BIS Innovation Hub

Project Mariana

Cross-border exchange of wholesale CBDCs using automated market-makers

Final report

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Contents

Executive summary

Foreign exchange (FX) is the largest financial market in the world, trading about $7.5 trillion a day (BIS (2022b)). It operates 24 hours a day, five and a half days a week. Project Mariana looks to the future and envisions a world in which central banks have issued central bank digital currencies (CBDCs) and explores how foreign exchange (FX) trading and settlement might look. Mariana borrows ideas and concepts from decentralised finance (DeFi) and studies whether so-called automated market-makers (AMMs) can simplify FX trading and settlement with a view to enhancing market efficiency and reducing settlement risk.

Project Mariana is a proof of concept (PoC) for a global interbank market for spot FX featuring both an AMM and wholesale CBDCs (wCBDCs). In the PoC, wCBDCs circulate on domestic platforms and so-called bridges allow them to be moved on to a transnational network that hosts the AMM.

Project Mariana extends previous experimentation on cross-border settlement using wCBDC arrangements and distributed ledger technology. It successfully demonstrates the technical feasibility of the proposed architecture and adds novel insights on the potential of tokenisation in three dimensions.

First, wCBDCs are implemented as smart contracts, enabling central banks to manage their wCBDC without the need to directly operate or control the underlying platform. Their design followed best practices from the public blockchain space, building on a widely used standard (ie ERC-20), as well as enabling upgradeability.

Second, bridges may serve as a mechanism to enable broader interoperability in an emerging tokenised ecosystem. As implemented in the PoC, they may enable the seamless and safe transfer of wCBDC between domestic platforms and the transnational network without manual intervention. The bridge design features controls and safeguards and ensures resilience through on-chain (ie bridge smart contracts) and off-chain (ie communication between bridge smart contracts) infrastructure managed by central banks.

Third, the AMM, as tested and calibrated in Mariana, fulfilled requirements based on selected FX Global Code (FXGC) principles. It delivers the contours of a possible future tokenised FX market that has a number of potential benefits. These include supporting simple and automated execution of FX transactions, providing options to broaden the range of currencies, eliminating settlement risk and enabling transparency. However, the use of AMMs requires the pre-funding of liquidity and their adoption would therefore entail a significant departure from the ex post funding (deferred net settlement) in use in today's FX markets.

The Mariana PoC was a first step towards understanding the potential benefits and challenges of AMMs for wholesale FX transactions using wCBDCs. Further work is needed on a range of aspects. Clearly, cyber attacks have repeatedly uncovered vulnerabilities of blockchain and DeFi technology, often with considerable damage to the parties involved. Therefore, while tokenisation and DeFi may have potential benefits, a thorough investigation of security questions is needed. More broadly, future work could extend Mariana into three areas. First, moving beyond technical feasibility, the commercial viability of AMMs for wholesale FX transactions vis-à-vis existing arrangements requires clarification. Collaboration between relevant stakeholders in FX markets would be required to enable such exploration. Second, tokenisation may raise questions about monetary policy implementation, from very specific ones (eg remuneration of wCBDCs) to very broad ones (eg monetary policy instruments building on DeFi ideas and concepts). Third, further work is needed to understand the role of central banks and wCBDCs in a broader tokenised ecosystem potentially including stablecoins, tokenised deposits and financial instruments, such as tokenised bonds and securities.

Project Mariana is a collaboration between the BIS Innovation Hub (BISIH), Bank of France, Monetary Authority of Singapore and Swiss National Bank. The project is purely experimental and does not indicate that any of the involved central banks intend to issue CBDC or endorse DeFi or a particular technological solution.

Acronyms, abbreviations and definitions

AMM	Automated market-maker. For the purpose of Mariana, this is a decentralised exchange using a bonding curve and a liquidity pool to price and exchange tokenised assets (ie a constant function market-maker).
API	Application programming interface.
Blockchain explorer	A blockchain explorer is software to retrieve and visualise real-time and historical data about transactions, addresses, blocks, smart contracts and other network metrics.
Bridge	A bridge enables the transfer of tokenised assets across different DLT networks.
Bonding curve	A bonding curve is a function determining the relative price of the assets traded through an AMM.
CBDC	Central bank digital currency.
CHF	Swiss franc.
Consensus mechanism	A consensus mechanism is any method used to achieve agreement within a decentralised network.
DeFi	Decentralised finance.
Denial of service	A denial of service attack is a cyber attack in which a malicious actor aims to render a computer or infrastructure unavailable to users by interrupting its normal functioning.
DLT	Distributed ledger technology.
DvP	Delivery versus payment.
EUR	Euro.
ERC	Ethereum request for comment. ERCs describe standards on Ethereum.
ERC-20	ERC-20 is a standard for fungible tokens.
FX	Foreign exchange.
FXGC	FX global code.
Liquidity pool	A liquidity pool (LP) is a smart contract with the ability to hold and transfer tokenised assets based on pre-defined logic.
LOB	Limit order book.
LP token	A liquidity pool token represents a claim on a share of the liquidity pool.
On-chain, off-chain	On-chain (off-chain) usually refers to data that is stored and processed on (or outside) a blockchain.
PoC	Proof of concept.
PvP	Payment versus payment.
Relayer	A relayer is a communication protocol between different DLT networks.
RTGS system	Real-time gross settlement system.
Settlement risk	Settlement risk is the risk that one party to a trade of assets will fail to deliver the asset owed.
SGD	Singapore dollar.

Slippage	Slippage is the difference between the current spot price and the realised price of a trade.
Smart contract	A smart contract is a program stored on a distributed ledger technology (DLT) platform that executes based on pre-defined logic.
wCBDC	A wholesale CBDC (wCBDC) is a CBDC available to commercial banks and other licenced financial institutions.

1. Introduction

Foreign exchange (FX) is the largest financial market in the world, trading about $7.5 trillion a day (BIS (2022b)). It operates 24 hours a day, five and a half days a week. In this market, commercial banks, central banks, brokers, asset managers, corporates and retail investors trade currencies using a range of instruments including spot, outright forwards, swaps and options. FX trading generally relies on either direct (bilateral) or indirect (brokered) relations with dealers. When relations with dealers are brokered, limit order books (LOBs) are typically used to maintain digital logs of existing orders to match buyers and sellers (Chaboud et al (2023)). Settlement usually occurs with delays of up to two days and settlement risk remains an issue (Glowka and Nilsson (2022)).

Project Mariana looks to the future and envisions a world in which central banks have issued tokenised forms of central bank money that are available to commercial banks and other financial institutions – so-called wholesale central bank digital currencies (wCBDCs).[1] It investigates how wCBDCs originating from different jurisdictions can be traded and settled safely and efficiently. Mariana borrows ideas and concepts from decentralised finance (DeFi), where cryptoassets are traded and settled immediately via so-called automated market-makers (AMMs).[2] AMMs are smart contracts that allow traders to exchange one cryptoasset – or tokenised assets more generally – for another, by drawing on a common pool of liquidity.[3] Prices are determined by a pre-specified algorithm.

