Integrated Multi-Chain Architecture for Organizational Interoperability

Abstract—**This paper explores the development of integrated multi-chain architectures in response to the growing adoption of blockchain technology. As organizations increasingly operate across multiple platforms, also known as "blockchain islands", there is a need to address the challenges of interoperability between these isolated systems. The study proposes a "top-down" approach that prioritizes end-to-end processes and data flows at the enterprise level before considering supporting systems. The proposed architecture includes four crucial perspectives and focuses on the Orchestrator and Confidence Calculator modules, which align with the key layers in the organizational architecture and enable decentralized workflows and probabilistic guarantees of state finality across chains. However, challenges remain in terms of heterogeneity, standards, controls, and semantic alignments. By applying enterprise architecture techniques, this research aims to bridge these challenges and accelerate mainstream adoption. Further validation is required to promote organizational interoperability.**

Index Terms—**Blockchain, Interoperability, Multi-chain architecture, Enterprise integration, Service composition, Organizational architecture.**

I. Introduction

Over the last few years, the adoption of blockchain technology has seen rapid growth beyond cryptocurrencies in mainstream enterprise applications [1]. Leading organizations across banking, supply chain, healthcare, and even governments are investing significantly in decentralized ledger technologies to address trust and transparency challenges in digital services. However, most blockchains have been developed as standalone networks without interoperability [2], [3].

As blockchain application development matures, organizations now have a presence across multiple blockchain platforms and networks, both public mainnets and private consortiums hosted through cloud services. While each network serves a specific purpose, this heterogeneous architecture poses challenges in harnessing collective capabilities across blockchain systems.

Enabling such multi-chain architectures requires overcoming both managerial and technological hurdles to ensure seamless interoperation across organizational boundaries. Though point solutions like bridges and relays allow asset transfers across select networks [4], they do not account for the overall information system architecture and its relationship to the enterprise environment. This leads to fragmented experiences for organizations seeking to leverage synergies across blockchain networks. Common organizational architectures in information technology, particularly in the context of enterprise applications and services, include several models. Industry architectures such as service-oriented (SOA) and microservice-oriented systems design business processes and organizational workflows [5], [6].

A successful precedent in information systems architecture is the service-oriented architecture (SOA) paradigm, which composes modular services to support end-to-end business processes and data flows [7]. Similarly, a comprehensive approach is required to fully realize the combined potential of multiple chains. This entails an integrative architecture to coordinate workflows, data integration, and application logic across different chains from an organizational perspective. As blockchain ecosystems diversify into platforms optimized for particular use cases, their specialized strengths can be combined into adaptable network architectures. Technical interconnectivity alone is insufficient without addressing managerial and architectural considerations from an organizational standpoint. Realizing the collective value proposition requires a holistic approach centered on end-to-end vision and the architectural integration of business processes across chains. This is the main focus of this research.

The rest of the paper is organized as follows: Section 2 discusses the state of art across key areas like blockchain interoperability frameworks, organizational architecture models, and service-oriented architecture. Section 3 reviews related works applying organizational and service composition architecture to integrate blockchain-based services. Section 4 outlines the research goals and questions guiding this research. Section 5 presents the proposed modular architecture for multi-chain integration spanning four crucial perspectives. Section 6 examines open challenges and future research directions whilst discussions and conclusions are presented in Section 7.

II. Background

Blockchain is a distributed ledger technology that enables decentralized parties to share data and processes securely without requiring a central authority. By establishing a common record of chronological transactions and business events replicated across multiple entities, organizations can coordinate activities end-to-end, achieve process visibility, eliminate disputes, and build trust across organizational boundaries [8], [9]. Blockchain streamlines workflows, contracts, and supply chains by replacing human-based verification methods with cryptographically-secured peer-to-peer automation and authorization [10], [11].

A. Blockchain interoperability

The blockchain industry has expanded into numerous platforms and niche chains catering to specific applications or assets [2], [3]. For instance, Ethereum provides a Turing-complete smart contract engine, Bitcoin focuses on peer-to-peer payments, Hedera Hashgraph delivers high throughput for enterprises, and other chain target domains such as supply chain provenance (VeChain), identity management (Indy), and decentralized storage (Filecoin). As blockchain adoption has increased, organizations now deal with dozens of ledgers and find themselves operating in a multi-chain world [12], [13]. However, the flip side of tailored chains tends to function in silos [3], [14], creating fragmentation across different "blockchain islands". This prevents the harnessing of the collective capabilities.

