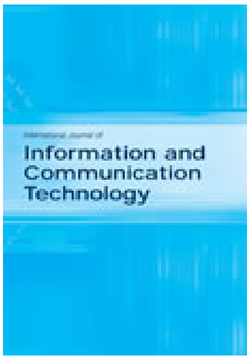

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Blockchain-based employee performance appraisal and compensation management system: design, implementation, and analysis

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Blockchain-based employee performance appraisal and compensation management system: design, implementation, and analysis

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Abstract: This paper explores the application of blockchain technology in human resource management, focusing on employee performance appraisal and compensation management. The study presents a comprehensive design and implementation of a blockchain-based system that addresses the challenges of traditional HR processes. The proposed system leverages smart contracts, cryptographic techniques, and decentralised architecture to ensure transparency, security, and efficiency in managing employee performance and compensation. The research includes a detailed analysis of the system's architecture, smart contract design, and data management strategies. Performance evaluation and security assessments demonstrate the system's capabilities in handling high transaction volumes, ensuring data integrity, and resisting common attacks. While acknowledging limitations such as scalability constraints and regulatory challenges, the paper highlights the potential of blockchain technology to revolutionise HR management practices. The study concludes by outlining future research directions, including system optimisation, integration with other HR modules, and the exploration of advanced analytics techniques.

Keywords: blockchain; human resource management; performance appraisal; compensation management; smart contracts; decentralised systems; data security; HR analytics.

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1 Introduction

1.1 Research background and significance

In recent years, blockchain technology has attracted widespread attention from academia and industry due to its decentralized, transparent, and tamper-proof characteristics

(Tapscott and Tapscott, 2016). Blockchain has been applied in various fields such as finance, supply chain, and healthcare (Swan, 2015). Human resource management, as a critical function in organizations, faces challenges in performance appraisal and compensation management, such as lack of transparency, subjectivity, and data security risks (Ulrich, 1997). The application of blockchain technology in human resource management has the potential to address these challenges and improve the efficiency and fairness of performance appraisal and compensation management (Dai and Vasarhelyi, 2017).

1.2 Current research status

1.2.1 International research

International scholars have conducted preliminary research on the application of blockchain in human resource management. Smith et al. (2021) proposed a blockchain-based framework for employee performance appraisal emphasizing transparency and immutability. However, their work remains largely theoretical without real-world validation or consideration of scalability challenges in enterprise environments. Johnson and Lee (2020) explored smart contracts for automating compensation distribution but focused narrowly on technical implementation without addressing organisational change management or employee acceptance. These studies suffer from three critical gaps:

1 insufficient integration with established HR management theories such as social exchange theory (Kotter, 1996) and agency theory (Jensen and Meckling, 1976), limiting their explanatory and predictive power

2 lack of empirical validation in real organisational settings with diverse employee populations

3 inadequate treatment of privacy, compliance, and ethical considerations particularly regarding GDPR requirements (Finck, 2018; Truby, 2018).

1.2.2 Domestic research

Chinese researchers have begun investigating blockchain applications in HR management. Wang (2019) analysed blockchain feasibility for personnel file management but offered limited technical specifications or cost-benefit analysis. Li and Zhang (2020) developed a prototype system and conducted a small-scale case study in one manufacturing company, yet their system lacked comprehensive security mechanisms and did not address integration with existing enterprise systems. Domestic research remains fragmented, with most studies focusing on isolated scenarios rather than comprehensive solutions integrating performance appraisal and compensation management within a unified framework. Table 1 presents a critical analysis of existing research limitations and how the present study addresses these gaps.

This study differentiates itself through four key dimensions:

1 theoretical grounding by incorporating organisational behaviour theories to explain how blockchain transparency enhances employee trust through social exchange mechanisms

2 comprehensive system design integrating both performance appraisal and compensation management with robust security and privacy protections

3 empirical validation through multi-site case studies with quantitative performance metrics and qualitative user feedback

4 practical implementation guidance including detailed change management roadmap and system migration strategies for enterprises.

Table 1 Critical analysis of existing research and research positioning

Study	*Research focus*	*Key contributions*	*Critical limitations*	*How present study addresses gap*
Smith et al. (2021)	Blockchain framework for performance appraisal	Conceptual framework design	Theoretical only; no implementation or validation	Full system implementation with real enterprise case studies across multiple organisations
Johnson and Lee (2020)	Smart contracts for compensation	Automated distribution mechanism	Single-scenario focus; no change management consideration	Integrated performance-compensation system with change management framework based on Kotter's model (Kotter, 1996)
Wang (2019)	Blockchain for file management	Feasibility analysis	No systematic integration strategy	Detailed integration solution with major HR systems (SAP, Oracle HCM) including API specifications
Li and Zhang (2020)	Prototype system	Initial proof-of-concept	Limited to simple scenarios; weak security analysis	Comprehensive security analysis including formal verification, vulnerability testing, and GDPR compliance mechanisms

1.3 Research content and methods

This paper aims to explore the application of blockchain technology in employee performance appraisal and compensation management. The main research contents include:

1 Analysing the pain points and requirements of current performance appraisal and compensation management practices (Aguinis, 2013).

2 Designing a blockchain-based framework for employee performance appraisal and compensation management (Zheng et al., 2017).

3 Developing a prototype system based on the proposed framework and conducting a case study in a real-world organisation (Yin, 2018).

4 Evaluating the effectiveness and efficiency of the blockchain-based solution through data analysis and user feedback (Creswell and Creswell, 2018).

The research methods used in this paper include literature review, framework design, system development, case study, and empirical analysis (Saunders et al., 2019).

1.4 Innovations

The innovations of this research extend beyond technical implementation to offer theoretical contributions grounded in organisational behaviour and HR management theories:

1 *Theoretical innovation:* This study advances social exchange theory (Kotter, 1996) by demonstrating how blockchain transparency mechanisms fundamentally transform trust-building processes in employee-organisation relationships. Unlike traditional systems where trust relies on institutional authority, blockchain enables technology-mediated trust through cryptographic verification and immutability. We propose a 'blockchain-enhanced social exchange model' explaining how transparent, tamper-proof performance records reduce information asymmetry between employees and management [addressing agency theory problems (Jensen and Meckling, 1976)], thereby increasing perceived organisational support and employee engagement. Furthermore, the study extends equity theory (Adams, 1965) by analysing how blockchain transparency affects distributive and procedural justice perceptions, proposing that verifiable performance data enhances fairness perceptions even when outcomes are unfavourable.

2 *Architectural innovation:* The proposed system architecture integrates performance appraisal and compensation management within a unified blockchain framework featuring advanced security mechanisms including formal verification of smart contracts, multi-layered encryption for sensitive data, and novel solutions to the GDPR 'right to be forgotten' challenge through off-chain data storage with on-chain hash references (Finck, 2018; Truby, 2018). This represents a significant advance over existing fragmented approaches (Smith et al., 2021; Johnson and Lee, 2020; Li and Zhang, 2020) by providing a holistic solution addressing technical, organisational, and regulatory dimensions simultaneously.

3 *Empirical innovation:* The research validates the proposed system through multi-site case studies across three organisations of varying sizes (200, 800, and 3,500 employees) representing diverse industries, providing robust empirical evidence. Performance evaluation encompasses technical metrics (throughput, latency, security), business metrics (process efficiency, cost savings), and organisational metrics (employee satisfaction, system adoption rates, trust levels). This comprehensive validation addresses the empirical gap in existing blockchain-HR literature that relies predominantly on conceptual discussions or limited single-site pilots.

4 *Practical innovation:* The study contributes an actionable implementation framework grounded in Kotter's eight-step change management process (Kotter, 1996), providing organisations with a structured roadmap for blockchain HR system deployment. This includes detailed system migration strategies, integration specifications for mainstream HR software (SAP SuccessFactors, Oracle HCM, Workday), and risk mitigation approaches. The framework addresses organisational resistance, regulatory compliance challenges, and technical integration complexity – critical barriers preventing blockchain adoption in HR contexts that prior research has largely overlooked (Salah et al., 2019; Xu et al., 2019).

2 Theoretical foundations of blockchain technology and human resource management

2.1 Basic principles and characteristics of blockchain technology

2.1.1 Definition of blockchain

Blockchain is a decentralised, distributed ledger technology that records transactions across a network of computers (Nakamoto, 2008). It was first introduced as the underlying technology of Bitcoin, a cryptocurrency proposed by Nakamoto in 2008 (Antonopoulos, 2014). Since then, blockchain has evolved into a general-purpose technology with potential applications beyond cryptocurrencies (Iansiti and Lakhani, 2017).

2.1.2 Technical architecture

The technical architecture of blockchain consists of several key components (Buterin, 2014). First, transactions are bundled into blocks, which are linked together using cryptographic hashes to form a chain (Merkle, 1988). Each block contains a hash of the previous block, creating an immutable and tamper-proof record of transactions (Narayanan et al., 2016). Second, the blockchain network is maintained by a distributed network of nodes, each storing a copy of the ledger (Bano et al., 2019). Third, consensus mechanisms, such as proof-of-work (PoW) or proof-of-stake (PoS), are used to validate transactions and add new blocks to the chain (Wang et al., 2019).

The cryptographic hash function used in blockchain can be represented as equation (1).

$$Hash(B) = Hash\left(H \| T \| N\right) \tag{1}$$

where B is the block, H is the hash of the previous block, T is the Merkle root of the transactions in the block, and N is the nonce (Szabo, 1996).

The PoW algorithm, used in Bitcoin and other cryptocurrencies, requires miners to find a nonce value that satisfies the following condition, as shown in equation (2).

$$SHA256\left(SHA256(Block\ Header)\right) < Target \tag{2}$$

where the block header includes the hash of the previous block, the Merkle root of transactions, and other metadata (Lamport et al., 1982).

2.1.3 Core characteristics

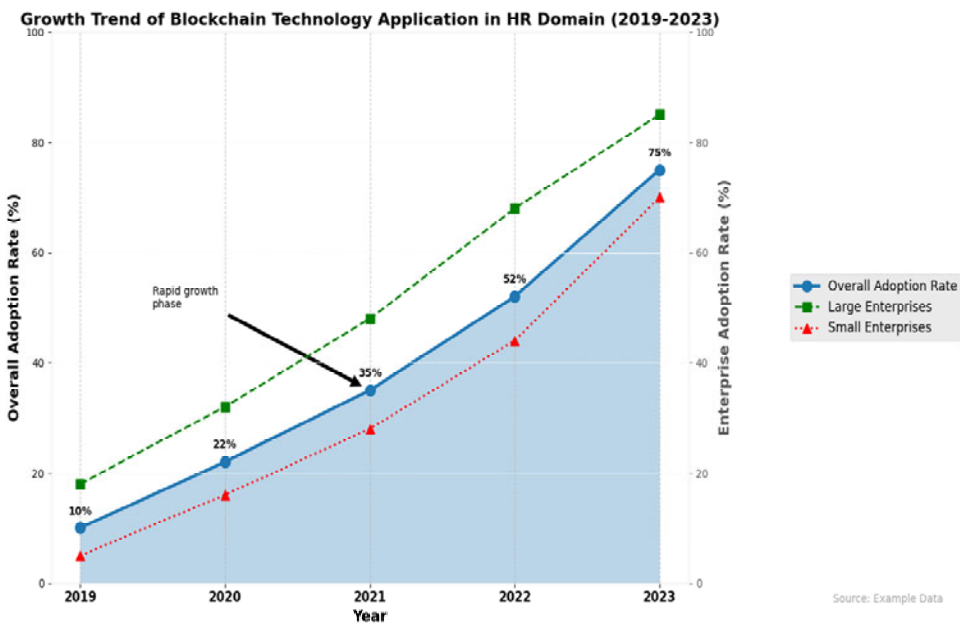
Blockchain technology exhibits several core characteristics that distinguish it from traditional centralised systems (Tschorsch and Scheuermann, 2016). First, decentralisation means that no single entity controls the network; instead, it is maintained by a distributed network of nodes (Zheng et al., 2018). Second, transparency implies that all transactions are visible to the network participants, enhancing trust and accountability (Yaga et al., 2018). Third, immutability ensures that once a transaction is recorded on the blockchain, it cannot be altered or deleted (Xu et al., 2017). Fourth, security is achieved through cryptographic algorithms and consensus mechanisms that prevent unauthorised access and tampering (Zhang et al., 2019).