This project examines if this new approach can simplify existing interbank FX processes. It also explores whether this approach can contribute to enhancing cross-border payments through improved transparency and reduced settlement risk. To this end, it tests three main components, in particular (i) a common technical standard for interoperability between wCBDCs; (ii) so-called bridges for wCBDC transfers between different networks; and (iii) an AMM for the FX trading and settlement.

Mariana extends previous work looking at the feasibility of cross-border and FX transactions using wCBDC arrangements and distributed ledger technology (DLT) platforms (Bech et al (2023), BISIH et al (2022b) and BISIH (2023)).[4] It is a joint proof of concept (PoC) between the BIS Innovation Hub (BISIH), Bank of France, Monetary Authority of Singapore and Swiss National Bank. The project is purely experimental and does not indicate that any of the involved central banks intend to issue CBDC or endorse DeFi or a particular technological solution.

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1 Tokenisation refers to the process of representing claims in the financial industry digitally on programmable platforms (BIS (2023) and Aldasoro et al (2023)).

2 Cryptoassets are a type of private sector digital asset that is expressed primarily through cryptography and distributed ledger or similar technology.

3 Smart contracts refer to applications, on distributed ledger technology, that can trigger an action if pre-specified conditions are met.

4 Arrangements involving multiple CBDCs are commonly called multi-CBDC arrangements (Auer et al (2021)).

This report describes the experimental setup of Mariana, its findings, and operational and policy considerations for central banks. Section 2 provides a project overview. Section 3 details the solution design. Results and considerations relating to the experiment and its related setup are discussed in Sections 4 and 5. Section 6 concludes.

2. Project overview

This section describes the overall objective of the project, the high-level architecture, and the functional requirements of the core architectural components.

2.1 Objectives

The primary objective of Project Mariana was to build a PoC of a 24 hours a day, seven days a week wCBDC ecosystem with an interbank FX market based on an AMM.[5] The experiment looks at the trading and settlement of spot FX transactions between commercial banks involving hypothetical euro (EUR), Singapore dollar (SGD) and Swiss franc (CHF) wCBDCs.[6] These FX transactions can serve multiple purposes, including cross-border payments.[7] A secondary objective was to understand the role of so-called liquidity-providers for an AMM. In particular, the project sought to explore how the amount of liquidity available to the pool, as well as how the parameterisation of the pre-defined algorithm, affect market liquidity (ie the ease with which wCBDCs can be traded for one another).

These two objectives are mapped into corresponding use cases at the centre of the experiment (discussed below). *Use case 1* focuses on FX transactions using wCBDCs in an AMM. *Use case 2* considers the liquidity provision by commercial banks to facilitate FX transactions.

Several aspects are out of scope for Project Mariana, in particular AMM governance models (eg type and activities of operators), governance models for domestic platforms and the transnational network,[8] non-functional aspects (eg technical performance and privacy), linkages or integration with existing systems and processes (eg real-time gross settlement (RTGS) systems and remuneration of central bank money) and legal aspects (eg the status of a transnational network and the wCBDC therein).

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5 See Auer et al (2023) for a discussion of AMMs and the technologies of decentralised finance.

6 This report refers to commercial banks for simplicity. Depending on the access policy of a central bank, use of wCBDC may be available to other financial institutions.

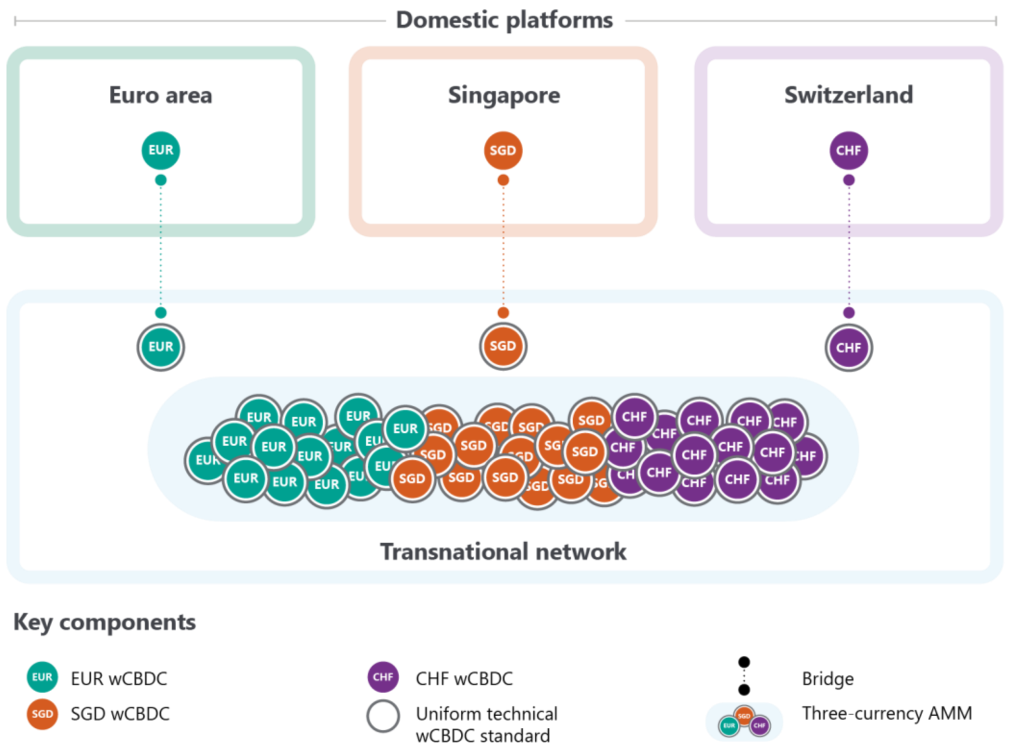
7 For instance, commercial banks may act on behalf of end-users making cross-border payments, facilitate global liquidity or seek to optimise portfolio risk management.

8 For the purpose of the experiment, the domestic platforms are assumed to be managed and operated by the respective central banks.

2.2 High-level architecture

The PoC consists of three wCBDC platforms representing the euro area, Singapore and Switzerland, respectively, and a transnational network which hosts the AMM (Graph 1). Both the platforms and the network are based on blockchain technology. The individual domestic platforms are connected to the transnational network via so-called bridges. A bridge is a mechanism that enables interoperability across blockchains by facilitating the transfer of tokens, smart contract instructions or data between two chains.

