Research Paper Series

Atomic Settlement: Potential Implications of DLT-based Compressed Settlement Cycles

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Executive Summary

The financial sector is undergoing a transition toward shorter settlement cycles, led by the U.S. adoption of a T+1 settlement cycle and other economies, such as the EU and UK, scheduling their transactions accordingly. Within this context, Atomic Settlement, enabled by Distributed Ledger Technology (DLT), makes it possible to further reduce settlement timing and enables the simultaneous settlement of transactions. While the introduction of these technologies could enhance market efficiency and mitigate counterparty risk, they also pose challenges that may require a restructuring of market infrastructure and the business models of financial players. This paper aims to explore the opportunities presented by a DLT-based Atomic Settlement cycle, while also analyzing the potential challenges to financial markets.

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Atomic Settlement: Potential Implications of DLT-based Compressed Settlement Cycles

Martina Arcodia Valerio Ciminelli Nicola Mazzoni
Caterina Papetti

Efficient and timely post-trade settlement processes play a key role in reducing systemic risks and fostering resilient financial markets. Shortening settlement cycles leads to lower counterparty risk, greater liquidity, and fewer transaction failures. Considering this, in May 2024, the US and Canada adopted a T+1 post-trade cycle, shifting from the classic T+2 framework, with several benefits in terms of reducing failure rates and margin requirements. Following the results of these countries, others, such as the UK, Switzerland, and the EU, started planning to move to a shorter and more aligned settlement cycle in the coming years. Furthermore, with the evolution of financial innovation, the feasibility of adopting a simultaneous settlement cycle has been made possible by leveraging DLT and smart contracts, with the potential to further reduce counterparty risk, minimize the need for intermediaries, and significantly lower operational costs and capital requirements. Atomic settlement represents the market application of a simultaneous settlement mechanism where the exchange of assets between parties occurs simultaneously and irrevocably, eliminating settlement risk. However, as outlined by Lee, Martin, and Muller [19] distinguishing between instant and atomic settlement remains crucial, as they address different aspects of settlement efficiency and risk management. Specifically, the instant settlement does not incorporate atomic features and refers to a transaction process in which trades are settled immediately after execution. However, it does not guarantee atomicity-meaning that both parties may not receive their assets at the same moment. While simultaneous atomic cycles could enhance efficiency and mitigate risks, a non-atomic instant settlement mechanism could severely impact market integrity, requiring even greater oversight by central intermediaries. The analysis will first focus on explaining the current evolution of settlement cycles and the benefits a shorter cycle could bring to economic systems, particularly exploring the US's shortened cycle and the EU's next steps. The second part will provide a brief overview of how DLTs and related environments work. Finally, the research will highlight the characteristics of Atomic Settlement and analyze the potential impacts on the financial market infrastructure of the adoption of an Atomic Settlement Cycle that relies on DLTs.

1. The Evolution of Settlement Cycles

Settlement plays a crucial role in the current financial market infrastructure. In financial transactions, counterparties fulfill their contractual obligations through the exchange of securities and funds, which is executed via settlement operations. In financial markets, trading and settlement typically occur at different times. The period between the trade date ("T") and the settlement date is known as the settlement cycle. Settlement plays a crucial role in financial transactions by ensuring an efficient, accurate, and secure exchange of assets and funds. This process serves two key functions:

- **Reduction of Counterparty Risk:** it ensures that both investors and institutions receive what was agreed upon, reducing the risk of failed deliveries or counterparty default.
- **Financial System Stability:** a well-functioning settlement system helps reduce credit and counterparty risks, helping prevent systemic crises and preserving market trust.

Several parties are involved in the settlement process, including:

- **Transaction Counterparties:** investors, financial institutions, and traders;
- **Financial Intermediaries:** brokers, custodian banks, and clearinghouses that facilitate settlement;
- **Central Securities Depositories (CSDs):** institutions responsible for safekeeping and settlement of financial instruments.

Settlement systems have evolved significantly over time to adapt to the increasing complexity and pace of financial markets. The shift towards digital systems has enabled a reduction in both settlement times and operational costs. Additionally, mechanisms like netting[1] have optimized liquidity management by minimizing the number of required transactions. The introduction of clearinghouses has been pivotal in automating the settlement process, improving security, and mitigating settlement risks. A quicker settlement cycle allows market participants to reallocate capital and securities more efficiently, improving overall market liquidity. In a T+n settlement model (where "n" refers to the number of business days until settlement), investors cannot reinvest or access funds until the transaction is finally finalized. Reducing this cycle helps financial institutions optimize their operations and improve market efficiency. In recent years, many financial markets have increasingly shortened the settlement cycle. In May 2024, the U.S. shifted from a T+2 to a T+1 settlement cycle, while European regulators and market participants are considering a similar transition to align with global best practices. Looking ahead, emerging technologies like blockchain and distributed ledger technology (DLT) can deeply modify the current financial market infrastructure affecting the future of the settlement cycles. These technologies could make settlement faster, more transparent, and more secure, minimizing errors and reducing the risk of fraud. Over time, they could redefine how financial transactions are settled, leading to the adoption of real-time settlement solutions.

1.1 The U.S. Model: from T+2 to T+1

In 2024, the U.S. officially moved to a T+1 settlement cycle, meaning transactions are settled one business day after the trade date. Historically, the settlement period was T+5, meaning transactions were completed five business days after execution. This extended timeframe was necessary because investors had to physically deliver stock certificates, requiring sufficient time for processing and payment transfers. Over time, advances in technology and risk mitigation efforts have progressively shortened this timeframe. The Securities and Exchange Commission (SEC) first reduced the settlement cycle to T+3 in the 1990s and then to T+2 in 2017. In May 2024, after extensive consultations and technological upgrades, the U.S., alongside countries like Canada and Mexico, transitioned to a T+1 settlement cycle. The timeline of this transition is as follows:

- **February 2022:** the SEC began a review of the settlement cycle and gathered feedback from the financial sector.
- **February 2023:** the SEC officially announced its decision to shorten the settlement cycle from T+2 to T+1, setting May 28 2024, as the implementation date.
- **May 2023:** major financial institutions began operational testing to prepare for the new standard.

[1] Netting is a process used in the financial sector that, through a compensation system, allows for the reduction in the number and value of transactions to be settled between two or more counterparties. Instead of conducting multiple separate payments or exchanges, the parties agree on a "net balance" to be settled, which represents the total amount one party owes to the other after offsetting all reciprocal amounts or securities. Netting can involve two counterparties, referred to as bilateral netting, or more than two counterparties, referred to as multilateral netting.

- **December 2023-April 2024:** simulations and tests were conducted to ensure the resilience of the new system.
- **May 2024:** the T+1 settlement cycle officially takes effect for most U.S. markets transactions.

This shift marks a significant milestone, driven by technological evolution and increasing trade volumes. Under T+1, if an investor sells shares on a Wednesday, the transaction will settle the following Thursday, assuming it's a business day. This means the securities will be officially transferred to the buyer's account and funds to the seller's account one business day after execution. The adoption of T+1 has required market participants to accelerate operational timelines:

- **Order Submission:** participants must submit transaction details (buy/sell parties, quantities, etc.) by 7:00 PM (Eastern Time) on the trade date (T+0).
- **Clearing Discrepancy Resolution:** any discrepancies must be resolved by the end of the same trading day (T+0).
- **Transaction Confirmation:** transactions must be confirmed by the end of the trading day (T+0), with a suggested industry deadline of 9:00 PM (Eastern Time).

The main goals and benefits of this shorter settlement cycle include:

- **Mitigation of Counterparty and Market Risk:** the faster settlement minimizes exposure to insolvency risks between parties.
- **Improved Liquidity and Market Efficiency:** a faster settlement allows investors to reinvest capital more quickly.
- **Adaptation to Technological Advancements:** the reduction in settlement time has been made possible by improvements in digital infrastructure.
- **Increased Transparency, Speed, and Security:** a faster cycle increases predictability and reduces operational inefficiencies.

Despite the benefits, transitioning to T+1 has also introduced several challenges:

- **Post-Trade Infrastructure Adjustment:** financial institutions needed to update their systems to handle the new cycle.
- **Increased Operational Efficiency Requirements:** the reduced settlement time demands greater precision in clearing and settlement processes.
- **Impact on International Participants:** foreign investors, operating across different time zones, must adjust to tighter timeframes to complete transactions.

The following are the main performance indicators observed in the first days of operation of the T+1 settlement cycle, with reference to the affirmation rates, fail rates, and the impact on the clearing fund. The analysis highlights the variations compared to the previous T+2 system and the related implications for market efficiency and stability [9].

- **Affirmation Rates (ref. Figure 1):** the data shows that the transition to T+1 has significantly improved affirmation rates across various market segments. The overall affirmation rate has increased from 73% (January 2024) to 94.55% (May 29, 2024), with particularly notable increases in the custodian/investment manager segment (+33.29 percentage points) and in prime brokers (+17.6 percentage points).
- **Fail Rates (ref. Figure 2):** with the shift to T+1, the transaction fail rate has decreased, with the CNS Fail Rate dropping from 2.01% to 1.90%, and the DTC Non-CNS Fails reduced from 3.24% to 2.92%. This indicates greater efficiency in the settlement process, reducing the risk of incomplete transactions.

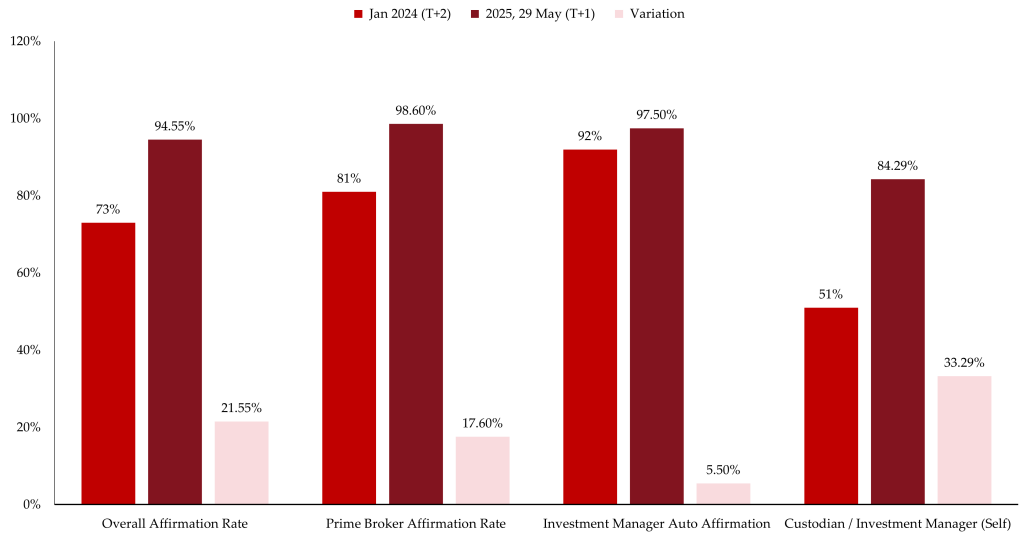

FIGURE 1: Affirmation Rate Improvement

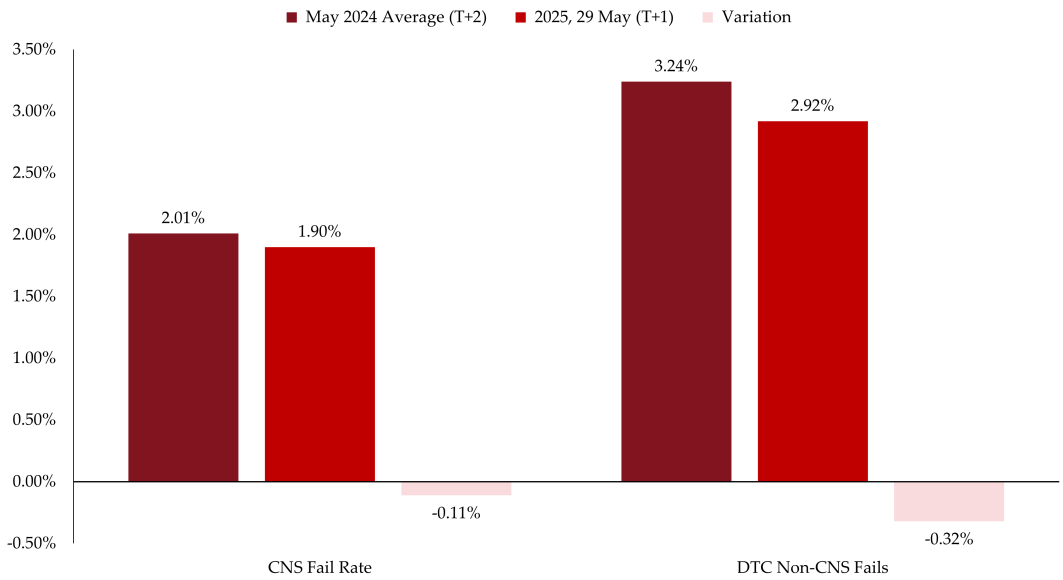

FIGURE 2: Fail Rate Reduction

- **Clearing Fund Impacts (ref. Figure 3):** the transition to T+1 has led to a significant reduction in the margin requirements for clearing, with the NSCC Clearing Fund decreasing by 29% (-3.7$ billion) from the past quarterly average of 12.8 $ billion, and by 25% (-3.1$ billion) from the past month average value of 12.2$ billion. This increase in efficiency helps improve the overall liquidity of the market.

