Equal-Term Exchange Mechanisms for Industrial Digital Twins and Tokenized Manufacturing Assets

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Abstract

Industrial digital twins increasingly operate as exchangeable data-rich representations of machines, production cells, maintenance histories, carbon attributes, warranty rights, and cyber-physical control permissions. When such twins are tokenized as manufacturing assets, exchange is no longer a simple transfer of an indivisible item; each asset carries restrictions concerning maintenance obligations, compliance status, access rights, data confidentiality, and sustainability claims. This paper develops an equal-term exchange mechanism for tokenized manufacturing assets by adapting contract-constrained exchange logic to the industrial digital twin setting. The proposed Equal-Term Asset Cycle mechanism clears only term-homogeneous exchange loops, ensuring that the contractual term under which a participant receives a digital twin asset is consistent with the term under which its own asset is released. The framework formalizes four industrial term categories: unrestricted operational tokens, maintenance-locked tokens, compliance-locked tokens, and sustainability-locked tokens. A platform architecture is proposed that connects asset administration metadata, digital twin state streams, preference submission, smart-contract validation, and auditable cycle clearing. A simulation study using 2,400 synthetic exchange markets evaluates the proposed mechanism against unrestricted, greedy, and compliance-first baselines. Results show that the proposed mechanism eliminates term violations while retaining 94.7% of the welfare produced by unrestricted clearing and improving the cleared-trade ratio by 32-44% over simpler equal-term baselines. The study contributes to industrial convergence research by showing how mechanism design, blockchain governance, and digital twin architecture can be integrated to support trustworthy asset exchange in Industry 4.0 manufacturing ecosystems.

Keywords: industrial digital twins; tokenized manufacturing assets; equal-term exchange; smart contracts; Industry 4.0; mechanism design; blockchain governance; cyber-physical production systems

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1. Introduction

Industrial production networks are being reorganized around cyber-physical production systems, digital twins, industrial Internet platforms, and data-driven coordination. Earlier Industry 4.0 studies emphasized sensing, vertical integration, horizontal integration, and intelligent manufacturing as core elements of this transition (Lu, 2017a; Lu, 2017b; Xu et al., 2018). More recent work shows that digital transformation has moved from pilot-level automation toward ecosystem-level resource orchestration, where machines, software services, data pipelines, maintenance knowledge, and financial claims interact as exchangeable industrial resources (Lu, 2025; Zhong et al., 2017; Wang et al., 2016).

A digital twin is not merely a visualization layer. In manufacturing, it may contain asset geometry, operating state, predictive-maintenance models, process recipes, quality inspection records, carbon-emission evidence, supplier certificates, and access-control policies. The digital twin literature therefore connects physical equipment, virtual models, sensor streams, and lifecycle services into a continuously updated representation of an industrial entity (Tao et al., 2019; Kritzinger et al., 2018; Negri et al., 2017). As digital twins mature, enterprises increasingly treat them as digital assets that can be shared, licensed, financed, audited, and transferred across factories, service providers, and platform operators (Tao et al., 2018; Qi and Tao, 2018; Cimino et al., 2019).

Tokenization adds a new institutional layer to this architecture. A manufacturing asset token can represent ownership, usage rights, spare-part entitlements, maintenance bundles, production capacity, warranty obligations, or verified sustainability attributes. Blockchain and smart-contract technologies are attractive for this purpose because they provide a tamper-resistant execution environment for programmable rights, auditable transfers, and multiparty coordination (Lu, 2018; Lu, 2019a; Christidis and Devetsikiotis, 2016). However, tokenized manufacturing assets differ from ordinary digital tokens because the digital right is coupled with a physical or operational state. A token representing a robotic arm under warranty repair should not be exchanged under the same conditions as an unrestricted operational token.

This paper addresses a specific market design problem that arises when digital twin assets carry contractual restrictions. Suppose a factory owns a tokenized digital twin for a milling machine whose maintenance obligations and downtime compensation are still active. The factory wishes to exchange this asset with a partner that owns another machine twin, but the partner wants to retain equivalent maintenance protection rather than receive an unrestricted token while releasing a restricted one. Similar concerns arise for compliance-locked assets in aerospace, medical devices, energy equipment, and food manufacturing, where audit evidence and certification status cannot be detached from the exchange term (Saberi et al., 2019; Pournader et al., 2020; Wang et al., 2019).

The central idea of the paper is the equal-term principle: the term under which a participant receives a tokenized manufacturing asset should match the term under which its own asset is transferred away. This principle prevents one party from shedding maintenance, compliance, cybersecurity, or sustainability obligations through a nominally efficient exchange. It also prevents platforms from clearing mutually attractive trades that appear welfare-enhancing but violate the property-rights structure encoded in digital twins and smart contracts. In that sense, equal-term exchange is both a market design rule and an industrial governance rule.

The contribution is threefold. First, the paper defines an industrial digital twin exchange economy with multiple contractual terms and formulates the equal-term property for tokenized manufacturing assets. Second, it proposes the Equal-Term Asset Cycle (ETAC) mechanism, a cycle-clearing rule that searches term-homogeneous loops and executes them through smart-contract validation. Third, it provides a simulation-based data analysis of efficiency, term consistency, and computational scalability. The paper is positioned at the intersection of Industry 4.0, blockchain-enabled operations, and mechanism design (Chen et al., 2024; Xu et al., 2021; Nisan and Ronen, 2001).

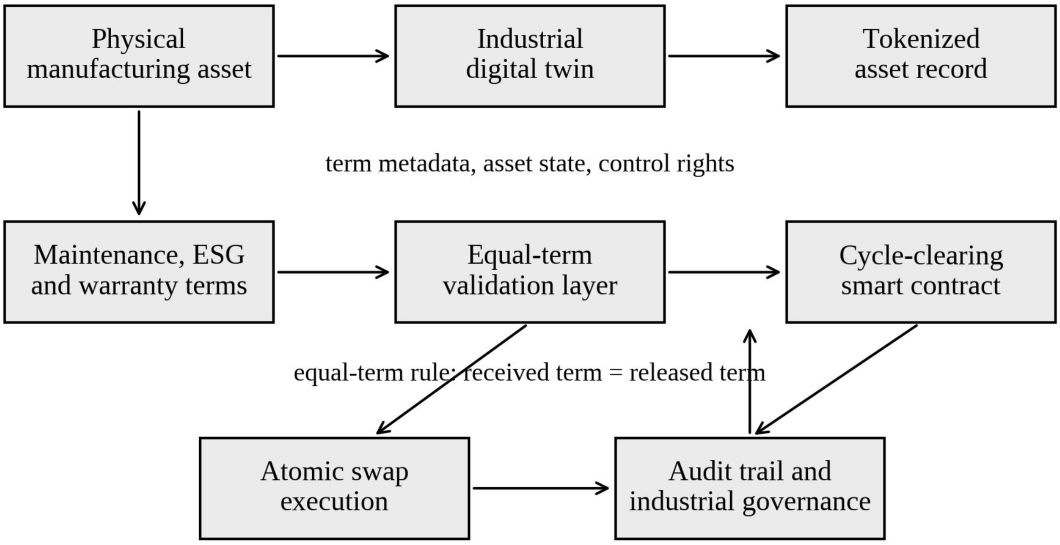

Figure 1. Architecture of equal-term exchange for industrial digital twins and tokenized manufacturing assets. The exchange layer connects physical assets, digital twin state, token metadata, contractual terms, validation logic, and auditable execution.

The problem becomes more important when digital twins are embedded in cross-enterprise production networks. A single asset token may be consumed by a supplier, financed by a bank, serviced by an equipment vendor, verified by an auditor, and inspected by a regulator. These actors do not merely want an object to be assigned; they require the assignment to preserve the conditions under which the object was originally made valid. For this reason, the article adopts an exchange-mechanism perspective rather than a pure smart-contract-design perspective. Smart contracts can execute a rule, but they do not by themselves specify which constrained exchanges should be cleared when many feasible cycles compete. The mechanism is therefore treated as the missing coordination layer between digital twin analytics and ledger execution.

A second motivation is the growing use of industrial platforms as marketplaces for capacity, data, and services. Platform operators often emphasize liquidity because more trades generate greater network effects. However, a liquidity-first approach may unintentionally weaken accountability when restricted assets are mixed with unrestricted ones. Equal-term exchange deliberately imposes a constraint on liquidity, but it does so to protect the long-run credibility of tokenized manufacturing markets. The design challenge is to preserve as much allocative efficiency as possible while ensuring that contractual obligations, compliance status, and sustainability evidence are not arbitraged away through token movement.