Mariana high-level architecture | Graph 1

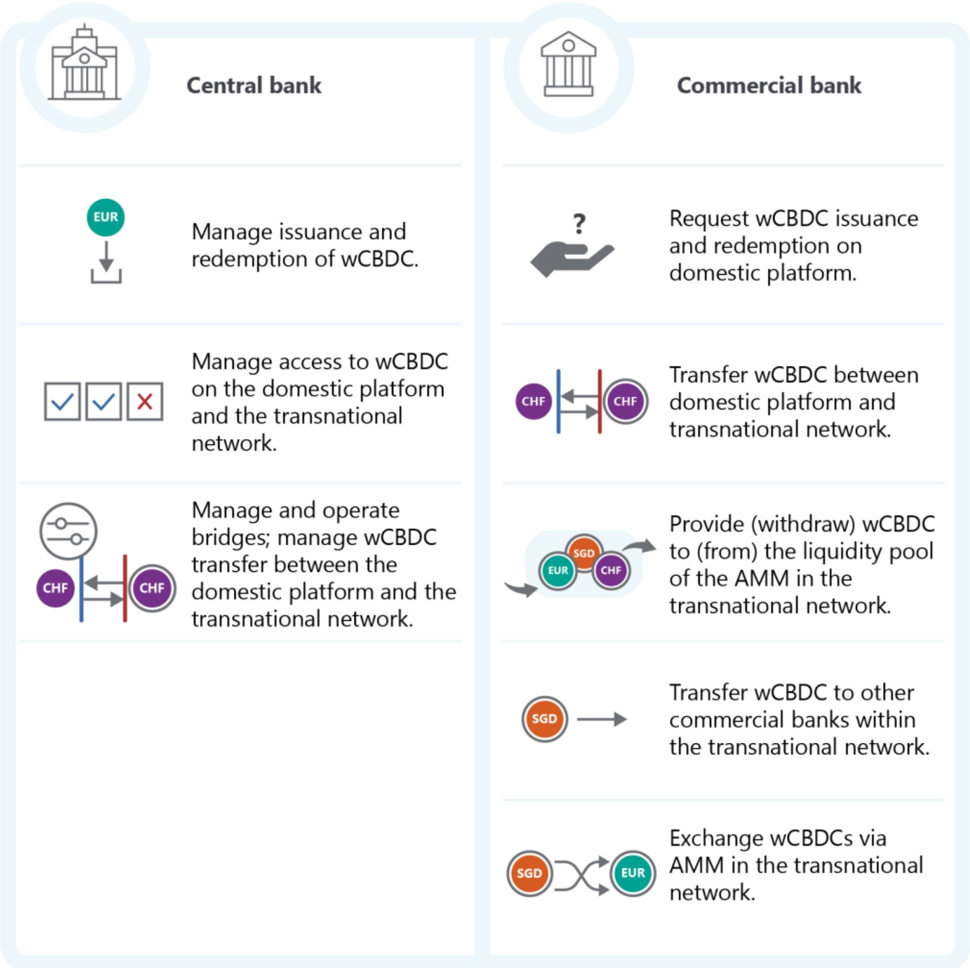


There are two types of institution in the Mariana ecosystem: central and commercial banks (Graph 2). A central bank manages access to its wCBDC on both the domestic platform and the transnational network. It also controls access to the bridges between the platform and the network. Central banks issue and redeem wCBDC only on their respective domestic platforms.

Commercial banks can utilise and transfer wCBDC within both the domestic platform and transnational network. They use a bridge to move wCBDC between a domestic platform and the transnational network. Upon transfer to the transnational network, the wCBDCs adopt a uniform technical standard which facilitates their use in the AMM. In the AMM, commercial banks can instantly trade and settle one wCBDC for another and generate revenue by contributing liquidity.

The technical work is complemented by analysis of operational and policy aspects, eg wCBDC management as well as trade-offs associated with bridges and FX trading and settlement using an AMM.

Institutions and roles — Graph 2



Box A: AMMs – a primer

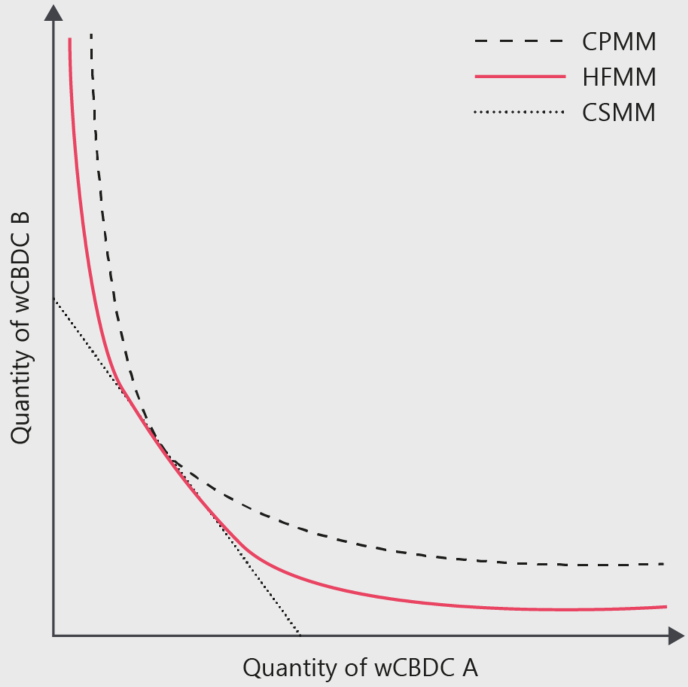
In DeFi, AMMs are the standard for the decentralised exchange and settlement of cryptoassets such as stablecoins. Instead of matching buy and sell orders (eg through an LOB), an AMM is a smart contract that holds cryptoassets, or tokenised assets more generally, in a liquidity pool and acts as the counterparty for liquidity-taking trades (eg FX transactions).[①] Prices are set through a pre-defined algorithm, the so-called bonding curve (eg Auer et al (2023) and Mohan (2022)).

A wide range of bonding curves have been proposed and used (Graph A1). The simplest form is a constant sum market-maker (CSMM) for a two-token pool. It requires that the sum of the two asset balances in the pool before and after a trade must be equal to a constant. The slope of the curve is constant, implying a constant exchange rate. This curve has an obvious drawback, which is that the pool can be depleted due to the exit of a single asset.

Alternatively, in a constant product market-maker (CPMM), the product of token balances in the pool remains constant. The price for a small trade relative to the size of the pool can be approximated by the ratio of the tokens in the pool, usually referred to as the spot price. In a CPMM, pools cannot be depleted due to the exit of a single asset, as the price of an asset in the pool goes towards infinity if its quantity approaches zero (reflected by the slope of the bonding curve).

Other more complex models of AMMs include constant mean market-makers (CMMMs), in which the pricing is determined by a weighted average of tokens in the pool, and combinations of constant mean and constant sum market-makers, so-called hybrid function market-makers (HFMMs). CMMM and HFMM bonding curves may be shaped and adjusted, eg to minimise slippage around currently traded prices. Such AMMs are typically calibrated to the volatility of the underlying assets, eg keeping prices within narrow bands despite the changing composition of the pool.

AMM bonding curve examples — Graph A1



An AMM requires both liquidity-takers and providers. Liquidity-takers can trade tokenised assets against the pool, and are then liable for transaction costs consisting of fees and so-called slippage. Slippage is the difference between the current spot price and the realised price of a trade, which depends on the shape of the bonding curve and the amount of liquidity in the pool relative to the size of the trade.

