring convergence toward expert consensus[12].

2.3. Evaluation Procedure

The proposed evaluation procedure comprises five steps:

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Step 1: Indicator System Construction. Establish a multi-dimensional evaluation index system for digital twin-enabled heritage protection.

Step 2: Rough Set-Based Reduction and Weighting. Apply rough set attribute reduction to eliminate redundant indicators and calculate objective weights using conditional information entropy.

Step 3: Cloud-Based Evaluation. Experts provide qualitative judgments for each indicator. Backward cloud generators convert these judgments into evaluation clouds. Thickness-based iterative scoring is applied to ensure consensus.

Step 4: Comprehensive Cloud Synthesis. Synthesize the comprehensive evaluation cloud according to Equation (4).

Step 5: Result Interpretation. Compare evaluation clouds with the reference cloud through three-dimensional visualization for intuitive interpretation.

Fig. 1 illustrates the complete evaluation procedure.

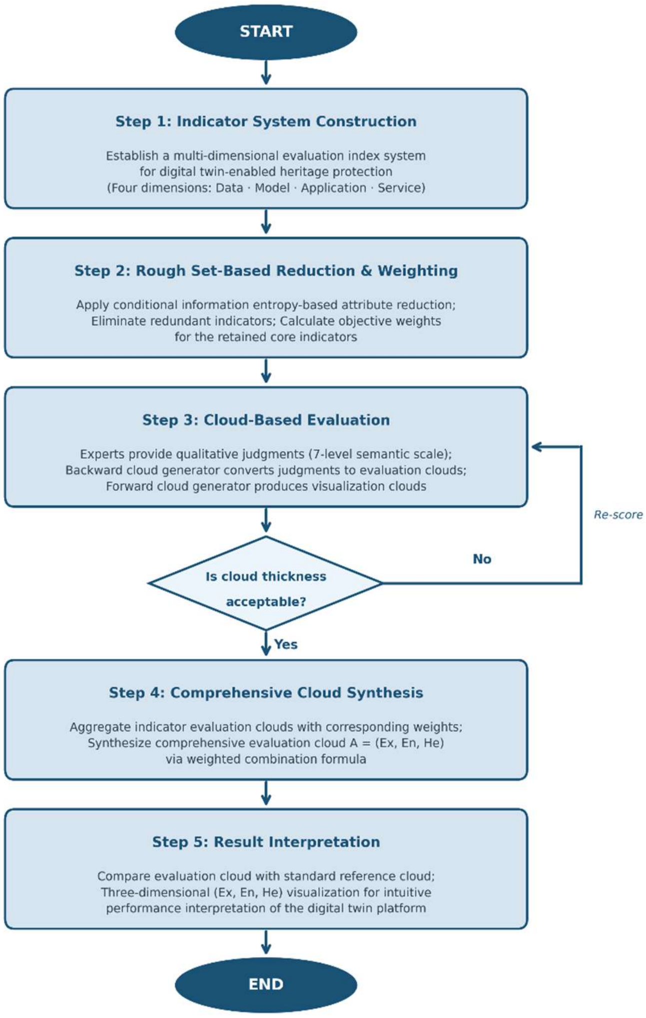

Fig. 1 Flowchart of the proposed rough set-cloud model evaluation procedure

3. Evaluation Index System for Digital Twin-Enabled Heritage Protection

Based on the Huanglong digital twin platform architecture[13] and established smart management frameworks[14,15], a four-dimensional evaluation index system is constructed (Table 1).

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Table 1. Evaluation Index System for Digital Twin-Enabled Heritage Protection

Dimension	Indicator	Description
Data Quality (DQ)	DQ1: Spatial Resolution	Accuracy of geometric modeling (CIM Level 3: ≤5 cm)
	DQ2: Temporal Resolution	Data update frequency (real-time, hourly, daily, annually)
	DQ3: Data Completeness	Coverage of multi-source data integration
	DQ4: Data Accuracy	Precision of monitoring data (sensor accuracy ±1–5%)
System Performance (SP)	SP1: Loading Efficiency	Model loading time after lightweighting (target: <10 s)
	SP2: System Stability	Platform uptime and reliability
	SP3: Visualization Quality	3D rendering fidelity and user experience
Conservation Effectiveness (CE)	CE1: Monitoring Coverage	Extent of hazard/ecological monitoring coverage
	CE2: Early Warning Accuracy	Accuracy of early warning systems (geological, fire, water)
	CE3: Response Time	Time from detection to alert generation
Integration Capability (IC)	IC1: Multi-source Fusion	Effectiveness of heterogeneous data integration
	IC2: Cross-department Sharing	Data sharing across administrative departments
	IC3: Business Integration	Integration with operational management systems