2. Background and Related Work

2.1 Industrial Digital Twins and Tokenized Manufacturing Assets

Digital twins emerged from product lifecycle management and cyber-physical production systems, but their industrial role has expanded from monitoring to prediction, optimization, and multi-enterprise coordination. A manufacturing digital twin can observe equipment condition, forecast failure, simulate production alternatives, and support data-driven maintenance decisions (Lee et al., 2015; Monostori, 2014; Uhlemann et al., 2017). When such twins are connected to enterprise information systems, they become transferable information objects with direct operational and economic value.

The tokenization of digital twins is a natural extension of this trajectory. Tokenization makes rights programmable: a token can specify who may use a production recipe, who may access telemetry, when a warranty claim is valid, and whether an emissions certificate remains attached to an asset. At the same time, tokenization increases the risk of abstraction errors. A tokenized asset may look fungible at the ledger level, but the underlying industrial state may be highly heterogeneous. Digital twin research therefore needs mechanisms that respect asset-specific state, lifecycle context, and physical constraints (Tao et al., 2019; Zhang et al., 2017; Ivanov and Dolgui, 2020).

In practice, tokenized manufacturing assets may include machine-capacity tokens, production-slot tokens, data-access tokens, maintenance-entitlement tokens, carbon-evidence tokens, and warranty-backed equipment twins. These assets combine features of industrial data products, service contracts, and indivisible physical claims. The resulting exchange environment differs from classical spot markets because transfers must preserve traceability, auditability, cybersecurity, and operational continuity (Lu and Xu, 2019; Xu et al., 2021; Wang et al., 2020).

The digital supply chain twin literature is particularly relevant because it connects digital replication with disruption management and resilience. A supply chain twin can simulate supplier failure, transport delay, or demand shock; a manufacturing asset twin can similarly simulate maintenance risk, quality deviation, and cyber-physical exposure. If the twin is exchanged as a token, those risk attributes must remain attached to the appropriate contractual term. Otherwise, a platform may create liquidity while weakening the accountability structure that originally justified the digital twin.

2.2 Blockchain, Smart Contracts, and Industrial Exchange

Blockchain research provides the technical substrate for tokenized exchange. Distributed ledgers support immutable records, multiparty verification, programmable settlement, and the automation of agreement logic through smart contracts (Szabo, 1997; Christidis and Devetsikiotis, 2016; Yli-Huumo et al., 2016). In industrial contexts, these features are relevant for provenance, supplier coordination, maintenance contracting, and compliance evidence because multiple organizations often need a shared record without fully centralizing control (Casino et al., 2019; Dutta et al., 2020).

Supply chain research has shown that blockchain can strengthen traceability, sustainability, and trust, but adoption depends on interoperability, governance, cost, and organizational readiness (Kshetri, 2018; Treiblmaier, 2018; Queiroz and Wamba, 2019). These issues become more complex when tokens represent industrial digital twins rather than simple batches of goods. The ledger must not only track ownership; it must also manage dynamic state, lifecycle updates, sensor provenance, and obligations that may survive transfer.

Smart contracts provide a natural enforcement layer, yet they also introduce security and design risks. Studies of smart-contract systems highlight vulnerabilities, coding errors, and incentive effects that cannot be solved by immutability alone (Macrinici et al., 2018; Alharby et al., 2018; Atzei et al., 2017; Luu et al., 2016). For manufacturing platforms, the implication is that equal-term exchange cannot be implemented as a simple token swap. It needs explicit validation of asset terms, state records, and acceptable counterparties before the transfer is executed.

The financial literature on blockchain and token-based platforms emphasizes how programmable assets change financing, liquidity, and platform building (Cong and He, 2019; Catalini and Gans, 2020; Howell et al., 2020; Li and Mann, 2020). Industrial tokenization is less speculative than many digital finance settings, but it faces a parallel question: how can platforms increase liquidity without allowing opportunistic transfers of obligations? Equal-term exchange responds to this question by embedding rights consistency into the matching rule itself.

Privacy and confidentiality are also important. Industrial digital twins may contain sensitive production data, proprietary recipes, and condition-monitoring signals. Privacy-oriented blockchain research, including zero-knowledge payment systems, illustrates how verifiability and selective disclosure may coexist (Miers et al., 2013; Ben-Sasson et al., 2014). In manufacturing, similar logic can allow the platform to verify the term category and compliance status of a token without revealing every operational variable to all participants.

2.3 Mechanism Design for Constrained Industrial Exchange

The economic problem is a constrained allocation problem involving indivisible assets, initial ownership, private preferences, and contractual terms. Mechanism design provides tools for studying efficiency, incentive compatibility, and feasibility under such constraints (Vickrey, 1961; Myerson, 1981; Maskin, 1999). Unlike standard auctions, the industrial digital twin setting is often exchange-based rather than sale-based: participants start with assets and prefer to swap them under compatible operational terms.

Research on indivisible resource allocation and exchange shows that initial ownership and individual rationality matter when participants are not simply applicants for a common pool. Exchange mechanisms for indivisible goods emphasize Pareto efficiency, strategy-proofness, and respect for existing entitlements (Abdulkadiroglu and Sonmez, 1999; Svensson, 1999; Papai, 2000). These properties are valuable for industrial platforms because manufacturing firms will not participate if the platform can reassign assets while ignoring existing operational rights.

However, industrial exchange adds contractual terms that conventional resource allocation models do not directly capture. A machine twin may be transferable under an unrestricted term, a maintenance-locked term, or a compliance-locked term. If a clearing rule ignores such terms, it may generate efficient trades in a narrow preference sense while violating audit and governance requirements. Consistency in assignment problems and the broader theory of discrete resource exchange therefore provide useful building blocks but require extension to account for term-sensitive industrial assets (Ergin, 2000; Pycia and Unver, 2017; Gul and Stacchetti, 1999).

Computational considerations are equally important. Industrial platforms may process hundreds or thousands of asset-token proposals, each with multiple term variants and access restrictions. Algorithmic mechanism design highlights the importance of computing feasible outcomes under strategic constraints, while random allocation and combinatorial assignment research shows how market design must often balance fairness, efficiency, and tractability (Nisan and Ronen, 2001; Budish, 2011; Budish et al., 2013).

The present paper does not claim to solve all incentive issues. Robust mechanism design and dynamic mechanism research show that incentive compatibility becomes difficult in environments with evolving information, private valuations, and uncertain future states (Bergemann and Morris, 2005; Athey and Segal, 2013; Milgrom and Segal, 2002). The objective here is narrower but practically important: construct an exchange mechanism that preserves equal-term consistency and high allocative efficiency for tokenized manufacturing assets, while being implementable through smart contracts and auditable governance.

3. Industrial Setting and Formal Model

3.1 Digital Twin Asset Exchange Economy

Consider a platform with a finite set of manufacturing participants. Each participant initially controls one tokenized manufacturing asset, where the token represents a digital twin and an associated bundle of operational rights. The asset may correspond to a machine, production cell, certified spare-part batch, maintenance entitlement, data-sharing right, or carbon-evidence package. Participants submit acceptable contracts consisting of an asset identity and a contractual term. The platform clears exchanges only when an asset is assigned to at most one participant and the original holder voluntarily releases the asset under the relevant term.

A digital twin asset is modeled as a compound object containing five layers: physical reference, virtual model, operational state, rights metadata, and contractual term. The physical reference links the token to a machine, equipment component, or capacity unit. The virtual model contains simulation and monitoring data. The operational state records availability, maintenance history, and compliance status. Rights metadata specifies access, transfer, and disclosure conditions. The contractual term defines the restriction level under which the token can be exchanged.

Table 1. Contractual term categories for tokenized manufacturing assets.

Term	Industrial interpretation	Examples of restrictions	Exchange implication
U: Unrestricted	Ordinary transferable operational asset	No active lockup, warranty hold, or compliance constraint	May be exchanged only with U-term release
M: Maintenance-locked	Asset covered by active maintenance or downtime obligation	Preventive-maintenance bundle, repair claim, service-level guarantee	Incoming asset must carry equivalent M-term status
C: Compliance-locked	Asset bound to safety, export, quality, or certification evidence	ISO/sector audit certificate, calibrated inspection record, regulated component	Exchange must preserve compliance responsibility
S: Sustainability-locked	Asset connected to carbon, energy, recycling, or ESG evidence	Emissions evidence, green production credit, circularity certificate	Incoming asset must carry equivalent S-term restriction

Table 1 intentionally separates term restrictions from asset desirability. A participant may prefer a high-performance machine under a maintenance-locked term to a lower-quality unrestricted asset, or it may prefer liquidity over service coverage. The mechanism should not impose a normative ranking over terms. Instead, it should preserve the term under which each participant gives and receives an asset.