All trading in AMMs – and in DeFi more generally – is pre-funded. Specifically, trading and settlement is collapsed into one single transaction, eliminating settlement risk using payment-versus-payment (PvP) or delivery-versus-payment (DvP) mechanisms, preventing netting and making clearing redundant.

A liquidity-provider to the AMM receives a tokenised claim representing the share of their contribution in the pool (so-called liquidity pool (LP) tokens). This share determines the compensation for their contribution, which is paid by liquidity-takers through transaction fees. Liquidity-providers are compensated for the opportunity costs of liquidity provision and the so-called divergence loss (also called impermanent loss).

Divergence loss arises from changes in market prices of assets and the arising arbitrage opportunities for liquidity-takers.[2] Specifically, whenever the price of an asset in a liquidity pool differs from other market prices, arbitrageurs can buy (sell) a token below (above) market price from (to) the pool at the expense of the liquidity-providers. As a result, the liquidity-providers end up owning less of the asset that gained value and more of the one that lost value. The more prices diverge from the initial price at the time of the contribution by the liquidity-provider, the larger the divergence loss of the liquidity-provider. This loss is realised once liquidity-providers withdraw the tokenised asset from the pool.

① For this project, an AMM is a decentralised exchange using a bonding curve and a liquidity pool to price and exchange tokenised assets (ie a constant function market-maker). See Xu et al (2023).

② Divergence loss is the equivalent of adverse selection cost in LOB markets.

2.2 Functional requirements

As part of the project scoping, functional requirements were developed for the three core components of the PoC – the wCBDCs, the bridges and the AMM. All requirements were informed by discussions with central banks, financial institutions and experts from the DeFi community.[9]

wCBDC requirements

The functional wCBDC requirements ensure that central banks can manage access, issuance, transfer and redemption.[10]

C.1 Each central bank is the sole issuer of wCBDC in its currency.

C.2 Each central bank grants wCBDC access to commercial banks, with the ability to apply differentiated eligibility criteria on the domestic platform and on the transnational network.

C.3 Each central bank can prevent commercial bank(s) from receiving or transferring wCBDCs.

C.4 Each central bank can recover wCBDC from commercial banks whose access to wCBDCs has been revoked.

C.5 Each central bank can monitor transactions involving its wCBDC.

Bridge requirements

The functional bridge requirements ensure wCBDC transferability between the domestic platform and the transnational network.

B.1 Each bridge enables the transfer of wCBDC between the respective domestic platform and the transnational network 24 hours a day, seven days a week.

B.2 Each central bank grants access to commercial banks to the respective bridge for the transfer of wCBDC.

B.3 Each central bank's balance sheet remains unaffected by the transfer of wCBDC between the respective domestic platform and the transnational network.

B.4 wCBDCs on the respective domestic platforms and the transnational network are fungible.

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9 Project Mariana benefited from industry input at the Singapore Fintech Festival 2022, the Point Zero Forum 2022 and 2023 in Zurich, and exchanges with BNP Paribas, Citi, DBS, Standard Chartered and UBS.

10 The wCBDC requirements are similar to those developed by previous BISIH projects (eg BISIH et al (2021), BISIH et al (2022a), BISIH et al (2022b) and BISIH et al (2022c)).

AMM requirements

The functional AMM requirements seek to promote a robust, fair, liquid, open and transparent FX market supported by resilient infrastructure, building on relevant principles from the FXGC.[11]

A.1 The AMM provides a reference price for FX transactions.

A.2 FX rates are transparent to all market participants (FXGC Principle 12).

A.3 The mechanism determining the FX rate minimises the impact from large transactions (FXGC Principle 9).

A.4 Access to the AMM is transparent to participating commercial banks (FXGC Principle 37).

A.5 Disproportionate liquidity provision to the AMM is possible, ie commercial banks can provide or remove liquidity in one or more currencies.

A.6 Liquidity-providers can measure their positions in the AMM at any time (FXGC Principles 27 and 31).

A.7 The AMM does not incentivise undesirable trading practices (FXGC Principle 9).

[11] www.globalfxc.org/fx_global_code.htm.

3. Solution design

This section describes the solution design of the Mariana PoC based on the three core components – the wCBDCs, the bridges and the AMM.[12] Graph 3 presents an overview, including (i) the three domestic platforms with their respective central banks; (ii) three commercial banks (one from each jurisdiction for illustrative purposes); (iii) the bridges; and (iv) the transnational network with the three-currency AMM. The experimental infrastructure was designed to operate 24 hours a day, seven days a week. The wCBDCs in this context may exist indefinitely.[13]

The key design features of the three components, including the processes related to the use cases (discussed below), can be accessed and managed through a front-end application built for Project Mariana.

The PoC was based on blockchain technology and smart contracts, leveraging open source software as much as possible. Specifically, domestic platforms were built on permissioned versions of Ethereum (Hyperledger Besu) and the transnational network was built on a public Ethereum testnet (Sepolia).[14]

3.1 wCBDC design

In the PoC, wCBDCs are implemented as smart contracts and their design followed good practices from the public blockchain space. The different wCBDC smart contracts are compliant with the ERC-20 standard.[15] The standard enables wCBDC interoperability, in particular the use of the three currencies in the AMM.

The ERC-20 standard allows for the addition of custom features. In the Mariana experiment, the following wCBDC management features were implemented, accessible through the Mariana front-end application:

- *Issuance and redemption* – wCBDC is issued (redeemed) directly to (from) commercial banks on the domestic platforms (Requirement C.1).
- *Access control* – each central bank controls access to its wCBDC by maintaining so-called allow lists for the domestic platform and the transnational network, respectively. The allow lists specify commercial banks that are eligible to hold, transfer and receive wCBDC. The PoC allows for differentiated access to the domestic platform and the transnational network (Requirement C.2).