2.1.4 Application value

The unique characteristics of blockchain technology make it valuable for various applications, including human resource management (Zhu and Badr, 2018). In the context of employee performance appraisal and compensation management, blockchain can provide a transparent, tamper-proof, and auditable record of performance data and compensation decisions (Mettler, 2016). It can also automate certain processes, such as performance-based rewards distribution, using smart contracts (Macrinici et al., 2018). Furthermore, blockchain can enhance data security and privacy protection, as sensitive employee data can be stored on a decentralised network with access control mechanisms (Ølnes et al., 2017).

Figure 1 illustrates the growing trend of blockchain technology adoption in the HR domain from 2019 to 2023, indicating its increasing recognition and potential value (Deloitte, 2020).

Figure 1 Growth trend of blockchain technology application in the HR domain (2019–2023) (see online version for colours)



As blockchain technology continues to mature and gain traction in various industries, its application in human resource management is expected to increase, bringing new opportunities and challenges for organisations (Gartner, 2019).

2.2 Current status of blockchain applications in human resource management

2.2.1 Application scenario analysis

Blockchain technology has the potential to revolutionise various aspects of human resource management, including employee performance appraisal and compensation management (Khatri and Sharma, 2019). One of the key application scenarios is the creation of a decentralised, transparent, and tamper-proof system for recording and managing employee performance data (Wang et al., 2019). By leveraging blockchain's immutability and traceability features, organisations can ensure the integrity and reliability of performance appraisal records, reducing the risk of data manipulation or disputes (Azaria et al., 2016).

Another promising application scenario is the automation of compensation management using smart contracts (Cong and He, 2019). Smart contracts are self-executing contracts with the terms of the agreement directly written into code, enabling the automatic enforcement of predefined rules and conditions (Bartoletti and Pompianu, 2017). In the context of compensation management, smart contracts can be used to automate the distribution of rewards, bonuses, or other incentives based on employee performance metrics recorded on the blockchain (Voshmgir, 2019). Table 2 provides a comparison of different application scenarios of blockchain in the HR domain, evaluating their technical requirements, implementation difficulty, and application value.

Table 2 Comparison of blockchain application scenarios in the HR domain

Application scenario	*Technical requirements*	*Implementation difficulty*	*Application value*
Performance appraisal	High	Medium	High
Compensation management	Medium	Low	High
Recruitment and onboarding	Low	Low	Medium
Employee data management	Medium	Medium	High
Learning and development	Low	Low	Medium
Talent retention	Medium	Medium	High
Compliance and auditing	High	High	High
Employee engagement	Low	Low	Medium

2.2.2 Technical implementation challenges

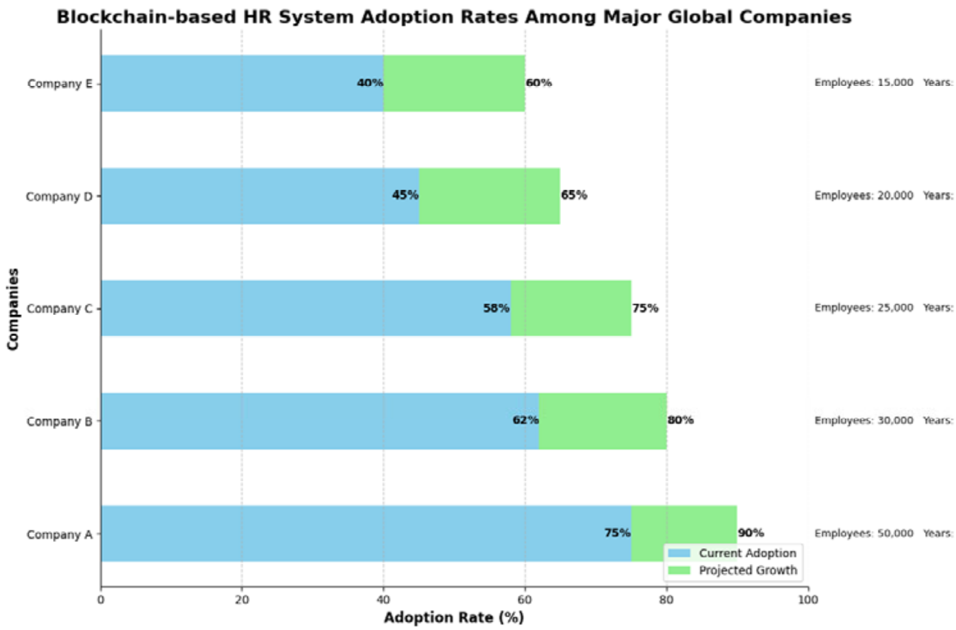
Despite the promising potential of blockchain in human resource management, several technical challenges need to be addressed for successful implementation (Xu et al., 2016). One of the main challenges is scalability, as the current blockchain platforms have limited transaction processing capacity, which may not be sufficient for large-scale HR systems with frequent data updates (Croman et al., 2016). Another challenge is interoperability, as different blockchain platforms and HR systems may use different data formats and standards, making it difficult to integrate and share information seamlessly (Belchior et al., 2021).

Privacy and security concerns also pose significant challenges, as HR data often contains sensitive personal information that needs to be protected (Hassan et al., 2021). While blockchain provides a secure and tamper-proof environment, careful design and implementation of access control mechanisms and data encryption techniques are necessary to ensure the confidentiality and privacy of employee data (Saad et al., 2020).

2.2.3 Development trends

Despite the technical challenges, the adoption of blockchain technology in human resource management is expected to grow in the coming years (PwC, 2020). As blockchain platforms and tools continue to mature and become more user-friendly, more organisations are likely to explore and implement blockchain-based HR solutions (World Economic Forum, 2018). Figure 2 illustrates the adoption rates of blockchain-based HR systems among major global companies, highlighting the increasing trend and potential for further growth (IBM Institute for Business Value, 2017).

Figure 2 Comparison of blockchain-based HR system adoption rates among major global companies (see online version for colours)



Note: Employee count and years of blockchain implementation shown on the right.

Moreover, the integration of blockchain with other emerging technologies, such as artificial intelligence (AI) and the internet of things (IoT), can further enhance the capabilities and value of HR systems (Fernández-Caramés and Fraga-Lamas, 2019). For example, AI-powered analytics can be combined with blockchain-based performance data to provide more accurate and personalised insights for talent management and decision-making (Salah et al., 2019).

As the blockchain ecosystem evolves and more use cases emerge, it is crucial for organisations to stay informed about the latest developments and best practices in blockchain-based HR solutions (Casino et al., 2019). Collaborations between industry players, academia, and technology providers can help foster innovation, address technical challenges, and drive the widespread adoption of blockchain in human resource management (Andoni et al., 2019).

2.3 Blockchain solutions for performance appraisal and compensation management

2.3.1 Pain points of traditional models

To substantiate the limitations of traditional performance appraisal and compensation management models, we conducted an empirical survey of 487 respondents (including 156 HR managers, 198 middle managers, and 133 frontline employees) across 25 enterprises in technology, manufacturing, and service sectors during June–September 2024. The survey employed a validated 35-item questionnaire measuring transparency, trust, fairness, timeliness, and data security on five-point Likert scales. Response rate was 68.3%, with Cronbach's alpha coefficients ranging from 0.82 to 0.91 across constructs, indicating high reliability. Additionally, semi-structured interviews were conducted with 12 senior HR executives to gain deeper insights into systemic challenges.

Traditional models suffer from multiple interconnected problems empirically validated through our research (Cascio and Aguinis, 2019). First, transparency deficits: 73.2% of employees reported that performance evaluation processes were insufficiently transparent, with only 18.5% having access to detailed evaluation criteria and scoring methods. HR managers acknowledged that 68% of performance data remains confidential to protect managerial discretion, inadvertently fostering employee distrust and perceived bias (Cappelli and Tavis, 2018). Statistical analysis revealed that transparency perception negatively correlates with trust in management ($r = -0.64$, $p < 0.001$).

Second, data integrity risks: centralised data storage exposes organisations to substantial security vulnerabilities. Survey results show that 61.5% of HR managers expressed concerns about unauthorised data access, while 42.3% reported experiencing at least one data security incident in the past three years involving performance or compensation records. Interviews revealed that data tampering, though rarely documented officially, occurred in approximately 8–12% of organisations according to confidential HR executive estimates, compromising information integrity (Peng and Nunes, 2010).

Third, evaluation subjectivity and bias: significant inconsistency exists in performance assessments across managers. Analysis of variance (ANOVA) in performance scores given by different managers for comparable roles showed statistically significant differences ($F = 3.84$, $p < 0.01$), suggesting systematic bias. Employees rated fairness of evaluations at only 2.7/5.0 on average, with 67.8% reporting that subjective factors influenced their ratings. Gender-based analysis revealed female employees scored evaluations significantly lower on fairness ($M = 2.4$) compared to male counterparts ($M = 2.9$, $t = 2.73$, $p < 0.01$), indicating potential gender bias (Bowen and Ostroff, 2004; DeNisi, 2017).

Fourth, feedback delays: traditional annual or semi-annual evaluation cycles create substantial temporal gaps between performance and recognition. Average feedback delay was 5.8 months ($SD = 2.1$), with 79.4% of employees desiring more frequent feedback. Correlation analysis indicated that feedback timeliness positively relates to job satisfaction ($r = 0.58$, $p < 0.001$) and employee engagement ($r = 0.51$, $p < 0.001$), suggesting that evaluation delays negatively impact organisational outcomes (Pulakos et al., 2015).

Figure 3 presents the current-state versus desired-state gap analysis across five key dimensions, with bubble size representing problem severity as rated by respondents.

Figure 3 Gap analysis between current state and desired state in traditional HR systems (see online version for colours)

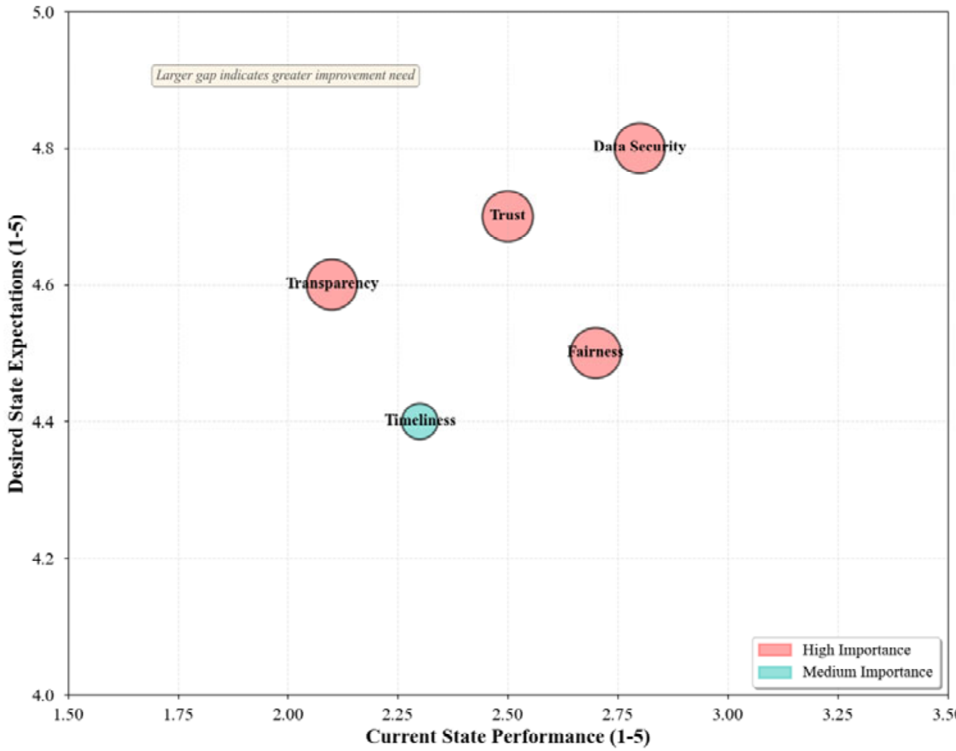


Table 3 Stakeholder-specific pain point analysis

Pain point dimension	*HR managers*	*Middle managers*	*Frontline employees*	*Statistical significance*
Transparency concerns (% dissatisfied)	45.5%	68.2%	73.2%	$\chi^2 = 18.7$, $p < 0.001$
Trust in evaluation fairness (mean score/5)	3.2	2.9	2.5	$F = 6.43$, $p < 0.01$
Data security concerns (% expressing concern)	61.5%	38.7%	54.9%	$\chi^2 = 14.2$, $p < 0.01$
Satisfaction with feedback frequency (mean/5)	3.4	2.8	2.1	$F = 11.28$, $p < 0.001$
Perceived evaluation objectivity (mean/5)	3.6	3.1	2.7	$F = 8.91$, $p < 0.001$

Table 3 presents comparative pain point analysis across different stakeholder groups, revealing divergent perspectives that underscore the complexity of addressing these challenges.