Interoperability is generally understood to be the capacity for different and separate blockchain networks that are dissimilar in nature to communicate and interact with each other [15]. It can span both public and private consortium chains. Existing blockchain interoperability frameworks identify multiple layers of increasing complexity, spanning technical implementations through legal and regulatory policies [16]. We propose consolidating these into two core interoperability dimensions.

- Structural Interoperability: Encompassing common interfaces, protocols, data formats, and integration components to technically link blockchain systems;
- Functional interoperability: This enables decentralized and coordinated cross-chain transactions to create end-to-end value flows across chains and ecosystem participants.

The former focuses on technical integration points, while the latter operates at the organizational level to deliver actual use cases.

Most existing solutions approach interoperability bottlenecks as technical challenges, first deferring organizational integration. We argue that a reverse approach is needed to analyze cross-chain applications and ecosystem objectives and then build a supportive technical architecture.

Two prevailing paradigms have emerged for architecting blockchain interoperability across networks [16]: multichain models directly incorporate native interoperability protocols into an umbrella ecosystem spanning integrated subsidiary chains, establishing common trust anchors and communication channels from the onset, as exemplified by Cosmos, Polkadot, and Avalanche. Alternatively, Cross-Chain Bridges retrofit specialized connectivity solutions to transfer data or assets between standalone blockchain networks post-deployment through bridges, oracles, relays, etc.

In reviewing innovations in the field, three aspects emerge [4]: Techniques describe elementary mechanisms enabling basic protocol interoperability via approaches like hash-locks or relays. Solutions can enhance existing techniques or introduce new mechanisms for improved capabilities, such as Blockchain Router architectures or inter-chain smart contracts. Implementations realize the techniques and solutions by manifesting them in dedicated platforms such as Cosmos and Bitcoin's Lightning Network. To these may be added frameworks that glue complementary components into holistic ecosystems, such as Hyperledger Cactus, delivering versatile interoperability [17]. While point solutions focus narrowly on asset transfers across chains, interoperability could evolve towards a more seamless and holistic integration of end-to-end workflow spanning systems. Solutions should offer a unified experience to leverage the combined potential across chains.

B. Organizational Architecture

Organizational architecture refers to the overall structure of an enterprise that encompasses internal departments, business processes, governance mechanisms, and external ecosystem linkages [18]. It provides a blueprint for how resources, information, and authority flow between elements fulfill an organization's objectives.

Four key interconnected aspects include [19]–[21]:

- Business Architecture: Covers core business functions, capabilities, processes, and the sequence of activities that capture how an organization delivers value. This connects the strategy to the operations;
- Data/Information Architecture: Details of information taxonomy, structure, quality, and analytics models that support business processes and leadership decision-making;
- Technology Architecture: Comprises software, infrastructure, and system interconnections powering the processing, movement, and storage of data and digital capabilities;
- Governance Architecture: Defines authority structures, policies, decision rights, and accountability models that dictate organizational behavior.

Emerging areas in organizational architecture span fostering connected ecosystems via APis and microservices, cloud-based agile architectures enabled by containers and devops, and mesh app architectures [22], [23].

Emerging technologies such as blockchain provide new architectural possibilities for organizations. Although blockchain may not entirely eliminate corporations, it expands the possibilities of organizational architecture [24]. One paradigm is the cross-organizational enterprise service bus (ESB) [25]. This architecture resembles traditional ESBs that integrate intra-firm systems, but is decentralized across firms and emphasizes sharing only the necessary data. A blockchain coESB can provide persistence, traceability, and a "shared truth" around business transactions and processes across organizations lacking conventional ESBs [25]. This helps to coordinate activities while preserving local control and privacy.

Initial evidence from cases such as the German Federal Office for Migration and Refugees suggests that blockchain can help coordinate cross-organizational processes without requiring centralized governance [25]). However, challenges regarding integration, standards, governance, and acceptance remain.

Despite growing interest, significant research gaps persist concerning implementation challenges and the blending of blockchain with organizational theory [24]. Practical organizational applications are still emerging. How blockchain reshapes organizational boundaries and architectures remains an open question, warranting further scientific inquiry.

C. SOA Architecture

The service-oriented architecture (SOA) paradigm aims to build flexible, reusable software systems from modular services that can be invoked to deliver custom experiences and overcome organizational challenges(Li, Zheng, and Dai 2021). Services encapsulate capability, which is made available via a formal interface hiding the underlying complexity [5].