Overall, in the initial months following implementation, several early trends have emerged:

- **Reduction in Default Risk:** the shorter exposure period effectively reduced the risk of default in transactions.
- **Improved Liquidity Management:** market participants have reported faster transaction settlements and more efficient capital use.
- **Initial Adjustment Costs:** many institutions have faced significant costs to update their systems, although the long-term benefits are expected to outweigh these costs.
- **Operational Challenges for International Investors:** foreign investors, especially in Europe,

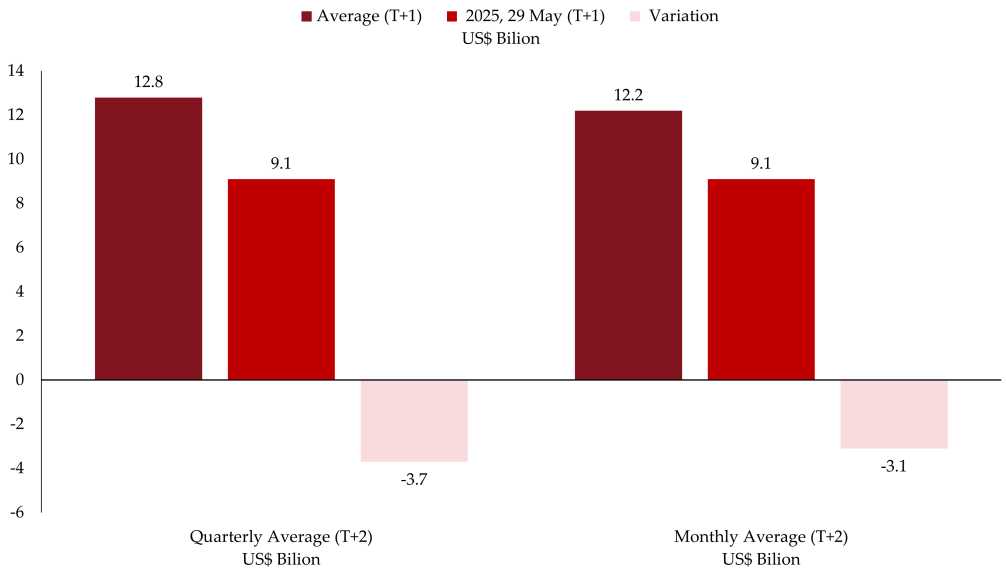

FIGURE 3: Margins Reduction

have faced difficulties due to the discrepancy between the U.S. T+1 cycle and the T+2 cycle in Europe. This has increased trading costs and reduced returns [21].

The success of T+1 implementation has sparked discussions about further reducing settlement times to T+0 settlement. With emerging technologies such as blockchain and asset tokenization, the financial market may move toward a nearly simultaneous settlement cycle in the near future. The full impact of the T+1 transition will continue to be assessed as financial institutions adapt to the new system, and more data will be collected on its effects on global markets.

1.2 European Settlement Model

In the past, the settlement cycle of securities transactions in the European Union was highly fragmented across different countries, making cross-border transactions costly and inefficient. This highlighted the need to harmonize securities settlement cycles to improve efficiency and mitigate financial market risks. To address this challenge, over the past years, the European settlement cycles have already undergone significant evolution:

- **October 2014:** the European settlement cycle moved from T+3 to T+2, a change that improved market efficiency and reduced counterparty risk. This shift was driven by the adoption of the CSDR (Central Securities Depositories Regulation)[2], which established a standardized settlement cycle across European member states, eliminating differences between countries. One of the key objectives of this move was to reduce systemic risk, achieved by creating a uniform system for securities depositories throughout the European Union. However, the adoption of the CSDR also posed some challenges. Businesses had to adapt to new technological and operational systems, which impacted costs and implementation timelines. Additionally, the need to comply with a uniform regulation required coordinated efforts across different jurisdictions, with some market participants initially struggling to adapt. Despite these challenges, the overall results have been positive, with greater stability and efficiency [18].
- **June 2015:** following the adoption of the CSDR and the shift to T+2, the European Union subsequently implemented the TARGET2-Securities (T2S) system. T2S is a pan-European platform for settling securities transactions across the euro area in a centralized and standardized

[2]The CSDR is an EU regulation that establishes a regulatory framework for Central Securities Depositories (CSDs), aimed at improving the security and efficiency of securities settlement operations. It was officially adopted by the European Parliament and the Council of the European Union on July 23, 2014, and became immediately binding across all EU member states. The CSDR introduced measures to harmonize settlement cycles, reduce operational risks, and enhance transparency, making cross-border transactions safer and contributing to the stability of the European financial system.

way. T2S marked a significant step toward integrating and harmonizing European markets by reducing settlement costs, improving transparency, and minimizing operational and systemic risks. Before the introduction of T2S, the settlement of securities transactions was fragmented through various national central securities depositories (CSDs), with operational differences and high costs for cross-border transactions. The platform made it possible to settle securities transactions more quickly and efficiently, laying the foundation for the future harmonization of the settlement cycle. The primary objective of T2S has been to centralize and standardize the settlement of securities transactions across the euro area, reducing operational complexity and lowering settlement costs for both domestic and cross-border transactions. Settlement occurs according to the Delivery versus Payment (DvP) principle, where the delivery of securities and payment happen simultaneously, reducing counterparty risk. Figure 4 summarizes how the platform operates.

After the US shift to a T+1 environment, Europe started to evaluate the feasibility of a compressed settlement cycle. As a result, analyses are underway to evaluate the Key reports published by the European T+1 Task Force in October 2024 and by ESMA in November 2024.

- **European T+1 Task Force Report:**[2] the report published in October 2023 by the European T+1 Task Force[14] laid the groundwork for transitioning to a T+1 settlement cycle in European financial markets. This document provided a detailed analysis of the regulatory, technical, and operational changes necessary to ensure a smooth and secure transition, outlining the key objectives and recommendations to align European practices with international standards. Central to this effort is coordination among stakeholders to enhance market efficiency, minimize risks associated with an uncoordinated transition, and align European practices with global standards. Key preliminary activities for accelerating settlement include: updating regulations, revisiting market standards, improving pre-settlement processes to optimize resources and standardize settlement instructions, identifying potential post-trade inefficiencies, and implementing necessary adjustments to facilitate the adoption of T+1. The report highlights the need for a structured transition period, estimated to be between 24 and 36 months, reflecting the complexity of the project. Furthermore, it provides an essential contribution to discussions led by the European Securities and Markets Authority (ESMA) for future implementation stages.

- **ESMA Report:**[15] in November 2024, ESMA published a report emphasizing the need for thorough market preparation to implement a shift in the European settlement cycle. The report stressed that such a significant change could not occur without effective coordination among all stakeholders. Therefore, ESMA recommends a well-planned transition period, during which in-depth testing will be conducted to ensure that settlement infrastructures can operate seamlessly. Other important points discussed in the report include:

  - **Technological Adaptation:** post-trading infrastructures, including central securities depositories and settlement platforms, must invest in upgrading their systems to support the shorter settlement cycle. These technological updates are crucial to prevent delays and inefficiencies that could compromise market stability.
  - **Regulatory Alignment at the European Level:** since different member states have adopted varying practices and regulations, ESMA insists on reviewing existing regulations to ensure consistency and harmonization across EU financial markets. Without proper regulatory coordination, the risk of fragmentation could increase, creating new operational hurdles.
  - **FX Transaction Management (ref. Figure 5):** moving to T+1 would compress the time for currency conversion, which could create challenges in managing liquidity and determining settlement timings. ESMA suggests reviewing current procedures to ensure the FX market can adapt without negatively impacting financial stability.
  - **Post-Implementation Monitoring:** once the T+1 settlement cycle is introduced, a monitoring system will be necessary to evaluate the actual effects of the transition and identify and address any issues without causing instability.

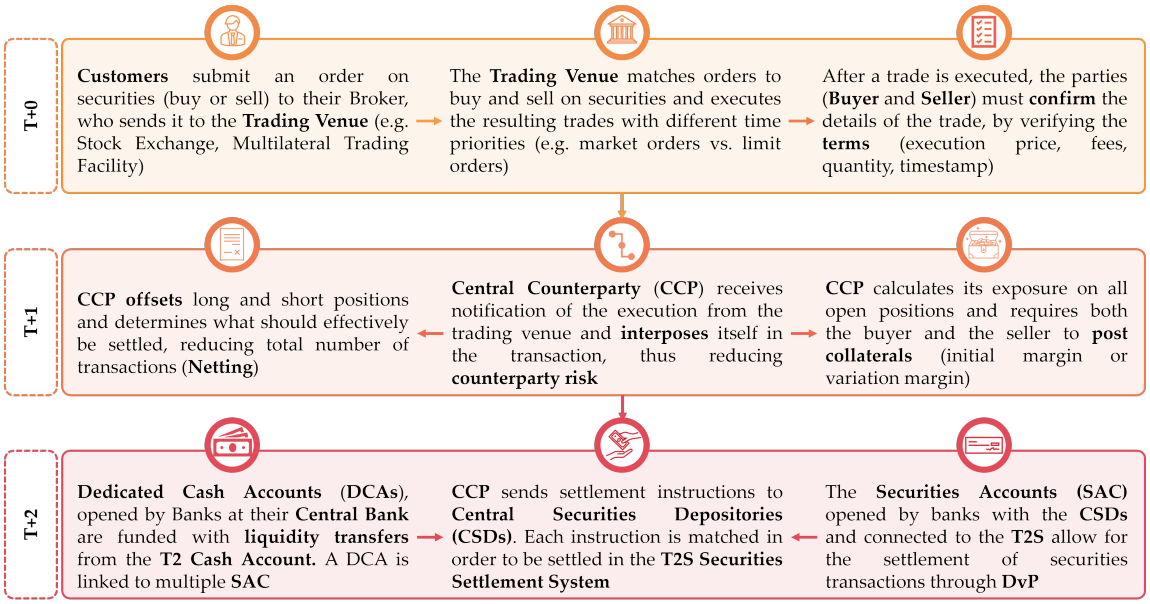

FIGURE 4: Target-2-Securities: How Does it Work[2]

