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An AHP-weighted Gray Rational Analysis (GRA) approach for blockchain consensus protocol selection

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Research Background

- **Industry Context:**
- Rapid growth and widespread adoption of blockchain technology across finance, healthcare, automotive, and public administration.
- Proliferation of diverse consensus protocols with distinct performance, security, and operational trade-offs.
- Increasing demand for energy-efficient, scalable, and secure distributed ledger systems.
- **Research Gap:**
- Lack of a comprehensive decision-making framework integrating both qualitative and quantitative criteria using advanced decision-making techniques.
- Limited application of integrated Multi-Criteria Decision-Making (MCDM) approaches for evaluating blockchain consensus algorithms across technical, environmental, and operational dimensions.

Research Objectives

- Identify the most critical criteria and sub-criteria (performance, sustainability, incentives, security & threat, decentralization) influencing consensus protocol selection.
- Evaluate and rank 20 mainstream blockchain consensus protocols based on quantitative and qualitative performance data.
- Propose an integrated MCDM framework combining Analytic Hierarchy Process (AHP) and Gray Rational Analysis (GRA) to facilitate consensus protocol selection.

Theoretical Framework

Analytic Hierarchy Process (AHP): Used to compute weights for dimensions and sub-criteria via pairwise comparison matrices.

Gray Rational Analysis (GRA): Utilized to evaluate, rank, and determine correlations among alternatives under complex criteria.

Integrated AHP-GRA Model: Combines subjective expert-driven criteria weighting with quantitative gray relational degree scoring for objective protocol ranking.

Conceptual Model: Dimensions (Performance, Sustainability, Incentives, Security & Threat, Decentralization) →Criteria Weights (AHP) →Relative Ranking of Protocols (GRA)

Research Methodology

- **Design:** Multi-Criteria Decision-Making (MCDM) quantitative framework.
- **Sample:** 20 leading blockchain consensus protocols across 10 consensus families.
- **Instrument:** Literature review, online distributed ledger explorers, and expert pairwise comparisons from 4 decision experts.
- **Analysis:** Integrated AHP for weight evaluation and GRA for distance/ranking calculation.
- **Reliability:** Consistency Ratio $(CR < 0.1)$ for AHP pairwise comparisons.
- **Validity:** Sensitivity analysis across 12 distinct weight-swapping scenarios to verify outcome stability.

Key Findings

- Performance (D_1; weight 0.3393) and Security & Threat (D_4; weight 0.3328) emerged as the primary criteria dimensions.
- Fault Tolerance (C_{11}; weight 0.1825), Transaction per Second (C_1; weight 0.0981), and Verification Speed (C_2; weight 0.0935) were the most critical individual sub-criteria.
- NEM (XEM; A_{19}, Proof of Importance) ranked as the most effective overall consensus protocol, followed by Cardano (A_9, DPoS-Ouroboros) and Nano (A_5, PoS-Block Lattice).
- Traditional Proof-of-Work (PoW) protocols ranked lower due to high energy consumption, poor scalability, and environmental concerns.

Academic Contribution

- Introduces the first integrated AHP-GRA framework specifically tailored for evaluating and selecting blockchain consensus protocols.
- Aggregates qualitative and quantitative data across 15 criteria for 20 leading consensus protocols into a single evaluation dataset.
- Provides empirical validation through comprehensive sensitivity analysis, demonstrating model resilience under varying decision-maker priorities.