RESEARCH GUILD

CROSS-CHAIN COLLABORATION REPORT (RG002)

JANUARY 2023

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PREFACE

This is a community-based research report intended to provide research insight for blockchain enthusiasts, entrepreneurs, community managers and developers across chains generally, and within Cardano's Project Catalyst community specifically.

This report aims to provide a comprehensive literature review of cross-chain collaboration as a blockchain industry practice, for the purpose of analysing problems, solutions and opportunities within the next 6–9-month period, and beyond. Although we have done our best to capture a breadth of sources, this study is non-exhaustive. Due to the limitations of time and scope of this report, some research and projects that are currently providing cross-chain solutions, or who have solutions in development, may unfortunately be omitted.

Although funded by Cardano, this report seeks to be somewhat blockchain agnostic by not taking preference for one project over another. We take the position that holistic solutions will not necessarily be found in any one blockchain or blockchain community, but in the willingness for members of multiple communities to work together to find solutions. Even though our recommendations focus on research implications for the Cardano community, we invite other blockchain communities to find applicable implementations where they can.

There may also be current or prospective arguments for or against certain blockchains, projects, communities or individuals, or a degree of criticism or controversy of which this project may not be aware. This project aims to take a neutral stance in either regard. Furthermore, the purpose of this report is to identify current cross-chain collaboration problems and solutions visible within online documentation, while seeking to avoid bias wherever possible. Overall, we hope that this report will serve as a discussion document and resource for future researchers and innovators in the field.

ABSTRACT

Interoperability is a complex problem with no easy solutions, as evidenced in the methodical and iterative development of blockchain 3.0 networks, the challenging upgrades and transitional phases arising and the challenges and stakes facing a competitive global DLT industry. However, what is less understood are the ways in which disparate blockchain communities collaborate together to address industry-wide challenges. This Cross-Chain Collaboration report answers a community call: *how might we create connections and collaboration between Cardano and other blockchains?* Nested in this question are inquiries around how blockchain communities communicate and work together (or not), the state of cross-chain interoperability and short-term cross-chain development projections across the industry. The report includes a comprehensive literature review to explore existing research on cross-chain collaboration and interoperability in academia and industry, and draws themes from this research by summarizing key concepts, analyzing outstanding problems and solutions, and identifying opportunities for future study and innovation. The research also highlights the importance of cross-chain interoperability protocols and standards, as well as the need for collaborative tools and approaches to support growth of the industry as a whole. However, there is a lack of coordinated social research that investigates how blockchain communities' function and work together, as well as engagement barriers caused by fierce community tribalism, market competition and legacy system thinking. The project has been conducted from a relatively agnostic position on blockchain development in order to support collaborative research and practices across the entire blockchain ecosystem. The final report will be freely disseminated to the blockchain community to serve as a discussion document and resource for future researchers and innovators in the field.

Key words: Blockchain, Cross-Chain, Distributed Ledger Technology, Interoperability, Collaboration, Community, Project Catalyst, Cardano, Research.

REPORT CONTENTS

1.0 EXECUTIVE SUMMARY

1.1 REPORT OVERVIEW

This report was funded through Fund 8 of Project Catalyst, a decentralized funding platform for the Cardano blockchain launched in August 2020, which is currently in its tenth round. Fund 8 was launched on February 24, 2022 and distributed $16M worth of the Cardano native cryptocurrency ada among 368 winning proposals. The Research Guild, a team of skilled researchers, was formed to address the lack of coordinated research in the Catalyst community and to **investigate opportunities and strategies for cross-chain collaboration** on the Cardano blockchain, and their implications for other blockchain communities.

1.1.1 RESEARCH PURPOSE

The purpose of this report is to answer the Cross-Chain Collaboration campaign question: **'How might we create connections and collaboration between Cardano and other blockchains in the next six months?'** Nested in this question are inquiries around how Cardano and other blockchain communities communicate and work together (or not), the state of cross-chain interoperability and short-term cross-chain development projections across the industry. The report provides **key research insights and recommendations** that can be funded and implemented by the Cardano and wider blockchain community for the purposes of building industry-wide cross-chain collaboration strategies and initiatives.

1.1.3 RESEARCH APPROACH

The Research Guild has conducted **a comprehensive literature review to investigate cross-chain collaboration on the Cardano blockchain.** The review aims to explore existing research on cross-chain collaboration and interoperability in academia and industry, and draws themes from this research by summarizing key concepts, understanding outstanding problems and solutions, and opportunities for future study and innovation. The research is being conducted from a relatively agnostic position on blockchain development in order to support collaborative research and practices across the entire blockchain ecosystem.