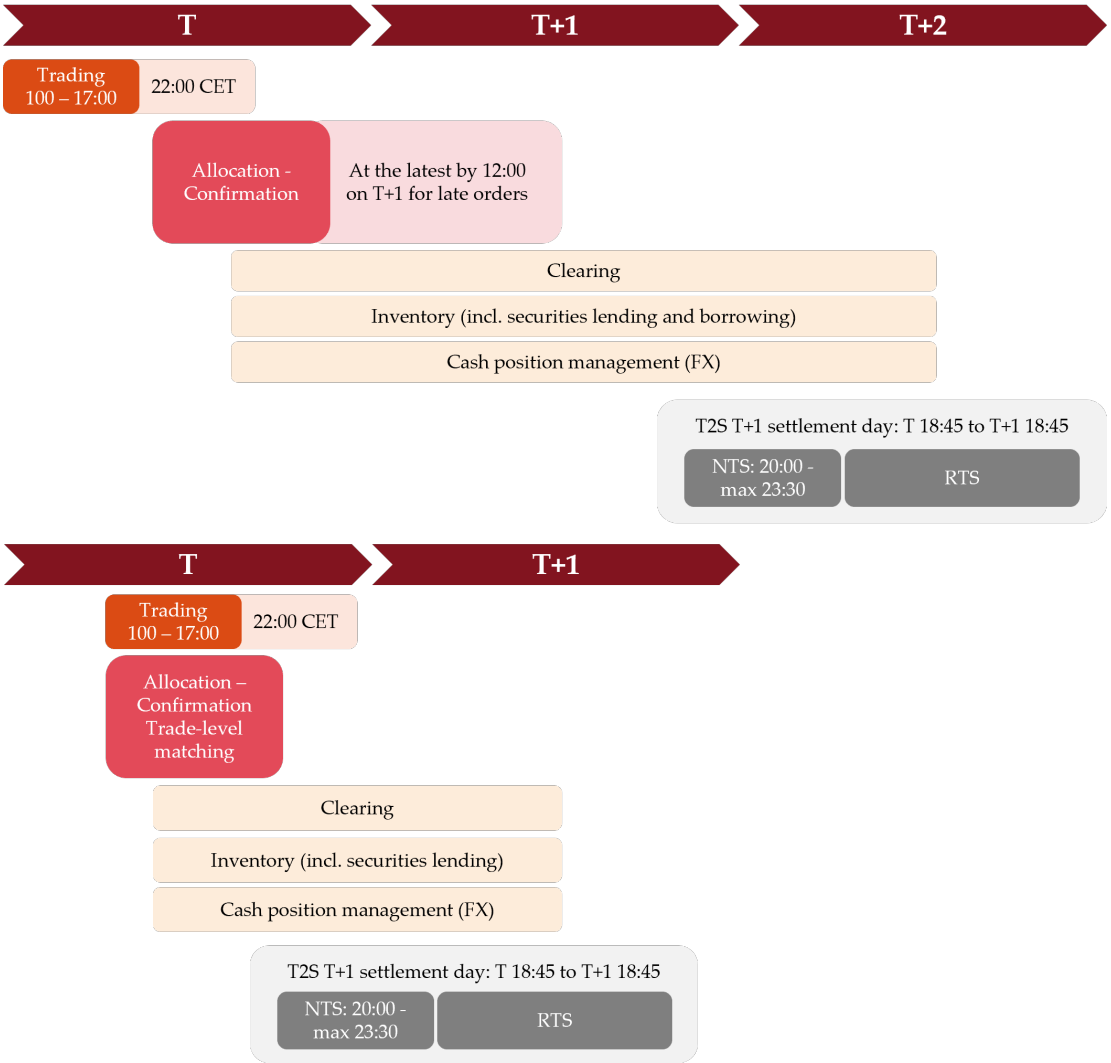

FIGURE 5: Potential Evolution Form T+2 to T+1[15]

1.2.1 European Commission Proposal

Based on these analyses and recommendations, On February 12, 2025, the Commission published a proposal[13] to reduce the settlement cycle to T+1 by October 11, 2027. Key challenges identified include:

- **Infrastructure Adaptation:** market participants will need to update their technological systems to support the accelerated settlement process.
- **Operational Risk Management:** the reduced settlement time may increase the likelihood of settlement errors, requiring more effective solutions to mitigate risks.
- **Harmonization Across Member States:** ensuring a coordinated transition is crucial to prevent fragmentation and regulatory misalignment.

The proposed amendment to EU Regulation No. 909/2014 (CSDR) aims to shorten the settlement cycle for securities transactions to just one business day (T+1), enhancing the efficiency of settlement services and strengthening the competitiveness of European financial markets. Both the European Commission's analysis and ESMA's report highlight the long-term benefits of this transition, including increased automation, reduced risk exposure, lower margin requirements, and the elimination of costs associated with misalignment across jurisdictions. Over time, these advantages are expected to exceed the initial investment needed for implementation. While T+1 settlement is already technically and legally feasible within the EU, the complexity of its financial markets - due to the diversity of participants and systems - makes a coordinated approach at the EU level essential. A harmonized transition will prevent market fragmentation and provide legal certainty for financial operators. Under the principle of subsidiarity established by Article 5 of the Treaty on the European Union, EU action is essential to facilitate a smooth and timely transition, helping the EU remain competitive as global markets shift to faster settlement cycles. The adoption of T+1 in the EU would offer benefits similar to those already observed in the US, including:

- **Greater Capital Efficiency:** shortening the settlement period would enable financial institutions to utilize available funds more quickly, optimizing cash flows.
- **Lower Counterparty Risk:** with less time between trade and settlement, the risk of default is reduced, enhancing market stability.
- **Increased International Competitiveness:** aligning with the U.S. and other advanced markets would be crucial for attracting global investment and ensuring European markets remain competitive.
- **Reduced Margin Requirements:** the shorter settlement cycle will reduce the need for margin maintenance with central counterparties (CCPs), positively impacting operational costs and market competitiveness.
- **Fewer Settlement Failures:** the adoption of T+1 will encourage more automation and standardization, reducing settlement errors and related penalties.

The next steps for the transition to T+1 in the EU are as follows:

- **2025-2026:** discussion of the proposal in Parliament and Council;
- **2026:** approval of the regulation;
- **2026-2027:** transition period and operational adjustments;
- **Ocotber 2027:** official implementation of T+1.

The transition to T+1 is an important step for the EU, aiming to enhance efficiency, liquidity, and global competitiveness. However, its implementation will require careful coordination between regulators, financial infrastructures, and market participants, along with significant technological investments. The success of this transition will depend on the EU's ability to overcome operational challenges and ensure appropriate regulatory adaptation.

1.3 T+0 and Beyond: the India Case and the Future of Settlement Cycles

India is emerging as one of the most dynamic and innovative financial markets globally, driven by a strong commitment to modernizing its trading and settlement infrastructure. After successfully implementing the T+1 settlement cycle in 2023, the country introduced a voluntary T+0 option, further solidifying its position at the forefront of market efficiency. A key factor enabling India's adoption of T+0 is its robust digital infrastructure. The Unified Payments Interface (UPI), which revolutionized instant payments in the country, has demonstrated the feasibility of real-time financial operations, creating a favorable environment for accelerating settlement cycles in capital markets. Additionally, India is home to two of the world's largest and most sophisticated central securities depositories-the National Securities Depository Limited (NSDL) and the Central Depository Services Limited (CDSL)-which play a crucial role in ensuring transaction efficiency and security. With T+0, trades are executed and settled on the same day, eliminating the settlement risk associated with longer cycles. This shift not only mitigates counterparty risk but also enhances overall market liquidity. Moreover, adopting T+0 could increase the attractiveness of India's stock market for global investors by providing faster and more efficient access to capital, enabling more dynamic investment strategies. The success of this initiative could position India as a global benchmark for simultaneous settlement, paving the way for even more advanced models like atomic settlement. In this scenario, trade execution and settlement occur simultaneously, reducing settlement failures and further improving market efficiency. If widely adopted, T+0 and atomic cycles could influence other emerging economies and developed markets to reconsider their settlement cycles to remain competitive in an increasingly fast-paced and digital financial landscape.

2. Digital Ledger Technologies

As financial transactions continue to evolve, traditional settlement mechanisms often face delays, counterparty risks, and inefficiencies. Atomic settlement is a DLT-based process that ensures the simultaneous exchange of assets without intermediaries and relies heavily on the principles of DLT to function securely and efficiently. Understanding the functioning of Distributed Ledger Technologies (DLTs) is therefore essential for grasping the impact that introducing a DLT structure fostering an atomic settlement cycle could have on the current financial market infrastructure. DLT is a decentralized system that enables the secure and transparent recording, sharing, and synchronization of data across multiple participants. Unlike traditional centralized databases, where a single entity controls the data, DLT ensures that information is distributed in identical copies between the nodes that comprise the network, enhancing security, transparency, and resilience. One key feature of DLTs is that ledger information is continuously and simultaneously updated across all network nodes with every transaction. DLT serves as the foundation for various applications, including blockchain technology, cryptocurrencies, and decentralized finance (DeFi). DLT exhibits several key characteristics that differentiate it from conventional centralized systems:

- **Decentralization:** unlike traditional ledgers maintained by a central authority, DLT distributes data across multiple nodes and each participant in the network maintains a copy of the ledger, reducing the risk of a single point of failure.
- **Transparency and Immutability:** every participant can see each transaction recorded on a DLT and every node, once data is validated, contains the same immutable information.
- **Consensus Mechanism:** DLT operates through Consensus Mechanisms, ensuring that all participants agree on the state of the ledger. For example, some common consensus algorithms include Proof of Work (PoW), Proof of Stake (PoS), and Byzantine Fault Tolerance (BFT).
- **Cryptography:** DLT uses cryptographic techniques to secure transactions and prevent unauthorized modifications. Digital signatures and encryption ensure data integrity and authenticity.

2.1 How the Ledger Works

A distributed ledger is a digital record of transactions maintained across multiple nodes in a decentralized network. Unlike traditional centralized ledgers, where a single entity has control,

DLT ensures that all participants have access to an identical copy of the ledger, reducing the risk of fraud and data manipulation. Initially, a user initiates a transaction, which is broadcast to the network and verified by multiple nodes. Once verified, the transaction is added to the ledger through a consensus mechanism. Finally, the updated ledger is synchronized across all participating nodes. This decentralized approach enhances security and transparency, as no single entity can alter the ledger without network-wide agreement. Different types of distributed ledgers exist, each with unique structures and functionalities. In Blockchain (e.g. Bitcoin, Ethereum, Hyperledger) transactions are grouped into blocks, which are cryptographically linked in a sequential chain. Each block contains a reference to the previous block, ensuring immutability. In Directed Acyclic Graphs (DAGs) (IOTA, Hedera Hashgraph) transactions are structured in a graph rather than blocks. Instead of miners, users confirm previous transactions, reducing energy consumption. Hybrid Ledgers combine elements of blockchain and DAG to optimize scalability, security, and speed. They are used for enterprise applications requiring both transparency and privacy.

2.2 Consensus Mechanism

A key aspect of any distributed ledger (DLT) is how participants agree on transaction validity. Without a central authority to verify and approve transactions, decentralized networks rely on consensus mechanisms to maintain integrity and security. These mechanisms ensure all ledger copies stay synchronized and only legitimate transactions are recorded. A major challenge in decentralized environments is coordinating participants to agree on updates. This issue relates to the Byzantine Generals Problem, where some nodes may act maliciously or provide incorrect information, risking network inconsistency or attacks like double-spending. To prevent such issues, DLTs use specific consensus algorithms that help the network determine which updates should be applied. Several notable mechanisms include:

- **Proof of Work (PoW)**: used by Bitcoin, PoW relies on a "Mining Process that requires the network components to solve high-level computational problems to validate the information and update the ledgers" [7]. These complex cryptographic puzzles, known as hash functions, demand significant computational power, making the process highly energy-intensive. The first miner to solve the puzzle broadcasts the solution to the network, and if many nodes verify its correctness, the new block is added to the blockchain. This mechanism ensures security by making it computationally impractical for malicious actors to alter past transactions, as they would need to do again the work for all subsequent blocks faster than the rest of the network combined.