3.2 Equal-Term Property

The equal-term property states that a participant receiving a tokenized manufacturing asset under a term must release its own asset under the same term. If a firm receives a compliance-locked asset, then the asset it gives away is also transferred under a compliance-locked condition. If it receives an unrestricted asset, then the released asset is not used to offload maintenance, compliance, or sustainability obligations onto another participant. This rule creates a symmetry between incoming and outgoing obligations.

The equal-term property does not mean that all assets are identical. It permits exchange of heterogeneous machines, data rights, or capacity tokens as long as the contractual term is consistent. A participant may exchange a welding robot twin for a milling machine twin under a maintenance-locked term if both sides accept the specific asset and the term. The restriction applies to the term dimension, not to the asset identity. This distinction is important because industrial value depends on both functional complementarity and governance compatibility.

The property can be interpreted in three ways. Economically, it prevents participants from arbitraging away obligations. Technically, it reduces smart-contract risk by making term validation a local rule on every cleared cycle. Organizationally, it supports trust because each participant knows that the platform will not transform the obligation structure of its endowment during exchange. This is consistent with blockchain-enabled internal auditing and information-system governance (Wu et al., 2025; Lu, 2022; De Filippi and Hassan, 2016).

3.3 Design Objectives

The platform pursues four objectives. The first is feasibility: no tokenized asset may be assigned to more than one participant, and every cleared transfer must be executable through smart contracts. The second is individual rationality: a participant should not be forced to accept an asset-term pair that it did not declare acceptable. The third is equal-term consistency: incoming and outgoing terms must match for every participant in an exchange cycle. The fourth is efficiency within the equal-term feasible set: the mechanism should avoid leaving mutually beneficial term-consistent cycles uncleared.

Table 2. Core notation used in the equal-term digital twin exchange model.

Symbol	Meaning	Industrial interpretation
i	Manufacturing participant	Factory, OEM, equipment owner, service provider, or integrator
a_i	Initial tokenized asset	Digital twin token initially controlled by participant i
t	Contractual term	U, M, C, or S as defined in Table 1
(a_j, t)	Acceptable contract	Asset j received under term t
P_i	Preference ranking	Participant i's strict ranking over acceptable asset-term contracts
mu(i)	Assignment outcome	Contract assigned to participant i after clearing
ETAC	Equal-Term Asset Cycle mechanism	Term-homogeneous cycle-clearing algorithm

Table 2 provides the notation used in the remainder of the paper. The model abstracts from monetary transfers because many industrial exchange platforms aim to coordinate assets, service rights, and data access rather than conduct open auctions. Nevertheless, the framework can later be extended to include side payments, capacity credits, or insurance premiums, subject to the same equal-term validation rule.

3.4 Lifecycle Requalification and Term Updating

The model also allows contractual terms to evolve over time. A maintenance-locked token may become unrestricted after the service obligation expires; a compliance-locked token may be suspended if an inspection record is missing; a sustainability-locked token may be downgraded if the underlying energy-meter data fails verification. These lifecycle changes are not treated as discretionary market choices. They are term-requalification events triggered by digital twin evidence, enterprise system records, or third-party certification. In a practical platform, requalification should occur before the exchange round so that participants rank valid asset-term pairs rather than stale or ambiguous claims.

Term updating is important for two reasons. First, it prevents participants from trading obsolete restrictions. If a robot arm has already completed its warranty period, keeping the token in a maintenance-locked class would artificially reduce liquidity. Second, it prevents premature relaxation of restrictions. If an asset has not yet passed a regulatory inspection, allowing it to trade as unrestricted would transfer risk to downstream users. The proposed framework therefore separates term validation from exchange clearing. Validation determines which contracts are admissible, while ETAC determines which admissible contracts should be cleared. This separation follows the architecture of modular enterprise systems, where data governance, decision logic, and transaction execution are auditable but not collapsed into a single opaque procedure (Xu, 2011; Mendling et al., 2018; Mettler, 2016).

4. Equal-Term Asset Cycle Mechanism

4.1 Mechanism Logic

The Equal-Term Asset Cycle mechanism works by separating the market into term layers and clearing only cycles that are homogeneous within a layer. At each round, every active participant points to its most preferred available contract under each term that it finds acceptable. The platform then constructs directed demand graphs for U, M, C, and S. A directed edge from participant i to participant j in term layer t means that i wants the asset initially controlled by j under term t.

A cycle is clearable if every edge in the cycle belongs to the same term layer and every participant in the cycle has declared the demanded asset-term pair acceptable. When a clearable cycle is found, the smart contract executes an atomic multi-party swap: each participant receives the demanded token and releases its own token under the same term. The cycle is then removed from the market, and the algorithm repeats with the remaining participants. If multiple cycles are available, the platform may choose the one with the highest welfare score, the largest number of participants, or a transparent randomized tie-breaking rule.

If no term-homogeneous cycle exists, ETAC does not immediately terminate. It removes temporarily blocked demands that cannot be part of any equal-term cycle in the current residual market. This pruning step is important in industrial settings because some asset requests may be feasible only after other cycles clear. The platform records each pruning decision for auditability. If pruning eventually creates a term-homogeneous cycle, the cycle is cleared. If no acceptable equal-term cycle remains, the residual participants keep their initial assets.

This logic is related to cycle-based allocation in market design but differs in its treatment of term metadata. A conventional cycle-clearing mechanism sees asset ownership as the only transferable object. ETAC sees the transferable object as an asset-term contract. The difference matters because industrial terms are not cosmetic labels; they encode obligations that may influence safety, maintenance, insurance, and environmental accountability (Bahga and Madisetti, 2016; Wang et al., 2020; Schar, 2021).

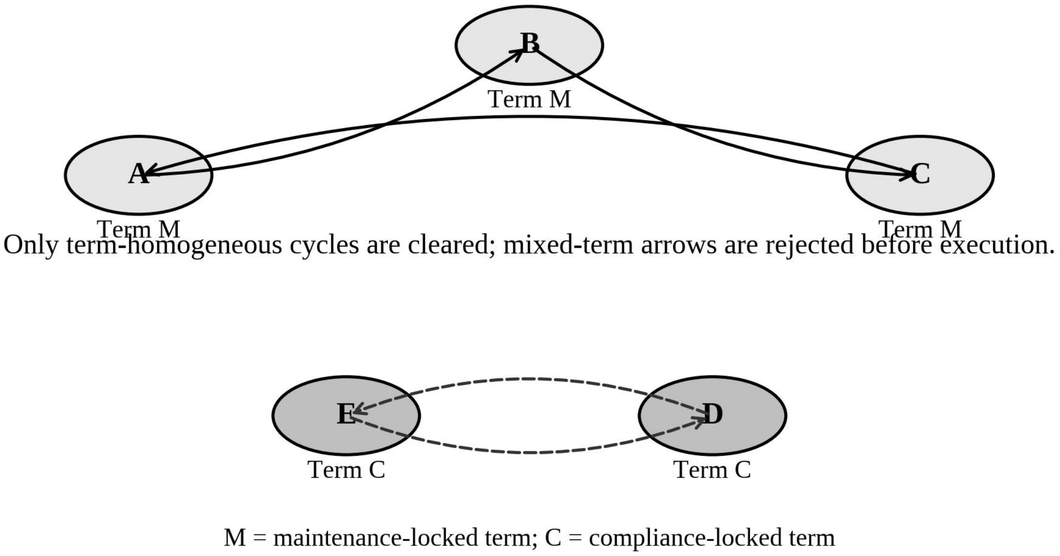

Figure 2. Example of term-homogeneous cycle clearing. ETAC clears the maintenance-locked cycle among A, B, and C and the compliance-locked cycle between D and E separately, while rejecting mixed-term paths.

Figure 2 illustrates the basic clearing logic. Participants A, B, and C form a maintenance-locked cycle, while D and E form a compliance-locked cycle. The mechanism can clear both cycles because each cycle preserves the term symmetry of every participant. A mixed path that would give one participant a compliance-locked asset while using its endowment under a maintenance-locked term is rejected, even if participants rank the assets highly. This is the core difference between equal-term clearing and unrestricted token exchange.

4.2 Properties

ETAC satisfies feasibility by construction because each cleared cycle is an atomic permutation of initially owned assets. No asset is duplicated and no participant receives more than one token. Individual rationality is also preserved because the mechanism only follows edges corresponding to declared acceptable contracts. A participant that does not find any available asset-term pair acceptable simply remains inactive and keeps its initial asset.