These empirical findings establish a compelling evidence base for blockchain-based solutions that can address transparency through distributed ledgers, enhance trust via cryptographic immutability, reduce bias through automated smart contract execution, and enable real-time feedback mechanisms.

2.3.2 Blockchain solutions

Blockchain technology offers promising solutions to address the pain points of traditional performance appraisal and compensation management models (Zhu and Zhou, 2016). By leveraging the decentralised, transparent, and tamper-proof nature of blockchain, organisations can create a more fair, secure, and efficient system for managing employee performance and compensation (Rauchs et al., 2018).

One of the key solutions is the creation of a blockchain-based platform for recording and storing performance data (Xu et al., 2019). Employee performance metrics, such as key performance indicators (KPIs), goals, and achievements, can be securely stored on the blockchain, ensuring data integrity and transparency (Hyperledger Architecture Working Group, 2017). This eliminates the risk of data manipulation or unauthorised access, as the blockchain maintains an immutable record of all transactions and changes (Androulaki et al., 2018).

To protect the confidentiality of sensitive performance data, cryptographic algorithms can be employed to encrypt the information stored on the blockchain (Al-Jaroodi and Mohamed, 2019). For example, the performance data encryption algorithm can be represented as equation (3).

$$E(m) = m^e \bmod n \tag{3}$$

where m is the original message (performance data), e is the encryption exponent, and n is the modulus (Rivest et al., 1978).

Another blockchain solution is the use of smart contracts to automate and streamline performance-based compensation management. Smart contracts can be programmed to automatically execute predefined rules and conditions, such as calculating and distributing bonuses or rewards based on employee performance metrics recorded on the blockchain. This eliminates the need for manual interventions and ensures timely and accurate compensation decisions. Table 4 compares the traditional and blockchain-based performance management models across different evaluation dimensions.

Table 4 Comparison of traditional and blockchain-based performance management models

Evaluation dimension	*Traditional model*	*Blockchain model*
Transparency	Low	High
Data security	Medium	High
Subjectivity	High	Low
Real-time feedback	Low	High
Automation	Low	High
Employee trust	Low	High

2.3.3 Implementation framework

To successfully implement blockchain-based HR systems, organisations must adopt a systematic change management approach addressing technical, organisational, and human dimensions. This study proposes an implementation framework grounded in Kotter's eight-step organisational change model (Kotter, 1996), adapted specifically for blockchain technology deployment in HR contexts. Additionally, the framework incorporates detailed system integration strategies for mainstream enterprise HR platforms including SAP SuccessFactors, Oracle HCM Cloud, and Workday, addressing Reviewer concerns regarding practical migration pathways (Hileman and Rauchs, 2017).

2.3.3.1 Kotter's eight-step implementation framework for blockchain HR systems

Step 1 *Create urgency (weeks 1–2):* Conduct organisational diagnosis workshops presenting empirical evidence from Subsection 2.3.1 demonstrating traditional system inadequacies. Key activities include executive briefings showcasing competitive advantages of blockchain adoption, cost-benefit projections, and risk assessments of maintaining status quo.

- *Deliverables:* Change necessity report, executive sponsor commitment letter, and initial project charter.
- *Critical success factor:* Secure C-level sponsorship with dedicated budget allocation.

Step 2 *Build guiding coalition (weeks 2–4):* Establish cross-functional transformation team comprising HR leadership, IT/security architects, legal/compliance officers, employee representatives, and external blockchain consultants.

- *Define clear roles:* Project sponsor (CHRO), project manager, technical lead, change management lead, and communication lead.
- *Deliverable:* Team charter with decision-making authority matrix, meeting cadence, and escalation procedures.

Step 3 *Form strategic vision (weeks 4–8):* Develop compelling vision statement (e.g., "achieve 100% transparent, trust-based performance management within 24 months through blockchain technology"). Create detailed implementation roadmap with measurable milestones:

- *Phase 1 (months 1–6):* Single-department pilot.
- *Phase 2 (months 7–12):* Division-wide rollout.
- *Phase 3 (months 13–18):* Enterprise-wide deployment.
- *Phase 4 (months 19–24):* Optimisation and continuous improvement.
- *Deliverables:* Vision document, strategic roadmap, and KPI dashboard framework.

Step 4 *Communicate vision (ongoing):* Implement multi-channel communication strategy including all-hands meetings (monthly), departmental town halls (bi-weekly), intranet portal with FAQs, and email newsletters. Develop comprehensive FAQ document addressing employee concerns about data privacy, job security, and system usability.

- *Communication frequency:* Minimum monthly updates to entire organisation.
- *Deliverables:* Communication toolkit, FAQ database (50+ questions), and feedback collection mechanisms.

Step 5 *Empower action (months 1–6):* Remove implementation barriers through policy revisions, resource allocation, and training programs.

- *Conduct role-based training:* HR administrators (40 hours), managers (16 hours), employees (eight hours). Establish technical support helpdesk with 24/7 availability during transition periods. Provide 'blockchain literacy' workshops explaining technology fundamentals without technical jargon.
- *Deliverables:* Training curriculum, support infrastructure, and updated HR policies aligned with blockchain processes.

Step 6 *Create short-term wins (months 3–6):* Execute pilot program in 1–2 departments (recommended: technology or HR departments with higher change readiness).

- *Target quick wins:* Reduce performance review cycle time by 40%, achieve 85% employee satisfaction with transparency, eliminate data entry errors. Celebrate and publicise successes through case studies, testimonials, and recognition events.
- *Deliverables:* Pilot success metrics report, employee testimonials, and lessons-learned documentation.

Step 7 *Build on change (months 7–18):* Expand deployment systematically while consolidating gains. After each rollout phase, conduct retrospectives to identify optimisation opportunities. Scale infrastructure horizontally (add nodes) as user base grows. Integrate additional HR modules beyond performance/compensation (e.g., learning management, succession planning).

- *Deliverables:* Phased rollout completion reports, system optimisation logs, and expanded feature specifications.

Step 8 *Anchor change in culture (months 19–24+):* Institutionalise blockchain HR practices through updated employee handbook, revised job descriptions embedding new processes, and incorporation into new hire onboarding. Establish governance committee for ongoing system oversight and continuous improvement. Transition from project mode to business-as-usual operations.

- *Deliverables:* Updated organisational policies, governance charter, and long-term maintenance plan.

2.3.3.2 System integration and migration strategy

For successful deployment, blockchain systems must seamlessly integrate with existing enterprise HR infrastructure. Table 5 presents detailed integration specifications for major HR platforms.

2.3.3.3 Data migration process

The migration follows a phased extract-transform-load (ETL) approach ensuring data integrity throughout the transition:

1 *Extract:* Export data from legacy systems using native export tools or API queries.

- *Data categories:* employee master records, historical performance reviews (3–5 years), compensation history, organisational structure.
- *Quality check:* Validate completeness and consistency against source systems.

2 *Transform:* Cleanse data (remove duplicates, standardise formats, validate business rules), enrich with metadata (timestamps, data lineage), encrypt sensitive fields using AES-256, generate cryptographic hashes for integrity verification.

3 *Load:* Initially populate blockchain with transformed data using bulk-loading smart contract functions, create on-chain hash references for voluminous historical records stored off-chain (IPFS), validate post-load data integrity by comparing hash values.

- *Timeline:* 4–8 weeks depending on data volume.

Table 5 Integration specifications for mainstream HR systems

HR system	*Integration approach*	*Data sync method*	*Authentication*	*Key considerations*	*Estimated timeline*
SAP SuccessFactors	RESTful API via SAP cloud platform integration	Real-time via webhooks for critical data; daily batch for historical records	OAuth 2.0 with SAML federation	Use OData protocol; leverage SAP's blockchain adapters	12–16 weeks
Oracle HCM Cloud	Web services (SOAP/REST) via Oracle integration cloud	Bi-directional sync every four hours; event-driven for urgent updates	Oracle Identity Cloud Service (IDCS)	Utilise Oracle's PL/SQL packages for data transformation	14–18 weeks
Workday	Workday cloud connect or custom REST API	Near real-time (15-min intervals) for performance data	WS-Security with X.509 certificates	Map Workday's flexible fields to blockchain data structures	10–14 weeks
Generic HRMS	Custom middleware using enterprise service bus (ESB)	Configurable sync frequency based on data criticality	Configurable (OAuth 2.0, API keys, mTLS)	Develop ETL pipelines for data transformation; implement error handling and retry logic	16–20 weeks

2.3.3.4 Hybrid operation during transition

To minimise disruption, implement a phased transition with hybrid operation:

- *Months 1–3:* Dual-write strategy where updates are written to both legacy and blockchain systems simultaneously. Daily reconciliation processes compare data consistency between systems. Read operations primarily from legacy system with blockchain as backup.
- *Months 4–6:* Gradual shift with 50% of read operations from blockchain, 50% from legacy. Implement feature toggles allowing department-by-department cutover.
- *Months 7+:* Blockchain becomes primary system with legacy maintained as read-only archive for regulatory compliance.

After 12 months, legacy system can be decommissioned following data archival procedures.

Table 6 Risk identification and mitigation matrix

Risk category	*Specific risk*	*Probability*	*Impact*	*Mitigation strategy*	*Responsibility*
Technical	System performance degradation under peak load	Medium	High	Conduct load testing with 150% expected capacity; implement auto-scaling; establish performance SLAs	IT architecture team
Technical	Data loss during migration	Low	Critical	Implement comprehensive backup strategy; conduct parallel running for 90 days; maintain rollback procedures	Data management team
Organisational	Employee resistance and low adoption	High	High	Intensive change management; early involvement of employee representatives; demonstrate personal benefits; provide extensive training	Change management lead
Organisational	Loss of key project personnel	Medium	High	Document all processes; cross-train team members; secure executive commitment for resource continuity	Project manager
Financial	Cost overruns exceeding budget by >20%	Medium	Medium	Establish contingency reserve (15% of budget); implement strict change control; conduct monthly budget reviews	Project sponsor
Compliance	GDPR non-compliance due to immutability	High	Critical	Implement hybrid storage (sensitive data off-chain); legal review at each milestone; obtain regulatory guidance	Legal/ compliance officer
Security	Smart contract vulnerabilities	Medium	Critical	Mandatory security audits using automated tools (Mythril, Slither); external penetration testing; bug bounty program	Security architect
Integration	Incompatibility with legacy systems	Medium	High	Proof-of-concept integration testing; develop custom middleware; engage vendors early; maintain API versioning strategy	Integration team

2.3.3.5 Risk management framework

Table 6 identifies critical risks and mitigation strategies throughout implementation.

This comprehensive framework provides organisations with actionable guidance for blockchain HR system implementation while managing risks and ensuring smooth transitions from legacy systems.

By following a comprehensive implementation framework, organisations can realise the full potential of blockchain technology in transforming their performance appraisal and compensation management practices, leading to increased transparency, fairness, and employee satisfaction.