- **Proof of Stake (PoS)**: unlike PoW, PoS selects validators based on the amount of cryptocurrency they stake. The more tokens a participant locks up, the higher their chances of being chosen to validate transactions, e.g. Ethereum, after transitioning from Proof of Work (PoW) to Proof of Stake (PoS), uses a system in which validators must deposit 32 ETH to participate in transaction validation and network security.

- **Delegated Proof of Stake (DPoS)**: DPoS is an evolution of PoS, that allows network participants to vote for a limited number of trusted validators who then handle transaction confirmations.

- **Proof of Authority (PoA)**: PoA mechanism defines predefined trusted public entities that act as validators. This configuration permits a faster and less costly environment in exchange for a reduction of the degree of decentralization of the network.

- **Proof of Capacity (PoC)**: this mechanism is based on the storage power of the network participants. The validators must store a pool of hash solutions in a memory space and every time a new block of the chain is created, they must search for the solutions inside their storage. The bigger the memory space they have at their disposal, the bigger the probability is of having the solution of the hash in the downloaded pool of solutions.

- **Proof of Burn (PoB)**: this mechanism bases its trusted validation process on the requirement of "burning" tokens to become a network validator. This configuration requires that validators destroy a certain number of tokens, removed from the network circulation, to participate in the "mining" of new nodes.

- **Byzantine Fault Tolerance (PBFT)**: "Byzantine Fault Tolerance Models" (BFT-Models) refer to a multitude of architectures that aim to solve the Byzantine Generals'problem ensuring that the consensus within a network is reached even if a third of the participants act malevolently. The most notable are:
  - **Practical Byzantine Fault Tolerance (PBFT)**: PBFT environments are based on a voting round system where at least two-thirds of the network must agree on the validity of a transaction.
  - **Delegated Byzantine Fault Tolerance (DBFT)**: in the DBFT environment, network participants choose a delegation of participants that has to carry the burden of reaching the consensus for the network"[6].

2.3 DLT Architectures

Distributed Ledger Technology (DLT) can be categorized into permissionless and permissioned architectures based on how participants access and interact with the network. Each model offers distinct advantages and trade-offs in terms of decentralization, security, efficiency, and governance:

- **Permissionless Architecture**: a public ledger, where everyone can join the network, validate transactions, and maintain a copy of the ledger without requiring approval from a central authority. The most famous permissionless architecture is Blockchain, and another is Ethereum, a decentralized smart contract platform with a transition to PoS for better scalability.
- **Permissioned Architecture**: a restricted network where access and participation are controlled by a governing entity. Unlike public blockchains, only authorized participants can validate transactions, maintain the ledger, or execute smart contracts. Permissioned DLTs are also divided into:
  - **Permissioned Private**: where "the transaction validator role is in the hand of the Central Authority" [7].
  - **Permissioned Consortium**: where validators are a small group of participants.

2.4 Smart Contracts

Smart contracts are "computer protocols with pre-determined conditions that ensure the automatic execution of an agreement, with no need for a central authority, where the conditions are met"[7].

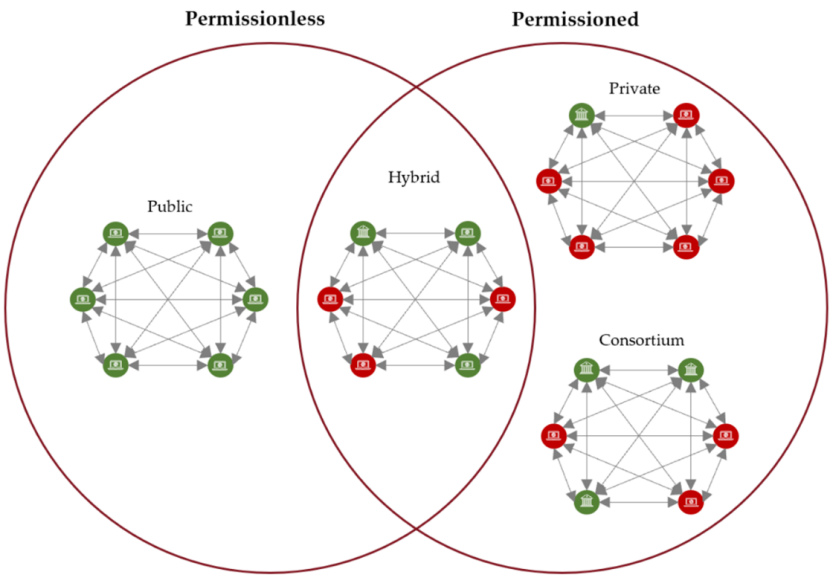

FIGURE 6: DLT Architectures[7]

Security SC

Contract Address: 0x4da138a2
Owner Address: 0xac45f07b

ISIN: xxxxx
Supply: 1m

Current balances:
(...)

Corporate actions:
(...)

FIGURE 7: Security Smart Contract

Settlement SC

Contract Address: 0x1d34a6a3
Owner Address: 0x2c451e9f

Mode: DvP

Code:
Check instructions
Check if security arrived
Check if hash arrived
If both: send to respective receiver
If not both: Send back to original owner
If time expired: Send back to original owner

FIGURE 8: Settlement Smart Contracts

These contracts eliminate the need for intermediaries by directly executing transactions once the conditions embedded in their code are met. They rely on cryptographic security, ensuring transparency, immutability, and trust among participants. Structurally, a smart contract consists of a unique contract address, state variables that store data related to execution, functions that define operational rules, event logs for tracking contract activities, and permissions that determine which entities can interact with it. Smart contracts can be broadly classified into various categories based on their function, two important types are [17]:

- **Security Smart Contracts**: smart contracts designed to automate and enforce security-related tasks, such as asset transfers, access control, and encryption, ensuring safe transactions and interactions on blockchain networks.
- **Settlement Smart Contracts**: smart contracts used to automate the finalization of financial transactions, ensuring that all conditions are met for the transfer of assets or payment, often used in trading or insurance settlements.

Security Smart Contracts[17] (ref. Figure 7) are crucial for issuing, managing, and transferring digital representations of financial instruments like stocks and bonds. They enable the digitization of financial assets, facilitating their trading and management on blockchain platforms. Key functions include the issuance of digital securities, ownership tracking, automation of corporate actions, and regulatory compliance. For instance, a company issuing tokenized shares through a smart contract can ensure that only authorized investors can trade them, adhering to regulations. Typically, a security smart contract includes issuer details, a link to an ISIN for traditional databases, transaction transfer functions, and an indicator of collateralization eligibility, ensuring compliance with regulations while offering an efficient method for digital asset management.
Settlement smart contracts[17] (ref. Figure 8) streamline asset transfers and payments by enforcing predefined rules, particularly in instant payments and financial clearing, removing the need for

intermediaries like banks and clearinghouses. A key feature is atomic settlement, where the simultaneous exchange of securities and payments mitigates counterparty risk. These contracts operate through a unique address for receiving and sending cash amounts and tokens. This structure minimizes human error and ensures fast, efficient transactions. The execution of an atomic settlement involves two key transactions. First, the contract is called with sender instructions, which specify details such as the euro and securities sender addresses, the amounts involved, and a timestamp that determines when the transaction should be completed.
If both sides fulfill their commitments within the specified timeframe, the contract executes the exchange, transferring the assets to the respective parties. If the required amounts are not received by the deadline, the contract automatically invalidates the transaction, returning any assets sent and notifying central banks to take necessary actions, such as penalizing the party responsible for the failure.
Such atomic transactions are widely used in permissionless blockchains through swap contracts or decentralized exchanges (DEXs), a platform that allows users to trade assets directly from their wallets without intermediaries. By ensuring that both legs of a transaction occur simultaneously, these contracts enhance security and efficiency in financial settlements while minimizing counterparty risk.

2.5 Oracles

Oracles play a crucial role in DeFi and especially for Smart Contract because they allow them to access real-world data, permitting them to connect the network to outside data and verify if determined conditions that occur outside the DLTs and are necessary for the execution of actions are met. For instance, in Decentralized Assurance "their function is to permit the smart contracts' algorithms to determine if a claim should be paid or not"[6]. There are several types of oracles, each serving different purposes:

- **Inbound Oracles**: fetch real-world data and bring it onto the blockchain. Examples include price feeds for cryptocurrencies and commodities.
- **Outbound Oracles**: send blockchain-generated data to external systems, such as triggering payments or notifications.
- **Software Oracles**: obtain data from online sources like APIs, databases, and websites.
- **Hardware Oracles**: interact with physical devices, such as IoT sensors, to transmit real-world information to smart contracts.
- **Human Oracles**: rely on individuals or groups to verify and submit data to the blockchain.
- **Centralized Oracles**: operated by a single entity, providing data from a specific source.
- **Decentralized Oracles**: aggregate data from multiple sources to enhance reliability and prevent manipulation, unlike centralized oracles.

Oracles typically work by [22]:

1. **Collecting data** from external sources (e.g., APIs, websites, IoT devices).
2. **Validating and verifying** the data for accuracy.
3. **Formatting the data** to be compatible with blockchain protocols.
4. **Submitting the data** to smart contracts on the blockchain.

This process enables smart contracts to execute based on real-world events and conditions, greatly expanding their functionality and applicability.

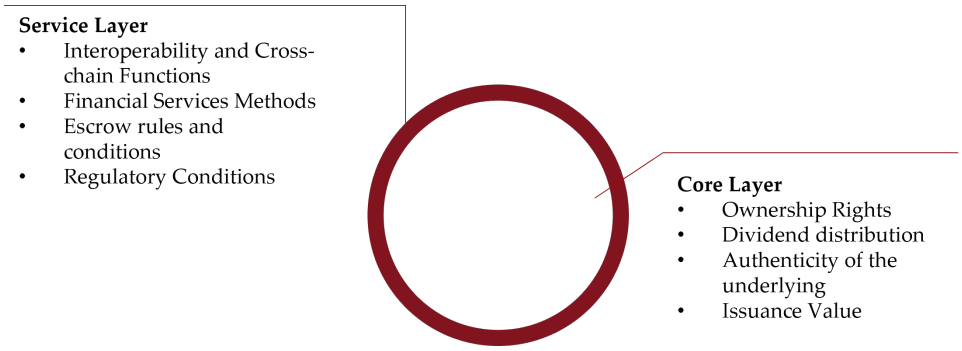

FIGURE 9: Token Anatomy[7]

2.6 Tokens

Tokens are digital assets exchanged among participants in a distributed ledger technology (DLT) network. They can represent any form of value or claim, from real estate property to intellectual property rights, by embedding specific conditions within smart contracts that govern their creation, issuance, and management. Unlike traditional assets, tokens are programmable, allowing them to be tailored to distinct economic, regulatory, and governance purposes. Their classification depends on their underlying function, regulatory compliance, and economic characteristics. Additionally, tokens can be structured into two different layers that determine their characteristics: the Core Layer, which defines the fundamental logic and governing rules of the token within the platform, and the Service Layer which determines key attributes like ownership rights, issuance value, and other defining characteristics.
There exist a lot of possible types of tokens, some examples follow:

- **Utility Tokens**: provide access to specific services, products, or functionalities within a given ecosystem.
- **Security Tokens**: represent financial instruments such as equity, debt, or derivatives that are subject to regulatory frameworks.
- **Payment Tokens**: function as a medium of exchange and store of value, similar to traditional currencies.
- **Stablecoins**: a subset of payment tokens, are pegged to an underlying asset, typically a fiat currency, to maintain a stable value and facilitate seamless transactions without volatility concerns.
- **Governance Tokens**: enable holders to participate in decision-making processes within decentralized systems.
- **Non-Fungible Tokens (NFTs)**: represent unique digital assets that are indivisible and non-interchangeable. They are commonly used for digital art, gaming assets, intellectual property rights, and identity verification. Unlike fungible tokens, NFTs contain metadata that distinguishes each asset, ensuring its authenticity and provenance.

