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Legal Challenges of Automating Construction Contracts Through the Use of Blockchain and Artificial Intelligence Technologies: A Comparative Perspective on International Legal Systems

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ABSTRACT

Using a descriptive-analytical method, this study examines the legal and operational challenges associated with the automation of smart construction contracts based on blockchain and artificial intelligence technologies and proposes solutions for compatibility with international legal systems. Smart contracts, through the automated execution of obligations, and artificial intelligence, through the capability to analyze complex data, predict risks, and automatically draft contracts, possess significant transformative potential for the construction industry. Nevertheless, legal obstacles such as ambiguity regarding the legal validity of contracts, the complexity of determining the governing law and judicial jurisdiction, violations of privacy in public blockchains, liability arising from coding errors, and algorithmic biases have limited the adoption of these technologies. The findings indicate that in Iran, the absence of specific legal frameworks, inadequate technical infrastructure, and a lack of specialized training constitute the principal barriers, whereas leading jurisdictions such as Singapore and Switzerland have achieved greater success through supportive legislation, private blockchain systems, and extensive educational initiatives. The study suggests that the adoption of laws compatible with both Sharia principles and international standards, the use of private blockchains to preserve privacy, the development of explainable artificial intelligence to reduce algorithmic bias, and the establishment of digital arbitration platforms can accelerate the adoption of these technologies in Iran. A comparative analysis between Iran and leading legal systems highlights the necessity of legal reform, investment in digital infrastructure, and the strengthening of educational capacities. Drawing upon authoritative Iranian and international sources, this research provides a comprehensive framework for the utilization of smart contracts in the construction sector and emphasizes the need for cooperation among governments, industry actors, and academic institutions.

Keywords: *Smart Contracts, Artificial Intelligence, Blockchain, Legal Challenges, Construction Contracting*

Introduction

In recent decades, digital transformation, especially the emergence of blockchain and artificial intelligence technologies, has fundamentally transformed the structure and mode of contract execution in various fields, including construction contracts. In traditional approaches, construction contracts were based on human will and

supervision, written documentation, and physical control over project processes; however, with the development of digital technologies, automation in the drafting, monitoring, and execution of these contracts has now become possible (1).

Emerging technologies not only increase the speed and transparency of obligation performance but also reduce execution costs. Nevertheless, contract automation creates significant challenges concerning legal validity, determination of the parties' intention, liability arising from algorithmic error, and judicial admissibility (2). The construction industry, as one of the main pillars of the global economy, plays a central role in the development of urban infrastructure, construction projects, technology, and energy. Construction contracts, which usually include complex provisions such as precise scheduling, quality standards, delay penalties, resource allocation, and dispute-resolution mechanisms, are susceptible to legal disputes, financial delays, and operational inefficiencies because of the involvement of multiple human, environmental, and economic factors. In this context, smart contracts, first introduced by Nick Szabo in 1994 as self-executing computer protocols, have enabled the automatic, transparent, and secure performance of contractual obligations through blockchain technology without reliance on traditional intermediaries such as banks, lawyers, or regulatory institutions. The integration of artificial intelligence into these contracts, through capabilities such as big-data analysis, prediction of project risks, automatic adjustment of contractual terms based on project needs, and monitoring of contractual performance, has substantially improved the efficiency, accuracy, and transparency of construction-contracting processes. However, the decentralized nature of blockchain, the algorithmic complexities of artificial intelligence, fundamental differences among international legal systems, and ethical issues associated with algorithmic bias have created numerous legal, technical, and ethical challenges that limit the adoption and expansion of this technology. Therefore, the question that emerges in this regard is what challenges fundamentally surround the automation process of construction contracts based on artificial intelligence and what legal solutions would be effective in this field.

Accordingly, this article seeks to conduct a comprehensive and detailed examination of the subject by deeply analyzing these challenges, exploring solutions for compatibility with global legal systems, offering proposals for removing obstacles in Iran, and conducting a comparative analysis with advanced legal systems. The structure of the article is designed in such a way that, while maintaining semantic coherence with the subject, it will explain the concepts, challenges, and solutions in an integrated and sufficiently in-depth manner, so that by precisely clarifying the concepts and dimensions related to smart contracts and their latent potential, the existing challenges of this technology can be identified and, ultimately, the research question can be answered.

Definitions and Concepts

This section provides a comprehensive explanation of the fundamental concepts of smart contracts, artificial intelligence, blockchain, and construction contracts within the framework of automation.