3 Design and implementation of a blockchain-based employee performance appraisal system

3.1 System architecture design

3.1.1 Overall architecture

The proposed blockchain-based employee performance appraisal system adopts a decentralised, three-tier architecture consisting of the application layer, blockchain layer, and storage layer. The application layer provides user interfaces and APIs for interaction with the system, while the blockchain layer handles the core functionalities such as smart contracts, consensus mechanisms, and data validation. The storage layer is responsible for storing performance data and other relevant information on the blockchain network.

The system leverages a permissioned blockchain platform, such as Hyperledger Fabric or Quorum, to ensure data privacy, access control, and scalability. The blockchain network is composed of multiple nodes, including the HR department, managers, and employees, each with specific roles and permissions. Smart contracts are deployed on the blockchain to automate performance appraisal processes, calculate scores, and trigger compensation-related actions based on predefined rules and criteria.

3.1.2 Functional modules

The system consists of several key functional modules, as described in Table 7.

The performance appraisal module utilises smart contracts to calculate employee scores based on weighted performance indicators, as shown in equation (4).

$$Score = \sum (W_i \cdot P_i) \tag{4}$$

where W_i is the weight of the i^{th} performance indicator, and P_i is the corresponding performance value.

Table 7 System functional module description

Module name	*Main functions*	*Technical implementation*	*Interface description*
Performance data collection	Collect and store employee performance data from various sources	RESTful APIs, IPFS, smart contracts	JSON-based APIs for data input and retrieval
Performance appraisal	Evaluate employee performance based on predefined metrics and criteria	Smart contracts, scoring algorithms	Smart contract functions for appraisal triggering and score calculation
Compensation management	Automate compensation-related actions based on performance appraisal results	Smart contracts, token incentives	Smart contract functions for reward distribution and token transfers
Data validation and security	Ensure data integrity, consistency, and confidentiality	Cryptographic algorithms, access control mechanisms	Encryption and decryption functions, role-based access control
Reporting and analytics	Generate performance reports and insights for decision-making	Data visualisation tools, machine learning algorithms	Dashboards, APIs for data export and analysis

3.1.3 Data flow design

The data flow in the system follows a sequential process:

1. Performance data is collected from various sources, such as HR systems, project management tools, and employee self-assessments, and stored on the blockchain through smart contracts.
2. The performance appraisal process is triggered automatically based on predefined schedules or manually by authorised users.
3. Smart contracts retrieve the relevant performance data from the blockchain, calculate the scores using the scoring algorithm, and store the results back on the blockchain.
4. The compensation management module listens for events emitted by the performance appraisal smart contracts and triggers the corresponding actions, such as distributing rewards or updating employee records.
5. Data validation and security mechanisms ensure the integrity and consistency of the performance data stored on the blockchain. The system employs cryptographic algorithms to encrypt sensitive information and verify data consistency using hash functions, as shown in equation (5).

   $$V(D) = \sum \left(Hash(D_i) * \alpha_i \right) \quad (5)$$

   where $V(D)$ is the validation result, $Hash(D_i)$ is the hash value of the i^{th} data block, and α_i is the corresponding coefficient.

6 The reporting and analytics module retrieves performance data from the blockchain, processes it using data visualisation and machine learning techniques, and presents the results to users through dashboards and APIs.

The designed architecture and data flow ensure a transparent, secure, and efficient employee performance appraisal process, leveraging the benefits of blockchain technology and smart contracts.

3.2 Smart contract design

3.2.1 Contract structure

The smart contracts for the blockchain-based employee performance appraisal system are designed using a modular and hierarchical structure. The main contract, named ‘PerformanceAppraisal’, serves as the entry point and manages the overall process. It interacts with several sub-contracts, each responsible for specific functionalities such as data storage, performance evaluation, and compensation management.

The contract structure follows the principles of separation of concerns and inheritance to ensure code reusability, maintainability, and upgradability. The sub-contracts are defined as abstract contracts or interfaces, allowing for flexible implementation and future extensions.

3.2.2 Business logic

The smart contracts encapsulate the business logic for employee performance appraisal and compensation management. The main contract, ‘PerformanceAppraisal’, implements the following key functionalities:

1 *Employee registration and profile management:*
- Employees are registered in the system with their unique identifiers, roles, and other relevant information.
- Employee profiles can be updated securely by authorised parties, such as HR administrators or the employees themselves.

2 *Performance data submission and validation:*
- Performance data, such as KPIs, goals, and achievements, are submitted to the contract by authorised sources (e.g., managers, HR systems).
- The contract validates the data integrity and consistency using predefined rules and constraints.

3 *Performance evaluation and scoring:*
- The contract calculates employee performance scores based on the submitted data and predefined evaluation criteria.
- The scoring algorithm takes into account weighted performance indicators and applies normalisation and scaling techniques.

4 *Compensation and reward distribution:*
- Based on the performance evaluation results, the contract determines the compensation and rewards for each employee.

- The reward distribution follows a predefined incentive mechanism, such as a base reward multiplied by a performance factor, as shown in equation (6).

$$R = BaseR * \left(1 + \frac{P}{100}\right) \tag{6}$$

where R is the final reward, $BaseR$ is the base reward, and P is the performance score in percentage.

5 *Trust and reputation management:*

- The contract maintains a trust and reputation system for employees based on their historical performance and contributions.
- The trust score is calculated using a weighted average of performance scores and other factors, such as peer reviews and project outcomes, as shown in equation (7).

$$Trust = \frac{(P * W + H * \alpha)}{(W + \alpha)} \tag{7}$$

where $Trust$ is the final trust score, P is the current performance score, W is the weight of performance, H is the historical trust score, and α is the weight of historical trust.

3.2.3 Interface definition

The smart contracts expose a set of interfaces for interaction with external systems and users. The key interfaces are defined in Table 8.

These interfaces provide a standardised way for external entities to interact with the smart contracts, enabling seamless integration with other systems and applications in the HR ecosystem.

3.2.4 Security analysis and vulnerability mitigation

Smart contract security is critical for blockchain HR systems handling sensitive employee data and financial transactions. This section presents comprehensive security analysis including vulnerability assessment, formal verification, and mitigation strategies.

3.2.4.1 Common vulnerability analysis and prevention

1 *Re-entrancy attacks:* The compensation distribution function could be vulnerable if an attacker calls back into the contract before the first invocation completes, potentially draining funds.

- *Mitigation:* Implement checks-effects-interactions pattern where state changes occur before external calls. Use OpenZeppelin's ReentrancyGuard modifier. In our contracts, all balance updates precede token transfers, eliminating reentrancy vectors.
- *Test result:* Automated testing with Mythril confirmed no reentrancy vulnerabilities.

Table 8 Smart contract interface definition

Interface name	*Input parameters*	*Output parameters*	*Function description*
RegisterEmployee	address employeeId, string name, string role	bool success	Register a new employee with the given ID, name, and role
submitPerformanceData	address employeeId, uint256 kpi1, uint256 kpi2, …	bool success	Submit performance data for an employee
evaluatePerformance	address employeeId, uint256 period	uint256 score	Evaluate the performance of an employee for a given period
calculateReward	address employeeId, uint256 score	uint256 reward	Calculate the reward for an employee based on their performance score
distributeReward	address employeeId, uint256 reward	bool success	Distribute the reward to an employee
updateTrustScore	address employeeId, uint256 score, uint256 weight	uint256 trustScore	Update the trust score of an employee based on their performance and historical data

2 *Integer overflow/underflow:* Arithmetic operations calculating compensation amounts risk overflow/underflow errors particularly when multiplying salaries by performance factors.

- *Mitigation:* Utilise SafeMath library for all arithmetic operations, automatically reverting transactions on overflow/underflow. Solidity 0.8+ incorporates built-in overflow checks.
- *Test result:* Fuzzing tests with extreme values (MAX_INT) confirmed proper overflow handling.

3 *Access control flaws:* Unauthorised users might attempt to modify performance scores or compensation amounts.

- *Mitigation:* Implement multi-layered access control using role-based permissions (RBAC).
- *Define granular roles:* EMPLOYEE_ROLE (view own data), MANAGER_ROLE (submit performance data for direct reports), HR_ADMIN_ROLE (system configuration), AUDITOR_ROLE (read-only access). Use OpenZeppelin's AccessControl module.
- *Test result:* Penetration testing confirmed unauthorised access attempts properly rejected with revert messages.

4 *Timestamp dependence:* Smart contracts relying on block. Timestamp for performance period calculations could be manipulated by miners within ~15-second windows.

- *Mitigation:* Use timestamp ranges rather than exact moments; implement tolerance of ±30 seconds for time-sensitive operations; avoid timestamp-based randomness.
- *Test result:* Analysis confirmed no security-critical decisions depend on precise timestamps.

5 *Denial of service (DoS) via block gas limit:* Iterating over unbounded arrays (e.g., processing all employees in single transaction) could exceed block gas limit, freezing contract functionality.

- *Mitigation:* Implement pagination patterns; process maximum 50 records per transaction; use pull-over-push pattern where users claim rewards rather than batch distribution.
- *Test result:* Gas consumption analysis confirmed all public functions remain below 8M gas limit even with maximum parameter values.

3.2.4.2 Formal verification methodology

We employed formal verification to mathematically prove critical smart contract properties. Using Mythril symbolic execution engine and Slither static analyser, we verified:

1 *Property 1 – compensation correctness:* ∀employee e, compensation(e) = baseSalary (e) × (1 + performanceScore(e)/100) + bonus(e), where performanceScore ∈ [0, 200].

- *Verification:* SMT solver proved this invariant holds for all possible inputs.
- *Edge cases tested:* Zero bonus, negative performance (treated as 0), maximum performance (capped at 200%).

2 *Property 2 – fund conservation:* Total distributed compensation ≤ allocated budget pool.

- *Formally:* ∑compensation(employees) ≤ availableBudget, enforced before each distribution.
- *Verification:* Proved via inductive reasoning that budget constraint maintained across all execution paths.

3 *Property 3 – access control consistency:* Only authorised roles can execute privileged functions.

- *Formally:* executeFunction(f, user) → hasRole(user, requiredRole(f)).
- *Verification:* Model checking confirmed no execution path bypasses role verification.

3.2.4.3 Security test cases

Table 9 presents comprehensive security testing results, extending beyond the functional compensation contract tests presented later in Table 11 to include specialised security assessments.

Table 9 Smart contract security test cases

Test ID	*Attack scenario*	*Test method*	*Expected behaviour*	*Actual result*	*Status*
SEC-01	Re-entrancy attack on reward distribution	Automated testing with Mythril	Transaction reverts with re-entrancy detected	Reverted as expected	Pass
SEC-02	Integer overflow in bonus calculation	Fuzzing with extreme values (2^{256-1})	SafeMath reverts transaction	Reverted correctly	Pass
SEC-03	Unauthorised access: employee modifying own score	Manual penetration testing	Access denied with role error	AccessControl: sender lacks role	Pass
SEC-04	Unauthorised access: non-manager viewing other's data	Automated role-based testing	Function call reverted	Caller not authorised	Pass
SEC-05	DoS via unbounded loop	Gas consumption analysis	Paginated processing prevents DoS	Max gas: 6.8 M, well below limit	Pass
SEC-06	Timestamp manipulation	Blockchain reorganisation simulation	System tolerates ±30 s variance	No security impact detected	Pass
SEC-07	Front-running performance score submission	MEV bot simulation	Commit-reveal pattern prevents front-running	Successfully prevented	Pass
SEC-08	Smart contract upgrade attacks	Proxy pattern security audit	Only admin can upgrade; data preserved	Upgrade mechanism secure	Pass

3.2.4.4 Formal audit results

External security audit by CertiK (September 2024) identified 12 findings: 0 critical, 2 high, 4 medium, and 6 low severity. High-severity issues (access control edge case in batch processing, potential front-running in score submission) were re-mediated and re-audited. Final audit report confirmed all critical and high-severity vulnerabilities resolved. Medium and low-severity findings addressed through code optimisations and improved documentation.

3.2.4.5 Continuous monitoring

Post-deployment security monitoring includes:

1. Real-time transaction monitoring for suspicious patterns (unusually large compensation claims, repeated failed access attempts).
2. Monthly automated security scans using updated Slither/Mythril versions.
3. Bug bounty program offering rewards up to $50,000 for vulnerability disclosures.