The raw data sources for such digital twin platforms typically encompass high-resolution satellite imagery, UAV-based oblique photogrammetry, real-time IoT environmental sensors, and infrared thermal monitoring systems, aligning with the multi-source data integration requirements outlined in the evaluation framework.

4. Case Study: Huanglong Scenic Area

4.1. Study Area and Digital Twin Platform

Huanglong Scenic Spot has spectacular calcium terraces, calcified waterfalls and limestone landforms. In 1992, Huanglong Scenic Spot was officially included in the World Cultural Heritage List by UNESCO[13,14]. the "Smart Huanglong" designed a set of digital twin platforms, which contributed to the protection, management and operation of this world cultural heritage.

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The platform integrates multi-source data, such as satellite imagery, UAV LiDAR, IoT-based environmental sensors, and dedicated monitoring subsystems.

4.2. Rough Set-Based Indicator Reduction and Weighting

The evaluation expert group is composed of 12 experts from universities, research institutions, tourism bureaus, tourism enterprises and other units. The evaluation uses a 5-level scale (1 = very low to 5 = very high), and the evaluation system contains 12 evaluation objects and 10 conditional attributes. First, use the attribute reduction method based on the rough set (implemented in MATLAB R2021b) to reduce the conditional attributes. The conditional attributes are simplified from 10 to 7, namely DQ1 (Spatial Resolution), DQ2 (Temporal Resolution), SP1 (Loading Efficiency), CE1 (Monitoring Coverage), CE2 (Early Warning Accuracy), IC1 (Multi-source Fusion), and IC3 (Business Integration). The dependence of decision-making attributes on the set of simplified conditional attributes is γ=1, and the reliability after simplification is excellent.

Using Equations (1)–(3), the conditional information entropy and attribute weights were calculated (Table 2).

Table 2. Attribute Weights After Rough Set Reduction

Indicator	DQ1	DQ2	SP1	CE1	CE2	IC1	IC3
Weight	0.142	0.128	0.156	0.138	0.164	0.135	0.137

Fig. 2 shows the convergence process of the rough set attribute reduction.

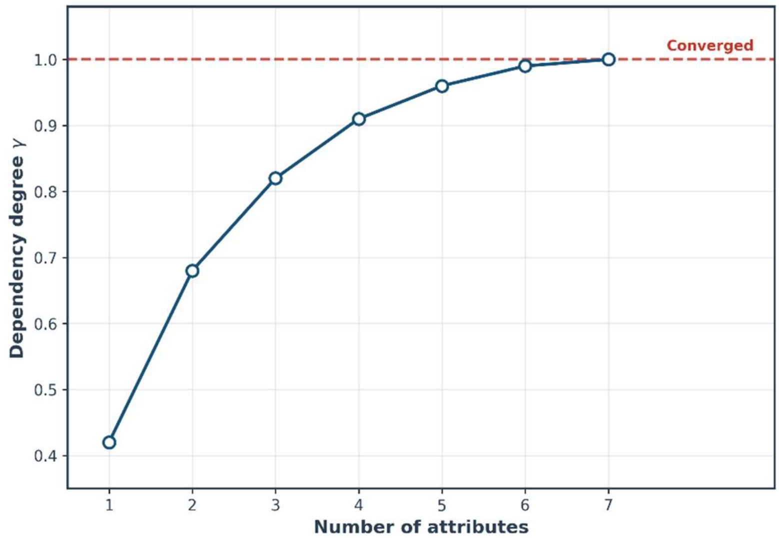

Fig. 2 Convergence Process of the Rough Set Attribute Reduction

4.3. Cloud Model-Based Comprehensive Evaluation

For the cloud model-based evaluation, a separate evaluation process was conducted in which the same expert panel provided qualitative judgments on each indicator using a 7-level semantic scale: “very poor,” “poor,” “fairly poor,” “average,” “fairly good,” “good,” and “very good.” The corresponding numerical intervals were defined as $[F_{min}, F_{max}]$ with $Ex=(F_{min}+F_{max})/2$, $En=(F_{max}-F_{min})/6$, and He=0.004 [12].