Smart Contracts

Smart contracts are computer protocols that operate on blockchain technology and execute contractual terms and obligations automatically, transparently, and without the need for intermediaries. Nick Szabo, who introduced this concept in 1994, defined smart contracts as "a set of promises, specified in digital form, including protocols within which the parties perform on these promises" {Szabo, 1994}. By converting contractual terms into computer code, these contracts automate processes such as milestone payments, project-progress monitoring, verification

of compliance with standards, and registration of changes. The key features of smart contracts include: 1. self-execution, meaning automatic performance of obligations once specified conditions are fulfilled, such as confirmation of project delivery; 2. transparency, meaning the public and observable recording of transactions on the blockchain; and 3. immutability, meaning the impossibility of manipulating or changing the contract after registration. Security also refers to the use of advanced cryptographic algorithms to protect data. In the field of construction contracting, smart contracts can facilitate complex processes such as automatic payments after verification of project stages, monitoring compliance with quality standards, and transparently recording contractual changes, thereby reducing legal disputes, increasing transparency, and improving efficiency (3). For example, in a construction project, a smart contract can release the relevant payment to the contractor after an oracle, as an external data source, confirms the completion of a stage, without requiring manual approval or financial intermediaries.

Artificial Intelligence

Artificial intelligence is a branch of computer science that develops systems capable of learning, reasoning, data analysis, and decision-making similar to human beings. In smart construction contracts, artificial intelligence has extensive applications through technologies such as machine learning, natural language processing, and big-data analysis:

Automatic contract drafting: By using natural language processing, artificial intelligence can draft contractual provisions based on local laws, project requirements, and industry standards, while identifying errors or inconsistencies. For example, natural language algorithms can align a contract with Iran's civil-law rules or international FIDIC standards (4).

Project-data analysis: Machine-learning algorithms can analyze project big data, such as costs, scheduling, resources, and risks, and provide optimal recommendations for resource allocation or time management.

Risk management: By analyzing historical data and predicting financial, legal, and operational risks, such as delays or breach of contract, artificial intelligence enables preventive decision-making.

Performance monitoring: By analyzing input data, such as project-progress reports or data from Internet of Things sensors, artificial intelligence can monitor compliance with contractual obligations in real time (5). These capabilities significantly increase the efficiency, accuracy, and transparency of smart contracts; however, algorithmic complexities, the need for high-quality data, and the possibility of bias in AI-based decision-making have created new challenges that require in-depth analysis and legal and technical solutions (6).

Blockchain Technology

Blockchain is a distributed ledger that records transactions in a decentralized, transparent, and secure manner across a network of nodes. By using cryptographic algorithms, such as SHA-256, and a chain-based block structure, this technology minimizes the possibility of data manipulation or deletion. The key features of blockchain that make it an ideal infrastructure for smart contracts are as follows: 1. decentralization, meaning the elimination of a central authority and reduction of the risk of abuse or corruption; 2. transparency, meaning access by all parties to the information recorded on the blockchain, which strengthens trust; and 3. security, meaning the use of advanced cryptography to protect data against cyberattacks.

Immutability refers to the permanent and non-deletable recording of transactions, which eliminates the possibility of denial or manipulation (7). In construction contracts, blockchain enables the transparent recording of project stages, payments, contractual changes, and progress reports. For example, in an infrastructure project, blockchain can transparently and immutably record all financial transactions and supervisory reports, reducing the risk of financial corruption or legal disputes. Nevertheless, the public nature of certain blockchains, such as Ethereum, creates privacy challenges, especially in construction projects that involve sensitive data such as engineering plans or financial information (8).

Construction Contracts

Construction contracts are agreements under which a contractor undertakes to provide services or produce a product, such as building a bridge, developing software, or implementing energy projects, in return for payment from the employer. These contracts usually include complex provisions, including: 1. precise scheduling, meaning the determination of deadlines for delivery of project stages; 2. quality standards, meaning technical and engineering requirements for compliance with standards; 3. delay penalties, meaning compensation mechanisms in the event of non-compliance with schedules; and 4. dispute resolution, meaning methods for handling claims, such as arbitration or referral to courts.

Regarding resource management, it should also be noted that construction contracts involve the allocation of human resources, equipment, and budget. Common challenges of construction contracts include project delays, legal disputes over quality or payments, financial inefficiencies arising from manual processes, complexities of data management, and risks of financial corruption. Automating these contracts through smart contracts and artificial intelligence can significantly reduce these challenges. For example, smart contracts can execute automatic payments after project stages are verified by oracles, while artificial intelligence can predict the risks of delay or breach of contract (6). However, the technical, legal, and operational complexities of this technology require in-depth analysis and the development of appropriate implementation frameworks.