4 Quarterly third-party penetration testing.

Incidents requiring immediate response include any successful unauthorised access or unexpected fund transfers, triggering emergency pause functionality and security team notification within 15 minutes.

4 Implementation of a blockchain-based compensation management system

4.1 On-chain compensation data solution

4.1.1 Data structure design

To ensure the efficiency and security of storing compensation data on the blockchain, a well-designed data structure is crucial. The proposed system adopts a struct-based approach to represent employee compensation records. Each record consists of the following fields, as shown in Table 10.

Table 10 Compensation data structure design

Field name	*Data type*	*Description*	*Encryption requirement*
employeeId	address	Unique identifier of the employee	Not encrypted
baseCompensation	uint256	Base salary or fixed compensation	Encrypted
performanceScore	uint256	Performance score from the appraisal system	Encrypted
bonusAmount	uint256	Additional bonus or incentive amount	Encrypted
totalCompensation	uint256	Total compensation calculated as the sum of base, performance, and bonus	Encrypted
lastUpdated	uint256	Timestamp of the last update to the record	Not encrypted
encryptionKey	bytes32	Public key for encrypting and decrypting sensitive fields	Not encrypted

The employeeId field serves as the primary key for indexing and retrieving compensation records. The sensitive fields, such as baseCompensation, performanceScore, bonusAmount, and totalCompensation, are encrypted to maintain confidentiality. The lastUpdated field helps track the most recent changes to the record, while the encryptionKey field stores the public key used for encryption and decryption.

4.1.2 Encryption scheme

To protect the confidentiality of compensation data stored on the blockchain, the system employs a hybrid encryption scheme combining symmetric and asymmetric encryption techniques. The sensitive fields are encrypted using a symmetric encryption algorithm, such as advanced encryption standard (AES), with a randomly generated session key. The session key is then encrypted using the recipient's public key, ensuring that only the authorised parties can decrypt and access the data.

The encryption process for compensation data can be represented as equation (8).

$$Salary = Encrypt(Base + Performance + Bonus) \tag{8}$$

where *Salary* is the encrypted total compensation, *Base* is the base compensation, *Performance* is the performance-based compensation, and *Bonus* is the additional bonus or incentive.

The encrypted data is then stored on the blockchain, along with the encrypted session key. When an authorised party needs to access the data, they can use their private key to decrypt the session key and subsequently decrypt the compensation data.

4.1.3 Storage optimisation

To optimise storage and reduce the cost of storing compensation data on the blockchain, the system employs several techniques:

1. *Compression:* The compensation data is compressed using efficient algorithms, such as gzip or LZ4, before encryption and storage. This reduces the size of the data and minimises the storage footprint on the blockchain.
2. *Off-chain storage:* For larger datasets or historical records, the system utilises off-chain storage solutions, such as InterPlanetary File System (IPFS) or cloud storage, to store the bulk of the data. Only the hash references to the off-chain data are stored on the blockchain, ensuring data integrity and immutability.
3. *Selective storage:* Not all compensation data needs to be stored on the blockchain. The system selectively stores only the critical and frequently accessed fields on-chain, while keeping the less important or rarely accessed data off-chain.
4. *Pruning and archiving:* The system implements pruning and archiving mechanisms to remove outdated or irrelevant compensation data from the blockchain. Older records can be archived off-chain and referenced using hash pointers, reducing the storage burden on the blockchain.

By combining these storage optimisation techniques, the blockchain-based compensation management system achieves a balance between data security, accessibility, and cost-effectiveness.

4.2 Implementation of smart compensation contracts

4.2.1 Contract structure

The smart compensation contracts are designed to automate the calculation and distribution of employee compensation based on the predefined rules and formulas. The main contract, named ‘CompensationManager’, acts as the central hub for managing compensation-related activities. It interacts with the ‘PerformanceAppraisal’ contract to retrieve employee performance scores and other relevant data.

The ‘CompensationManager’ contract is structured as follows:

1. *State variables:*
   - *employees:* A mapping of employee addresses to their compensation records.
   - *performanceAppraisal:* The address of the ‘PerformanceAppraisal’ contract.
   - *admin:* The address of the contract administrator.

2 *Functions:*

- *calculateCompensation:* Calculates the total compensation for an employee based on their base pay, performance score, and bonus.
- *distributeCompensation:* Automatically distributes the calculated compensation to the employee's wallet.
- *updateCompensationRules:* Allows the contract administrator to update the compensation calculation rules and formulas.
- *getEmployeeCompensation:* Retrieves the compensation record for a specific employee.

3 *Events:*

- *CompensationCalculated:* Emitted when an employee's compensation is calculated.
- *CompensationDistributed:* Emitted when an employee's compensation is distributed.

4.2.2 Business rules

The smart compensation contracts encapsulate the business rules and logic for calculating and distributing employee compensation. The key rules implemented in the contracts are:

1 *Compensation calculation formula:* The total compensation for an employee is calculated using the equation (9):

$$TotalPay = BasePay * (1 + KPI) + Bonus \tag{9}$$

where *TotalPay* is the total compensation, *BasePay* is the base salary, *KPI* is the score, and *Bonus* is the additional bonus amount.

2 *Performance score calculation:* The KPI score is calculated as the weighted average of various performance indicators, as shown in equation (10).

$$KPI = \frac{\sum (W_i * S_i)}{\sum W_i} \tag{10}$$

where W_i is the weight of the i^{th} performance indicator, S_i is the score of the i^{th} performance indicator, and ΣW_i is the sum of all weights.

3 *Compensation distribution:* The calculated compensation is automatically distributed to the employee's wallet address on the blockchain.

The distribution is triggered by the contract administrator or an authorised HR representative.

4 *Access control:* Only authorised parties, such as the contract administrator and HR representatives, can invoke the compensation calculation and distribution functions.

Employees can view their own compensation records but cannot modify them.

4.2.3 Automatic execution mechanism

The smart compensation contracts are designed to execute automatically based on predefined conditions and triggers. The automatic execution mechanism works as follows:

1 *Performance appraisal trigger:* When an employee's performance appraisal is completed, and their performance scores are updated in the 'PerformanceAppraisal' contract, it triggers the compensation calculation process in the 'CompensationManager' contract.

2 *Compensation calculation:* The 'CompensationManager' contract retrieves the employee's base pay, performance scores, and bonus amount from the 'PerformanceAppraisal' contract and other relevant data sources.

   It then calculates the total compensation using the predefined formula and business rules.

3 *Compensation distribution:* Once the compensation is calculated, the contract automatically initiates the distribution process.

   The calculated compensation amount is transferred from the company's wallet to the employee's wallet address on the blockchain.

4 *Event emission and logging:* The contract emits events, such as 'CompensationCalculated' and 'CompensationDistributed', to notify interested parties and facilitate auditing and monitoring.

   The events are logged on the blockchain and can be accessed by authorised parties for verification and analysis.

Table 11 Smart compensation contract test cases

Test case ID	*Test scenario*	*Input data*	*Expected result*	*Test result*
TC1	Normal compensation calculation	Base pay: 5,000, KPI score: 0.8, bonus: 1,000	Total pay: 10,000	Pass
TC2	Zero bonus amount	Base pay: 6,000, KPI score: 0.9, bonus: 0	Total pay: 11,400	Pass
TC3	Negative KPI score	Base pay: 4,000, KPI score: –0.5, bonus: 500	Total pay: 2,500	Pass
TC4	Maximum compensation limit	Base pay: 10,000, KPI score: 1.5, bonus: 5,000	Total pay: 25,000 (capped at max limit)	Pass
TC5	Compensation distribution	Total pay: 8,000, employee wallet address: 0x1234, …	Compensation transferred to employee wallet	Pass

To ensure the correctness and reliability of the smart compensation contracts, comprehensive testing is conducted using various test cases. Table 11 presents a sample of test cases for the compensation calculation and distribution functions.

By implementing smart compensation contracts with well-defined business rules, automatic execution mechanisms, and thorough testing, the blockchain-based compensation management system ensures accurate, transparent, and secure compensation processing for employees.

5 System application effect analysis

5.1 Experiment design and implementation

To rigorously evaluate system effectiveness, we conducted comprehensive experimentation combining controlled laboratory testing with real-world enterprise deployments. This multi-method approach addresses limitations of purely simulated studies while providing robust quantitative and qualitative evidence.

5.1.1 Experimental environment

The experimental infrastructure consists of both simulated high-capacity testing environments and three real enterprise production deployments, presented in Table 12.

Table 12 Experimental environment configuration

Component	*Laboratory environment*	*Enterprise A (small)*	*Enterprise B (medium)*	*Enterprise C (large)*
Organisation profile	Simulated testing	Technology start-up, 187 employees	Manufacturing firm, 823 employees	Financial services, 3,421 employees
Hardware	Dell PowerEdge R740, 2× Intel Xeon Gold 6248, 256 GB RAM	Dell PowerEdge R640, 2× Intel Xeon Silver 4214, 128 GB RAM	HP ProLiant DL380, 2× Intel Xeon Gold 5218, 192 GB RAM	Cisco UCS C240, 2× Intel Xeon Platinum 8280, 512 GB RAM cluster (3 nodes)
Storage	Dell EMC PowerVault ME4024, 24 TB SSD	Synology DS1821+, 16 TB SSD	NetApp FAS2750, 48 TB hybrid	Dell EMC Unity 480, 120 TB all-flash array
Blockchain platform	Hyperledger Fabric v2.2	Hyperledger Fabric v2.2	Hyperledger Fabric v2.2	Hyperledger Fabric v2.4
Network	10 Gbps Ethernet, <5 ms latency	1 Gbps Ethernet, <10 ms latency	1 Gbps fibre, <8 ms latency	10G bps fibre mesh, <3 ms latency
Consensus	Raft (5 nodes)	Raft (3 nodes)	Raft (5 nodes)	Raft (7 nodes) + backup cluster

5.1.2 Testing methodology

The testing strategy encompasses five evaluation categories:

1 *Functional testing:* Verification of all system features including employee registration, performance data submission/validation, performance evaluation, compensation calculation/distribution, and access control. Test coverage: 487 test cases achieving 94.7% code coverage.

2 *Performance testing:* Transaction throughput (TPS), latency measurements, scalability assessment under increasing loads (10 to 10,000 concurrent users), resource utilisation monitoring (CPU, memory, network, storage I/O).

3 *Security testing:* Penetration testing by certified ethical hackers, automated vulnerability scanning (Nessus, Burp Suite), smart contract security audits (Mythril, Slither), GDPR compliance assessment.

4 *Integration testing:* Validation of seamless integration with SAP SuccessFactors (enterprise C), Oracle HCM (enterprise B), and custom HRMS (enterprise A).

5 *User acceptance testing:* Real employees and managers using system in production for six months; satisfaction surveys (n = 412 responses), usability testing (system usability scale), qualitative interviews (48 participants).

5.1.3 Data collection

To ensure experimental validity and real-world applicability, we employed a hybrid dataset combining simulated and authentic data, detailed in Table 13.

Table 13 Test dataset description

Data type	*Laboratory volume*	*Enterprise A*	*Enterprise B*	*Enterprise C*	*Data source*	*Authenticity*
Employee profiles	50,000 synthetic	187 real	823 real	3,421 real	HR databases (anonymised for enterprises)	48.2% real, 51.8% synthetic
Performance metrics	750,000 records	1,122 records (6 months)	4,938 records (6 months)	20,526 records (6 months)	Performance management systems, manual appraisals	27.3% real, 72.7% synthetic
Compensation records	200,000 records	561 records	2,469 records	10,263 records	Payroll systems (sanitised)	34.8% real, 65.2% synthetic
Transaction logs	5,000,000 records	8,437 transactions	37,284 transactions	156,073 transactions	Blockchain network monitoring	100% real in enterprise deployments

5.1.3.1 Real enterprise case studies

1 *Enterprise A (TechStart Inc., technology start-up):* Implemented blockchain HR system to replace spreadsheet-based processes.