2.7 DeFi

Decentralized Finance (DeFi)[3] is a financial ecosystem built on DLTs that aims to eliminate intermediaries such as banks and financial institutions. It enables permissionless access to financial services, including lending, borrowing, trading, and yield farming, using smart contracts to automate transactions. A DeFi environment is structured into three core layers:

- **Settlement Layer**: the foundational layer based on Decentralized Ledger Technology (DLT), which ensures the execution and updating of financial transactions across the network. Ethereum, Solana, Polygon, and Cardano are popular blockchains in this space.

[3]For a more detailed analysis of the topic see [7].

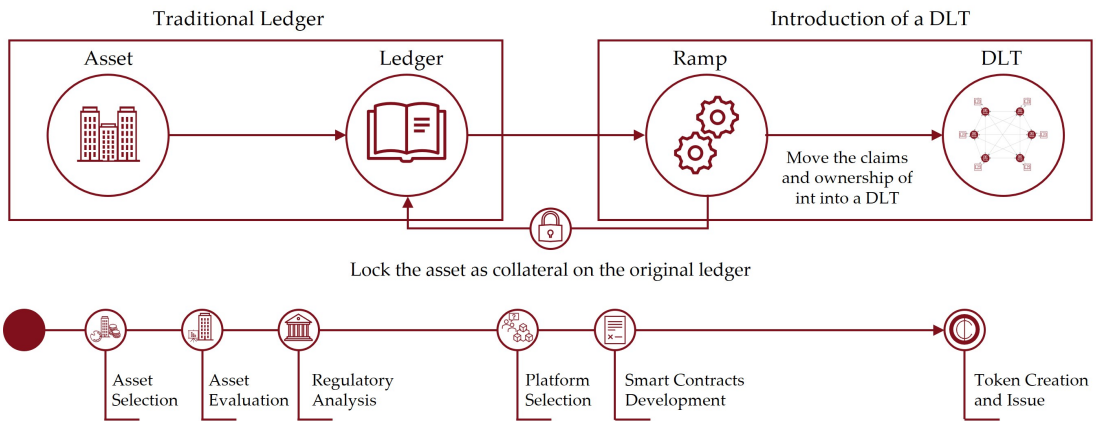

FIGURE 10: Asset Tokenization[6]

- **DLT Application Layer**: "this layer defines the protocols and the services that are offered within the network, including also the native crypto asset that is exchanged within the environment"[6].
- **Interface Layer**: the top layer represents the user interface, through which users interact with the DeFi environment.

3. Atomic Settlement

DLTs and DeFi environments aim to enhance the financial system by reducing centralization and making transactions more efficient, leveraging the automation guaranteed by smart contracts, and controlling failures and fraud through consensus mechanisms. DLT-based environments could play a pivotal role in fostering the compression of the settlement cycles beyond the T+n standard through atomic settlement processes which could guarantee near-simultaneous transaction settlement. Atomic settlement refers to a type of transaction in which all phases are executed simultaneously or not executed at all. The term "atomic" refers to the indivisibility of the components. Real-time settlement is, by nature, difficult to implement in traditional financial infrastructures where rights transfer accounts and payment accounts are separate, requiring reliance on a technological architecture like DLTs that can enable atomic settlement. In contrast to traditional payment and securities settlement systems, which are generally based on centralized infrastructures where market participants connect to a central database, in DLT systems a database is shared across a network distributed in identical copies among the nodes and its data are accessible to the network's members, who can also actively participate in its operation.
For a centralized settlement system to be gradually decentralized into an atomic settlement system, it is necessary to proceed with the tokenization of Real World Assets (RWAs). Tokenization can be defined as the process that allows the recording of real-world assets from traditional ledgers to DLTs. The technical process that enables the transfer from the traditional ledger to the digital ledger requires a "ramp" that locks assets in their platform of origin as collateral for the tokens, which are then issued on the programmable platform. The real-world asset, or claim, continues to exist off-chain, but its rights are transferred on-chain through token issuance. This process usually involves six main phases, briefly summarized in the Figure 10:

1. Asset Selection;
2. Asset Evaluation;
3. Regulatory Analysis;
4. Platform Selection;
5. Smart Contracts Development;

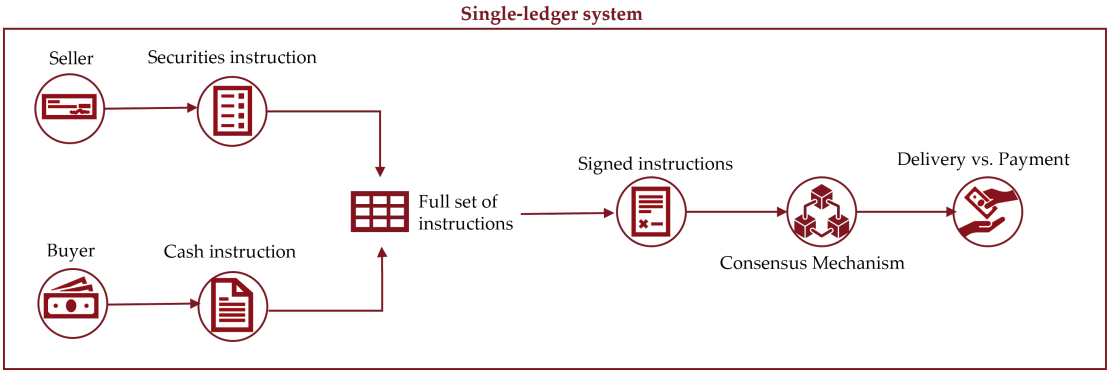

FIGURE 11: Single Ledger Atomic Settlement

6. Token Creation and Issue[4].

In the specific case of atomic settlement systems, the assets to be tokenized will be cash (payment leg) and securities (delivery leg), making the token vs. token (TvT) transfer possible. However, DLTs could also be used to foster hybrid solutions where only one leg is tokenized and settled on-chain, with securities settled by transferring account-based securities in exchange for cash tokens (AvT transfer) or transferring security tokens in exchange for cash in accounts (TvA transfer)"[4].

3.1 Atomic Settlement Architectures

This paragraph delves into the three main settlement architectures that DLTs can foster: Single-Ledger Settlement, Cross-Chain Settlement, and hybrid Asset vs. Token (AvT) Settlement. Single-Ledger Settlement is used within a single blockchain environment while cross-chain settlement practices facilitate exchanges between different environments. Meanwhile, hybrid architectures exploit bridges and oracles to link the standard systems and verify the off-chain status of the account, ensuring the settlement of the tokenized leg on-chain.

3.1.1 Single Ledger Atomic Settlement

This type of transfer can be executed on a single ledger or across two separate ledgers. If the security tokens and cash tokens exist on the same ledger, an atomic settlement smart contract can be used to coordinate the clearing and settlement process. When a single blockchain network is used, atomic settlement is executed through the network's consensus algorithm (see "Digital Ledger Technologies") according to the following simplified process (ref. Figure 11):

- Both counterparties have access to the same DLT platform. The counterparty originally holding the securities creates the instruction for the securities leg, while the counterparty holding the currency creates the instruction for the cash leg. At this preliminary stage, neither of the instructions has been digitally signed yet.
- The securities counterparty sends its part of the instruction, without a signature, to the cash counterparty, which verifies the contents of the securities instruction and combines it with its cash instruction, thereby creating a complete set of instructions composed of information on the Sender and Receiver, the asset involved in the transaction, the amount of the asset and the cash in exchange, and the digital signature of the cash counterparty.
- The securities counterparty, at this stage, verifies the complete instruction and signs its part. Once signed by both counterparties, the complete instruction is submitted to the blockchain's consensus mechanism.
- Following the consensus mechanism algorithm of the specific blockchain used, the complete set of duly signed instructions is verified, and the result is written on the distributed ledger.

[4]For a more comprehensive explanation see[7].

- If the transaction is validated, the cash token and the security tokens are instantly and simultaneously transferred to their respective recipients, achieving DvP (Delivery versus Payment). If the transaction is not validated, the tokens remain with their original owners.

Transaction failure in a single ledger approach could occur at any step of the process described above. For example, if the cash counterparty finds that the securities counterparty's instruction contains errors, it will not proceed with combining it with its own instructions. As a result, the process is suspended, the instruction is not confirmed by the consensus mechanism, and no update is recorded on the ledger. Consequently, the cash and securities will remain with the original holders and can be immediately used in other transactions.

3.1.2 Cross-Ledger Systems

If the two tokens are instead registered on two different ledgers, the settlement must occur via cross-chain payments, requiring interaction between distinct blockchain systems. This process is enabled by smart contract protocols such as Hashed Time-Locked Contracts (HTLC)[5], which ensures synchronization without the need for a centralized intermediary, using hash lock and time lock features, specifically:

- **Hashlock**: a condition requiring the presentation of a secret value (called the preimage) to unlock the payment.
- **Timelock**: a time limit, expressed in blocks or real-time, within which the payment must be completed. If the payment is not executed within this time, it is canceled, and the funds are returned to the sending party.

As well outlined by the ECB and the Bank of Japan (2018)[12], a DvP settlement using HTLC can occur in the following way (ref. Figure 12):

- **The seller** generates a cryptographic key (X) and the corresponding hash function (Y = H(X)). The seller uses this hash to lock the security tokens on its ledger with a specified time limit (e.g., four hours). The seller then creates an instruction with two states:

  1. To send the securities to the buyer using the hash (Y) if the buyer provides X that satisfies the hash function or;
  2. If the time limit expires, return the securities to the seller.

  The seller, finally, signs and submits the signed instruction to the securities consensus mechanism. Following the implemented consensus mechanism of the platform, the submitted securities instruction is verified and confirmed, and results are written on the ledger in the securities DLT platform.

- **The buyer** verifies the content of the committed securities instruction and if confirms it, locks the cash token on their ledger with a shorter time limit (e.g., two hours). The buyer creates a conditional instruction to either send the cash token to the seller using the hash (Y) or return it to the buyer after two hours. The conditional instruction is signed and submitted to the buyer's consensus mechanism. Following the implemented consensus mechanism of the platform, the submitted securities instruction is verified and confirmed, and results are written on the ledger in the cash DLT platform.

- **The seller** verifies the cash instruction of the buyer and eventually reveals the secret (X) into a second cash instruction signed and submitted to the consensus algorithm of the cash DLT platform. The consensus mechanism verifies the content of the second cash instruction and, in the event of a positive outcome from the check, proceeds to write the result on the distributed ledger. Upon the occurrence of this condition, the cash amount is transferred from the buyer's account to the seller's account.

[5] HTLC refers to a type of smart contract used in blockchain applications to mitigate counterparty risk by creating a time-based escrow that utilizes a cryptographic passphrase. HTLC transactions use multiple signatures consisting of a private and public key to verify and validate transactions.