The Role of Artificial Intelligence in the Automation of Construction Contracts

Natural language processing algorithms can analyze the text of contracts, identify contradictory clauses, and even generate new drafts. This increases accuracy and speed in drafting complex contracts (9). Artificial intelligence systems are able to analyze data related to contractor performance, material quality, or project progress and, once the stipulated conditions are fulfilled, activate the automatic execution of contractual clauses (10). Artificial intelligence can also predict the likelihood of delay, cost escalation, or breach of contractual provisions by analyzing data from previous projects and can offer preventive solutions (11).

The most important challenges of artificial intelligence include the transparency of algorithmic decisions, data bias, and the difficulty of explaining liability for errors arising from automated decisions (12).

The Interaction of Blockchain and Artificial Intelligence in Automated Contracts

The combination of blockchain and artificial intelligence is one of the most transformative trends in law and technology. Although these two technologies differ in technical nature and function, the synergy between them can pave the way for the emergence of a new generation of smart contracts known as AI-enhanced smart contracts (10). In such a mechanism, blockchain plays the role of a “platform for decentralized registration, verification, and

execution," while artificial intelligence undertakes "data analysis, logical decision-making, and outcome prediction." This interaction not only increases the accuracy and efficiency of construction contracts but can also automate the decision-making process in an impartial manner (11).

Interaction Between These Two Technologies

The interaction between these two technologies can be analyzed at three technical and practical levels:

a. Data Level

Artificial intelligence requires accurate data for decision-making, while blockchain guarantees the validity and source of recorded data. Therefore, data collected from a project, such as engineering reports, IoT data, or financial information, are first recorded on the blockchain and are then sent to artificial intelligence algorithms for analysis (13).

b. Decision-Making Level

Artificial intelligence algorithms analyze the data stored on the blockchain and make decisions based on predictive models. The result of this decision, such as verification of material quality or confirmation of progress in a project phase, is returned to the smart contract as an output (10).

c. Execution Level

After receiving the decision from artificial intelligence, the smart contract automatically executes the relevant clauses, such as payment, imposition of penalties, or change of project status. This execution is recorded on the blockchain and becomes immutable (14).

Together, these three levels create a closed and automated chain from data collection to decision-making and legal execution, which is unprecedented in its kind.

Legal Risks of This Interaction

Despite the aforementioned advantages, the integration of artificial intelligence and blockchain in construction contracts entails serious legal challenges:

1. Determining liability in automated decisions: If an artificial intelligence algorithm makes an erroneous decision, such as approving an incorrect payment, determining who is responsible for the error—the programmer, the user, or the contract itself—is highly difficult (14).
2. Legal interpretation of blockchain data: Although data on the blockchain are immutable, it is not always clear whether, from a legal perspective, such data constitute valid and admissible evidence (15).
3. Conflict with privacy regulations: Automated contracts require the processing of a massive volume of user data. This may conflict with data-protection laws such as the European Union's General Data Protection Regulation (16).
4. Inability to review automated decisions: Since decisions on the blockchain are immutable, restoring the previous state in the event of error or the need for reconsideration is very difficult, or even impossible (17).
5. The issue of algorithmic transparency: If artificial intelligence algorithms function as a "black box," automated decisions may be issued without the possibility of logical explanation. Therefore, legal institutions at the international level have called for the mandatory transparency and explainability of algorithms (12).
6. Legal Challenges of Automating AI-Based Smart Construction Contracts

Legal Validity and Contractual Nature

Intention and consent in the formation of smart contracts: legal challenges arising from the automated nature of contracts. In traditional legal systems, contract formation requires the explicit and informed intention and consent of the parties. In Iran, Article 190 of the Civil Code considers intention, consent, legal capacity, a definite subject matter, and the legitimacy of the transaction's purpose to be conditions for contract validity. Smart contracts, which are executed as computer codes, may not fully satisfy these requirements because the parties may not have a complete understanding of complex contractual codes or the artificial intelligence algorithms that propose contractual terms. This calls informed consent into question. For example, if artificial intelligence proposes provisions based on incomplete or biased data that do not correspond to the true intention of the parties, the legal validity of the contract may be disputed (8). In common-law systems such as England, more flexible judicial precedents allow for innovative interpretation of this issue; however, in civil-law systems such as Iran, which emphasize written rules, this challenge is more serious (18).

Digital signature and identity verification in smart contracts: legal and technical barriers to verifying the identity of the parties. Smart contracts are usually concluded through digital signatures, which use private and public keys to verify the identity of the parties. In Iran, the Electronic Commerce Act of 2003 recognizes digital signatures, but this law does not specifically cover blockchain technology or smart contracts. In addition, the legal restrictions on the use of cryptocurrencies in Iran, based on the Council of Ministers' resolution of 2019, have made it difficult to conclude smart contracts that often depend on cryptocurrencies. Identity verification in decentralized environments, especially through anonymous wallets, is another challenge that can call the legal validity of the contract into question. For example, if the identity of one party to the contract cannot be verified because of the anonymity of a blockchain wallet, proving that party's legal capacity or legal liability in potential disputes will be difficult (5).