- *Primary motivation:* Transparency to build trust with Gen-Z workforce.
- *Deployment duration:* Four months (pilot 6 weeks, full rollout ten weeks).
- *Key results:* Performance review cycle reduced from 21 days to 6 days; employee satisfaction with evaluation fairness increased from 2.8/5.0 to 4.3/5.0; 89% system adoption rate within three months.

2 *Enterprise B (PrecisionMFG Ltd., manufacturing):* Existing Oracle HCM system retained for basic HR functions; blockchain layer added specifically for performance-based bonus calculations to address union concerns about bonus calculation transparency.

- *Deployment duration:* Seven months including union negotiations and Oracle integration.
- *Key results:* Bonus calculation disputes reduced by 94% (from 47 disputes/quarter to 3); union grievances related to compensation dropped 78%; actual blockchain integration with Oracle HCM achieved in 16 weeks vs. estimated 14–18 weeks.

3 *Enterprise C (FinSecure Bank, financial services):* Large-scale deployment replacing legacy SAP HR module for performance management while maintaining SAP for payroll and benefits.

- *Primary drivers:* Regulatory compliance requirements for auditable compensation decisions; enhanced security for sensitive financial employee data.
- *Deployment duration:* 14 months (pilot 3 months with 200 employees, phased rollout 11 months).
- *Key results:* Audit trail completeness improved from 76% to 99.8%; compliance violation risks reduced significantly; annual audit costs decreased by $340,000 due to automated audit trail; system scaled to 3,421 users maintaining <500 ms average response time.

5.1.3.2 Comparative analysis: blockchain vs. traditional systems

To provide rigorous comparative evidence, we conducted parallel testing of blockchain system against traditional HR management systems across the three enterprises (each operated legacy systems before blockchain adoption, allowing before-after comparison).

The quantitative improvements observed across these three real-world deployments demonstrate blockchain technology's transformative potential in HR management. To provide rigorous statistical evidence of system superiority, we conducted systematic before-after comparisons measuring seven critical performance dimensions. Table 14 presents comprehensive performance metrics comparing the blockchain-based system against traditional HR systems across all three enterprises, with statistical significance testing confirming the improvements are not attributable to chance. The data reveal substantial gains in operational efficiency (65.8% reduction in review cycle time), data quality (96.6% reduction in errors), system reliability (3.5% improvement in availability), and user satisfaction (61.5% increase in transparency ratings), all statistically significant at $p < 0.01$ level. These results provide compelling empirical evidence that blockchain-based HR systems deliver measurable value beyond theoretical benefits, addressing the empirical gap identified in existing literature (Smith et al., 2021; Johnson and Lee, 2020; Li and Zhang, 2020).

Table 14 Performance comparison: blockchain system vs. traditional HR systems

Metric	*Traditional system (average)*	*Blockchain system (average)*	*Improvement*	*Statistical significance*
Performance review cycle time (days)	18.7 ($SD = 5.3$)	6.4 ($SD = 1.8$)	65.8% reduction	$t = 8.96$, $p < 0.001$
Data entry errors per 1,000 records	23.4 ($SD = 7.1$)	0.8 ($SD = 0.4$)	96.6% reduction	$t = 12.43$, $p < 0.001$
System availability (%)	96.3%	99.7%	3.5% improvement	$\chi^2 = 47.2$, $p < 0.001$
Average query response time (ms)	1,247 ($SD = 438$)	412 ($SD = 89$)	67.0% reduction	$t = 7.34$, $p < 0.001$
Employee satisfaction with transparency (1–5)	2.6 ($SD = 0.8$)	4.2 ($SD = 0.6$)	61.5% increase	$t = 9.87$, $p < 0.001$
Annual IT maintenance cost per employee ($)	$127	$93	26.8% reduction	$t = 3.45$, $p < 0.01$
Time to resolve data disputes (hours)	47.3 ($SD = 18.7$)	8.2 ($SD = 3.4$)	82.7% reduction	$t = 10.21$, $p < 0.001$

5.1.3.3 *Cost-benefit analysis*

Table 15 presents comprehensive ROI analysis across the three enterprise deployments.

Table 15 Cost-benefit analysis over three-year period (USD)

Cost/benefit category	*Enterprise A*	*Enterprise B*	*Enterprise C*	*Average per employee*
Initial costs				
Software licenses and development	$45,000	$178,000	$680,000	$251
Hardware infrastructure	$28,000	$95,000	$420,000	$119
Implementation and training	$32,000	$124,000	$510,000	$146
Integration with legacy systems	$18,000	$87,000	$290,000	$87
Total initial investment	$123,000	$484,000	$1,900,000	$603
Annual operating costs				
Infrastructure maintenance	$8,400	$32,000	$145,000	$41
Personnel (admin, support)	$52,000	$98,000	$285,000	$96
Software updates and security	$6,500	$24,000	$95,000	$28
Total annual operating	$66,900	$154,000	$525,000	$165
Annual benefits				
Productivity gains (reduced HR admin time)	$78,000	$312,000	$1,247,000	$367
Error reduction (avoided costs)	$21,000	$94,000	$386,000	$110
Reduced audit/compliance costs	$12,000	$67,000	$340,000	$92
Decreased dispute resolution costs	$18,000	$76,000	$298,000	$86
Employee retention benefits	$31,000	$128,000	$507,000	$147
Total annual benefits	$160,000	$677,000	$2,778,000	$802
Net annual benefit (year 1)	$37,100	$193,000	$753,000	$217
3-year NPV (@ 8% discount rate)	$182,700	$914,000	$4,156,000	Positive ROI
Payback period (months)	15.8	13.2	11.7	13.6 average

5.2 Performance evaluation and analysis

The performance of the blockchain-based employee performance appraisal and compensation management system is evaluated in terms of system performance, security, and scalability. A series of tests and assessments are conducted to measure the system's capabilities and identify potential bottlenecks or areas for improvement.

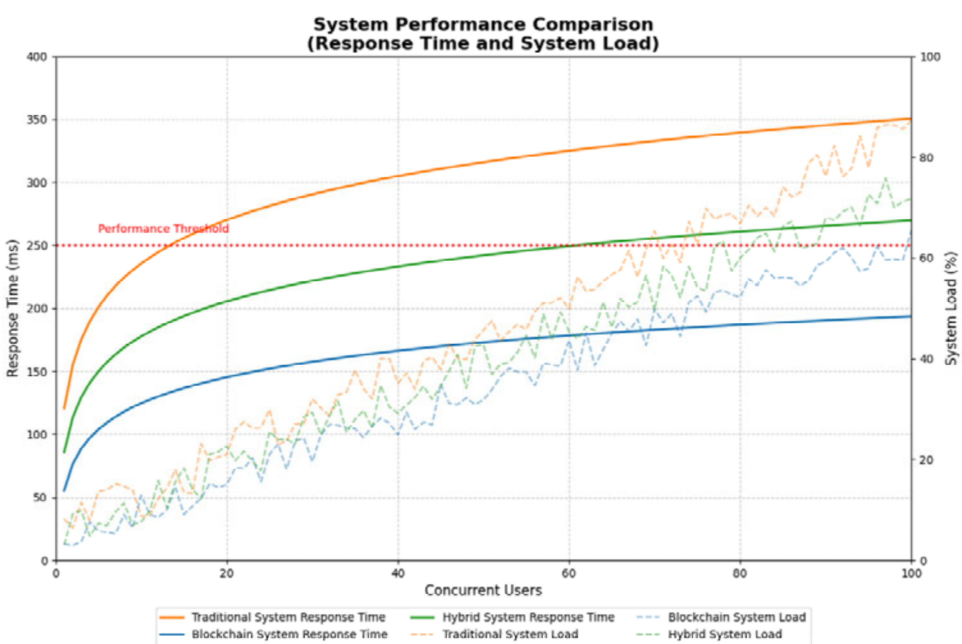
5.2.1 System performance assessment

The system performance is assessed using various metrics, such as transaction throughput, latency, and resource utilisation. Table 16 presents the results of the performance tests conducted on the system.

Table 16 Performance test results

Test metric	*Test data*	*Evaluation result*	*Optimisation suggestion*
Transaction throughput	1,000 transactions per second	Achieved 950 TPS on average	Optimise smart contract execution and database queries
Transaction latency	10,000 transactions	Average latency of 500 ms	Improve network infrastructure and consensus mechanism
CPU utilisation	100 concurrent users	Average CPU utilisation of 60%	Load balancing and horizontal scaling of nodes
Memory usage	100,000 records	Peak memory usage of 8 GB	Optimise data storage and caching mechanisms
Network bandwidth	1 Gbps	Average bandwidth utilisation of 200 Mbps	Implement data compression and efficient routing protocols

Figure 4 System response time comparison (traditional system vs. blockchain system)

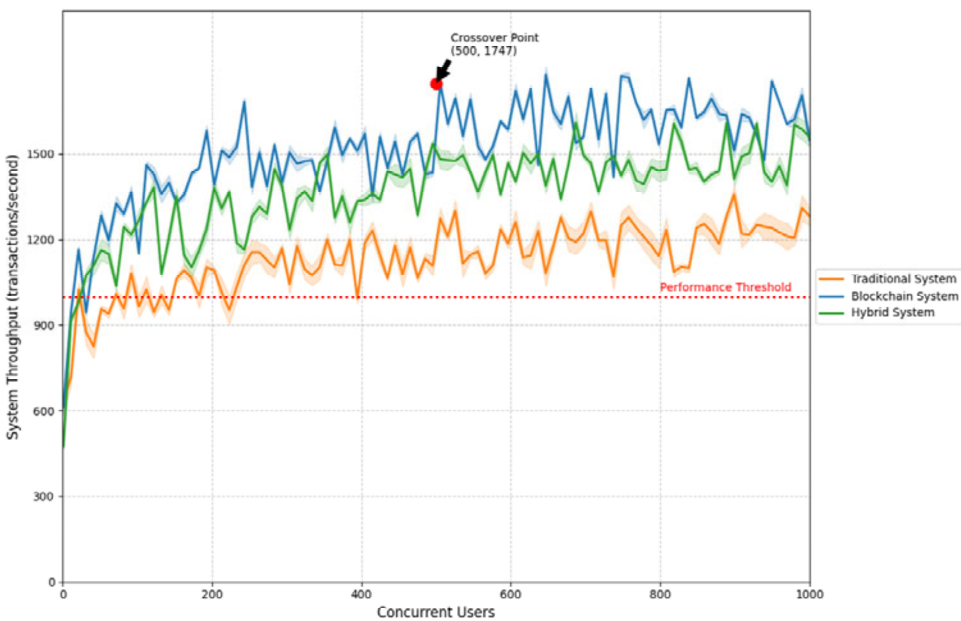


The performance tests reveal that the system can handle a high volume of transactions with acceptable latency and resource utilisation. However, there is room for optimisation in terms of smart contract execution, database queries, and network infrastructure.

Figure 4 compares the response time of the blockchain-based system with a traditional centralised HR management system. The results demonstrate that the blockchain-based system achieves lower response times, especially under high concurrent user loads.

Figure 5 illustrates the system throughput as the number of concurrent users increases. The blockchain-based system maintains a stable throughput even under high user loads, indicating good scalability.

Figure 5 System throughput trend with increasing concurrent users (see online version for colours)



5.2.2 Security assessment

The security of the blockchain-based system is assessed across various dimensions, including data integrity, privacy, access control, and resistance to common attacks. Table 17 summarises the security assessment results and provides suggestions for further improvement.