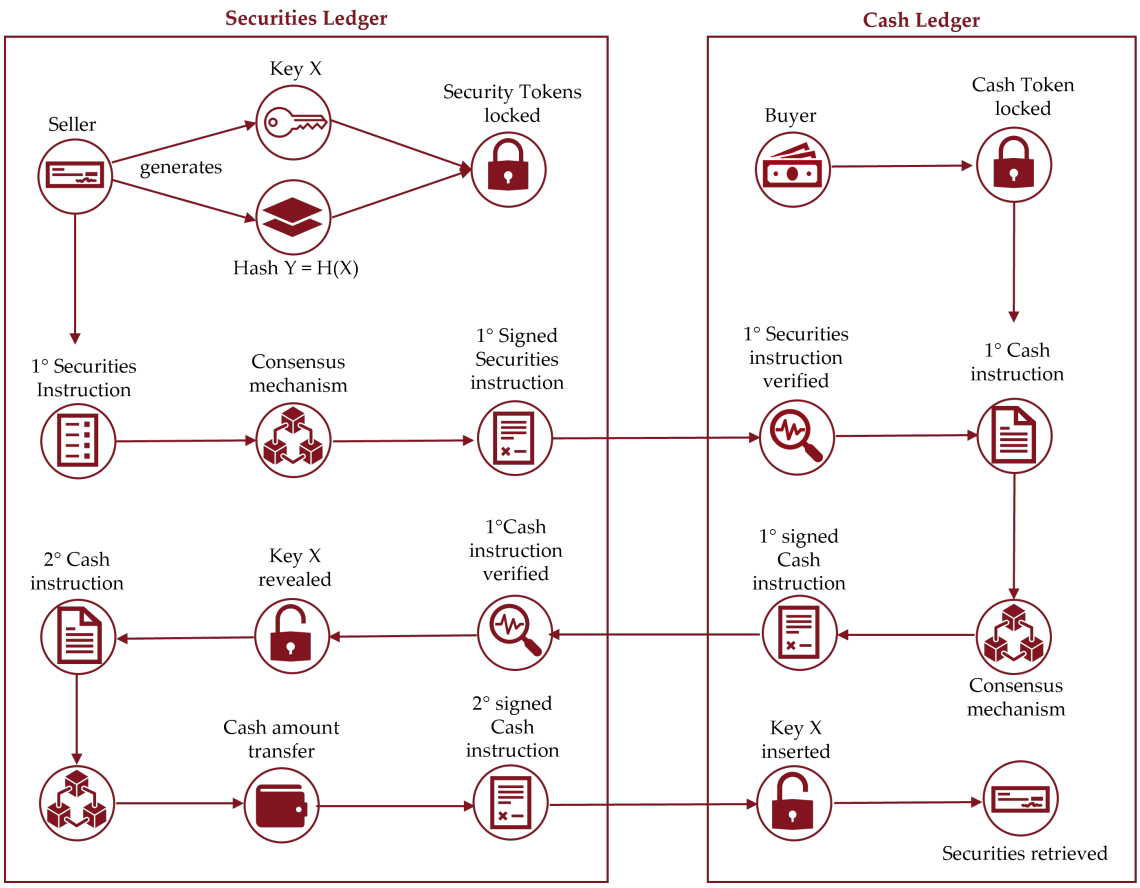

FIGURE 12: Cross-ledger systems

- **The buyer** can then use the secret (X) received in the second cash instruction and proceed to create a second securities instruction by inserting the secret value of (X). Once signed, the instruction is submitted and checked by the platform's consensus algorithm, which verifies its content and proceeds to write the results on the ledger to unlock and retrieve the security tokens.

Compared to single-ledger systems, a settlement failure in HTLC systems could potentially result in counterparty risk exposure for one of the two parties involved in the transaction. In HTLC systems, the risk is particularly linked to the functioning of the time lock, as it is true that if, after the completion of the first set of instructions (securities and cash), the securities counterparty does not submit the second cash instruction within the predefined locking time, the cash and securities are returned to their respective original holders. However, it is equally true that in the case where the securities counterparty has already received the cash leg while the other counterparty has not submitted the second instruction within the predefined locking time, the securities counterparty will also be refunded the securities leg, leaving the cash counterparty exposed to principal risk.

3.1.3 Hybrid Solutions

In addition to Token vs. Token (TvT) systems, which have a greater impact but are more complex to implement, industry practices highlight the use of 'hybrid' systems. These architectures rely on the tokenization of only one of the transaction's legs (ref. Figure 13):

- **AvT:**[4] in this configuration, the settlement involves a delivery leg in a traditional account-based securities system and a tokenized payment leg on a DLT. In an Asset vs. Token (AvT) environment, after the affirmation process, the securities are transferred through the traditional financial system-either directly to the counterparty's account or via a custodian or CSD. Once the securities transfer is confirmed, this information is communicated via a bridge or oracle

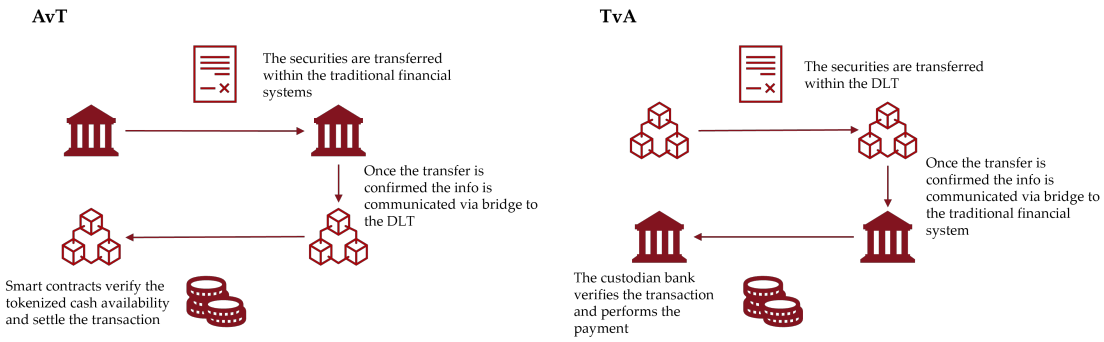

FIGURE 13: AvT and TvA Solutions

to the DLT environment. A smart contract then checks if tokenized money is available in the buyer's on-chain wallet. If sufficient funds are available, the smart contract transfers the tokenized cash to the seller's on-chain wallet, finalizing the settlement.

- **TvA:**[4] in this configuration, the settlement involves a delivery leg on a DLT-based system (tokenized securities) and a payment leg in a traditional account-based cash system. In a Token vs. Account (TvA) environment, after the affirmation process, the security tokens are transferred on-chain from the seller's wallet to the buyer's wallet, according to the smart contract rules. Once the token transfer is executed on-chain, an oracle or bridge notifies the traditional financial system. A custodian or bank then verifies the transaction and processes the corresponding cash transfer in the off-chain banking system.

Despite the fact that these configurations could exploit bridges and oracles to coordinate the execution of both legs in order to achieve a near-atomic settlement, it is also possible to implement a configuration that follows the traditional settlement cycle. In such a setup, the two legs, the delivery of securities and the payment of cash are settled in separate phases, aligning with standard T+n settlement cycles rather than executing simultaneously. In this configuration bridges and oracles ensure the consistency of the reconciliation process between the on-chain and the off-chain leg. A hybrid solution could be easier to adopt in the initial stages by traditional financial systems, with less impact on both IT architectures and business models. Integrating bridges and oracles to provide a link within DLT environments could ensure smooth settlement flows and mitigate operational risks. An example of a hybrid infrastructure is given by the Bond-i, the first DLT-based tokenized bond, issued by the World Bank and arranged by the Commonwealth Bank of Australia (CBA). The Bond-i can be purchased and traded as a tokenized security on the chain, while the cash settlement occurs separately via fiat money in a traditional bank account.

3.2 Market Applications

Within the growing popularity of DLTs and DeFi environments, examples of the application of atomic settlement architectures have spread more widely. In particular, the following highlighted solutions carried out by consolidated financial institutions need to be cited:

- **JP Morgan's Kynexis:** previously known as Onyx, Kynexis is the private permissioned blockchain-based platform developed by JP Morgan that provides a scalable, and efficient infrastructure for digital payments, asset tokenization, and financial transactions. The platform relies on blockchain-based accounts where deposit tokens are stored and used to perform exchanges that allow assets, that were once recorded in separate ledgers, to be integrated into a single ledger, fostering atomic settlement of various assets and ensuring automated maturity with high precision. With transactions occurring on a single ledger, users have access to a consolidated and transparent record, enhancing clarity and efficiency in the settlement process.

- **SIX Digital Exchange (SDX):** SDX, powered by SIX Swiss Exchange, is a fully regulated blockchain-based asset exchange and central depository, adhering to FINMA requirements

and strict legal and compliance standards. The SDX platform leverages blockchain technology to enhance transparency, speed, and automation in financial markets, offering several different services that comprehend digital asset issuance, trading, settlement, and custody. Leveraging the DLT structure, SDX ensures a near-simultaneous transaction settlement through atomic settlement procedures, in particular, the trading venue verifies with the DLT-based Central Securities Depository whether the participants have sufficient tokenized assets or tokenized cash available for the transaction before confirming it.

- **Euroclear D-FMI:** D-FMI is a DLT-based platform, developed by Euroclear, that supports the issuance, distribution, and primary market settlement of fully dematerialized international securities through its D-SI (Digital Securities issuance) service. The platform is fully interconnected with Euroclear's legacy platform, which permits tokenizing cash from legacy accounts into D-FMI's tokens. The primary market settlement will follow a fully atomic settlement environment, where instructions are entered, matched, and positioned in the D-FMI based on participants' securities and cash tokens. The bridges between D-FMI wallets and legacy ones permit the movement of securities into Euroclear accounts for secondary market trading.

- **Eurosystem DLT-based wholesale central bank money settlement:** the EU[10], with the goal of fostering an integrated European market for digital assets, conducted between May and November 2024 (the DLT pilot regime started on March 2023) a series of exploratory tests to assess the feasibility of the development of a DLT platform for wholesale transaction settlement processing over 200 transactions for a total value of 1.59 billion euros. During the trial, three different solutions were also tested to facilitate interaction between TARGET Services and DLT platforms. In February 2025[11], the ECB stated its intention to extend the initiative to settle transactions recorded on DLT in central bank money through a two-track approach that consists:

  - **Platform Development:** the Eurosystem will, at the earliest feasible time, develop a DLT-based platform to settle transactions in central bank money while guaranteeing interoperability within the TARGET system. (A roadmap is still not disclosed yet and will be announced at the proper time).
  - **International Operations:** the Eurosystem will also explore a more integrated, long-term solution for settling DLT-based transactions in central bank money that will extend also to international operations (e.g. FX settlement).

- **The 2nd phase of the Stella Project of ECB and Bank of Japan:** the joint project of the ECB and BoJ examined the ways in which Delivery vs Payment settlement can be conceptually designed and technically achieved in a DLT environment, based on prototypes from three DLT platforms: Corda, Elements, and Hyperledger Fabric.

  - **Atomic Settlement on Corda:** project Stella tested the use of Corda for delivery versus payment (DvP) on a single DLT. In the test, the Corda network consisted of four nodes: two dedicated to cash and two dedicated to securities. The test used a "soft-locking" mechanism to prevent nodes from simultaneously using the same input states, with the possibility of unlocking them if the transaction remained pending for too long. Assets were self-issued by the cash and securities nodes, respectively for the buyer and the seller. The DvP transaction was executed in a single flow and finalized atomically, meaning that each update to the ledger was recorded simultaneously, preventing one participant from spending their balance without the others being able to do so.
  - **Atomic Settlement on Elements:** the test conducted on the Elements platform focused on executing Delivery versus Payment (DvP) transactions on a single distributed ledger. The Elements platform provided specific functionalities, such as the ability to issue multiple assets with encrypted identifiers and amounts, while maintaining auditability. The network used in the test consisted of multiple nodes that managed both cash and securities and relied on cryptographic mechanisms to ensure transaction security. On the Elements platform, transactions were executed using the Unspent Transaction Outputs (UTXO) model, which ensures that assets cannot be spent more than once. Consensus

was reached through the verification of transactions by participating nodes, ensuring simultaneous and irreversible recording of transactions on the ledger, thus preventing double-spending risks.

– **Atomic Settlement on Fabric:** in the Fabric network setup used in the Stella project, an order and two organizations have been used each managing a peer that acted as an endorser and a Certificate Authority. Atomic settlement on the Fabric platform was ensured through the use of the platform's endorsement policy. This policy included an "AND" condition, whereby the transaction was recorded on the ledger only if the results of the seller and buyer were identical. Delivery versus Payment (DvP) transactions were executed using chain code, which recorded each action in the platform's ledger. Each counterparties' balance was stored as a series of deltas in the state database to avoid using a single key representing the total balance.