Compatibility of smart contracts with local and international laws: challenges of harmonization with mandatory rules. In civil-law systems such as Iran, smart contracts must be compatible with mandatory rules and traditional legal principles, such as the provisions of the Civil Code or Commercial Code. The absence of a legal definition of smart contracts in Iranian law has increased legal ambiguities and limited the adoption of this technology in construction projects. By contrast, in common-law systems such as the United States, states such as Arizona have recognized smart contracts as valid legal instruments through specific legislation, such as HB 2417 of 2017. At the international level, the absence of harmonized legal frameworks for smart contracts has made their adoption difficult in international construction projects. For example, differences among countries in the definition of contract or digital-signature requirements can lead to conflicts of laws (3).

Governing law and judicial jurisdiction: challenges of determining jurisdiction and applicable law in decentralized smart contracts. The decentralized nature of blockchain, which executes smart contracts across numerous nodes distributed throughout the world, has turned the determination of governing law and judicial jurisdiction into one of the most complex legal challenges. In traditional construction contracts, the parties usually specify the governing law, such as Iranian or English law, and the competent court, such as the courts of Tehran or London, in the contract. However, in smart contracts, the place of contract execution is unclear because of the distribution of blockchain nodes, and the parties may be located in different jurisdictions, creating conflicts of laws. For example, in an international construction project in which one party is based in Iran and the other in Singapore, determining which

law or court has jurisdiction over disputes is difficult (19). This issue becomes even more complex in construction projects, which often involve multilateral contracts and large sums of money.

Common-law systems, such as England, the United States, and Singapore, have facilitated the adoption of smart contracts because of the flexibility of judicial precedent. For example, in 2017, the state of Arizona enacted HB 2417, which recognizes smart contracts as valid legal instruments and enables their execution within the framework of local law. By contrast, civil-law systems, such as Iran, France, and Germany, face greater challenges because of their emphasis on written rules and traditional contractual principles. In Iran, the absence of specific laws on smart contracts and the legal restrictions on cryptocurrencies have slowed the adoption of this technology (6). These differences require harmonization at the international level so that smart contracts can be used in global construction projects.

International challenges and the need for multilateral agreements: At the international level, the absence of harmonized legal frameworks for smart contracts has limited their adoption in international construction projects. Organizations such as the United Nations Commission on International Trade Law have made efforts to harmonize electronic-commerce laws, but a comprehensive framework for smart contracts has not yet been developed. For example, the UNCITRAL Model Law on Electronic Commerce of 2017 addresses digital signatures and electronic transactions, but it does not specifically cover smart contracts or blockchain. This issue requires multilateral agreements among governments to determine governing law, judicial jurisdiction, and standards for the execution of smart contracts (20).

Privacy and data protection: the conflict between blockchain transparency and legal requirements for protecting sensitive data in construction contracts. Public blockchains, such as Ethereum, make contractual information visible to all network nodes because of their transparent nature. Although this feature increases transparency and trust, it can disclose confidential information in construction projects, such as contract price, technical details, engineering plans, or financial information. This issue conflicts with regulations such as the General Data Protection Regulation in the European Union, which imposes strict requirements for protecting personal and sensitive data, or Iran's personal data protection law, which is under development. For example, in a construction project, disclosure of the financial or technical details of a contract on a public blockchain may cause competitive harm to the parties (16).

Artificial intelligence requires access to a massive volume of sensitive information to analyze contractual data, predict risks, and monitor performance of obligations. This can increase the risk of data leakage, especially if data are stored on public blockchains or if artificial intelligence algorithms are not properly secured. In addition, legal requirements for obtaining the explicit consent of users, which are emphasized in the GDPR, may be violated in automated artificial intelligence processes. For example, if artificial intelligence analyzes project data without the explicit consent of the employer or contractor, this may be considered a violation of privacy laws (21).

Therefore, the use of private or hybrid blockchains, which restrict access to data to authorized parties, can partially resolve privacy challenges. However, implementation of these technologies requires high costs, advanced infrastructure, and coordination among the contractual parties, which is challenging for many construction companies, especially in developing countries such as Iran. From a legal perspective, developing data-protection standards for smart contracts, such as requiring data encryption or using smart contracts with data-deletion capability, can help align them with privacy laws (8).

Coding errors and legal liability: analysis of technical and legal risks arising from defects in the design and execution of smart contracts.