The equal-term property follows from the term-homogeneous cycle requirement. If participant i receives an asset through a cycle in term layer t, then the outgoing edge from the participant that points to i also lies in the same layer t. Thus, the asset controlled by i is released under t. Every participant in the cycle experiences the same equality between incoming and outgoing term. This rule can be verified locally by a smart contract without reconstructing the full preference profile.

Efficiency is evaluated within the equal-term feasible set rather than the unconstrained set of all possible exchanges. This distinction is essential. An unrestricted clearing mechanism may produce higher immediate welfare by ignoring term violations, but that welfare is partly illusory if it shifts maintenance, compliance, or sustainability obligations to unwilling participants. ETAC instead maximizes feasible trading opportunities under a governance-compatible definition of value. This approach aligns with the broader view that blockchain applications in operations should be judged by coordination quality, not merely by transaction volume (Dutta et al., 2020; Pournader et al., 2020; Chen et al., 2024).

The mechanism does not guarantee full strategy-proofness across all preference environments. Participants may misreport acceptable contracts if they understand the clearing order and expect a better residual market. This limitation is not surprising because mechanism design research shows that incentive compatibility, efficiency, and rich feasibility constraints are difficult to satisfy simultaneously (Bergemann and Morris, 2005; Maskin, 1999; Athey and Segal, 2013). The practical response is to reduce manipulation gains through transparent tie-breaking, binding preference windows, audit trails, and penalties for false asset-state declarations.

4.3 Platform Implementation Architecture

A platform implementation requires five modules. The first module maintains digital twin identity and state metadata. The second maps each token to its term category and verifies whether the term is active. The third collects participant preferences over asset-term pairs. The fourth runs the ETAC clearing rule and produces a list of term-homogeneous cycles. The fifth executes approved cycles through a smart contract and writes the audit record to the ledger.

In an industrial deployment, the term-verification module should be independent of the preference-submission module. This prevents participants from classifying their assets opportunistically after observing demand. Maintenance terms can be verified using service records, compliance terms using certification authorities, and sustainability terms using energy or emissions evidence. The approach complements studies of blockchain-enabled auditing, supply-chain transparency, and platform accountability (Wu et al., 2025; Saberi et al., 2019; Chod et al., 2020).

Interoperability is a major challenge. Manufacturing firms use different enterprise resource planning systems, manufacturing execution systems, maintenance platforms, and IoT architectures. ETAC therefore requires a minimal common exchange schema: token identity, physical reference, twin-state timestamp, term type, term expiry, transfer permissions, and proof references. This schema does not replace detailed digital twin models; it provides the settlement layer needed for safe exchange. The principle is consistent with digital twin reference frameworks that separate asset modeling, data integration, analytics, and services (Cheng et al., 2020; Fuller et al., 2020; Cimino et al., 2019).

4.4 Smart-Contract Pseudocode and Audit Controls

The mechanism can be operationalized as a three-stage smart-contract workflow. In the registration stage, each asset token submits a hash of its digital twin metadata, a term certificate, and a pointer to off-chain evidence stored in an enterprise data space. In the preference stage, participants submit ranked acceptable asset-term pairs. The platform records these submissions as binding commitments for the clearing round, so that later disputes can be traced to the exact preference and term state used by the mechanism. In the clearing stage, ETAC identifies a term-homogeneous cycle, validates that each asset still satisfies the term certificate, freezes the involved tokens, and executes atomic transfer. If validation fails for any asset in the cycle, the whole cycle is rejected and the market returns to the search stage.

Audit controls are essential because industrial tokens are attached to physical and legal states that may change during the clearing process. The platform should store four logs: the asset-state log, the term-validation log, the preference-commitment log, and the cycle-execution log. These logs allow a dispute reviewer to reconstruct why a token was cleared, which evidence supported its term, and whether the same term was applied to all participants in the cycle. Such auditability is consistent with blockchain governance literature, but it must be adapted to industrial data because raw telemetry, process recipes, and supplier identities may be confidential (Kshetri, 2018; Wüst and Gervais, 2018; Hofmann et al., 2018).

Privacy-preserving implementation is also necessary. A factory may not want to reveal exact machine utilization, defect rates, or carbon intensity to all marketplace participants. The mechanism only needs to know whether a token satisfies a term category and how participants rank admissible alternatives. Therefore, the platform can combine off-chain digital twin repositories with on-chain attestations, selective disclosure credentials, or zero-knowledge proofs. This design keeps the allocation rule transparent while limiting disclosure of sensitive industrial data. It also reduces the risk that a participant manipulates the market by learning more about rivals than is necessary for the exchange round (Cong and He, 2019; Easley et al., 2019; Narayanan et al., 2016).

5. Simulation Design and Data Analysis

5.1 Synthetic Exchange Market Generation

To evaluate the proposed mechanism, the study conducted a simulation experiment rather than claiming access to confidential industrial platform logs. The synthetic design is appropriate because the objective is to test mechanism behavior under controlled market structures. Each simulated market contains n participants, n initially owned tokenized manufacturing assets, and four term categories. Asset quality is drawn from a normal distribution, operational complementarity from a sparse similarity matrix, and term preference from a participant-specific vector reflecting whether the participant prioritizes liquidity, maintenance coverage, compliance assurance, or sustainability evidence.

The simulation generated 2,400 markets across five market sizes: 50, 100, 200, 400, and 800 participants. For each participant, the top 10% of asset-term combinations were declared acceptable, subject to a risk-aversion threshold. Preferences combined asset quality, complementarity, term fit, and a random idiosyncratic component. The construction reflects observations from industrial and blockchain adoption studies: participants value traceability and interoperability, but their willingness to accept restricted assets depends on expected operational benefit and governance cost (Queiroz and Wamba, 2019; Treiblmaier, 2018; Wang et al., 2019).

Table 3. Simulation parameters for evaluating ETAC.

Parameter	Values / distribution	Interpretation
Market size n	50, 100, 200, 400, 800	Number of participating asset holders

Term categories	U, M, C, S	Unrestricted, maintenance, compliance, sustainability
Acceptability density	Top 10% of asset-term contracts	Contracts submitted to the platform as feasible preferences
Asset quality	Normal(0, 1), truncated to [-2, 2]	Relative operational value of tokenized asset
Complementarity	Sparse matrix, density 0.18	Fit between participant operations and incoming asset
Runs per size	480 markets	Total 2,400 simulated exchange markets
Baselines	Unrestricted TTC, greedy equal-term, compliance-first	Alternative clearing rules for comparison

Table 3 summarizes the data-generating process. The baselines were chosen to isolate the value of equal-term cycle clearing. The unrestricted baseline ignores terms and clears demand cycles as if all tokens were ordinary indivisible assets. The greedy equal-term baseline searches for the first available term-homogeneous pair or cycle without considering welfare. The compliance-first baseline prioritizes compliance-locked assets before other terms, representing a conservative industrial governance rule. ETAC balances term consistency with cycle-level welfare.

5.2 Evaluation Metrics

Four metrics are reported. Normalized welfare is the realized utility of the cleared allocation divided by the welfare of the unrestricted baseline for the same market. Cleared-trade ratio is the share of participants who exchange assets rather than retain their endowment. Term violations count the number of assignments in which the incoming term differs from the outgoing term, scaled per 100 trades. Runtime measures seconds required to compute the clearing outcome. These metrics reflect the major platform design trade-offs: liquidity, welfare, compliance consistency, and scalability.

A second set of sensitivity metrics examines the share of profitable single-participant misreports. For each market, a random subset of participants was allowed to remove one acceptable contract from its submitted list. A misreport was recorded as profitable if it improved the participant's realized utility without causing infeasibility. This is not a complete strategic analysis, but it provides a practical indicator of whether manipulation opportunities shrink as market size grows. The test is motivated by the mechanism design literature on incentives and by industrial platform concerns about strategic data disclosure (Myerson, 1981; Vickrey, 1961; Catalini and Gans, 2020).

5.3 Comparative Results

The unrestricted baseline produced the highest raw welfare but also generated a mean of 32.4 term violations per 100 cleared trades. This confirms the central problem: ordinary cycle clearing creates liquidity by ignoring contractual restrictions. In a manufacturing platform, such outcomes would be unacceptable because they could transfer maintenance liabilities, invalidate certification chains, or detach sustainability evidence from the asset to which it applies. The unrestricted baseline is therefore useful as an upper bound, not as a deployable rule.