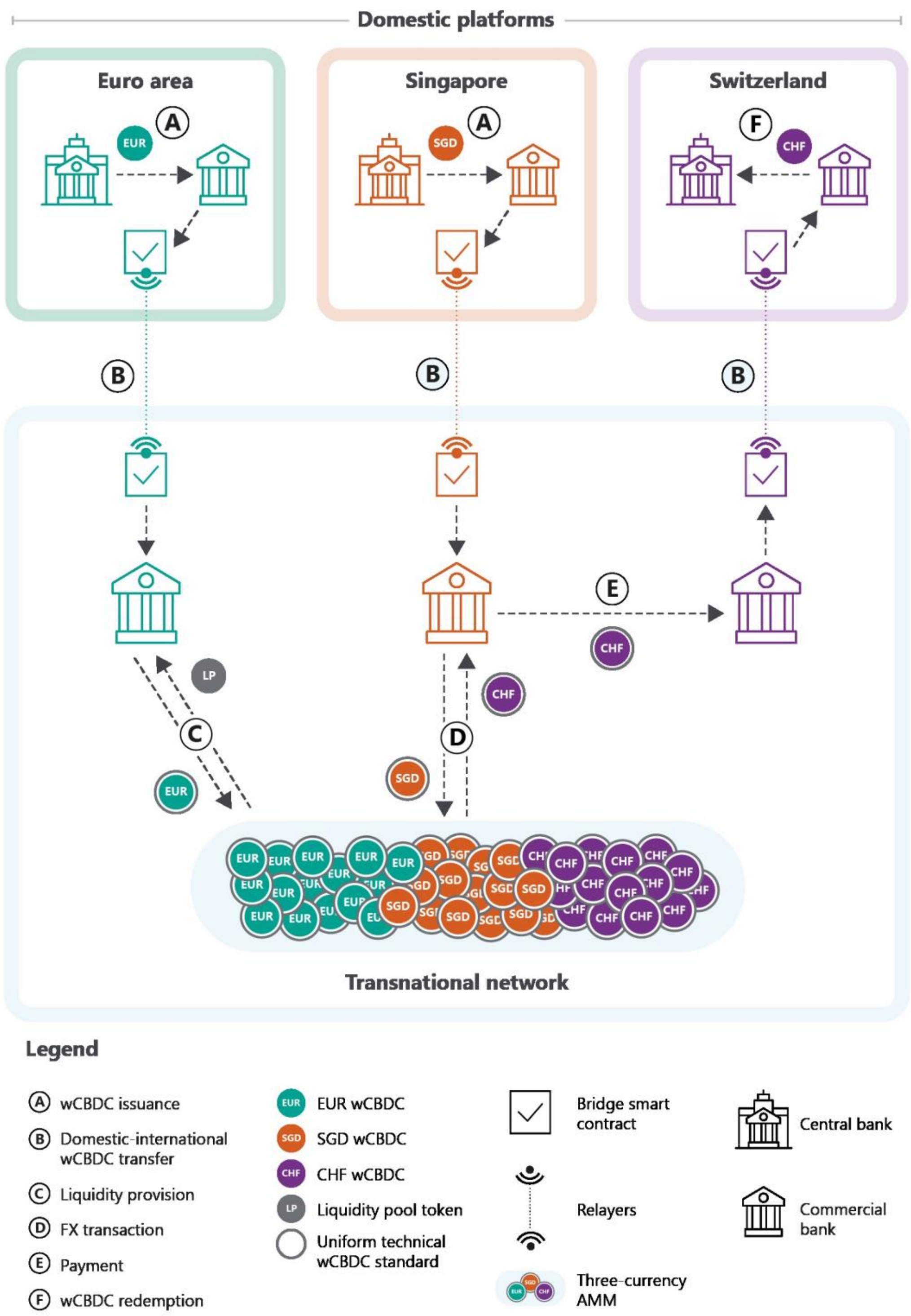
[12] The development of the experimental infrastructure was supported by BlockFold and OpenZeppelin.

[13] wCBDC that may exist indefinitely is also referred to as overnight wCBDC. An overnight wCBDC may nevertheless be converted into central bank reserves at the holder's request (Bech et al (2023)). Linkages or integration with existing systems and processes (eg RTGS systems) were out of scope for this experiment.

[14] Ethereum mainnet is where actual value transactions occur. In addition to mainnet, there are several public testnets such as Sepolia. These are networks used to test applications in a production-like environment.

[15] ERC-20 standard is a widespread token standard for fungible crypto assets (eg stablecoins) that establishes base level functionality such as transfer rules, balance queries and metadata (ie name and symbol).

Mariana solution design Graph 3



- *Recovery* – each central bank can recover wCBDC from a commercial bank that has been removed from an allow list (Requirements C.3 and C.4). The recovery of wCBDCs is an emergency feature, ensuring that wCBDCs remain in active circulation.
- *Pause transactions* – each central bank can pause transactions involving its wCBDC (Requirement C.3), eg in response to operational disruptions on- or off-chain. Pausing also stops the issuance, redemption and recovery of wCBDC, and the updating of associated allow lists.
- *Upgradeability* – central banks can upgrade their wCBDC smart contracts without operational disruptions, ie wCBDCs can remain in active circulation while features can be changed, added or removed.[16]

wCBDC transaction monitoring (Requirement C.5) was implemented using web-based blockchain explorers (eg building on open source software), which are commonly used to retrieve and visualise real-time and historical data about transactions, addresses, blocks, smart contracts and other metrics from Ethereum and other public blockchains.

3.2 Bridge design

The bridges implemented in Mariana enable commercial banks to transfer wCBDC between a domestic platform and the transnational network. Central banks manage and operate their respective bridges. In particular, they manage access through dedicated allow lists (Requirement B.1). For the experiment, all commercial banks with wCBDC on the domestic network have access to the corresponding bridge.

Each bridge is implemented as a set of two smart contracts – one for the domestic platform (domestic bridge smart contract) and one for the transnational network (transnational bridge smart contract) – and so-called relayers. The domestic bridge smart contract takes (releases) wCBDC into (from) custody for transfers to (from) the transnational network.[17] The transnational bridge smart contract releases (burns) a corresponding amount of wCBDC. Relayers, hosted off-chain (eg on central bank servers or in the cloud), process instructions between the smart contracts and ensure synchronisation of information on both sides of the bridge.

The relayer architecture is key to mitigating risks of cyber attacks while increasing the resilience and availability of the transfer process (Requirement B.3). In Mariana, a consensus mechanism among relayers was implemented, requiring multiple relayers to confirm a transaction before further processing. Specifically, six relayers were implemented per bridge, where three were dedicated to each direction (ie three relayers from the domestic to the transnational network and vice versa). Two

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[16] The Mariana wCBDC implementation uses a so-called proxy pattern (ERC-1822). A proxy contract acts as a "middleman" between a user and the actual implementation contract and contains a reference to the implementation contract. This reference can be updated to another implementation contract without affecting the usage or the underlying state of the ledger.

[17] A bridge cannot transfer any asset other than the corresponding wCBDC (eg a bridge between the Swiss domestic platform and the transnational network can only transfer CHF wCBDC).

out of the three relayers must confirm the initiating transaction for continued successful processing to take place.[18]

The bridge transfer process that can be monitored in the Mariana front-end application ensures control over wCBDC in circulation (Requirement B.2) and supports wCBDC fungibility through automation (Requirement B.4). Specifically, for a domestic to transnational transfer, the domestic bridge smart contract takes wCBDC into custody, inducing a state change (ie an update of the blockchain) on the domestic platform and setting the wCBDC transfer to pending. The state change is picked up by the relayers and processed. Once two out of the three relayers confirm the transaction, the instruction is passed to the transnational bridge smart contract, which in turn releases the corresponding amount of wCBDC and completes the transfer process. A similar process applies to transfers from the transnational network to the domestic platform.