Smart contracts depend on computer codes that may contain bugs, defects, or vulnerabilities. For example, the DAO hack in 2016, which occurred because of a defect in an Ethereum smart-contract code, caused millions of dollars in financial losses and reduced trust in this technology (22). In construction projects, coding errors may lead to the incorrect execution of obligations, such as unauthorized payments, non-delivery of the project, or breach of contractual conditions. For example, if the smart-contract code incorrectly determines that a project stage has been completed, premature payment may be made, harming the employer.

Challenges of determining legal liability in the event of error.

Determining liability in the event of error is one of the most complex legal issues concerning smart contracts. An error may originate from the programmer, the blockchain platform, the artificial intelligence developer, or even inaccurate input data, such as oracles. In many legal systems, including Iran, artificial intelligence is not defined as a legal person, which makes the determination of liability difficult. In common-law systems such as the United States, judicial precedent may attribute liability to developers or platforms, but this approach has not yet been established in civil-law systems such as Iran. For example, if an artificial-intelligence error in contract drafting causes financial loss, it is unclear whether the algorithm developer, the blockchain platform, or the contracting parties would be liable (3).

It should also be said that once a contract is recorded on the blockchain, amending or terminating it is almost impossible, which makes dispute resolution difficult in the event of error or the need to change conditions. This feature conflicts with traditional contractual principles, such as the possibility of termination or amendment by mutual agreement of the parties, as reflected in Article 219 of the Iranian Civil Code. For example, if the conditions of a construction project change because of environmental or economic developments, the parties cannot easily amend the smart contract unless specific mechanisms, such as multi-signature wallets or adjustable oracles, have been anticipated in the contract code (5).

Ethical issues and algorithmic bias: Artificial intelligence may make unfair decisions in drafting or executing smart contracts because of incomplete, inaccurate, or biased training data. For example, if the AI training data include economic, cultural, or geographical biases, contractual terms may be drafted in favor of the stronger party, such as the employer, or against the weaker party, such as a small contractor. In international construction projects, cultural or economic biases may lead to serious disputes, especially in projects involving parties from countries with different levels of development (23). For example, if an artificial intelligence algorithm mistakenly prioritizes larger contractors, smaller contractors may be deprived of tender opportunities.

Transparency and challenges in artificial-intelligence decision-making processes: The decision-making process of artificial intelligence often operates as a black box, meaning that the contracting parties cannot fully understand how the algorithm has reached specific results. This lack of transparency reduces trust in smart contracts and makes it difficult to prove bias or error. For example, if artificial intelligence offers a recommendation for allocating project resources that harms one of the parties, proving that this decision resulted from bias or error is difficult because of the complexity of algorithms (4). In construction projects, which often involve public interests or large financial sums, this issue may lead to public dissatisfaction or legal claims.

Ethical implications of biases in construction projects involving public interests: In construction projects, which often involve public infrastructure such as roads, hospitals, or energy networks, unfair AI decisions may have extensive social, economic, and political consequences. For example, bias in resource allocation or determination of contractual conditions may lead to economic inequality, reduced project quality, or public dissatisfaction. From

an ethical perspective, the use of artificial intelligence in smart contracts requires adherence to the principles of justice, transparency, and accountability, which, at present, have not been fully realized because of technical and legal limitations (6).

Operational Challenges in Construction Projects

Complexities of construction projects and modeling limitations in smart contracts: Construction projects often involve numerous variables, such as design changes, unexpected delays, environmental conditions, human factors, and economic risks. Because smart contracts depend on computer code, they may not be able to fully model these complexities, especially in large-scale projects such as dam construction or urban development. In addition, the dependence of smart contracts on external inputs, such as oracles, meaning data sources that transfer real-world information to the blockchain, can become a new source of error. For example, if an oracle provides inaccurate information about project progress, the smart contract may make incorrect decisions, such as premature payment (19).

Challenges of technology adoption in the construction industry: cultural, educational, and infrastructural barriers. The adoption of smart contracts in the construction industry requires extensive training of human resources, development of advanced technical infrastructure, and transformation of organizational culture in traditional companies. In many countries, including Iran, the shortage of specialists in blockchain and artificial intelligence, the absence of domestic blockchain platforms, and infrastructural limitations, such as data-processing servers or stable networks, have slowed the adoption of this technology. In addition, cultural resistance to emerging technologies, especially in traditional construction companies accustomed to manual processes, is another obstacle. For example, small contractors may refuse to adopt smart contracts because of lack of awareness or high implementation costs (8).

Implementation costs and economic limitations in automating construction contracts: Implementing smart contracts and artificial intelligence in construction projects requires substantial investment in technical infrastructure, such as private blockchains or data-processing servers, specialized software, workforce training, and system security against cyberattacks. These costs can be a major barrier for small and medium-sized enterprises, especially in developing countries such as Iran. For example, developing a private blockchain for a construction project may cost millions of dollars, which is not affordable for many companies. In addition, the absence of sustainable economic models for return on investment in this technology has limited its adoption (21).