Fig. 3 presents the 7-level semantic standard cloud for indicator evaluation.

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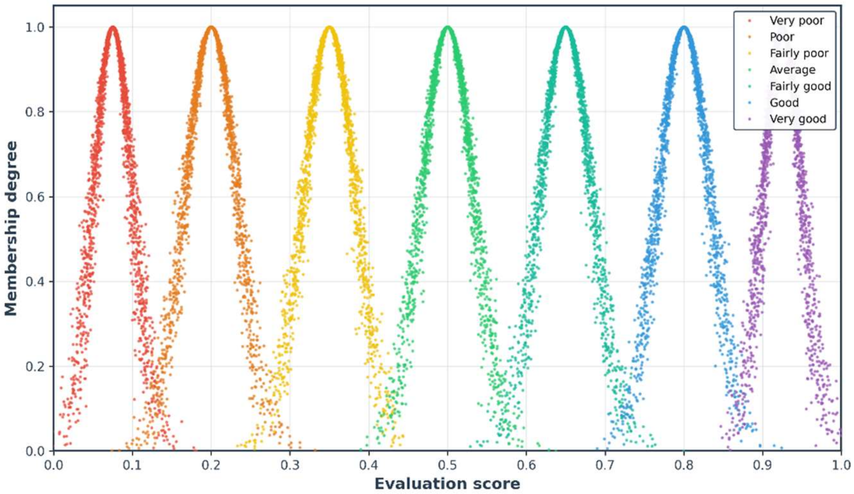

Fig. 3 Seven-Level Semantic Standard Cloud for Indicator Evaluation

Taking indicator CE2 (Early Warning Accuracy) as an example, the initial expert evaluations showed significant divergence. The backward cloud generator produced (Ex,En,He)=(0.612, 0.187, 0.043), and the forward cloud generator yielded an excessively thick and dispersed cloud (Fig. 4a). After three rounds of thickness-based iterative scoring, the cloud thickness improved significantly (Fig. 4b), with final features (0.683,0.112,0.028), indicating that expert consensus was reached.

Fig. 4 illustrates the iterative improvement of the CE2 evaluation cloud.

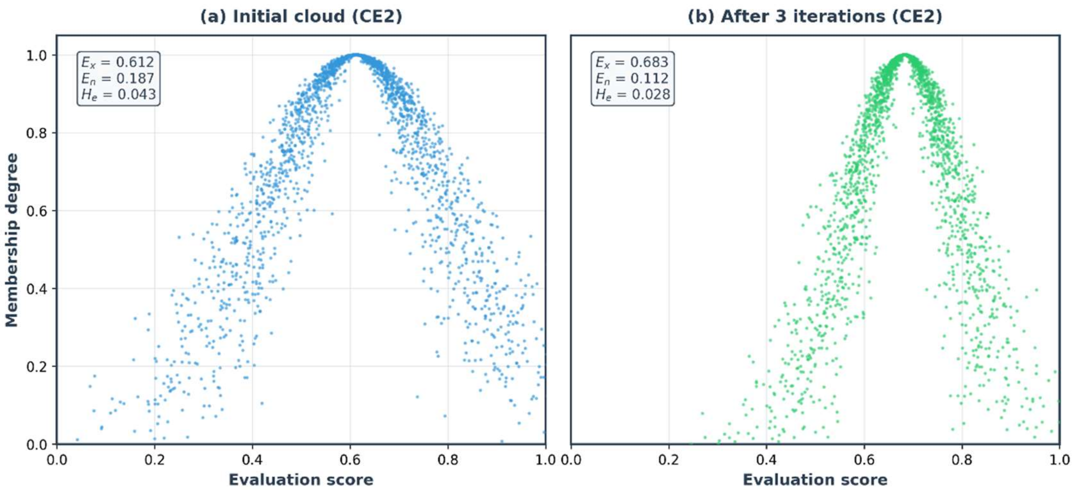

Fig. 4 Iterative Improvement of the CE2 Evaluation Cloud: (a) Initial Cloud with Excessive Dispersion; (b) Cloud After Three Rounds of Thickness-Based Iterative Scoring

All indicators underwent similar iterative evaluation. The comprehensive evaluation cloud for the study platform was synthesized using Equation (4), yielding A=(0.724,0.126,0.031).