Should a pending transaction not be confirmed by the relayers after a certain number of attempts, respective commercial and central banks are informed through an alert. The commercial bank could cancel the process which would release relevant wCBDC from the bridge transfer process.

[18] Three is the minimum number of relayers required to test the setup and related consensus mechanism. This approach could be generalised to any "*m* of *n*" strategy, where *m* is the number of confirmations of *n* relayers.

Box B: AMMs and good trading practice

Principle 9 of the FXGC states that undesirable trading practices should be avoided. Project Mariana has been designed such that the following desirable features are ensured:

1. Non-profitable order splitting – breaking trades into smaller tranches is not systematically profitable.
2. Divisibility of liquidity – the bonding curve incentivises trading against one large pool over trading against multiple smaller pools.
3. Pricing symmetry – buying and selling against the pool has the same price impact.
4. Non-profitable front running – the pricing function offers the least possible front-running profitability.
5. Non-profitable cyclical arbitrage – trading currencies A vs B, B vs C and C vs A is not systematically profitable.
6. Arbitrage-link efficiency – the pricing function allows price arbitrage between different markets for the same currencies.

Features (1) and (2) hold for the specification tested in Project Mariana. The other features depend on the parametrisation of the bonding curve, the size of the trade relative to the pool size and whether the pool is balanced. Generally, with little convexity of the bonding curve around the current trading price, small trades relative to the pool size and a balanced liquidity pool, features (3)–(6) hold approximately.

3.3 AMM design and calibration

Project Mariana evaluated several AMMs against the seven requirements listed in Section 2.2 and the six desirable features of good trading practice in Box B. While a number of designs met the requirements and were consistent with the desirable features, only one was selected for implementation. The chosen protocol was an HFMM as discussed in Egorov (2021).[19] This AMM contains several parameters to adjust both the shape of the bonding curve and the trading fees.

Relevant AMM design considerations as well as the procedure to calibrate the AMM parameters are outlined below.

AMM design

In order to avoid fragmentation of liquidity, the HFMM was designed as a three-token pool. All else equal, this design choice increases the amount of liquidity available to trade against in a single pool, increasing its chance of providing a reference price (Requirement A.1).[20]

[19] This project is experimental in nature and does not reflect endorsement of any protocol or product by any of the involved institutions.

[20] Generally, to support FX transactions in n currency pairs, n*(n–1)/2 bilateral pools would be needed. Every bilateral pool would need a given liquidity to support a fixed transaction size.

The HFMM has two key characteristics with regard to liquidity. First, the price impact of liquidity-taking trades can be controlled by adjusting the shape of the curve around the currently traded price (Requirement A.3), limiting the profitability of undesirable trading practices like front-running (Requirement A.7).[21] Second, it enables control of the fees for liquidity-taking trades, providing options adjust compensation for liquidity-providers.

Commercial banks take the role of both liquidity-providers and liquidity-takers. Liquidity-providers commit wCBDCs to the pool in either one, two or all three currencies (Requirement A.5). In return, liquidity-providers receive LP tokens reflecting the relative share of their contribution to the pool.[22] Moreover, LP tokens can be used to measure the underlying position in the liquidity pool (Requirement A.6).

As a liquidity-taker, a commercial bank can trade one wCBDC for another. Trading costs are determined by slippage (resulting from the shape of the bonding curve) and the fees.[23]

The Mariana front-end accesses application programming interfaces (APIs) to query spot FX rates as well as estimate prices for given liquidity-taking trades (Requirement A.2). Additionally, the name of participating banks in the AMM can also be retrieved (Requirement A.4).

AMM calibration

The parameters in the AMM were calibrated with the objective of replicating observed exchange rate movements from historical market data using the AMM while ensuring profitability for liquidity-takers and providers. Specifically, the calibration procedure assumes that an external FX market to the AMM exists (using historical data), and that traders try to align the prices in the AMM with these external prices to produce arbitrage profits.

At a high level, to replicate foreign exchange movements using the AMM, the calibration strikes a balance between the opposing objectives of the liquidity-taker and provider. On the one hand, a liquidity-taker wants to maximise profitability from arbitrage trading which is achieved with low fees and low slippage. On the other hand, a liquidity-provider wants to maximise profitability with high fees.[24]

21 Parameters of the bonding curve can be adapted to adjust slippage around currently traded prices. All else equal, small slippage reduces price volatility.

22 LP tokens are fungible and represent a claim against the underlying assets. In principle, they could be used as collateral in other transactions. However, this was out of scope for the project.

23 This PoC excludes network usage fees considerations. These fees typically only apply in public blockchain environments. In Ethereum, for instance, they are called gas fees.

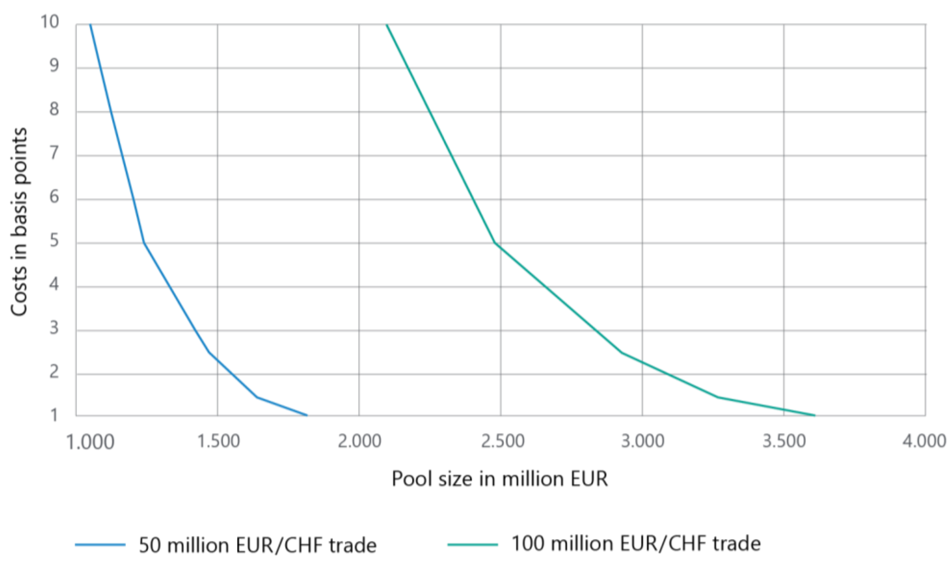
24 All else equal, (i) higher fees disincentivise trading but increase income from liquidity provision; (ii) higher slippage increases the price reaction of liquidity-taking trades, reducing their profitability while damping divergence loss for the liquidity-provider.

The calibration of parameters was performed by a relatively simple process, varying one parameter at a time, keeping all other values fixed. Importantly, this process does not yield an optimal set of parameters but ranges of values that yield acceptable results. Further testing would be required to assess the robustness of the calibration.