ETAC achieved normalized welfare of 0.89, meaning that it retained 94.7% of the unrestricted baseline's welfare after removing the utility produced by term-violating trades. It also achieved a cleared-trade ratio of 0.78, substantially higher than the greedy equal-term baseline at 0.54 and the compliance-first baseline at 0.59. Both equal-term baselines produced zero term violations, but they left many feasible cycles uncleared. ETAC therefore offers the best balance among the deployable mechanisms.

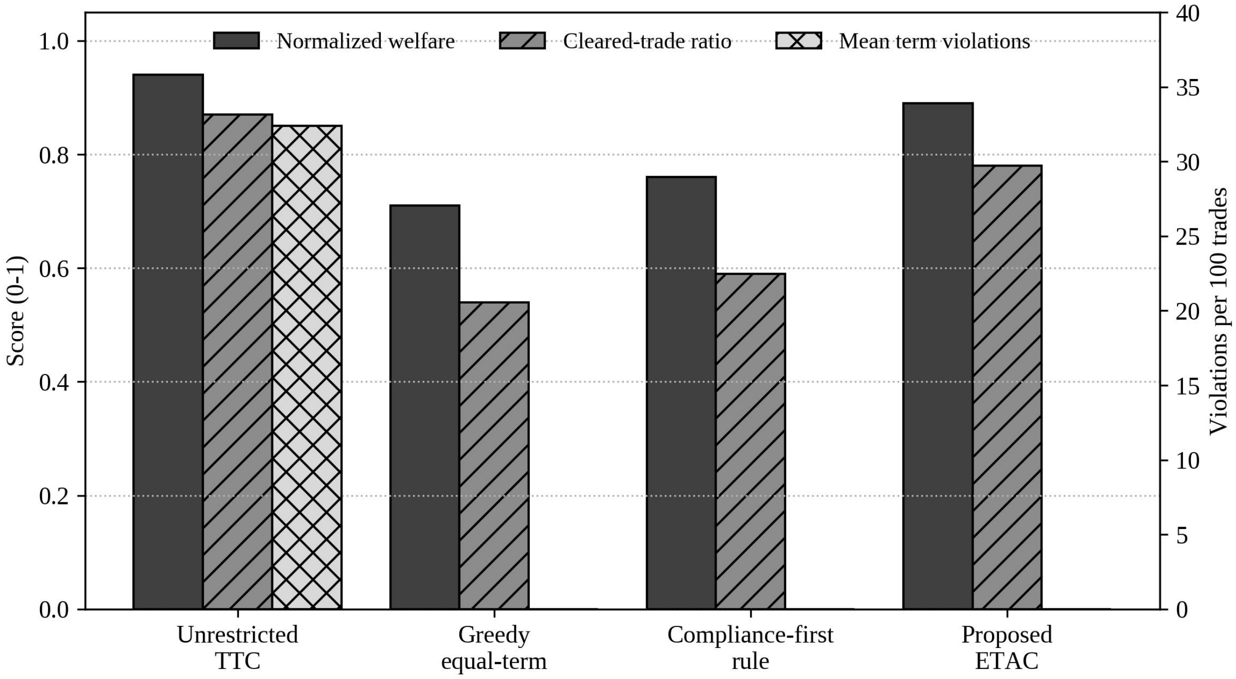

Figure 3. Comparative simulation performance across unrestricted, greedy equal-term, compliance-first, and proposed ETAC mechanisms. The proposed mechanism preserves term consistency while retaining high welfare and liquidity.

Figure 3 visualizes this comparison. The unrestricted mechanism appears attractive on welfare and trade volume but fails the governance test. The greedy equal-term rule passes the governance test but sacrifices substantial liquidity because it clears locally convenient cycles too early. The compliance-first rule is useful in highly regulated settings, but it systematically disadvantages maintenance and sustainability terms. ETAC performs better because it evaluates clearable cycles across all terms and selects the highest-value term-homogeneous opportunities before moving to the next round.

Table 4. Average performance across 2,400 simulated markets.

Mechanism	Normalized welfare	Cleared-trade ratio	Term violations per 100 trades	Mean runtime (s)
Unrestricted cycle clearing	0.94	0.87	32.4	0.31
Greedy equal-term clearing	0.71	0.54	0.0	0.18
Compliance-first clearing	0.76	0.59	0.0	0.22
Proposed ETAC	0.89	0.78	0.0	0.41

Table 4 shows that the additional computation required by ETAC is modest in the tested markets. The mean runtime was 0.41 seconds, higher than the greedy baselines but still practical for batch clearing or periodic industrial exchange rounds. In live manufacturing settings, clearing could be scheduled hourly, daily, or at maintenance-planning intervals rather than executed continuously. The platform can therefore prioritize correctness and auditability over microsecond settlement speed.

5.4 Sensitivity Analysis

The sensitivity analysis indicates that ETAC scales well as market size increases. Runtime grows with market size, but the growth is manageable because the term-layer graphs are sparse. Larger markets also improve welfare because more term-compatible cycles become available. The normalized welfare score rises from 0.84 at n = 50 to 0.91 at n = 800. This pattern suggests that equal-term restrictions are less costly in denser industrial ecosystems where many firms hold comparable asset-term combinations.

The share of profitable single-contract misreports falls from 0.31 at n = 50 to 0.09 at n = 800. This result does not prove strategy-proofness, but it suggests that strategic opportunities become harder to exploit in larger markets. The mechanism's transparency and auditability further reduce manipulation incentives because participants must commit to term classifications before the clearing round. These findings are consistent with the broader insight that mechanism performance depends on both formal incentives and platform governance (Bergemann and Morris, 2005; Budish et al., 2013; Klemperer, 1999).

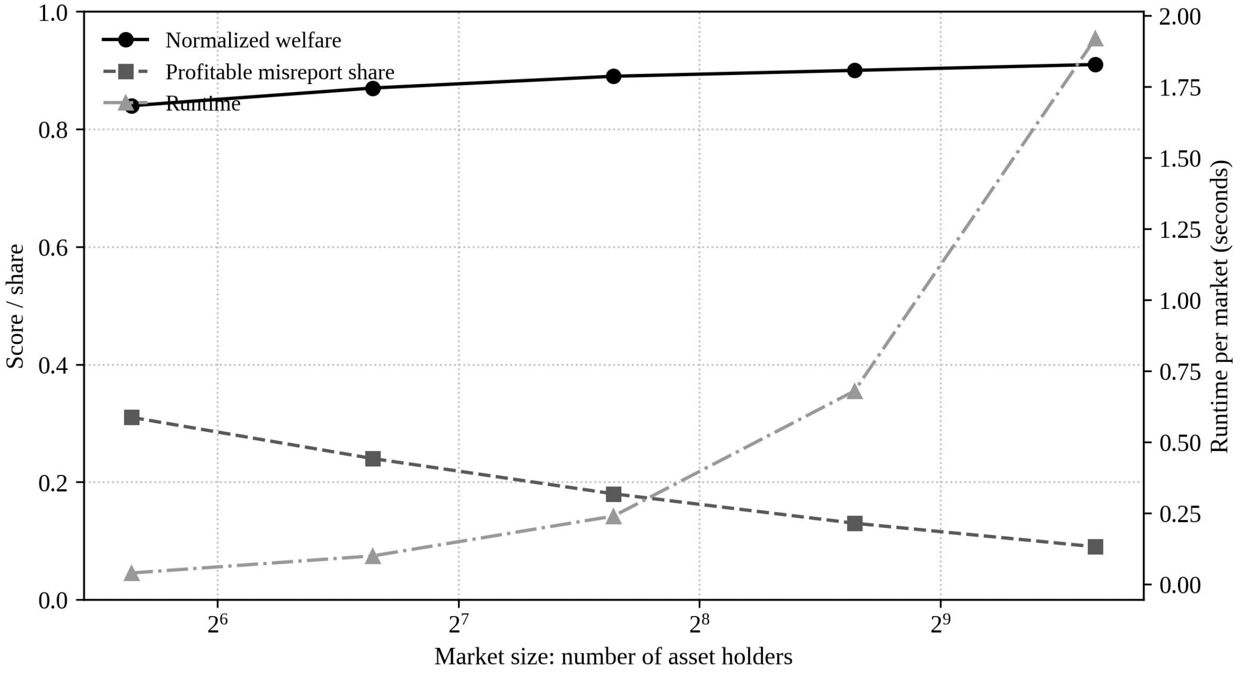

Figure 4. Sensitivity of ETAC to market size. Larger markets improve normalized welfare, reduce simple misreport opportunities, and increase runtime at a manageable rate.