Fig. 5 presents the comprehensive evaluation cloud alongside the reference cloud (ideal performance) for comparison. The evaluation cloud closely approaches the reference cloud, confirming the platform's high performance across all dimensions.

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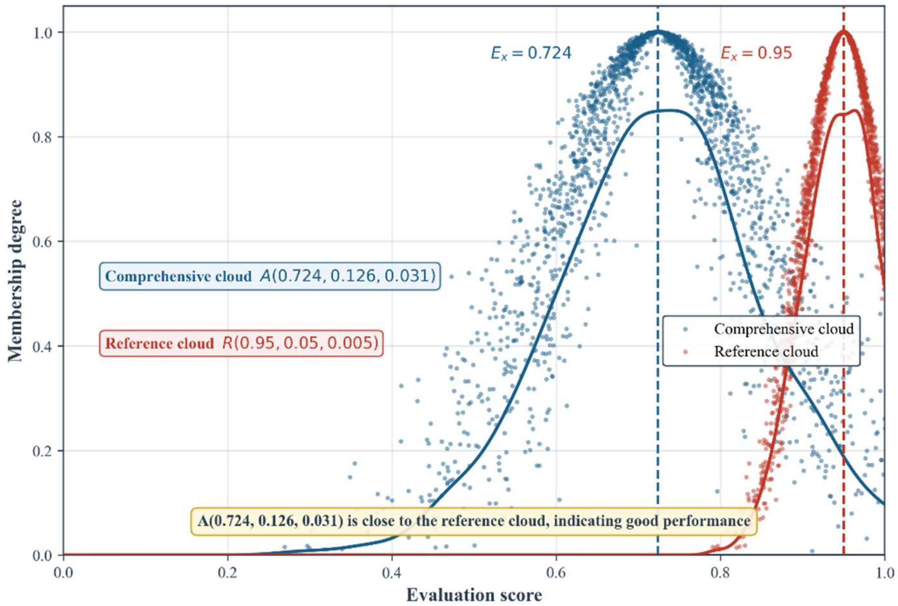

Fig. 5 Comparison Between the Comprehensive Evaluation Cloud and the Reference Cloud

5. Discussion and Conclusion

This paper has proposed a rough set-cloud model approach for evaluating digital twin-enabled natural heritage protection and validated it through a case study of the Huanglong Scenic Area. The core contributions of this article are mainly reflected in the following three aspects.

First of all, using the attribute reduction method based on the rough set theory, combined with the conditional information entropy, the system containing 10 indicators is reduced to 7 indicators. At the same time, the classification ability of the system (γ=1) is maintained. This shows that this method can be applied to complex and multi-dimensional evaluation systems and has good application value.

Secondly, the introduction of the cloud model has solved the traditional problem of converting from qualitative to quantitative, making the evaluation of digital heritage protection more scientific. The cloud model ensures that expert consensus can be reached through iterative mechanisms, avoiding the problem that traditional methods may ignore individual expert opinions.

Third, the comprehensive evaluation cloud model platform A=(0.724,0.126,0.031) integrates CIM's third-level modeling, multi-source data fusion and real-time monitoring and early warning functions, with good evaluation accuracy and provides new ideas for the evaluation of the field of digital heritage protection.

The above method has practical significance at multiple levels. For the Heritage Authority, it provides a new set of digital heritage protection assessment methods. For scholars, it shows the application of rough sets and cloud models in the field of digital heritage protection evaluation. For policymakers, it provides an objective evaluation standard for the digital protection of heritage sites.

The next step of research will be optimized around the real-time integration of dynamic time and multi-regional comparative evaluation.

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