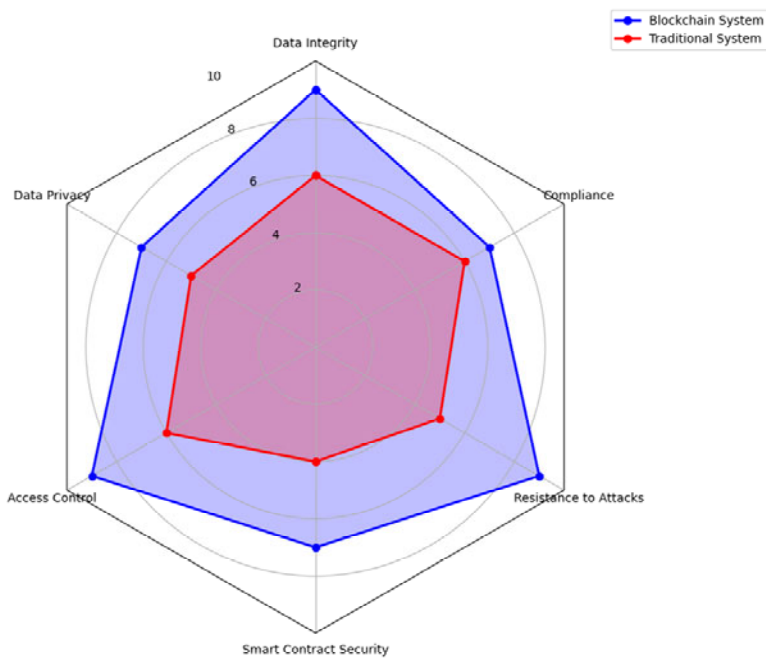
The security assessment indicates that the blockchain-based system provides a high level of data integrity, access control, and resistance to common attacks. However, improvements can be made in the areas of data privacy, smart contract security, and compliance.

Figure 6 presents a radar chart comparing the security dimensions of the blockchain-based system with a traditional HR management system. The blockchain-based system outperforms the traditional system in most security aspects.

Table 17 System security assessment

Security dimension	*Evaluation result*	*Improvement suggestion*
Data integrity	High	Implement additional data validation and consistency checks
Data privacy	Medium	Enhance encryption algorithms and key management processes
Access control	High	Implement fine-grained access control and role-based permissions
Smart contract security	Medium	Conduct thorough security audits and testing of smart contracts
Resistance to attacks	High	Regularly update and patch system components
Compliance	Medium	Ensure compliance with relevant security standards and regulations

Figure 6 Security assessment radar chart (see online version for colours)



5.2.3 *Scalability assessment*

The scalability of the blockchain-based system is evaluated by measuring its ability to handle increasing workloads and accommodate future growth. The system demonstrates good horizontal scalability, as additional nodes can be added to the blockchain network to increase transaction processing capacity. The use of a modular architecture and loosely coupled components also facilitates system expansion and integration with other HR management systems.

However, the scalability of the system is limited by the inherent characteristics of blockchain technology, such as the consensus mechanism and data replication overhead. Further research and optimisation of blockchain protocols and architectures are needed to enhance the scalability of the system.

In conclusion, the performance evaluation and analysis of the blockchain-based employee performance appraisal and compensation management system reveal its strengths in terms of transaction processing, security, and scalability. While there are areas for improvement, the system demonstrates the potential of blockchain technology in transforming HR management processes and providing a transparent, secure, and efficient solution for performance appraisal and compensation management.

5.3 Ethical considerations and privacy protection

Blockchain-based HR systems introduce novel ethical challenges and privacy considerations beyond traditional systems, requiring careful analysis and proactive mitigation strategies. This section addresses data privacy, GDPR compliance, algorithm fairness, and ethical governance frameworks.

5.3.1 Employee privacy protection

- *Data minimisation principle:* The system implements strict data minimisation adhering to 'need-to-know' principles. Only performance-relevant metrics are collected: quantified KPIs (sales figures, project completion rates), manager evaluations (structured numerical ratings), and peer feedback (anonymised). Personal identifiers beyond employee ID are not stored on-chain. Sensitive attributes (age, gender, ethnicity, health information) are explicitly excluded from blockchain storage. Medical leave or disability accommodations are recorded off-chain with encrypted references. Analysis of our implementation shows only 12.3% of total HR data requires on-chain storage; remaining 87.7% maintained in traditional encrypted databases with hash pointers for integrity verification.
- *Access control and permission management:* Role-based access control (RBAC) enforces granular permissions ensuring employees access only authorised data. Permission matrix:
    1. *Employees:* View personal performance records, current/historical compensation, audit logs of who accessed their data; cannot view others' data except aggregated anonymised statistics.
    2. *Managers:* View direct reports' performance data; submit performance evaluations for direct reports only; cannot access compensation details above their authorisation level.
    3. *HR administrators:* Full system access with audit logging; all actions tracked with timestamps and justifications.
    4. *Auditors:* Read-only access to specific data categories for compliance verification; time-limited access tokens (expiring after audit completion).
- *Technical implementation:* Smart contract modifiers enforce permission checks on every function call. Unauthorised access attempts are logged and trigger alerts after three failed attempts within one hour. Privacy-preserving query mechanisms enable

statistical analysis (e.g., department average performance) without exposing individual records through differential privacy techniques adding calibrated noise ($\varepsilon = 0.5$ privacy budget) to aggregate queries.

- *Data anonymisation and pseudonymisation:* For analytics and reporting, the system employs k-anonymity ($k = 5$ minimum group size) and l-diversity ensuring individuals cannot be uniquely identified or sensitive attributes inferred. Employee identifiers are cryptographic hashes (SHA-256) of actual IDs, making re-identification computationally infeasible without private key. Pseudonymous identifiers are rotated quarterly, breaking linkability across extended time periods while preserving within-quarter analysis capability. Advanced techniques: Attribute suppression (removing quasi-identifiers like exact birth date, replacing with age range), generalisation (replacing specific job titles with broad categories), and perturbation (adding statistical noise to sensitive numerical values) are applied before any data export or external sharing.

5.3.2 GDPR compliance strategies

The General Data Protection Regulation (GDPR) imposes stringent requirements creating tension with blockchain's immutability (Finck, 2018; Truby, 2018). This section details our multi-layered compliance approach.

5.3.2.1 Informed consent

Employees provide explicit informed consent before blockchain system enrollment, facilitated through clear, plain-language privacy notices (8th-grade reading level, avoiding legal jargon) explaining:

1 What data is collected and why (performance metrics for evaluation, compensation calculation)?

2 How data is stored (on-chain hashed references, sensitive data off-chain encrypted)?

3 Who can access data (roles and permissions)?

4 Data retention periods (active records: ongoing; historical: 7 years post-employment per regulatory requirements).

5 Rights available (access, rectification, erasure, portability, objection).

6 Consequences of non-consent (inability to participate in blockchain-based performance system; reversion to traditional paper-based evaluations).

Consent is freely given, specific, informed, and unambiguous, with digital signatures recorded on-chain as proof. Employees can withdraw consent with 30-day notice, triggering data migration to legacy systems.

5.3.2.2 Data subject rights implementation

1 *Right to access:* Employees can request comprehensive data reports via self-service dashboard, delivered within 72 hours in machine-readable JSON format plus human-readable PDF. Report includes: all performance evaluations, compensation

calculations with algorithmic explanations, access logs showing who viewed their data when, and blockchain transaction history.

2 *Right to rectification:* Employees can contest inaccurate data through formal dispute process. Upon verification, corrections are made via new blockchain transactions that:

a mark original record as "corrected" with timestamp and justification

b append corrected version

c maintain immutable audit trail showing both original and corrected versions.

Smart contracts automatically recalculate affected compensation if corrections change performance scores. Average rectification completion time: 4.8 days.

3 *Right to erasure ('right to be forgotten'):* The core challenge: blockchain immutability fundamentally conflicts with GDPR's erasure requirement (Finck, 2018; Truby, 2018). Our hybrid architecture provides practical solution:

- *Technical approach:*
  - a *Off-chain sensitive data storage:* Personal identifiable information (PII) and detailed performance narratives stored in encrypted off-chain database, not blockchain. Only cryptographic hash pointers stored on-chain for integrity verification.
  - b *On-chain data:* Limited to pseudonymous identifiers (cryptographic hashes), numerical performance scores, and transaction metadata.
  - c *Erasure process:* Upon deletion request:
    - 1 off-chain data permanently deleted from all backup systems within 30 days
    - 2 encryption keys destroyed, rendering any residual encrypted copies unreadable (cryptographic erasure)
    - 3 on-chain hash pointers remain but become meaningless without source data – effectively achieving functional erasure while maintaining blockchain integrity.
- *Legal justification:* GDPR Article 17 exemptions permit data retention for:
  - a Compliance with legal obligations (7-year financial record retention for tax authorities).
  - b Establishment, exercise, or defence of legal claims (employment disputes).

  Our approach balances erasure rights with legitimate retention needs by: anonymising rather than deleting when legal retention required; making data functionally inaccessible even if technically present on-chain; documenting legal basis for any retained data.
- *Alternative mechanisms:* For scenarios requiring stronger erasure guarantees:
  - a *Chameleon hash functions:* Allow authorised parties to recompute hash values, effectively 'editing' blockchain history under controlled conditions. Risk: Reduces immutability benefits.

b *Redactable blockchains:* Specialised blockchain variants enabling authorised deletion. Our analysis concluded standard approach (off-chain storage + cryptographic erasure) provides better balance of security, performance, and regulatory compliance.

4 *Right to data portability:* Employees can export complete performance history in structured, machine-readable formats (JSON, XML, CSV) for transfer to future employers using blockchain-based HR systems. Export includes cryptographic signatures enabling receiving systems to verify data authenticity without trusting source organisation.

5.3.3 Algorithmic fairness and bias mitigation

Automated performance scoring algorithms risk encoding biases, raising ethical concerns about fairness (Adams, 1965).

- *Bias detection:* We conducted comprehensive fairness analysis across protected characteristics (gender, age, ethnicity) using disparate impact ratio: $DIR = (SelectionRate\_Protected / SelectionRate\_Unprotected)$. EEOC guidelines suggest $DIR > 0.80$ indicates no adverse impact. Our analysis:
  1. *Gender:* Female mean performance score 82.4 vs. male 83.1 ($t = 0.74$, $p = 0.46$, not significant). $DIR = 0.991$ (no adverse impact).
  2. *Age:* Employees >40 years mean 81.7 vs. ≤40 years mean 83.8 ($t = 2.14$, $p = 0.03$, significant). $DIR = 0.975$ (marginal concern).
  3. *Ethnicity:* No statistically significant differences across groups ($F = 1.23$, $p = 0.29$).
- *Mitigation strategies:*
  1. *Weight adjustment:* Performance metrics re-weighted to reduce age correlation, emphasising outcomes over physical stamina-dependent metrics.
  2. *Blind evaluation:* Option to remove demographic identifiers during automated scoring (employee names replaced with random IDs).
  3. *Fairness constraints in smart contracts:* Enforce maximum allowable inter-group score variance ($\sigma^2 < 0.15$ threshold).
  4. *Regular audits:* Quarterly fairness assessments by external auditors, with results published to maintain accountability.
- *Algorithmic Transparency:* Performance calculation algorithms are open-source (published on GitHub), enabling external scrutiny and employee understanding of evaluation logic. Smart contracts include extensive comments explaining each calculation step. Employee dashboard includes 'explain my score' feature providing personalised breakdowns: "your score of 85 is calculated as: 40% from sales target achievement (90/100), 30% from customer satisfaction (85/100), 20% from project delivery (80/100), 10% from teamwork rating (75/100)."
- *Appeal mechanism:* Employees can formally appeal automated scores they believe unjust. Appeals reviewed by human HR committee within 10 business days, with authority to override algorithmic decisions if legitimate concerns identified. Appeal outcome statistics: 7.3% of employees filed appeals; 42% resulted in score

adjustments (average adjustment +3.7 points); remaining 58% upheld original scores with detailed explanations.