One of the most successful models of service orientation is the service-oriented architecture (SOA) [26]. SOA has emerged to address the challenges of connecting heterogeneous systems (often called enterprise application integration) through standards-based approaches [5], [7], [27]. It allows integration across platforms, languages, and diverse organizational systems. SOA has helped shift enterprise IT from monolithic applications to an ecosystem of composable services.

With the advent of cloud computing, these concepts have evolved into microservice architecture, where complex applications are built from independently deployable, granular services aligned to business capabilities [6]. Service orientation is ubiquitous in modern information technology landscapes.

One of the key points that emerge from service orientation is the service-oriented lifecycle. It includes service publication and discovery, service recommendation and selection, service composition into workflows, and service arbitration to resolve disputes [7], [27] These steps can be considered together or independently, depending on the use case. A key benefit afforded by SOA is service composition. It refers to the ability to combine individual and reusable services into composite applications, potentially spanning organizational boundaries and technologies. Several techniques can be used to achieve this: Choreography, Orchestration and Mediation [26].

The motivation behind composition is that most large-scale business processes require integration across many underlying systems [14]. Complex workflows can be modeled through the coordination and sequencing of services by decomposing end-to-end flows into logical building blocks aligned to services. This allows the creation of customized applications that match user needs by combining and reusing services. The addition of new services expands these possibilities.

Interoperability is a crucial aspect of service composition [26]. A composite service is typically represented by a composition pattern that reflects its underlying logic, which includes information flow and settings between services. To ensure proper functioning, the composite service must adhere to the interoperability schema [26], [28].

The effectiveness of model architecture and correct business alignment relies extensively on the interoperability between integrated services [6]. Protocols, data formats, and interfaces must enable seamless interaction.

With adequate interoperability, service composition creates platform and technology-agnostic solutions gluing diverse systems to deliver customized, automated business processes through the assembly of services [28]. This is relevant even for emerging paradigms, such as blockchain networks.

III. Related works

The integration of blockchain technology into enterprise architectures poses numerous open challenges, including business alignment, system governance, and technical connectivity hurdles [10], [29]. Although still emergent, several organizational blockchain use cases have already demonstrated the potential for trust establishment, dispute resolution, and auditability across traditional company boundaries [10]). However, methodologies for systematically assessing and assimilating decentralized apps to best leverage blockchain's architectural benefits remain underexplored in complex business environments [30]. Several studies have discussed the service composition approach for integrating different blockchains and smart contract functionalities.

A service-oriented approach using standard description languages (SCDL), directories () and protocols (SCIP) enables smart contracts to be interfaced as modular services [5]. This allows for the discovery and choreography of contract logic across chains.

A service-oriented semantic architecture based on smart contracts was designed for flexible discovery and selection of IoT resources across multiple blockchains [27]. Ontology-based annotations facilitate the registration and search for chain-based services.

An interchain workflow composition in Business Process Model and Notation (BPMN) has been proposed to orchestrate smart contract calls on different types of private/public blockchains [14]. The BPMN models provide a common representation for integrating control and data flows.

HyperService provides a unified environment for developing and executing decentralized applications (dApps) using different blockchains thanks to a dedicated programming framework [31].

The use of BPMN models has been validated for composing transactions and smart contracts on different private and public blockchains using a unified API [14]. Gateways handle the routing of requests and responses between chains.

An architecture combining a private blockchain and distributed P2P storage has been designed for a decentralized registry of services that facilitates inter-chain discovery [32]. The shared repository contains service metadata, bindings, and endpoints.

IV. Research Goals

The objective is to realize decentralized ecosystems through a “top-down” approach, placing organizational priorities as the driving force before technical considerations. The research questions were as follows:

1) How can enterprise ontologies and taxonomies be defined to model organizational contexts and priorities for cross-chain integration ?
2) How can we design a theoretical model that enables end-to-end vision processing across multiple decentralized blockchains ?
3) How can an SOA Architecture pattern be leveraged to compose modular blockchain services into end-to-end business processes aligned with organizational goals ?

