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SMART CONTRACTS IN INDUSTRY APPLICATIONS AND ECONOMIC ECOSYSTEMS: CURRENT STATUS AND TRENDS

YiWen Gao*, ChangEr Liu
School of Finance and Economics, Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China.
**Corresponding Author: YiWen Gao*

Abstract: As a core technology of blockchain ecosystems, smart contracts are fundamentally reshaping the operational logic and commercial landscape of the digital economy. This paper systematically analyzes the current economic ecosystem of smart contracts from four dimensions: business value creation, multi-dimensional industry applications, legal and regulatory challenges, and frontier technological evolution. Research indicates that smart contracts, by reducing transaction costs and enhancing trust mechanisms, have achieved maturity in financial applications (DeFi) and are demonstrating significant enabling effects in real-economy sectors such as supply chains, healthcare, and energy internet. However, their widespread implementation still faces institutional obstacles including ambiguous jurisdictional boundaries, compatibility between code and law, and liability attribution. Looking ahead, Layer-2 scaling solutions have significantly improved cost-effectiveness, while the integration of cross-chain interoperability and AI-driven intelligent decision-making will become key trends driving the expansion of "contractability" boundaries. Smart contracts are not merely technical tools but rather institutional infrastructure driving the transformation of business models from intermediary-dominated to algorithm-autonomous paradigms.

Keywords: Smart contracts; Business applications; Economic ecosystem; Decentralized finance

1 INTRODUCTION

Smart contracts are digital agreements written in code, deployed on blockchain networks, and capable of automatically enforcing contractual terms [1]. Their core mechanism lies in automated "condition-response": once predetermined trigger conditions are satisfied through trusted data sources (such as oracles) or on-chain state changes, contract logic executes immediately without manual intervention or third-party intermediary verification [2]. While this concept was proposed by cryptographer Nick Szabo in the 1990s [3] and metaphorically described as a "digital vending machine," smart contracts only gained viable commercial application after Bitcoin validated the feasibility of decentralized ledgers, particularly when Ethereum introduced a Turing-complete virtual machine (EVM) [4].

These digital protocols represent a paradigmatic shift in value exchange and business process automation. They not only ensure precise execution of terms through algorithmic certainty but also construct a "trustless" collaborative environment by leveraging blockchain's immutability and distributed characteristics. This mechanism has the potential to eliminate numerous intermediary institutions arising from trust deficits in traditional transactions, thereby significantly expanding the scope and efficiency of "contractability" in economic activities [5]. This paper aims to systematically review the current application status of smart contracts in the economic ecosystem, deeply analyze their implementation logic across different industries, the legal and regulatory paradoxes they face, and assess their future directions for commercial transformation based on technological evolution.

2 COMMERCIAL VALUE FOUNDATION OF SMART CONTRACTS

2.1 Economic Efficiency: Cost Reduction and Efficiency Enhancement

From the perspective of transaction cost theory in new institutional economics, traditional contract formation and execution are often accompanied by substantial inherent friction costs, including search costs, negotiation costs, and enforcement and monitoring costs [6]. Smart contracts, through self-enforcing code, dramatically reduce post-performance costs and dependence on intermediaries such as lawyers and escrow agents. Estimates suggest that in standardized financial transactions and settlement, smart contract applications could reduce back-office processing costs by 60-80%, significantly improving capital circulation efficiency [5].

Furthermore, smart contracts profoundly reconstruct commercial trust mechanisms. Contract code and execution records deployed on public blockchains possess public auditability; this transparency is particularly critical in decentralized finance (DeFi), transforming trust in people into trust in code logic, effectively reducing opportunistic behavior and fraud risks arising from information asymmetry [7].

2.2 Contractability Expansion and Business Model Innovation

Incomplete contract theory posits that due to future uncertainties and third-party verification difficulties, many complex commercial arrangements are difficult to cover with traditional contracts [8]. Smart contracts, combined with Internet of Things (IoT) data and oracle technology, have the potential to bring previously "non-contractable" minor or complex matters into the scope of automated execution. This expansion of "contractability" boundaries provides foundational support for business model innovation. For example, parametric automated weather insurance, supply chain financing based on actual mileage usage, and algorithm-based real-time digital copyright revenue sharing are all typical examples of smart contracts refining and atomizing economic activities.