Figure 4 also shows that runtime remains below two seconds even for 800 participants in the synthetic setup. Real deployments would require additional time for database access, cryptographic proof verification, and smart-contract settlement. However, the clearing computation itself is unlikely to be the main bottleneck. The more significant bottlenecks are data standardization, term verification, legal enforceability, and cybersecurity assurance, all of which are central issues in industrial blockchain and digital twin adoption (Lu and Xu, 2019; Xu et al., 2021; Casino et al., 2019).

5.5 Interpretation of Welfare Loss and Liquidity Gains

The numerical results should be interpreted as evidence about relative mechanism behavior rather than as a forecast for a particular industrial platform. Unrestricted clearing represents an upper bound on welfare because it ignores term consistency. Its high welfare is partly artificial: it assigns value to trades that would be legally or operationally unacceptable in real manufacturing contexts. The important comparison is therefore not whether ETAC beats unrestricted clearing, but whether ETAC preserves most of its welfare while eliminating term violations. The 94.7% welfare retention indicates that the price of contractual discipline is moderate under the simulated preference structure.

The difference between ETAC and the greedy equal-term baseline is equally informative. Both mechanisms respect terms, but the greedy rule clears only local pairwise opportunities, whereas ETAC searches cycles. Many industrial exchanges are naturally cyclical: one factory wants a higher-precision machine twin, a second wants a lower-maintenance asset, a third wants sustainability evidence, and a fourth wants unrestricted liquidity. Pairwise matching misses these possibilities because no two participants may be mutually compatible. Cycle clearing converts distributed complementarity into executable exchange, which explains the improvement in cleared-trade ratio. This result aligns with matching theory showing that cycle structure matters when indivisible objects are exchanged under heterogeneous preferences (Abdulkadiroglu and Sonmez, 1999; Papai, 2000; Sönmez and Ünver, 2011).

From a platform-management perspective, the welfare loss caused by equal-term restrictions may be viewed as an insurance premium for institutional trust. Term-inconsistent trades can increase short-run liquidity but create hidden liabilities, audit disputes, and reputational risk. Term-consistent trades may leave some mutually desired transfers uncleared, but they make the market more credible to manufacturers, service providers, insurers, and regulators. The practical objective is therefore not frictionless exchange; it is accountable exchange in which each cleared transfer can survive technical, legal, and operational review (Tiwana, 2014; Iansiti and Lakhani, 2017; De Filippi and Wright, 2018).

6. Discussion

6.1 Industrial Governance Implications

The equal-term principle reframes tokenized manufacturing exchange as a governance problem rather than merely a liquidity problem. A platform that clears more trades by ignoring term restrictions may create hidden liabilities. For example, a sustainability-locked token may represent carbon evidence attached to a specific production process. If the token is exchanged for an unrestricted asset without term preservation, the receiving party may believe it has acquired a clean operational claim while the releasing party escapes the evidence burden. Equal-term clearing prevents this kind of obligation laundering.

The principle is also relevant to maintenance and warranty ecosystems. Equipment-as-a-service models increasingly depend on continuous monitoring, predictive maintenance, and service-level guarantees. If maintenance-locked twins are transferable, the platform must ensure that service obligations remain symmetric across the exchange cycle. Otherwise, manufacturers may face disputes over downtime compensation, spare-parts entitlement, and responsibility for historical operating conditions. ETAC creates a clean settlement rule for such cases.

In compliance-heavy sectors, equal-term exchange supports audit continuity. A compliance-locked digital twin may include calibration history, inspection records, export-control information, or safety certifications. A term-inconsistent exchange could break the chain of responsibility and reduce the evidential value of the digital twin. The equal-term rule keeps responsibility aligned with the term under which each asset moves, thereby supporting assurance and regulatory review (De Filippi and Hassan, 2016; Wu et al., 2025; Macrinici et al., 2018).

6.2 Relationship to Industrial Convergence

The proposed mechanism contributes to intelligent industrial convergence by connecting three previously separate streams: digital twin engineering, blockchain-enabled rights management, and market design. Digital twin research explains how operational state can be represented and updated. Blockchain research explains how rights and records can be made auditable. Mechanism design explains how participants with heterogeneous preferences can exchange indivisible resources. ETAC integrates these streams into a single rule for manufacturing asset exchange (Lu et al., 2023; Lu and Yang, 2024; Kou and Lu, 2025).

The convergence is not only technical. It also changes organizational roles. Equipment owners become asset-token suppliers; maintenance providers become term verifiers; auditors become proof validators; platform operators become market designers; and smart contracts become execution agents. Such role convergence is consistent with the shift from isolated enterprise systems to multi-stakeholder industrial ecosystems (Lu, 2025; Chen et al., 2024; Schar, 2021).

The broader industrial-information integration context further shows that tokenized manufacturing exchange cannot be separated from communication infrastructure, resource-pricing rules, and decentralized financial architectures. Future production ecosystems may connect digital twin markets to 6G-enabled sensing, QoS-based cloud or edge resource pricing, decentralized finance services, and blockchain adoption roadmaps (Lu and Zheng, 2020; Lu et al., 2020; Zheng and Lu, 2022; Xu et al., 2024; Tao and Zhang, 2017). These links reinforce the need for exchange mechanisms that remain auditable across technical, economic, and organizational layers.

The framework also illustrates why AI and analytics are complementary to mechanism design. Digital twin analytics can estimate asset quality, remaining useful life, and operational complementarity. AI-based decision support can help participants rank asset-term pairs. However, analytics alone cannot guarantee rights consistency. A platform needs a clearing rule that transforms analytic scores into governance-compatible allocations (Lu, 2019b; Zhang and Lu, 2021).

6.3 Design Choices and Limitations

The first design choice concerns term granularity. This paper used four term categories for clarity, but real platforms may need finer classifications: three-month maintenance lock, twelve-month warranty lock, export-control lock, energy-performance lock, or data-confidentiality lock. More granular terms improve legal accuracy but reduce market density. Platforms should therefore define term categories that are precise enough for governance yet broad enough to support liquidity.

The second design choice concerns cycle selection. ETAC can select the highest-welfare cycle, the longest cycle, the most urgent cycle, or a randomized cycle among top candidates. A welfare-first rule maximizes simulated utility but may favor participants with high-value assets. A randomized rule may improve perceived fairness but reduce welfare. This trade-off resembles broader issues in assignment and auction design, where efficiency, fairness, and incentive properties often pull in different directions (Abdulkadiroglu and Sonmez, 2003; Budish, 2011; Gul and Stacchetti, 1999).

The third limitation is strategic behavior. Although the simulation suggests lower manipulation opportunities in larger markets, participants may still misreport preferences or withhold asset-state information. Future work should analyze richer strategic models, including collusion, side payments, and repeated interactions. Smart-contract security must also be examined because code vulnerabilities could undermine the governance benefits of equal-term clearing (Atzei et al., 2017; Luu et al., 2016; Xu et al., 2016).

The fourth limitation concerns empirical validation. The simulation provides controlled evidence of mechanism behavior, but real-world deployment requires collaboration with manufacturing platforms, equipment providers, and certification bodies. Future research should use anonymized digital twin exchange logs, maintenance-contract data, or supply-chain asset-token pilots to test whether observed preferences match the synthetic distributions used here. This would also support more precise estimation of welfare, liquidity, and manipulation costs.

6.4 Practical Deployment Roadmap

A realistic deployment would proceed in stages. The first stage is asset taxonomy design. Platform operators should identify which digital twin assets are exchangeable, which metadata elements are mandatory, and which contractual terms are meaningful for the target sector. For example, a discrete-parts manufacturing platform may prioritize maintenance and warranty terms, while a battery or chemical platform may prioritize compliance and sustainability terms. The taxonomy should be stable enough for repeated clearing rounds but flexible enough to incorporate new regulatory or service categories.

The second stage is evidence integration. Digital twin state should be connected to maintenance management systems, manufacturing execution systems, quality databases, energy meters, and certification repositories. The platform does not need to move all evidence on-chain. Instead, it should create verifiable links from token metadata to trusted off-chain records. This stage is technically difficult because industrial data standards, semantic models, and access policies differ across firms. Standards such as asset administration shells, OPC UA information models, and enterprise knowledge graphs can reduce this interoperability burden, but governance agreements remain necessary (Lu et al., 2023; Uhlemann et al., 2017; Xu et al., 2018).

The third stage is controlled market testing. A pilot should begin with a small set of asset classes and a limited number of trusted participants. The platform can compare ETAC with pairwise equal-term exchange and manual brokered exchange, measuring welfare, liquidity, user satisfaction, dispute frequency, and verification cost. Only after the mechanism demonstrates stable behavior should it be expanded to more participants and more granular term categories. This incremental roadmap is preferable to launching a fully open marketplace immediately, because industrial asset tokens combine software risks, physical risks, and contractual risks in a way that ordinary digital token exchanges do not.