This study aims to develop models and architectures centered on end-to-end alignment with enterprise priorities across specialized blockchain networks.
Our first paper presents a new blockchain application development paradigm that allows practitioners to combine modular, specialized blockchain services across heterogeneous networks into integrated applications that span multiple chains [33]. While identifying an innovative application development approach, it does not address the overall research challenges. Here, we highlight the core innovations for enabling decentralized workflows and present an enterprise architecture-based methodology for systematically translating organizational priorities into supportive integration layers.
To provide foundations for exploring the research questions around the organizational adoption of blockchain, we propose an architectural framework for cross-chain integration spanning key domains from business processes to technical systems.

V. Proposed Architecture

In order to address the organisational architectural layers [19]–[21], we consider four perspectives that the proposed architecture should match:

- Business Architecture – business motivations, value exchanges, cross-organizational processes
- Information Architecture – semantic models, shared ontologies, data interoperability
- Application Architecture - legacy systems, interfaces, smart contract integration
- Technology Architecture – protocols, platforms, infrastructure, consensus models

Figure 1 presents an overview of the proposed architecture with component mapping for each perspective.

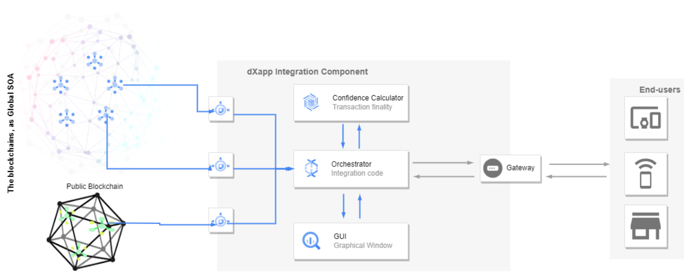

Fig. 1. Proposed Architecture

The Orchestrator component focuses on cross-chain workflows and decentralized business processes, modeling value exchanges and activities across organizations. It specifies the end-to-end process logic by integrating existing chains to orchestrate information flows, decisions, settlements, and finality computations across boundaries. Standards such as BPEL and BPMN provide declarative methods for capturing decentralized process flows.

1) Information Architecture: The Confidence Calculator component enables semantic alignment of multi-chain information quality, transparency, and reliability by defining common measures, formulas, and vocabulary around transaction concepts. Such semi-structured models facilitate a shared understanding across entities in a decentralized network.

2) Application Architecture: The Gateway API offers normalized interfaces, protocols, and abstractions to interact with underlying heterogeneous chains, ledgers, and contracts. It insulates clients from blockchain intricacies by handling the routing and translation. The Gateway bridges incumbent systems with emergent decentralized applications.

3) Technology Architecture: Blockchain platforms, infrastructure, and distribution mechanisms, such as consensus, underpin this solution. The Monitoring Dashboard enabled troubleshooting, risk management, and operational visibility. Together, these modular components enable the decentralization of the integration fabric and facilitate novel cross-chain architectures.
The proposed modular architecture introduces a comprehensive framework for cross-chain integration spanning four crucial perspectives. It promotes systematic analysis when mapping organizational priorities to technical realities. The decomposed model bounds complexity through discrete architecture facets aligned with blockchain concerns.

VI. Research Challenges and Perspectives

A. Theoretical Model for Confidence Calculator

A key innovation in the proposed architecture is the Confidence Calculator module, which provides probabilistic guarantees of the finality of state changes across different blockchain systems by computing numerical confidence scores for transactions.
The Confidence Calculator builds on several blockchain-specific concepts to derive its mathematical models for confidence levels [14]: confirmation depth, the number of extra blocks added after the one containing a particular transaction where more confirmations generally mean higher confidence; number of validating nodes–the more decentralized nodes that validate a transaction, the more immutable it becomes with permissioned chains having fewer validators than permissionless ones; and types of consensus protocols–different consensus schemes offer different probabilistic finality guarantees; for example, BFT protocols offer higher confidence per block than the Nakamoto consensus.
By applying analytical models and data to these parameters, the Confidence Calculator can translate blockchain-specific measures into unified confidence scores. These scores reflect metrics such as the percentage probability that a transaction will not be reversed after a certain number of blocks and the average expected time for a transaction to achieve cryptographic settlement finality.
By compiling these models for different blockchain integration points, businesses can configure parameterized thresholds in workflows. For example: “wait until transaction has more than 95% confidence of not getting reversed before shipping

order". This allows smart contract-driven processes to react to state changes across chains, based on mathematically grounded confidence levels.