3.3 Opportunities and Challenges of the Adoption of an Atomic Settlement Cycle

Atomic settlement based on DLT systems has the potential to profoundly innovate financial market infrastructures by allowing market participants to near-simultaneously settle securities transactions, thus reducing counterparty risk and increasing market efficiency. However, like other use cases of DLT technology, atomic settlement brings with it several challenges, primarily related to cybersecurity and the regulatory framework. The development of a financial system that exploits a DLT exchange environment that fosters the settlement through atomicity could create several enhancement opportunities:

- **Increased Efficiency and Speed:** DLT facilitates near real-time transaction processing, significantly increasing the speed of settlement. Traditional settlement cycles in financial markets can take up to several days (e.g., T+2 or T+3), while DLT-based systems can enable simultaneous settlement. This is particularly advantageous for financial institutions, for which delayed settlements can result in capital being tied up and liquidity constrained. Moreover, the absence of the role played by intermediaries results in a substantial reduction in transaction-related costs, as highlighted by Pinna and Ruttenberg[20], the crediting and debiting of investors' securities accounts could be performed with the same cost- and time-efficiency as that with which internalized settlement is currently carried out in the accounts of custodian banks. However, since it takes place in the distributed ledger, the segregation of securities in individual investors' accounts is carried out at no additional cost.

- **Principal Risk Reduction:** the use of DLT systems for securities transaction settlement could significantly mitigate the principal risk typically associated with traditional systems. In securities settlement, principal risk represents the risk that one party transfers securities or cash but does not receive the corresponding payment or asset in return, resulting in a significant loss. This risk can arise in any securities transaction, including those between financial institutions, banks, or between intermediaries and their clients. The atomic settlement, by ensuring a Delivery versus Payment (DvP) transaction, guarantees that the settlement of one obligation occurs if and only if the settlement of the linked obligation also takes place. This theoretically ensures a substantial reduction in the principal risk to which transaction participants are exposed. However, in single-ledger systems, the risk reduction is potentially total, as the securities leg and the cash leg are executed only in the final step of the process, and in case of failure to fulfill the obligation, the assets return to their original holders. In cross-ledger systems, the risk could arise if a counterparty fails to retrieve the securities before the expiration of the locking time, and the securities would be returned to the original holder who has already received the cash.

- **Cost Reduction:** a decentralized settlement system, by eliminating the need for intermediaries, can significantly reduce transaction costs associated with fees owed to Central Clearing Counterparties or settlement agents. According to a 2015 estimate, the use of DLT systems in the clearing and settlement market brings potential annual operational savings of up to approximately 20 billion dollars globally. Some of these efficiencies should have already been realized by market participants to date.

- **Increased Transparency:** as described in detail in Chapter 2, DLT provides a transparent and immutable record of all transactions on the ledger. Once a transaction is validated and added to the ledger, it cannot be altered or deleted. This ensures that the settlement process is transparent, reducing the potential for fraud and errors. The use of cryptographic algorithms in DLT ensures that only authorized participants can access transaction data, while the system remains transparent to all stakeholders. For further insights on the increased trust among market participants, see the paper by Catalini and Gans[5].

- **No need for cutoff windows:** in traditional securities settlement systems, cutoff windows represent specific periods during which transactions must be completed to be included in the scheduled settlement cycle. Currently, most securities are settled under a rolling cycle where trades are executed on day T and settled at a later date (typically one to three days later). DLT potentially enables the simultaneous transfer of assets between counterparties reducing the need for time-based coordination or windows. Unlike traditional settlement systems that require end-of-day or specific-time settlement windows to batch process transactions, DLT ensures that settlement occurs instantly, reducing settlement delays and by doing so reducing the time window in which one party may default after receiving its side of the transaction but before delivering its obligation. Furthermore, by eliminating cutoff windows, Atomic Settlement through DLT allows international financial markets to operate 24/7. At least on a regional level, traditional settlement systems already allow for instant transfers, as in the case of TARGET Instant Payment Settlement (TIPS) launched in 2018 by the Eurosystem to allow instant retail payments between banks across the EU to be settled in central bank money in real-time available 24 hours a day, 7 days a week, and 365 days a year.

Despite the opportunities for improvement and the potential benefits for the financial markets the development of an atomic settlement environment could create, the established procedures of financial markets and the necessary enhancement of technical infrastructures underlying a set of potential challenges that must be faced:

- **Technical Challenges:** the development of settlement systems based on blockchain technology requires the establishment of robust and reliable technological infrastructures. As well documented by Alshahrani et al.[1], current blockchain networks demonstrate inefficiencies in scalability, leading to problematic transaction per second (TPS) levels. For instance, Bitcoin and Ethereum can process between 7 and 20 transactions per second, with significant energy consumption. Considering the high volume of transactions processed daily by traditional financial infrastructures, the scalability and energy efficiency of blockchain technology represent a considerable challenge for market participants. To address this limitation, some blockchains, such as Ethereum, have already launched projects aimed at significantly increasing the number of transactions executed per second.

- **Security Risk:** although the decentralized nature of the chain makes DLTs less exposed to single points of failure, **Proof of Work (PoW)** and **Proof of Stake (PoS)** mechanisms are potentially vulnerable to cyber-attacks. A 2024 paper published by the Basel Committee on Banking Supervision has essentially confirmed that permissionless systems might be vulnerable to so-called "51% attacks"[3] in which a coordinated effort is put forward to control greater than 50% of the validation nodes or 50% of the staked native token and thus select which, and how, blocks are added to the blockchain. Furthermore, there is evidence of several smaller proof of work (PoW) blockchains that have experienced 51% attacks, but to date, no proof of stake (PoS) blockchain network has experienced a 51% attack.

- **Regulatory Challenges:** DLT-based atomic settlement introduces new regulatory and legal challenges. The existing regulatory frameworks in most jurisdictions are designed for traditional financial markets and intermediaries. As DLT eliminates the need for intermediaries, regulators face challenges in determining how to oversee and regulate decentralized networks. However, the Regulator has launched a series of regulatory initiatives aimed at creating a solid legal framework for assets traded on the blockchain [16].

- **Liquidity Constraints:** while atomic settlement mitigates principal risk, it may lead to liquidity constraints for market participants. In traditional systems, institutions have a time window (e.g., T+2) to settle transactions, allowing them to manage their liquidity needs more flexibly. Atomic settlement requires institutions to have sufficient liquidity or collateral at all times, which can be burdensome. As settlements are processed in real-time, atomic settlement systems would require banks to keep significant idle balances of money and assets. In a 2023 paper, FNA proposes a possible 'hybrid' solution to limit the liquidity absorption of atomic settlement, based on introducing an intermediate liquidity-saving service between the trading and settlement layers that clears transactions before they reach the settlement system. This service would slightly reduce the immediacy of some transactions but would still compress settlement times in wholesale markets by several orders of magnitude.

4. Implications of an Atomic Settlement Cycle on the Financial Market Infrastructure

The compression of the settlement cycles has always represented a fundamental shift in the core processes of financial markets with studies and market evidence showing that "efficient and timely processes reduce systemic risks and create resilient financial markets. Reduction of counterparty risk, increase in liquidity, and decrease in failure rates can all be achieved with shorter settlement cycles"[2]. In May 2024, the US moved from a T+2 settlement environment to a T+1 settlement for all securities eligible for settlement in the Depository Trust and Clearing Corporation (DTCC); this marked a milestone in the discussion on the benefits that a shorter settlement cycle could bring into financial markets. Following the US example, other nations (e.g. UK, and Swiss) started to outline their strategy to implement a similar shift in the settlement process. In February 2025, the European Commission proposed to shorten the settlement period for EU transactions from T+2 to T+1 within October 2027. The reasons why regulators promote a reduction of the settlement cycle are various and comprehended, as outlined in Chapter "The Evolution of Settlement Cycles".

- **Greater Capital Efficiency;**
- **Reduction of Counterparty and Market Risk;**
- **Reduction of Principal Risk;**
- **Increasing Liquidity;**
- **Fewer Settlement Failures.**

However, the reduction of settlement cycles affects the process and procedures of all the market participants requiring also infrastructure investment to fulfill the new timely obligations. As the reduction of settlement cycles accelerates and the widespread adoption of innovative financial frameworks the potential integration of DLTs and atomic settlement processes could offer an efficient way to enhance settlement and reduce operational complexities related to stringent timelines. While atomic settlement could be crucial in enhancing post-trade processes, its widespread adoption as a new standard could lead to impactful changes across the financial industry. In particular, the development of an atomic settlement cycle will require the redesign of business processes and strategies, with significant investments in enhancing IT architectures, pushing some market participants to rethink their roles and responsibilities within the financial market.

4.1 Potential Impacts on Market Participants

Moving to an atomic settlement cycle, supported by technologies such as DLTs, will significantly affect the current structure of financial market infrastructure[**?**], which relies on a centralized, well-established framework for its function. In particular, the effects on CCPs, CSDs, and banks will be twofold, impacting the foundations of traditional business models and requiring significant investment in IT infrastructure and interoperability. Below, we explore the implications for each of these key market participants:

- **Central Clearing Counterparties (CCPs):** CCPs play a central role in the actual financial market infrastructure acting as the connection between trading counterparties fostering credit risk reduction and stability of the financial markets. CCPs fulfill several functions that aim to ensure the functioning of the current financial markets such as:
  - **Counterparty Risk Reduction:** CCPs interpose between trading counterparties to mitigate the whole credit risk of trades.
  - **Position Netting:** CCPs provide to offset multiple transactions to reduce the number of actual settlements. **Margin Management:** CCPs collect and manage the collateral amounts of market participants necessary to avoid potential losses even in volatile market conditions. This implies the day-by-day valuation of the collateral adjustments that ensure that market participants can cover their obligations.

  The introduction of DLT infrastructures necessary to support an atomic settlement cycle will deeply modify the roles that CCPs play, in particular:
  - **Smart Contracts and Netting:** smart contracts could automatically embed the conditions of transactions netting if needed, reducing the importance of a central function that fulfills it.
  - **Reducing Margin Requirements:** in a DLT environment atomic settlement occurs only if both counterparties dispose of assets at the time of the trade, under penalty of transaction failure, reducing the importance of margin management in financial transactions.
  - **Reducing Principal and Counterparty Risk:** since atomic settlement requires pre-funded assets to be locked before execution, the risk of counterparty default and failed settlement is significantly reduced. This diminishes the role of CCPs as risk intermediaries, making their involvement less critical in certain transactions.

  The evolution of a financial market and the settlement cycle to an atomic-environment will potentially change the whole role of CCPs. Rather than fulfilling risk management and settlement functions, CCPs could evolve into governance entities acting as the designer and guarantor of smart contracts and network rules and conditions. In this new framework, CCPs could serve as network validators, ensuring compliance, standardization, and security within a decentralized financial infrastructure.

- **Central Securities Depository (CSD):** CSDs represent another key player in the current financial market infrastructure, providing the custody of dematerialized securities, their book-recording, and facilitating the transfer ensuring transaction settlement. They fulfill several important functions that guarantee the proper functioning of the financial system, in particular:
  - **Custody:** since the advent of dematerialized securities CSDs fulfill the role of securities custody centralizers. They keep the official book records of securities ownership mitigating the risk of erroneous recording, unauthorized transfers, and fraud.
  - **Settlement Services:** after a trade is performed, CSDs facilitate the transfer of securities and the payment transaction, ensuring that both sides of the trade fulfill their obligations. This implies that CSD ensures that the delivery of securities occurs only when the payment of the deal is performed, guaranteeing also the conclusion of the transaction.
  - **Corporate Actions Management:** CSDs manage corporate actions related to securities. These include dividend payments, overseeing stock split and reverse stock split, rights issues, and bond coupon payments.

  The transition to a DLT-based financial environment that supports an atomic-settlement cycle will deeply modify the business model of CSDs, in particular:
  - **Record Keeping and Custody:** in a DLT-based environment, as analyzed in Chapter 2, once a transaction is executed and validated, the record becomes immutable and is instantly updated across all nodes in the network. The DLTs exploit also consensus mechanisms to validate transactions before they are recorded ensuring the network against fraud.