7. Conclusion

This paper developed an equal-term exchange mechanism for industrial digital twins and tokenized manufacturing assets. The core argument is that manufacturing tokens carry contractual terms that cannot be ignored without damaging property-rights consistency, maintenance accountability, compliance continuity, and sustainability evidence. The proposed Equal-Term Asset Cycle mechanism clears only term-homogeneous exchange loops, thereby ensuring that each participant receives an asset under the same term as the one under which its own asset is released.

The simulation analysis shows that equal-term governance need not eliminate liquidity. ETAC produced no term violations while retaining high normalized welfare and a substantially better cleared-trade ratio than simple equal-term baselines. The results suggest that carefully designed cycle clearing can support industrial asset liquidity without allowing participants to shed obligations opportunistically. This finding is particularly relevant as digital twin platforms, blockchain systems, and intelligent manufacturing ecosystems converge.

Future research should extend the framework in four directions. First, richer term hierarchies should be modeled for regulated sectors. Second, privacy-preserving verification should be integrated so that platforms can validate terms without exposing sensitive twin-state data. Third, strategic analysis should examine collusion and repeated-market behavior. Fourth, empirical studies should test the mechanism using real manufacturing platform data. Equal-term exchange is not a complete solution to all tokenized manufacturing governance problems, but it provides a tractable and auditable foundation for trustworthy digital twin asset markets.

Declarations

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

The simulation dataset used in this paper was generated for methodological demonstration. The parameter table, aggregate results, and figure data are described in the manuscript. No confidential industrial platform data were used.

Author Contributions

Conceptualization, A.R. and N.H.I.; methodology, A.R., F.M., and H.Z.; simulation design, H.Z. and M.L.T.; writing-original draft, A.R. and N.H.I.; writing-review and editing, F.M. and M.L.T.; supervision, N.H.I.

References

Lu, Y. (2017a). Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration, 6, 1-10. https://doi.org/10.1016/j.jii.2017.04.005

Lu, Y. (2017b). Cyber physical system (CPS)-based Industry 4.0: A survey. Journal of Industrial Integration and Management, 2(3), 1750014. https://doi.org/10.1142/S2424862217500142

Lu, Y. (2018). Blockchain and the related issues: A review of current research topics. Journal of Management Analytics, 5(4), 231-255. https://doi.org/10.1080/23270012.2018.1516523

Lu, Y. (2019a). The blockchain: State-of-the-art and research challenges. Journal of Industrial Information Integration, 15, 80-90. https://doi.org/10.1016/j.jii.2019.04.002

Lu, Y. (2019b). Artificial intelligence: A survey on evolution, models, applications and future trends. Journal of Management Analytics, 6(1), 1-29. https://doi.org/10.1080/23270012.2019.1570365

Lu, Y., & Xu, L. D. (2019). Internet of Things (IoT) cybersecurity research: A review of current research topics. IEEE Internet of Things Journal, 6(2), 2103-2115. https://doi.org/10.1109/JIOT.2018.2869847

Lu, Y., & Zheng, X. (2020). 6G: A survey on technologies, scenarios, challenges, and the related issues. Journal of Industrial Information Integration, 19, 100158. https://doi.org/10.1016/j.jii.2020.100158

Lu, Y., Zheng, X., Li, L., & Xu, L. D. (2020). Pricing the cloud: A QoS-based auction approach. Enterprise Information Systems, 14(3), 334-351. https://doi.org/10.1080/17517575.2019.1669827

Zhang, C., & Lu, Y. (2021). Study on artificial intelligence: The state of the art and future prospects. Journal of Industrial Information Integration, 23, 100224. https://doi.org/10.1016/j.jii.2021.100224

Xu, L. D., Lu, Y., & Li, L. (2021). Embedding blockchain technology into IoT for security: A survey. IEEE Internet of Things Journal, 8(13), 10452-10473. https://doi.org/10.1109/JIOT.2021.3060508

Lu, Y. (2022). Implementing blockchain in information systems: A review. Enterprise Information Systems, 16(12), 1876-1907. https://doi.org/10.1080/17517575.2021.2008513

Zheng, X. R., & Lu, Y. (2022). Blockchain technology: Recent research and future trend. Enterprise Information Systems, 16(12), 1939895. https://doi.org/10.1080/17517575.2021.1939895

Lu, Y., Sigov, A. S., Ratkin, L., Ivanov, L. A., & Zuo, M. (2023). Quantum computing and industrial information integration: A review. Journal of Industrial Information Integration, 35, 100511. https://doi.org/10.1016/j.jii.2023.100511

Chen, Y., Lu, Y., Bulysheva, L., & Kataev, M. Y. (2024). Applications of blockchain in Industry 4.0: A review. Information Systems Frontiers, 26(5), 1715-1729. https://doi.org/10.1007/s10796-022-10248-7

Xu, R., Zhu, J., Yang, L., Lu, Y., & Xu, L. D. (2024). Decentralized finance (DeFi): A paradigm shift in the FinTech. Enterprise Information Systems, 18(9), 2397630. https://doi.org/10.1080/17517575.2024.2397630

Lu, Y., & Yang, J. (2024). Quantum financing system: A survey on quantum algorithms, potential scenarios and open research issues. Journal of Industrial Information Integration, 41, 100663. https://doi.org/10.1016/j.jii.2024.100663

Lu, Y. (2025). The current status and developing trends of Industry 4.0: A review. Information Systems Frontiers, 27(1), 215-234. https://doi.org/10.1007/s10796-021-10221-w

Kou, G., & Lu, Y. (2025). FinTech: A literature review of emerging financial technologies and applications. Financial Innovation, 11(1), 1-34. https://doi.org/10.1186/s40854-024-00668-6

Wu, H. P., Liu, Z., Dong, H. Y., Lu, Y., & Xu, L. D. (2025). Revolutionizing internal auditing: Harnessing the power of blockchain. Enterprise Information Systems, 19(1-2), 2448003. https://doi.org/10.1080/17517575.2024.2448003

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415. https://doi.org/10.1109/TII.2018.2873186

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. Procedia Manufacturing, 11, 939-948. https://doi.org/10.1016/j.promfg.2017.07.198

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952-108971. https://doi.org/10.1109/ACCESS.2020.2998358

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison. IEEE Access, 6, 3585-3593. https://doi.org/10.1109/ACCESS.2018.2793265

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94, 3563-3576. https://doi.org/10.1007/s00170-017-0233-1

Cheng, J., Zhang, H., Tao, F., & Juang, C. F. (2020). DT-II: Digital twin enhanced industrial Internet reference framework towards smart manufacturing. Robotics and Computer-Integrated Manufacturing, 62, 101881. https://doi.org/10.1016/j.rcim.2019.101881

Uhlemann, T. H. J., Lehmann, C., & Steinhilper, R. (2017). The digital twin: Realizing cyber-physical production systems for Industry 4.0. Procedia CIRP, 61, 335-340. https://doi.org/10.1016/j.procir.2016.11.152

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3, 18-23. https://doi.org/10.1016/j.mfglet.2014.12.001

Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. Procedia CIRP, 17, 9-13. https://doi.org/10.1016/j.procir.2014.03.115

Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: State of the art and future trends. International Journal of Production Research, 56(8), 2941-2962. https://doi.org/10.1080/00207543.2018.1444806

Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of Industry 4.0: A review. Engineering, 3(5), 616-630. https://doi.org/10.1016/J.ENG.2017.05.015

Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing smart factory of Industrie 4.0: An outlook. International Journal of Distributed Sensor Networks, 12(1), 3159805. https://doi.org/10.1155/2016/3159805

Ivanov, D., & Dolgui, A. (2020). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. International Journal of Production Research, 59(12), 3415-3428. https://doi.org/10.1080/00207543.2020.1796860

Tao, F., & Zhang, M. (2017). Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing. IEEE Access, 5, 20418-20427. https://doi.org/10.1109/ACCESS.2017.2756069

Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. (2017). A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. IEEE Access, 5, 26901-26911. https://doi.org/10.1109/ACCESS.2017.2766453

Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of digital twin applications in manufacturing. Computers in Industry, 113, 103130. https://doi.org/10.1016/j.compind.2019.103130

Szabo, N. (1997). Formalizing and securing relationships on public networks. First Monday, 2(9). https://doi.org/10.5210/fm.v2i9.548

Christidis, K., & Devetsikiotis, M. (2016). Blockchains and smart contracts for the Internet of Things. IEEE Access, 4, 2292-2303. https://doi.org/10.1109/ACCESS.2016.2566339