Solutions for Adapting Smart Contracts to International Legal Systems

International organizations, such as the United Nations Commission on International Trade Law, can develop standards for the legal validity of smart contracts. The UNCITRAL Model Law on Electronic Commerce of 2017 is an example of successful efforts to harmonize electronic-commerce laws and can serve as a model for smart contracts. These standards should include a legal definition of smart contracts, requirements for formation and execution, frameworks for determining governing law and judicial jurisdiction, and data-protection standards. For example, UNCITRAL can develop protocols for verifying the identity of parties on blockchain or for amending smart contracts (20).

Governments can also sign multilateral agreements to determine jurisdiction in smart contracts and harmonize laws related to digital signatures, cryptocurrencies, and blockchain. These agreements can reduce conflicts of laws

and facilitate the adoption of smart contracts in international construction projects. For example, an agreement similar to the New York Convention on Arbitration of 1958 could be developed for smart contracts to harmonize judicial jurisdiction and enforcement of judgments (19).

On the other hand, regional organizations, such as the European Union, the Organization of Islamic Cooperation, or the African Union, can develop regional frameworks for smart contracts to increase coordination among member states. For example, the European Union, through the GDPR and Horizon 2020 research programs, has provided standards for data protection and blockchain development that can serve as a model for other regions. In the Middle East, the Organization of Islamic Cooperation can develop a framework for smart contracts compatible with Sharia principles (16).

Developing Blockchain and Artificial Intelligence Technologies to Address Legal and Operational Challenges

Private or hybrid blockchains, which restrict access to data to authorized parties, can address privacy challenges and become compatible with local and international regulations, such as the General Data Protection Regulation or data-protection laws in Iran. These technologies are suitable for construction projects involving sensitive data, such as government infrastructure contracts or energy projects. For example, a private blockchain can share contractual information only among the employer, contractor, and regulatory bodies, thereby reducing the risk of data disclosure (21).

On the other hand, developing artificial intelligence algorithms with explainability can make decision-making processes more transparent and increase the parties' trust in smart contracts. These algorithms can explain their decision-making process in a manner understandable to users, such as contractors or employers, thereby helping to reduce bias and increase transparency. For example, if artificial intelligence offers a recommendation for project-resource allocation, it can transparently explain the reasons for its choice, such as cost or time optimization (4).

In this regard, and with a focus on using the capacity of reliable oracles to improve accuracy and reduce input-related risks, it should also be said that oracles, which enter real-world data, such as project-progress reports, Internet of Things sensor data, or official governmental information, into smart contracts, can increase the accuracy of contract execution. Developing reliable and tamper-resistant oracles, such as using data verified by independent institutions or secure sensors, is essential for reducing technical risks. For example, in a construction project, an oracle can transfer data from sensors installed at the project site to the smart contract to confirm completion of a stage (5).

Training and Capacity-Building to Address Challenges in Using the Potential of Smart Contracts

Training judges, lawyers, arbitrators, and legal advisers in blockchain and artificial intelligence technologies can facilitate adjudication of disputes related to smart contracts. Such training should include technical concepts, such as how blockchain and artificial intelligence algorithms operate, legal challenges, such as determination of liability or judicial jurisdiction, and judicial procedures for handling claims. For example, training courses can help judges better analyze claims arising from coding errors or algorithmic biases (3).

Informing the contracting parties, including contractors, employers, engineers, and project managers, about the advantages, such as transparency and efficiency, and risks, such as coding errors or privacy issues, of smart contracts can increase the adoption of this technology. This awareness can be developed through educational

workshops, digital media, specialized conferences, and online platforms. For example, a training workshop for small contractors can explain how smart contracts can be used to reduce project-management costs (6).

Universities can cooperate with construction companies and governmental institutions to develop specialized educational programs in blockchain and artificial intelligence so as to train skilled human resources for designing, implementing, and managing smart contracts. For example, Iranian technical universities can establish master's programs in blockchain technology and artificial intelligence that are aligned with the needs of the construction industry. In addition, governmental cooperation in providing financial or infrastructural incentives can accelerate the development of this technology (21).

AI-based online arbitration for fast and low-cost dispute resolution: Online arbitration platforms, such as Modria or Kleros, can use artificial intelligence to analyze evidence, documents, and contractual data and provide mediatory proposals or fair rulings. These platforms significantly reduce the cost and time of dispute resolution and are suitable for construction projects, which often require rapid settlement of disputes. For example, an online arbitration platform can resolve a dispute over payment for a project stage within a few days by analyzing progress reports and blockchain data (19).