- **Settlement Activities:** in an atomic settlement environment, the legs of transactions are exchanged simultaneously and only if both the securities and the payment amount are available in the parties' wallets. The checks and locks of the necessary resources to perform the transaction are carried out by smart contracts which also ensure the automatic and simultaneous execution of both legs. These procedures will lower the necessity to have a central party to ensure that the settlement steps are fulfilled.
- **Corporate Actions Management:** as for settlement procedures, even the management of CA could be performed automatically by smart contracts. These contracts would be programmed with the specific rules and rights governing corporate actions for the securities involved (e.g. the automatic payment of a bond coupon).

The role of CSDs in a DLT-based financial infrastructure could undergo a significant transformation. In particular, CSDs could develop and manage the DLTs on which transactions are executed and settled, acting as guarantors of the ledger's integrity and overseeing the proper execution of transactions. An example of this potential shift has already been demonstrated with the deployment of Euroclear's D-FMI.

- **Banks:** the shift from a T+n settlement environment to an atomic settlement cycle will deeply impact banks' business models, requiring the redesign of the infrastructure of lines of service and the restructuring of market strategies. In particular:
  - **Liquidity Management:** the actual settlement processes require transactions to be settled within n days (usually 1 or 2) after the trade is performed. The delay between execution and settlement to commit capital and securities in other operations, for instance, repos or O/N lending activities avoids capital from being idle. The main characteristic of atomic settlement is that in order to settle the transactions both capital and securities should be available and locked in each party's wallets to ensure a simultaneous transfer. The shift to atomic settlement means that capital and securities would no longer be as flexible for other operational uses. Banks would need to balance the need to provide liquidity for settlement with the costs of holding idle capital. In particular, under a positive rate regime, idle capital due to settlement requirements has a high cost, making it necessary to consider the cost opportunities for each operation that a bank would carry out with potential changes in how financial institutions deploy their capital. In addition, atomic settlement processes will have a huge impact on offsetting practices. Offsetting is a process where financial institutions net out multiple transactions, reducing both the amount of requirement capital needed and the number of transactions. For instance, in traditional settlement processes, netting allows firms to consolidate multiple trades, meaning they only settle the net difference instead of individual transactions, which helps save on liquidity. To lower the impact on banks' operations and ease the transition to a full atomic cycle, two solutions based on DLT could be developed:
    - **Transaction Fragmentation (ref. Figure 14):** after a transaction is performed smart contracts could be developed to reduce the transactions into smaller pieces each one settling through atomicity at a predetermined time but within the trade date. Consider for instance that in t, X and Y performed a share acquisition of 100.000 Euro:
      - In a full atomic environment smart contracts will check the resource's availability, lock them, and simultaneously transfer them between the wallets of two counterparties.
      - In a fragmented atomic environment, smart contracts will divide, for instance, the transaction into four smaller ones and will settle them through defined hours within the trade date. This will require the resource availability only at a determined hour within the day lowering the liquidity management challenge.
  - **Batched Atomic Settlement: (ref. Figure 15)** all trades conducted on a given trade date with a certain counterparty are aggregated by a smart contract, which automatically applies netting to offset positions. At the end of the trade date, smart contracts verify the liquidity requirements, ensuring that both parties have the necessary assets or funds

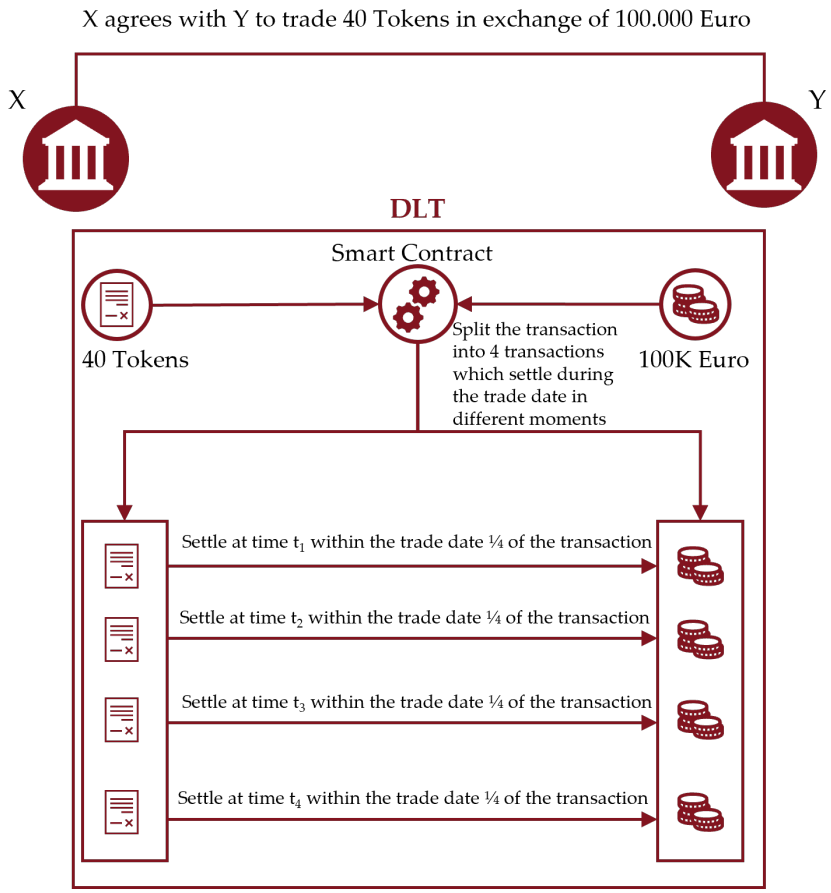

FIGURE 14: Transaction Fragmentation

locking the assets in each wallet. If the condition of availability is fulfilled then the settlement occurs simultaneously and atomically. This process will ensure an end-of-the-day atomic settlement ensuring the reduction of capital requirements to a standard atomic settlement environment.

Both of these solutions will be a strong middle way to improve financial innovation in banking and settlement procedures guaranteeing the atomicity of settlement but lowering the impact of near-real-time procedures will have on banks' business models. The eventual process of moving toward an atomic cycle could be smooth by developing hybrid solutions like the one above. Nevertheless, the introduction of a DLT-based market infrastructure environment will require important investments also in the IT architectures with the redesign of the flow chain between front office systems and their interactions within the back office structure with legacy systems that must be updated to ensure that they are capable of processing atomic settlements effectively. Also, banks and other market players should deploy solutions to enable interoperability within DLTs and other market platforms and develop effective bridge solutions and middleware that ensure structure and platform linkage and interoperability.

- **Custody and Depository Services:** banks, in particular depository banks, offer different lines of securities services related to the post-trade market cycle which include:
  - **Custody:** hold the safekeeping and the book records of their client's securities and cash accounts, ensuring ownership integrity and fraud avoidance.
  - **Settlement:** interface with CSD on behalf of their clients to facilitate and ensure the correctness of transactions guaranteeing that securities are delivered, and cash payments are settled.
  - **Collateral Management:** assist in the calculation of the margin requirements ensuring

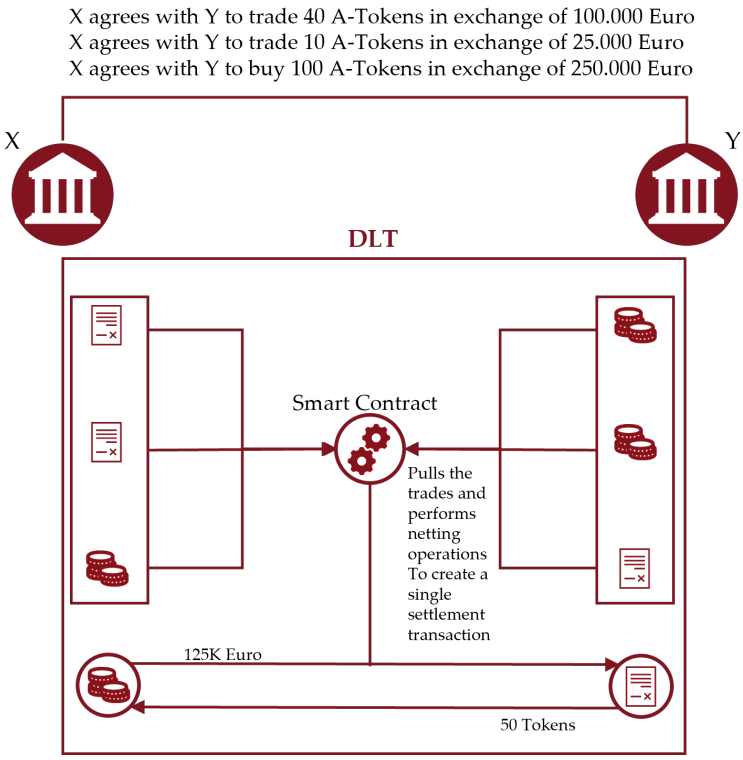

FIGURE 15: Batched Atomic Settlement

that clients provide the necessary collateral for derivatives trading or secured lending in order to avoid margin calls.

– **Corporate Actions Management:** manage the proper execution of CAs ensuring, for instance, the bonds' coupon payment and dividend distribution.

Reliance on DLTs to support the atomic settlement cycle will change how these services are carried out. As seen with CSDs, smart contracts could ensure the automatic and rigorous execution of each settlement operation and CA management, while the atomicity process will lower collateral management requirements. Asset custody on the other hand will be properly handled by the intrinsic features of DLTs. Considering so, banks could improve their services by implementing internal DLTs to handle and streamline custody and depository services. In a scenario where CSDs implement central DLT to manage the settlement-cycle activities, banks should build their DLTs to interface with it. This will require huge investments in the restructuring of IT architectures and collaboration among multiple actors in the markets to ensure interoperability and cross-chain settlement in a multi-platform environment. Despite that, banks through these new processes could foster the integrity of the process, lower operational risk, and cut costs in the long run.

5. Conclusions

The transition to a T+1 settlement in the US has become an important milestone for the structure of the current financial market infrastructure. In fact, following the American example, other countries, including also the UE, have developed a roadmap to move toward a more compressed life cycle and others are analyzing the steps to develop their schedule. A shorter settlement lifecycle could bring several benefits to the financial system lowering the overall credit and counterparty risk, reducing the trade failures, and reducing the margin requirements ensuring a more stable financial market. The spreading popularity of DLTs and their potential impacts on the market infrastructure and the will to foster a shorter settlement cycle have highlighted the feasibility of moving forward with a near-simultaneous settlement cycle. The benefits of the atomic settlement are numerous and include:

- **Increased Efficiency**;
- **Principal Risk Reduction**;
- **Cost Reduction**;
- **Increased Transparency**.

Nevertheless, the invasive technological and methodological shift required to sustain the transition to a DLT-based atomic settlement cycle hides significant challenges for all the market players. In particular, a so drastic change will modify the roles and business models of the main intermediaries involved in the market requiring also huge capital investments in the restructuring and renewing of IT architecture and operations flow. Banks in particular could see their business strategy overturned with unavoidable impacts on their returns. The approach that has to be taken into consideration for a smooth potential transaction to an atomic settlement cycle will indeed require careful analysis that must inevitably gauge hybrid solutions that could help in both reducing the business and IT investment impacts, such as:

- Models that enable a less stringent liquidity requirement within the trade date;
- Models that rely on settlement batches and offsetting with the occurrence at the end of the trade date;
- Hybrid version of the two.

Other than that, in order to achieve positive outcomes in a transaction to a DLT-based market infrastructure that supports an atomic cycle is indeed required a collaborative approach among each market player to fulfill the necessary interoperability and linkage between platforms and architectures. To summarize, the compression of settlement cycles has proven clear benefits for financial markets. However, transitioning to a fully atomic environment introduces significant challenges for market participants. This shift necessitates careful consideration of the approach that should be followed to ensure a smooth and minimally impactful transition, balancing the advantages of instantaneous settlement with the well-established operational and business processes of financial institutions. Hybrid solutions, interoperability frameworks, and strategic IT investments will be crucial to mitigating impacts while maximizing efficiency and risk reduction.

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