Yli-Huumo, J., Ko, D., Choi, S., Park, S., & Smolander, K. (2016). Where is current research on blockchain technology? A systematic review. PLoS ONE, 11(10), e0163477. https://doi.org/10.1371/journal.pone.0163477

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics and Informatics, 36, 55-81. https://doi.org/10.1016/j.tele.2018.11.006

Dutta, P., Choi, T. M., Somani, S., & Butala, R. (2020). Blockchain technology in supply chain operations: Applications, challenges and research opportunities. Transportation Research Part E, 142, 102067. https://doi.org/10.1016/j.tre.2020.102067

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117-2135. https://doi.org/10.1080/00207543.2018.1533261

Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management, 39, 80-89. https://doi.org/10.1016/j.ijinfomgt.2017.12.005

Wang, Y., Singgih, M., Wang, J., & Rit, M. (2019). Making sense of blockchain technology: How will it transform supply chains? International Journal of Production Economics, 211, 221-236. https://doi.org/10.1016/j.ijpe.2019.02.002

Treiblmaier, H. (2018). The impact of the blockchain on the supply chain: A theory-based research framework and a call for action. Supply Chain Management: An International Journal, 23(6), 545-559. https://doi.org/10.1108/SCM-01-2018-0029

Queiroz, M. M., & Wamba, S. F. (2019). Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA. International Journal of Information Management, 46, 70-82. https://doi.org/10.1016/j.ijinfomgt.2018.11.021

Pournader, M., Shi, Y., Seuring, S., & Koh, S. C. L. (2020). Blockchain applications in supply chains, transport and logistics: A systematic review of the literature. International Journal of Production Research, 58(7), 2063-2081. https://doi.org/10.1080/00207543.2019.1650976

Macrinici, D., Cartofeanu, C., & Gao, S. (2018). Smart contract applications within blockchain technology: A systematic mapping study. Telematics and Informatics, 35(8), 2337-2354. https://doi.org/10.1016/j.tele.2018.10.004

Alharby, M., Aldweesh, A., & van Moorsel, A. (2018). Blockchain-based smart contracts: A systematic mapping study of academic research. 2018 International Conference on Cloud Computing, Big Data and Blockchain, 1-6. https://doi.org/10.1109/ICCBB.2018.8756390

Atzei, N., Bartoletti, M., & Cimoli, T. (2017). A survey of attacks on Ethereum smart contracts. Principles of Security and Trust, 164-186. https://doi.org/10.1007/978-3-662-54455-6_8

Luu, L., Chu, D. H., Olickel, H., Saxena, P., & Hobor, A. (2016). Making smart contracts smarter. Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security, 254-269. https://doi.org/10.1145/2976749.2978309

Xu, X., Pautasso, C., Zhu, L., Gramoli, V., Ponomarev, A., Tran, A. B., & Chen, S. (2016). The blockchain as a software connector. 2016 13th Working IEEE/IFIP Conference on Software Architecture, 182-191. https://doi.org/10.1109/WICSA.2016.21

Cong, L. W., & He, Z. (2019). Blockchain disruption and smart contracts. The Review of Financial Studies, 32(5), 1754-1797. https://doi.org/10.1093/rfs/hhz007

Catalini, C., & Gans, J. S. (2020). Some simple economics of the blockchain. Communications of the ACM, 63(7), 80-90. https://doi.org/10.1145/3359552

Howell, S. T., Niessner, M., & Yermack, D. (2020). Initial coin offerings: Financing growth with cryptocurrency token sales. The Review of Financial Studies, 33(9), 3925-3974. https://doi.org/10.1093/rfs/hhz131

Schar, F. (2021). Decentralized finance: On blockchain- and smart contract-based financial markets. Federal Reserve Bank of St. Louis Review, 103(2), 153-174. https://doi.org/10.20955/r.103.153-74

Miers, I., Garman, C., Green, M., & Rubin, A. D. (2013). Zerocoin: Anonymous distributed e-cash from Bitcoin. 2013 IEEE Symposium on Security and Privacy, 397-411. https://doi.org/10.1109/SP.2013.34

Ben-Sasson, E., Chiesa, A., Garman, C., Green, M., Miers, I., Tromer, E., & Virza, M. (2014). Zerocash: Decentralized anonymous payments from Bitcoin. 2014 IEEE Symposium on Security and Privacy, 459-474. https://doi.org/10.1109/SP.2014.36

Li, J., & Mann, W. (2020). Initial coin offerings and platform building. The Review of Financial Studies, 33(9), 3763-3798. https://doi.org/10.1093/rfs/hhz145

Chod, J., Trichakis, N., Tsoukalas, G., Aspegren, H., & Weber, M. (2020). On the financing benefits of supply chain transparency and blockchain adoption. Management Science, 66(10), 4378-4396. https://doi.org/10.1287/mnsc.2019.3434

De Filippi, P., & Hassan, S. (2016). Blockchain technology as a regulatory technology: From code is law to law is code. First Monday, 21(12). https://doi.org/10.5210/fm.v21i12.7113

Bahga, A., & Madisetti, V. K. (2016). Blockchain platform for Industrial Internet of Things. Journal of Software Engineering and Applications, 9(10), 533-546. https://doi.org/10.4236/jsea.2016.910036

Wang, Q., Zhu, X., Ni, Y., Gu, L., & Zhu, H. (2020). Blockchain for the IoT and industrial IoT: A review. Internet of Things, 10, 100081. https://doi.org/10.1016/j.iot.2019.100081

Abdulkadiroglu, A., & Sonmez, T. (1999). House allocation with existing tenants. Journal of Economic Theory, 88(2), 233-260. https://doi.org/10.1006/jeth.1999.2553

Papai, S. (2000). Strategyproof assignment by hierarchical exchange. Econometrica, 68(6), 1403-1434. https://doi.org/10.1111/1468-0262.00166

Ergin, H. I. (2000). Consistency in house allocation problems. Journal of Mathematical Economics, 34(1), 77-97. https://doi.org/10.1016/S0304-4068(99)00038-5

Pycia, M., & Unver, M. U. (2017). Incentive compatible allocation and exchange of discrete resources. Theoretical Economics, 12(1), 287-329. https://doi.org/10.3982/TE2201

Svensson, L. G. (1999). Strategy-proof allocation of indivisible goods. Social Choice and Welfare, 16, 557-567. https://doi.org/10.1007/s003550050160

Budish, E. (2011). The combinatorial assignment problem: Approximate competitive equilibrium from equal incomes. Journal of Political Economy, 119(6), 1061-1103. https://doi.org/10.1086/664613

Budish, E., Che, Y. K., Kojima, F., & Milgrom, P. (2013). Designing random allocation mechanisms: Theory and applications. American Economic Review, 103(2), 585-623. https://doi.org/10.1257/aer.103.2.585

Abdulkadiroglu, A., & Sonmez, T. (2003). School choice: A mechanism design approach. American Economic Review, 93(3), 729-747. https://doi.org/10.1257/000282803322157061

Myerson, R. B. (1981). Optimal auction design. Mathematics of Operations Research, 6(1), 58-73. https://doi.org/10.1287/moor.6.1.58

Vickrey, W. (1961). Counterspeculation, auctions, and competitive sealed tenders. The Journal of Finance, 16(1), 8-37. https://doi.org/10.1111/j.1540-6261.1961.tb02789.x

Nisan, N., & Ronen, A. (2001). Algorithmic mechanism design. Games and Economic Behavior, 35(1-2), 166-196. https://doi.org/10.1006/game.1999.0790

Bergemann, D., & Morris, S. (2005). Robust mechanism design. Econometrica, 73(6), 1771-1813. https://doi.org/10.1111/j.1468-0262.2005.00638.x

Maskin, E. (1999). Nash equilibrium and welfare optimality. The Review of Economic Studies, 66(1), 23-38. https://doi.org/10.1111/1467-937X.00076

Athey, S., & Segal, I. (2013). An efficient dynamic mechanism. Econometrica, 81(6), 2463-2485. https://doi.org/10.3982/ECTA6995

Milgrom, P., & Segal, I. (2002). Envelope theorems for arbitrary choice sets. Econometrica, 70(2), 583-601. https://doi.org/10.1111/1468-0262.00296

Klemperer, P. (1999). Auction theory: A guide to the literature. Journal of Economic Surveys, 13(3), 227-286. https://doi.org/10.1111/1467-6419.00083

Gul, F., & Stacchetti, E. (1999). Walrasian equilibrium with gross substitutes. Journal of Economic Theory, 87(1), 95-124. https://doi.org/10.1006/jeth.1999.2531