Using the calibrated AMM, FX trading was subsequently simulated to assess the resulting trading costs as a function of trade size and liquidity pool size. Graph 4 shows examples using a 50 million and 100 million trade size in EUR/CHF. A 50 million EUR/CHF trade at a cost of 1 basis point, for instance, requires a pool size of roughly €1.8 billion.[25]

Results reveal two characteristics of the AMM used in Project Mariana. First, the marginal increase in the pool size required to reduce trading costs by some fixed amount increases as trading costs become smaller. That is, the lower trading costs are, the more additional liquidity is required to further decrease trading costs. Second, maintaining a certain level of trading costs when increasing the size of trades against the AMM requires an approximately proportional increase in the pool size. For instance, doubling the trade size requires doubling the pool size to maintain a given level of trading costs.

Trading costs and liquidity pool size for different trade sizes — Graph 4



[25] The pool is expressed in EUR equivalents, expressing the other currencies in terms of EUR using the spot exchange rates.

4. Use cases and testing

This section presents an overview of the two main use cases and related testing of the experimental infrastructure. The use cases as well as the testing were all executed through the Mariana front-end application with differing interfaces between the central and the commercial banks.

4.1 Use case overview

Graph 3 sketches how the two use cases – FX transaction and liquidity provision – are tested given the solution design. As a minimum requirement for the example shown in Graph 3, on the transnational network, the euro area commercial bank has access to the EUR wCBDC, the Singaporean commercial bank to the SGD wCBDC and the CHF wCBDC, and the Swiss commercial bank to the CHF wCBDC. Access to wCBDC is determined by the wCBDC allow lists managed by the respective central banks.

The commercial banks represented on domestic platforms and the transnational network are allow listed for their respective bridges (eg the euro area commercial bank for the bridge between the euro area's domestic platform and the transnational network).

Use case 1 is an FX transaction to facilitate cross-border payments. It is illustrated using the Singaporean and the Swiss commercial banks executing a cross-border payment from Singapore to Switzerland. In a first step, the Singaporean commercial bank requests issuance of SGD wCBDC (process A). It then transfers the SGD wCBDC to the transnational network using the bridge (process B). On the transnational network, the Singaporean commercial bank (i) executes the FX transaction, paying SGD wCBDC to receive CHF wCBDC, using the AMM (process D); and (ii) pays CHF wCBDC to the Swiss bank (process E). The Swiss bank transfers the newly received CHF wCBDC to the Swiss platform (process B). Finally, it redeems the wCBDC (process F).

Use case 2 is a liquidity provision by commercial banks to facilitate FX transactions. It is illustrated using the euro area commercial bank. The euro area commercial bank requests issuance of EUR wCBDC on the domestic platform (process A). It then transfers the EUR wCBDC to the transnational network using the bridge (process B). On the transnational network, the euro area commercial bank provides liquidity to the AMM, ie it pays EUR wCBDC to the AMM in return for a corresponding amount of LP tokens (process C).

4.2 Testing

The testing evaluated the two use cases subject to the functional requirements. Twenty-four test cases were defined, dividing the two use cases into various sub-activities.

Specifically, the testing covered (i) the allow listing of the hypothetical commercial banks on the domestic platforms as well as on the transnational network and the bridge, (ii) the issuance and redemption of wCBDCs on the domestic platforms, (iii) the bridging of currencies between the domestic platforms and the transnational network and (iv) all the processes required to execute FX transactions and (v) liquidity provision and withdrawal using the AMM. The Annex provides a snapshot of sample test transactions including transaction hashes.

5. Operational and policy considerations

This section discusses operational and policy considerations for central banks identified by the Mariana PoC for each of the core architectural components.

5.1 wCBDC considerations

The project highlights that central banks have options in terms of how to manage wCBDCs. wCBDCs were issued and redeemed on the domestic platforms whereas access was managed at (i) the platform level (domestically) or (ii) the token level (on the transnational network).[26] In principle, this allows for differentiated access policies on the domestic platforms and the transnational network, offering opportunities to broaden access to support FX trading in a currency. Broadening access to central bank money, however, raises intricate policy issues (Bech et al (2023)).

The wCBDCs based on smart contracts have many potential benefits. For instance, the ERC-20 token standard enables wCBDC interoperability while allowing additionally for the implementation of management features.[27] This was out of scope for Project Mariana but these features could, in principle, differ between central banks.

However, smart contracts also introduce new challenges and risks. For example, the 24 hours a day 7 days a week availability of wCBDC may increase operational complexities for central banks, eg to ensure consistent remuneration across different forms of central bank money (out ot scope for this PoC). Moreover, while the PoC demonstrates that central banks can manage their wCBDCs without necessarily owning or controlling the underlying platform, the wCBDC smart contracts may introduce new vulnerabilities. Specifically, it may introduce new types of security risks, which require a thorough review.[28]

5.2 Bridge considerations

Borrowing from existing implementations in DeFi, the bridges enable a seamless and automated wCBDC transfer between the domestic platforms and the transnational network. Despite discovered complexities in the development process, controls and safeguards were implemented based on central bank requirements.[29] More specifically, smart contracts on either side of the bridge and the relayers are managed by the respective central banks. This provides oversight and central bank control over

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[26] By assumption, domestic platforms are permissioned, ie access can be determined on the platform level. Different access mechanisms could be implemented, eg through allow lists as on the transnational network.

[27] This report does not suggest any token standard, but does shed light on the significance of standards.

[28] As part of the development phase, OpenZeppelin conducted a security review of the wCBDC design in the context of the Mariana PoC.

[29] A detailed security assessment of the bridges was out of scope.

the transfer process. The front-end application allowed central banks to monitor bridge transactions.

Safeguards are implemented through the relayer consensus and unidirectional communication, thereby mitigating risks of (i) forced shutdowns (eg through denial of service attacks) and (ii) the wrong entities receiving wCBDC (eg through compromised relayers). Furthermore, in principle, the architecture of the relayers would allow for the distribution across different infrastructures (eg on-premises and cloud providers), increasing resilience and availability as well as reducing risks of cyber attacks on the transfer process.

Overall, even though the experimental architecture was based on a uniform protocol standard (ie public and permissioned versions of Ethereum), the implementation of the bridges was complex. It required the interplay of three infrastructures: the domestic platform, the transnational network and the relayer infrastructure (hosted by the respective central banks). In particular, ensuring reliable and consistent communication between the networks proved to be challenging. Such challenges may be considerably greater for the establishment of bridges between platforms based on differing protocols.

5.3 AMM considerations

Mariana demonstrates the technical feasibility of a three-currency AMM for FX transactions using wCBDC. As designed, the AMM aligns with relevant FXGC principles as discussed in Section 2.2. It delivers the contours of a possible future tokenised FX market.

However, the use of AMMs requires the pre-funding of liquidity and their adoption would therefore entail a significant departure from the ex post funding (deferred net settlement) in use in today's FX markets. All else equal, pre-funding is costly and needs to be weighed against a range of potential benefits. These include:

- **Simple and automated execution of FX transactions**. In principle, it should be possible to integrate a Mariana-like AMM into cross-border payment solutions based on wCBDCs. From a technical perspective, an AMM may be extended to wCBDCs in any currency and may therefore able to be an alternative to current trading methods. However, an AMM does not, in and of itself, solve any underlying market or funding liquidity issues that might exist in a currency pair.