There is also the potential to apply machine-learning techniques and train learned models to serve as Confidence Calculators. As shown in recent research analyzing Bitcoin and Ethereum transaction data, machine learning methods like Bayesian classifiers, random forests, neural networks, and ensemble models can make reasonably accurate predictions on metrics such as transaction confirmation times [34], [35]. These models consider the characteristics of individual transactions, current blockchain conditions, and historical patterns in order to estimate confirmation-related probabilities. Similar principles can be applied to build data-driven Confidence Calculators that predict the likelihood of transaction finality, based on multivariate blockchain datasets. This demonstrates the potential of augmenting analytical models with predictive data-driven insights to enhance cross-chain workflows.

Thus, confidence calculators can be based on either derived statistical models or learned from transactional data leveraging AI/ML. However, both approaches warrant further research.

B. Orchestrator as an Integration component for Cross-Chain Orchestration

As the central integration component, the orchestrator is responsible for constructing collaborative business processes that span multiple, often disparate, blockchain systems belonging to autonomous parties. This introduces complexity on several fronts - from reconciling semantic terminology, regulatory policies, and data practices to exception handling routines and execution models between independent participants [9].

To enable seamless cross-chain orchestration, we need declarative standards to write an integration code that can abstract the proprietary languages of different smart contract platforms. While process modeling languages such as BPMN allow visual description of the sequence and control flows, they currently do not have native constructs to map the intricacies around decision rights, accountabilities, asset transfers, and information flows that arise in multi-chain processes [13].

This gap results in business logic being tightly coupled to the underlying technologies, hindering flexibility as networks evolve. One direction that shows promise is using BPEL definitions to model lower-level control flows, data transformations, exception handling routines, etc.

Further research on systematically modularizing cross-organizational processes, appropriately distributing accountability, and introducing version management methodologies is imperative. Environmental modeling techniques that encapsulate platform differences between participants as late as possible in the process also warrant deeper exploration to sustainably bridge the inherent blockchain and process heterogeneity across partner ecosystems.

C. Organizational Adoption Challenges

Realizing multi-chain ecosystems requires overcoming managerial and technological barriers around seamless interoperation across organizational boundaries. Although point solutions are emerging, adoption efforts overly focus on implementation specifics rather than unifying principles spanning structural interconnectivity, business process flows, and information interchange [36].

Our methodology applies Enterprise Architecture techniques like the Zachman Framework and TOGAF for methodically eliciting requirements across crucial integration facets - data semantics, application interfaces, communication protocols [19]–[21]. We translate these organizational priorities into modular architecture layers, providing the necessary technical connectivity while maximizing the adoption opportunities.

The goal is to realize decentralized integration through a "top-down" approach, placing organizational concerns as the driving force before lower-level blockchain specifics. Both organizational and technological perspectives require synchronized execution [10].

This warrants research on architectural models of organizations that comprehensively capture concerns about accountability, incentives, controls, evolution, etc. Such an "enterprise-aware" framework can drive blockchain solutions tailored to integration needs rather than vice versa. By unifying organizational objectives and technical interconnectivity layers through formal methods, the mainstream adoption of multi-chain ecosystems can be accelerated.

VII. Discussion and Conclusion

This paper presents ongoing research towards developing comprehensive models and architectures for end-to-end alignment with enterprise priorities across specialized blockchain networks. We propose a modular architecture that spans crucial integration perspectives, including business processes, information models, interfaces, and protocols.

The core innovations lie in the Orchestrator and Confidence Calculator components, which align with the key layers in organizational architecture. The Orchestrator focuses on cross-chain workflows and decentralized business processes, matching the business architecture layer by specifying end-to-end logic-integrating chains. The Confidence Calculator enables probabilistic guarantees on state finality, corresponding to the information architecture layer, by defining shared measures around transaction concepts and multi-chain data quality.

To further develop enterprise-focused models, we intend to apply architecture technique standards, such as TOGAF and the Zachman Framework. These provide systematic and structured methodologies for eliciting requirements across data semantics, application interfaces, communication protocols, and adoption challenges.

However, significant challenges remain around multi-chain maturity, which warrants further research. This includes developing declarative integration standards that sustainably bridge heterogeneity across parties, environment modeling techniques that encapsulate platform differences, and modularization of accountabilities in cross-organizational processes.

While this research establishes enterprise architecture foundations and perspectives, real-world validation through industry pilots is still required. The models presented here form ongoing research to progress organizational interoperability dialogue spanning multiple chains.

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