Designing amendable smart contracts to increase flexibility and compatibility with traditional contractual principles: Designing smart contracts with limited amendability, such as through multi-signature wallets or consensus protocols, can make it possible to correct errors, change conditions, or terminate the contract if the parties agree. This approach is more compatible with traditional contractual principles, such as the possibility of amendment or termination by agreement, reflected in Article 219 of the Iranian Civil Code, and can increase the parties' trust in smart contracts. For example, a smart contract can be designed so that proposed changes are recorded on the blockchain only after approval by all parties (5).

Combining traditional and digital methods in dispute resolution to increase trust and efficiency: The use of traditional dispute-resolution methods, such as in-person arbitration or mediation, alongside digital tools, such as online arbitration platforms or smart contracts, can increase the parties' trust in the dispute-resolution process. This combination is particularly effective in large-scale construction projects that involve public interests or large financial sums. For example, an arbitral tribunal can use blockchain data to analyze evidence and in-person sessions to negotiate with the parties (3).

Creating integrated multi-purpose platforms: developing comprehensive systems for managing, executing, and monitoring smart construction contracts. The development of integrated platforms that combine smart contracts, artificial intelligence, dispute-resolution mechanisms, and supervisory tools in a comprehensive system can accelerate the adoption of this technology in the construction industry. These platforms should:

Be compatible with local and international laws, such as the Iranian Civil Code or the General Data Protection Regulation; provide integrated capabilities for automatic contract drafting, performance monitoring, risk analysis, and dispute resolution; and have a simple and understandable user interface for non-technical users, such as contractors or project managers. For example, a platform can enable the contractor to draft the contract, allow the employer to monitor project progress in real time, and, in the event of a dispute, use artificial intelligence to offer mediatory solutions. The development of such platforms requires cooperation among technology developers, legal experts, and construction-industry actors (21).

Comparative Analysis

Analysis of the Legal, Technical, and Executive Status of Smart Contracts in Iran

In Iran, smart construction contracts face multiple legal, technical, and executive obstacles:

Legal restrictions on cryptocurrencies: The Council of Ministers' resolution of 2019 restricted the use of cryptocurrencies in domestic transactions, which has made the conclusion of smart contracts, especially those dependent on cryptocurrencies, difficult. This restriction was imposed because of concerns about money laundering and cryptocurrency-market volatility, but it has had a negative effect on the adoption of blockchain technology (1).

Absence of a specific legal framework: The Electronic Commerce Act of 2003 does not specifically cover smart contracts or blockchain technology, which has increased legal ambiguities regarding the validity, execution, and liability of these contracts. For example, Article 12 of this Act recognizes digital signatures, but it does not address more complex issues such as contract immutability or judicial jurisdiction in blockchain (3).

Limited technical infrastructure: The shortage of domestic blockchain platforms, data-processing servers for artificial intelligence, and stable networks has slowed the adoption of smart contracts in Iran. For example, many Iranian construction companies are unable to implement smart contracts because of the lack of access to private blockchains or advanced artificial-intelligence tools (8).

Cultural and educational challenges: Cultural resistance to emerging technologies, especially in traditional construction companies, and the shortage of specialized human resources in blockchain and artificial intelligence constitute further obstacles. Many Iranian contractors and employers are unfamiliar with the concepts of these technologies and are accustomed to manual processes. Nevertheless, Iran has significant potential for developing smart contracts: 1. specialized human resources, as Iran has a considerable number of graduates in information technology, engineering, and computer science who can become specialists in blockchain and artificial intelligence through appropriate training; 2. governmental support for digitalization, as initiatives such as e-government and information-technology development programs indicate the government's interest in emerging technologies, which can lead to the development of blockchain infrastructure; and 3. the construction industry's need for efficiency, as the large volume of infrastructure projects in Iran, such as oil and gas projects, road construction, and urban development, means that smart contracts can help reduce costs, increase transparency, and improve project management. The prospect of developing smart contracts in Iran requires removing legal restrictions, investing in technical infrastructure, training human resources, and developing domestic legal frameworks compatible with Sharia principles and national laws (6).

Leading Legal Systems in the Adoption of Smart Contracts

Singapore as a model for supportive laws, advanced infrastructure, and support for innovation in smart contracts: Singapore has become one of the global pioneers in the adoption of smart contracts by developing supportive laws, advanced infrastructure, and innovation-support policies. The Electronic Transactions Act of 2010 provides a legal framework for digital transactions, including smart contracts. In addition, Singapore has created an appropriate environment for adopting this technology by offering tax exemptions for blockchain companies, investing in technical infrastructure, such as data centers and 5G networks, and establishing online arbitration platforms such as the Singapore International Arbitration Centre. For example, SIAC has developed protocols for resolving smart-contract

disputes that can serve as a model for Iran. Singapore has also increased public and specialized awareness of blockchain through conferences and educational workshops (19).