- **Instant settlement**. Instant settlement is the result of a set of contingent actions, executing the trading and settlement instructions subject to slippage and fee limits. As a result, it ensures safe and secure wCBDC transactions and eliminates settlement risk through PvP. Overall, this may simplify risk management.

- **Transparency**. AMMs and the underlying blockchain technology may support transparency of market activity and thereby support market stability. Nevertheless, privacy-preserving mechanisms (eg stealth addresses as outlined in BIS (2022a)) may be put in place to support the privacy needs of market participants while providing the transparency required from a regulatory perspective.

- **Collateral**. LP tokens may offer new ways to utilise liquidity that are currently either pre-positioned or locked to support FX transactions and cross-border payments. As LP tokens are fungible and represent claims on wCBDCs (within a liquidity pool), they could be utilised as collateral in further transactions.[30] However, access to LP tokens would have to be explored in more detail, given that they may represent a claim on central bank money.

The Mariana PoC was only a first step to understand the potential benefits and challenges of AMMs for wholesale FX transactions using wCBDCs. Further research and experimentation will be required in this area and more broadly on AMMs in the journey towards a potential tokenised financial ecosystem.[31]

30 The use of LP tokens may ease liquidity concerns communicated by industry participants at various occasions, including the Singapore Fintech Festival 2022 and the Point Zero Forum 2023 in Zurich.

31 Traditional FX markets have been researched extensively (see Chaboud et al (2023) for an overview and the references therein). While still a comparatively small area, research on AMMs has been growing (eg Adams et al (2023), Barbon and Ranaldo (2022) and Xu et al (2023)).

6. Conclusion

Project Mariana looks into the future, envisaging a spot FX market building on the promises of tokenisation. It pioneers the use of AMMs for the cross-border exchange of wCBDCs, demonstrating technical feasibility while fulfilling central bank requirements and broader principles set by the FXGC. In particular, in the tested experimental setup, central banks are able to manage their wCBDC without necessarily operating or controlling the underlying infrastructure. Commercial banks can use the wCBDCs to engage in instant FX trading and settlement, avoiding credit and settlement risk and improving efficiency.

The project built on central bank autonomy within domestic platforms while extending the use of wCBDCs through interoperability and technical standardisation. It offers perspectives on ways to leverage open, transparent and composable technology and future-proof various domestic and regional wCBDC arrangements under development.[32] As a result, it introduces novel approaches in factoring the international dimension into a wCBDC ecosystem design, contributing to the work of the G20 roadmap to enhance cross-border payments.

Future work could deepen and broaden Project Mariana in three dimensions. First, the commercial viability of AMMs for spot FX transactions using wCBDCs may be explored. This would require collaboration with relevant stakeholders in existing FX markets. Several aspects could be investigated, including (i) the profitability of liquidity provision while keeping transaction costs competitive with existing FX markets; (ii) mechanisms to alleviate the costs of pre-funding (eg by introducing short-term credit); (iii) the economic use of liquidity pool tokens (eg in payments, repos and swaps); (iv) options to endow liquidity-providers with voting rights on the fee structure for liquidity-taking trades (eg as a tool to steer liquidity conditions in the AMM); (v) and the needs and opportunities for privacy-preserving technologies. Moreover, should AMMs move closer to implementation for traditional financial markets, appropriate governance mechanisms should be explored.

Second, building on the openness and composability of DeFi and smart contracts, Mariana offers the potential to broaden experimentation, eg exploring monetary policy implementation in a tokenised financial system. While out of scope for Project Mariana, questions related to the remuneration of wCBDCs could be one relevant aspect. More generally, tokenisation may open up the potential to adapt or improve existing monetary policy instruments, potentially leveraging ideas and concepts from DeFi.

Third, future work may consider the role of wCBDCs and central banks in a broader tokenised financial system, exploring elements of the blueprint for the future monetary system outlined in the BIS Annual Economic Report 2023 (BIS (2023)). This may cover a wide range of questions, including the design of (the) underlying programmable platform(s), the role of tokenised deposits and stablecoins, and the tokenisation of financial instruments as well as legal and regulatory aspects. Mariana

[32] Composability refers to the capacity to combine different smart contracts in a system, such as DeFi protocols (BIS (2022a), FSB (2022)).

provides a starting point for future considerations, eg in relation to the implementation of central bank requirements on programmable platforms, standardisation of (money) tokens, the role of interoperability mechanisms and the design of market arrangements in a tokenised world.

Clearly, further experimentation to understand the benefits and challenges of tokenisation is required – guided by the needs of central banks, financial market participants and end users. Collaboration among stakeholders will be key and the BISIH will continue to strive to break new ground on this journey together with its pioneering partners around the globe.

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Annex: Sample test transactions

Table A.1 provides a snapshot of selected test transactions, focusing on processes A-F outlined in Graph 3. Where available, the table lists transaction hashes from the transnational network (Ethereum Sepolia), which can be verified in a blockchain explorer (eg Etherscan).

Snapshot of selected test transactions — Table A.1

Process	Description	Domestic platform/ transnational network	wCBDCs/ LP tokens	Transnational network transaction hash
A	Issue wCBDC on domestic platform	*Domestic platform*	-	-
B	Transfer wCBDC from domestic platform to transnational network *(and reverse)*	*Domestic platform and transnational network*	*EUR* *SGD* *CHF (reverse)*	0x2d13d4aa1723c7de714461579ddc45e5ed544433be159672ca4113fcb0d39ecfs 0xb45c71aeafa872c9ae84c8031d55e86b66431e08375778100bc191f9dfeae61c 0x93fd5e59d490fe164fc75e10902b4ad511a90a31511b4dd4e2ba726587dba034
C	Provide liquidity to AMM in all three currencies Remove liquidity from the AMM in one currency	*Transnational network*	*EUR, SGD, CHF* *CHF*	0xf4e1a5286e60c7441ae9876472880e616066600c8b2de350cce3ed475e76eb77 0x305bd5261b3e1d1472b9fa95d09b83beacee9d14156fef9835db20b223d4a7c2
D	FX trading and settlement	*Transnational network*	*EUR/SGD* *SGD/CHF* *SGD/EUR*	0x59eab5a2fc1255f09c9d5d96d7482cb5eb3ebc171431eca6dfafe044258bbd56 0x5786122d01548d2b93943a68d0a9ffc7a20c025f964bcab343a8d33d0949206b 0x4817ac61f71d9bd7b4162664eb6da22676d6e1361c8ca77ed68be18580baeeb7
E	Payment	*Transnational network*	*EUR*	0x1603458b12698e04da4a8d3748e7153a2cb7d2d4e208a4003f2b3e86d37edb4c
F	Redeem wCBDC	*Domestic platform*	-	-

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