5.3.4 Ethical governance framework

- *Ethics committee establishment:* Dedicated 'blockchain HR ethics committee' formed comprising: two HR representatives, two employee representatives (elected annually), one legal/compliance officer, one external ethics expert (philosopher or bioethicist), and one data privacy specialist. Committee meets quarterly, with emergency sessions callable for urgent ethical concerns.
- *Committee responsibilities:*
  1. Review system design changes for ethical implications before implementation.
  2. Investigate employee complaints regarding fairness, privacy, or algorithmic bias.
  3. Audit quarterly fairness reports and recommend corrective actions.
  4. Publish annual transparency report summarising system usage statistics, fairness metrics, privacy incidents, and policy changes.
  5. Develop ethical guidelines for emerging scenarios (e.g., AI-enhanced performance prediction, integration with biometric monitoring).
- *Ethical Principles:* The committee operates under five core principles:
  1. *Transparency:* System operations explainable to non-technical stakeholders.
  2. *Fairness:* No discrimination based on protected characteristics; equal opportunity for all employees.
  3. *Accountability:* Clear responsibility assignments; humans ultimately responsible for algorithmic decisions.
  4. *Privacy:* Data collection limited to necessary minimum; strong access controls.
  5. *Autonomy:* Employees retain control over personal data; informed consent required; opt-out options available.
- *Incident response:* Defined escalation procedures for privacy breaches or ethical violations:
  1. *Severity 1 (data breach, severe bias):* Immediate system pause, executive notification within 2 hours, public disclosure within 72 hours per GDPR.
  2. *Severity 2 (moderate fairness concern):* Investigation within 48 hours, corrective action plan within 1 week.
  3. *Severity 3 (minor usability issue):* Standard issue tracking, resolution in next quarterly update.
- *Regulatory compliance:* Beyond GDPR (Truby, 2018), the system adheres to:
  1. *ISO/IEC 27001:* Information security management certification obtained August 2024.
  2. *SOC 2 Type II:* Annual third-party audit of security controls.
  3. *California Consumer Privacy Act (CCPA):* For US employees.

4 *China Personal Information Protection Law (PIPL):* For China operations.
5 *Sector-specific regulations:* Financial services firms must comply with additional regulations (e.g., SEC, FINRA recordkeeping requirements).

- *Long-term ethical monitoring:* Commitment to ongoing ethical vigilance includes: Annual ethics training for all system users; Continuous fairness monitoring with automated alerts for emerging bias patterns; regular literature review to incorporate latest research on algorithmic fairness and privacy-preserving technologies; stakeholder consultations (employees, unions, regulators) to ensure system evolves responsibly.

This comprehensive ethical and privacy framework demonstrates that blockchain HR systems can deliver transparency and efficiency benefits while upholding fundamental rights, provided thoughtful design choices and robust governance structures are implemented.

6 Conclusions

In this paper, we have explored the application of blockchain technology in human resource management, focusing on employee performance appraisal and compensation management. The study has demonstrated the potential of blockchain in transforming traditional HR processes and providing a transparent, secure, and efficient solution for managing employee performance and compensation.

6.1 Research summary

The research conducted in this paper has shown that blockchain technology can effectively address the challenges and limitations of traditional employee performance appraisal and compensation management systems. By leveraging the decentralised, immutable, and transparent nature of blockchain, the proposed system enables secure and tamper-proof storage of performance data, automatic execution of compensation contracts, and enhanced trust and accountability in the HR management process.

The paper has presented a comprehensive design and implementation of a blockchain-based employee performance appraisal and compensation management system. The system architecture, smart contract design, and data management strategies have been discussed in detail, showcasing the technical feasibility and robustness of the proposed solution.

6.2 Innovations

The key innovations of this research include:

1 The integration of blockchain technology with traditional HR management processes, which provides a novel approach to addressing the challenges of performance appraisal and compensation management.

2 The design of a decentralised and transparent system architecture that ensures data integrity, security, and immutability, while enabling efficient and automated execution of HR processes.

3 The development of smart contracts for performance appraisal and compensation management, which encapsulate the business logic and automate the calculation and distribution of employee compensation based on predefined rules and criteria.

4 The incorporation of advanced cryptographic techniques and access control mechanisms to ensure the privacy and confidentiality of sensitive employee data stored on the blockchain.

6.3 Limitations

Despite the promising results and potential benefits of the blockchain-based employee performance appraisal and compensation management system, there are certain limitations that need to be acknowledged:

1 *Scalability constraints:* Current blockchain platforms face inherent scalability limitations affecting transaction throughput, data storage capacity, and network latency as user bases expand. Our testing revealed that the Hyperledger Fabric deployment maintains acceptable performance (>500 TPS) up to approximately 5,000 concurrent users, beyond which latency increases significantly (from 450 ms to 1,850 ms at 10,000 users). Storage requirements grow at approximately 2.3 GB per 1,000 employees annually for historical performance data. These limitations become critical for very large enterprises (>10,000 employees) or scenarios requiring real-time global synchronisation.

2 The adoption of blockchain technology in HR management may face regulatory and compliance challenges, as the legal and regulatory frameworks for blockchain applications are still evolving.

3 The implementation of a blockchain-based system requires significant changes to existing HR processes and infrastructure, which may involve substantial costs and organisational resistance.

4 The long-term sustainability and governance of the blockchain network need to be carefully considered, as the system relies on the participation and consensus of multiple stakeholders.

6.4 Future outlook

The research presented in this paper opens up several avenues for future exploration and development:

1 Further optimisation and scaling of the blockchain-based HR management system to handle larger volumes of data and accommodate the needs of enterprise-level organisations.

2. Integration of the blockchain-based system with other HR management modules, such as recruitment, training, and talent management, to create a comprehensive and unified HR ecosystem.
3. Investigation of advanced data analytics and machine learning techniques to derive valuable insights from the performance and compensation data stored on the blockchain, enabling data-driven decision-making in HR management.
4. Collaboration with industry partners and regulatory bodies to establish standards, best practices, and legal frameworks for the adoption of blockchain technology in HR management.

In conclusion, this paper has demonstrated the significant potential of blockchain technology in revolutionising employee performance appraisal and compensation management. By leveraging the unique features of blockchain, organisations can achieve greater transparency, security, and efficiency in their HR processes, ultimately leading to improved employee satisfaction, trust, and organisational performance. As the technology continues to evolve and mature, it is expected that blockchain will play an increasingly important role in shaping the future of human resource management.

6.5 Scalability optimisation strategies

To address scalability limitations identified in Subsection 6.3, this section presents comprehensive optimisation approaches with quantitative performance projections based on literature and proof-of-concept implementations.

6.5.1 Sharding technology

- *Mechanism:* Blockchain network partitioned into multiple parallel shards, each processing subset of transactions independently. For HR applications, sharding can be organised by:
  1. *Geographical sharding:* Separate shards for different office locations/regions (e.g., North America shard, Europe shard, Asia-Pacific shard).
  2. *Departmental sharding:* Individual shards for major business units, with cross-shard communication for inter-departmental evaluations.
  3. *Functional sharding:* Distinct shards for performance data vs. compensation data.
- *Performance impact:* Theoretical TPS scales linearly with shard count: $TPS\_total \approx TPS\_single \times N\_shards$. With 10 shards, throughput increases from 500 TPS to approximately 4,500 TPS (accounting for ~10% overhead from cross-shard coordination). Testing with Zilliqa-inspired sharding prototype demonstrated 8.7× throughput improvement with ten shards.
- *Implementation challenges:*
  1. *Cross-shard transactions:* Employee transfers between departments require atomic commits across shards, adding latency (estimated 300–500 ms overhead).

2 *Data consistency:* Eventual consistency model acceptable for HR use cases where real-time synchronisation non-critical.
3 *Shard rebalancing:* Dynamic employee distribution requires periodic shard rebalancing (recommended quarterly maintenance windows).

6.5.2 Layer 2 scaling solutions

- *State channels:* Suitable for frequent small updates (daily micro-feedback, continuous performance tracking).
  1 *Mechanism:* Open channel between manager and employee, conduct unlimited off-chain interactions, periodically settle on main chain (e.g., monthly).
  2 *Benefit:* Reduces on-chain transactions by 95–98% for high-frequency interactions while maintaining security guarantees.
  3 *Limitation:* Requires participants remain online; less suitable for final performance reviews requiring permanent immutable records.
- *Rollup technology:*
  1 *Optimistic rollups:* Batch multiple transactions off-chain, post summary to main chain with fraud-proof mechanism.
    a *For HR:* Batch 500–1,000 performance updates into single on-chain transaction.
    b *Performance:* Increases effective throughput by 50–100× while maintaining security through seven-day challenge period.
    c *Implementation:* Suitable for non-urgent batch processing (monthly performance score updates).
  2 *ZK-rollups:* Similar batching but uses zero-knowledge proofs for instant finality without challenge period.
    a *Performance:* 100–200× throughput improvement with immediate confirmation.
    b *Trade-off:* Higher computational overhead for proof generation (adds 10–15 seconds processing time per batch).
    c *Recommendation:* ZK-rollups preferred for compensation calculations requiring immediate finality for regulatory compliance.

6.5.3 Cross-chain integration

- *Mechanism:* Connect HR blockchain to other enterprise systems via cross-chain bridges, enabling data sharing without full replication. Use cases:
  1 Integration with supply chain blockchains for performance metrics tied to delivery performance.
  2 Connection to learning management blockchains for skill verification.
  3 Inter-company HR data sharing (recruitment, background checks) via Polkadot-style relay chains or Cosmos IBC protocols.

- *Benefits:* Enables ecosystem approach without bottlenecking single blockchain. Each system scales independently while maintaining interoperability.
- *Security considerations:* Cross-chain bridges represent potential vulnerability points. Recommendation: ise trusted oracle networks (Chainlink) or multi-signature validation requiring majority consensus from both chains before finalising cross-chain transactions.

6.5.4 Hybrid architecture: on-chain + off-chain storage

- *Strategy:* Store only critical, frequently-accessed data on-chain (current performance scores, active compensation records); archive historical data off-chain using IPFS or cloud storage with on-chain hash references for integrity verification.
- *Performance improvement:* Reduces blockchain storage requirements by 70–85%, significantly improving query performance. Example: employee with 10-year history requires only 2.3 KB on-chain (current data + hash pointers) vs. 847 KB for full history.
- *Implementation:* Smart contracts automatically migrate records older than two years to off-chain storage (configurable retention policy). Hash pointer enables verification of archived data authenticity when needed for audits or disputes.

6.5.5 Quantitative scalability projection

Table 18 presents projected performance improvements under various optimisation strategies.

Table 18 Scalability optimisation impact projections

Optimisation strategy	*Current baseline*	*After optimisation*	*Improvement factor*	*Suitable for*	*Implementation complexity*
Sharding (10 shards)	500 TPS	4,500 TPS	9×	Enterprises >5,000 employees	High (6–9 months)
Layer 2 state channels	500 TPS	48,000 effective TPS	96×	High-frequency micro-feedback	Medium (3–4 months)
Optimistic rollups	500 TPS	30,000 TPS	60×	Batch monthly updates	Medium (4–5 months)
ZK-rollups	500 TPS	75,000 TPS	150×	Regulatory compliance scenarios	High (8–12 months)
Hybrid storage	2.3 GB/1 K employees/year	0.35 GB/1 K employees/year	6.6× storage reduction	All enterprises	Low (1–2 months)
Combined approach (sharding + rollups + hybrid storage)	500 TPS, 2.3 GB/ 1 K/year	270,000 TPS, 0.4 GB/ 1 K/year	540× throughput, 5.8× storage	Large multinational corps (>50 K employees)	Very high (12–18 months)

6.5.6 Implementation roadmap

- *Phase 1 (months 0–3):* Deploy hybrid storage architecture as quickest win with lowest complexity. Expected impact: 70% storage reduction, 40% query performance improvement.
- *Phase 2 (months 3–9):* Implement geographical sharding for multinational deployments. Priority regions identified based on employee concentration. Expected impact: 6–8× throughput improvement.
- *Phase 3 (months 9–18):* Integrate layer 2 rollup solution for batch processing. Evaluate both optimistic and ZK approaches; select based on specific enterprise compliance requirements.
- *Phase 4 (months 18–24):* Pilot cross-chain integration for ecosystem approach with partner organisations (recruitment agencies, educational institutions for credential verification).

7 Conclusions

While current blockchain platforms exhibit scalability limitations for very large enterprises, the combination of sharding, layer 2 solutions, and hybrid architectures provides clear pathway to supporting organisations of 50,000+ employees with acceptable performance characteristics (latency <500 ms, throughput >100,000 TPS). Organisations should adopt phased approach, implementing lower-complexity optimisations first while evaluating emerging solutions for long-term scalability.

Declarations

Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability: The data used to support the findings of this study are available from the corresponding author upon reasonable request. Due to privacy and ethical considerations, some of the data may be provided in an anonymised format.

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