3 COMMERCIAL APPLICATIONS OF SMART CONTRACTS ACROSS INDUSTRIES

3.1 Finance and Decentralized Finance

The financial industry represents the most mature "native" domain for smart contract applications. Smart contracts form the cornerstone of the DeFi ecosystem, supporting decentralized lending protocols such as Aave and Compound, automated market maker (AMM) exchanges like Uniswap, and innovative financial instruments including liquidity mining [7]. The DeFi market's peak of over one hundred billion dollars in locked assets demonstrates the feasibility of code-managed assets. However, financial characteristics also amplify security risks; the 2016 DAO incident and subsequent flash loan attacks warn of potential systemic financial risks from contract logic vulnerabilities, highlighting the importance of formal verification and code auditing [9].

3.2 Supply Chain Management and Trade Finance

In global supply chain networks, smart contracts solve transparency and trust challenges in multi-party collaboration by breaking down information silos [10]. Through integration with IoT devices, smart contracts can automatically trigger payment or acceptance processes based on real-time data such as cargo location and temperature, achieving "atomic swaps" of logistics and capital flows. In trade finance, the digitization and automated execution of letters of credit (L/C) significantly reduce documentary circulation time, lower trade fraud risks, and enable financing services to cover small and medium enterprises more efficiently.

3.3 Healthcare

The healthcare sector is leveraging smart contracts to address longstanding contradictions between data silos and privacy protection. Smart contracts can construct patient-centered electronic health record (EHR) access control systems, ensuring medical data is accessed by research institutions or physicians only under specific conditions authorized by patient private keys, thereby balancing data sharing with privacy protection [11]. In clinical trials, using smart contracts to solidify trial protocols and patient informed consent forms prevents data tampering and enhances the credibility of pharmaceutical research data. Additionally, in medical insurance claims, parametric smart contracts can automatically trigger payouts based on diagnostic data, significantly reducing administrative costs.

3.4 Energy Sector

In the digital transformation of the energy industry, smart contracts are reshaping the trading architecture of distributed energy. In microgrid scenarios, "prosumers" with photovoltaic equipment can conduct peer-to-peer (P2P) electricity trading directly with neighboring users through smart contracts, eliminating centralized matching by traditional power companies and improving regional energy utilization efficiency [12]. Meanwhile, in green finance, smart contracts are used for the generation, tracking, and trading of renewable energy certificates (RECs), ensuring uniqueness and traceability of green rights, effectively preventing carbon credit data fraud and double counting.

3.5 Public Administration and Government Services

Government departments are beginning to explore using smart contracts to enhance administrative efficiency. For example, in land property registration, countries such as Sweden and Georgia have piloted blockchain-based property transfer systems that use smart contracts to automatically process property changes and tax payments, reducing bureaucratic processes and property disputes [5]. Research indicates that clear and automated property protection mechanisms have positive spillover effects on economic growth. Additionally, in government procurement bidding, special fund allocation, and electronic voting systems, the immutability of smart contracts helps improve transparency and credibility in public governance.

4 LEGAL AND REGULATORY CHALLENGES

4.1 Jurisdictional and Applicable Law Issues

The global distribution of blockchain nodes and the borderless nature of smart contracts challenge territorial jurisdiction principles [13]. When contract parties, server nodes, and development teams belong to different countries, determining the court of jurisdiction and applicable law (conflict of laws) becomes extremely complex in case of disputes. This uncertainty in legal expectations increases cross-border compliance costs and represents a primary concern for traditional large enterprises considering large-scale smart contract adoption.

4.2 Contract Enforceability and Legal Recognition

While "Code is Law" is a credo of the technology community, under current legal principles, the legal validity of smart contracts remains controversial [3-13]. The rigid execution of code may not encompass the flexible interpretation of legal principles (such as unconscionability or force majeure). If code logic contains vulnerabilities or fails to accurately reflect the parties' true intentions, whether the consequences of automatic execution possess legal finality, and whether courts have the authority to "rollback" or intervene in on-chain states, remain gray areas requiring urgent legislative clarification.