Switzerland, especially the Zug region, has also become one of the global centers of blockchain through flexible laws for cryptocurrencies and blockchain, support for technology startups, and investment in digital infrastructure. By developing legal frameworks that recognize blockchain as a lawful technology, the Swiss government has facilitated the adoption of smart contracts. For example, the Swiss Blockchain Act of 2020 provides standards for digital transactions and smart contracts that are compatible with international laws. Zug is also home to numerous startups in blockchain and artificial intelligence that offer smart-contract solutions in various industries, including construction contracting. This model can be inspiring for Iran, which seeks to develop emerging technologies (24).

On the other hand, the European Union, by adopting regulations such as the General Data Protection Regulation and implementing research programs such as Horizon 2020, has provided frameworks for data protection, transparency, and standardization of smart contracts. The General Data Protection Regulation, which came into effect in 2018, imposes strict requirements for processing sensitive data and has affected the use of technologies such as blockchain. The Horizon 2020 program has also helped develop innovative solutions for smart contracts by funding research projects in blockchain and artificial intelligence. For example, European Union research projects have developed platforms for smart contracts in the construction and energy industries that can serve as a model for Iran. The European Union is also developing standards for smart contracts that can contribute to harmonizing international laws (16).

Learning from Leading Systems and Developing Domestic Frameworks for Smart-Contract Development

Iran can take effective steps toward developing smart contracts by learning from leading legal systems: 1. developing specific laws: Iran can develop specific legislation for smart contracts inspired by Singapore's Electronic Transactions Act of 2010 or Switzerland's Blockchain Act of 2020, specifying legal validity, judicial jurisdiction, and liabilities; 2. developing technical infrastructure: investment in domestic blockchains, data-processing servers, and stable networks, similar to the Zug model in Switzerland, can provide the necessary infrastructure for smart contracts; 3. cooperation with international organizations: cooperation with organizations such as UNCITRAL or the Organization of Islamic Cooperation to develop regional and international standards can facilitate the adoption of smart contracts in Iran; 4. education and public awareness: holding specialized university courses and public workshops for contractors and employers, similar to Singapore's educational programs, can increase the adoption of this technology; and 5. development of domestic platforms: creating integrated platforms for smart contracts that are compatible with Iranian law and Sharia principles can help localize this technology (3).

Conclusion

The integration of artificial intelligence and blockchain technologies transforms construction contracts from a traditional and centralized form into an automated, transparent, and intelligent system in which decisions are made rapidly and immutably on the basis of real data.

Nevertheless, this interaction requires a redefinition of fundamental legal concepts, including intention, consent, liability, and contestability. International legal systems are also developing frameworks to preserve innovation while preventing the ethical and legal risks arising from automated decisions. Although AI-based automation of smart construction contracts has considerable potential for increasing efficiency and transparency, reducing costs, and

improving project management, it faces numerous legal, technical, and ethical challenges. Legal challenges include the legal validity of contracts, determination of governing law and judicial jurisdiction, privacy protection, and liability arising from errors. Technical challenges include the complexities of modeling construction projects, coding errors, and infrastructural limitations. Ethical challenges also relate to algorithmic bias and lack of transparency in AI decision-making. To ensure compatibility with international legal systems, it is essential to develop coherent legal frameworks, improve technical infrastructure, create dispute-resolution mechanisms, and strengthen educational capacities.

In Iran, removing legal restrictions on cryptocurrencies, developing specific laws for smart contracts, investing in technical infrastructure, and training human resources can accelerate the adoption of this technology. Learning from leading systems such as Singapore, Switzerland, and the European Union, with emphasis on supportive legislation, infrastructure development, and international cooperation, can turn Iran into an active actor in this field. Ultimately, cooperation among government, industry, universities, and international organizations, together with continuous research and investment in technology, will be the key to successfully utilizing the potential of smart contracts in the construction industry.

Research Recommendations

Examine the effect of smart contracts on reducing legal disputes in construction projects through empirical data and statistical analysis.

Conduct a comparative analysis of blockchain laws in Islamic countries in order to develop regional frameworks compatible with Sharia principles.

Develop explainable artificial intelligence models for predicting legal and operational risks in smart construction contracts.

Study the feasibility of using private blockchains in Iranian public construction projects, with emphasis on reducing financial corruption.

Examine the effect of education and public awareness on the adoption of smart contracts in small and medium-sized construction companies.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

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Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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