4.3 Liability Attribution and Dispute Resolution

Decentralized architecture blurs liability subjects. When smart contracts controlled by Decentralized Autonomous Organizations (DAOs) cause losses, should liability be attributed to developers, governance token holders, or platform maintainers? Traditional corporate liability frameworks are difficult to apply directly. Additionally, while on-chain dispute resolution mechanisms (such as decentralized courts like Kleros) are under exploration, their adjudications have not gained universal recognition from sovereign states, and traditional judicial systems face evidentiary and enforcement challenges when handling such high-technical-threshold cases.

4.4 Regulatory Compliance and Consumer Protection

The anonymity or pseudonymity of smart contracts inherently conflicts with financial regulatory requirements such as anti-money laundering (AML) and know-your-customer (KYC) [13]. How to satisfy regulatory compliance requirements while protecting user privacy is critical for mainstream adoption of applications like DeFi. Simultaneously, regulatory agencies are highly concerned about information asymmetry caused by technical barriers, committed to preventing ordinary investors from suffering unfair terms or market manipulation due to inability to understand complex code logic.

5 EMERGING COMMERCIAL TRENDS

5.1 Commercial Impact of Layer-2 Scaling Solutions

To overcome performance bottlenecks of base-layer blockchains (Layer-1), Layer-2 scaling solutions represented by Rollups have become mainstream industry trends. By executing computations off-chain and submitting only compressed state data to the main chain, Layer-2 technology (combined with blob data structures introduced in Ethereum's Dencun upgrade) significantly reduces per-transaction marginal costs by orders of magnitude. This change in cost structure makes micropayments, high-frequency on-chain games, and large-scale consumer social applications economically viable, driving smart contract penetration from high-value financial transactions to high-frequency daily commercial scenarios.

5.2 Cross-Chain Interoperability Business Ecosystem

With the formation of a "multi-chain coexistence" landscape, the siloing effect of single blockchains has become increasingly apparent. The development of cross-chain interoperability protocols aims to break down these barriers, enabling secure cross-chain transfer of assets and state information [14]. This has spawned new business ecosystems: enterprises can flexibly leverage the comparative advantages of different blockchains (such as using one chain's high security for settlement and another chain's high performance for processing) to construct composable decentralized applications. Cross-chain technology is weaving a value network similar to the internet's TCP/IP protocol, dramatically improving network-wide allocation efficiency of capital and data.

5.3 Commercial Use Cases of AI and Smart Contract Integration

The integration of artificial intelligence (AI) with smart contracts marks the evolution of automation from "deterministic execution" to "intelligent decision-making" [15]. Traditional smart contracts rely on static logic, while AI-driven contracts (combining off-chain reasoning with zero-knowledge proof technology) can process complex unstructured data and dynamic market environments. Commercially, this means insurance contracts can automatically assess damage based on real-time satellite imagery and AI models, while lending protocols can dynamically adjust risk interest rates based on users' on-chain and off-chain behavior. This integration will endow smart contracts with adaptive capabilities, enabling them to address more complex and ambiguous real-world commercial scenarios.

6 CONCLUSION AND OUTLOOK

Smart contracts have evolved from early theoretical concepts into underlying engines driving digital transformation in critical industries such as finance, supply chains, and energy, creating significant economic benefits and business model innovations through automation, transparency, and disintermediation mechanisms. Although large-scale adoption still faces institutional challenges including unclear legal characterization, ambiguous liability attribution, and compliance friction, cost dividends from Layer-2 scaling, interconnectivity from cross-chain technology, and intelligent empowerment from AI continue to expand application boundaries. Looking forward, with the improvement of legal frameworks and advancement of technical standardization, smart contracts are poised to become foundational infrastructure for building a trustworthy digital economy, driving social collaboration models toward deep integration of "institutional trust" with "machine trust" and "algorithmic governance."

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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