1.1.4 RESEARCH FINDINGS

The key findings in this report are grouped around **problems, solutions, and opportunities related to cross-chain collaboration and interoperability**. The problems identified include challenges within blockchain networks, interoperability protocols, scalability, security, technology constraints, and user experience. Key solutions arising include a review of novel approaches, atomic swaps and protocols, Polkadot and Cosmos solutions, as well as sidechains and bridges. The report also identifies opportunities for the development of blockchain 3.0 networks, enhanced atomic transactions, privacy networks, multi-bridge infrastructures, industry 4.0 integration, and ongoing Project Catalyst proposals.

Overall, there was clear consensus surrounding **the importance of cross-chain interoperability protocols and standards**, as well as **the need for collaborative tools and cohesive approaches** for industry growth as a whole. Social approaches to the topic were focused more on industry conferences, education and marketing services, creative collaborations and workshop engagement. However, there is **a lack of coordinated social research** that investigates how blockchain communities' function, how they work together and what their barriers to engagement are.

The majority of **the literature addressed technical approaches to interoperability**, including the ongoing call for platforms with fast read/write speeds, low transaction costs, and easy data access and authorization management to support cross-chain integration. In this area, constraints in cross-chain smart contract communication; security and scaling inefficiencies between chains; fragmented programming models; a lack of generic token exchange protocols and duplication of effort among projects.

On a macro-level, this report found that **blockchain interoperability, scalability, and security are major intertwined challenges** facing the industry. Blockchain interoperability is hindered by fragmentation between blockchain communities and limitations on liquidity movement, as well as the difficulty of achieving community consensus for protocol changes. Scalability is impacted by bottlenecks, low transaction efficiency, and high confirmation latency. Security is a concern due to the vulnerability of cross-chain bridges to hacks, as well as the lack of clarity around which bridging mechanisms are secure. In addition, decentralized applications that require off-chain data may create a larger attack surface for hackers.

Novel solutions for bridging, sidechains and relays (such as parachains, and XCMP) may address some of these issues, but these also come with their own limitations and trade-offs. **Fierce community tribalism may enforce barriers** to collaboration and communication that can lead to **missed opportunities for DeFi** and other domains. These social engagement barriers may also be reinforced by market competition and legacy system thinking. To address these issues, there is **a need for ongoing research and development in the area of cross-chain interoperability and collaboration**.

1.2 REPORT RECOMMENDATIONS

The recommendations drawn from the above findings include: supporting the development of a multi-chain wallets integrated with Cardano and other blockchain networks, creating a collaborative security framework for cross-chain bridges, a comprehensive EVM-inspired peer-chain architecture, as well as collaborating through existing interchain protocols and standards working groups. Other recommendations focus on prioritizing the development of industry data standards, exploring extant cross-chain solutions such as Polkadot, Cosmos and Interledger, and researching and utilizing techniques and protocols for cross-chain data sharing. The three section recommendations comprising our investigation include:

1) developing a collaborative platform to enhance cross-chain community and end-user experiences;
2) creating an open-source cross-chain standardisation forum; and
3) establishing an industry wide cross-chain collaboration fund.

1.3 IMPLEMENTATION BENEFITS

Implementation of the above recommendations could provide the following benefits: improved interoperability and collaboration within the blockchain community, addressing hard challenges presented by scalability and security, better implementation of a network of sidechains for enhanced transaction throughput and connectivity, streamlining trust and communication between different blockchain systems, encouraging the use of multi-token crypto wallets and exchanges, the development of industry data standards, strategic exploration of existing cross-chain solutions, utilizing techniques and protocols for cross-chain data sharing, and coordinated capacity through shared tools, standards and resources. Research insights in the areas of cross-chain community engagements, protocols, transactions, networks, scalability and security are also advantageous.

1.4 RISK SUMMARY

Risks associated with the implementation of these recommendations include: the potential for security vulnerabilities in the development of a multi-chain wallet or cross-chain collaboration platform, which could lead to the loss of user assets or data. There is the risk of technological constraints, as the development of a comprehensive EVM-inspired peer-chain architecture and cross-chain protocol may be complex and require significant resources and expertise. Additionally, there is the risk of user adoption, as the development of a collaborative platform and user-friendly UI may not be sufficient to encourage widespread adoption of cross-chain services. There is the risk of competition and duplication of effort, as other blockchain communities may also be developing similar solutions, leading to potential conflict or duplication of resources.

1.5 REPORT CONCLUSION

The problems and solutions identified in this report provide an opportunity for global blockchain participants to use these insights to further ideate, investigate, plan, map, strategize, collaborate, and build future solutions, something that is integral to the blockchain and emerging technologies industries. **Overall, this report aims to serve as a discussion document and resource for future researchers and innovators in the field**.

2.0 INTRODUCTION

2.1 SECTION OVERVIEW

Along with Scalability and Sustainability, Interoperability is one of the three intertwined pillars of Cardano blockchain's roadmap (Cardano.org., n.d.-b), and it is what sets it and similar ecosystems apart as Blockchain 3.0 models. However, interoperability is a complex problem with no easy solutions, as evidenced in the experimental and iterative nature of blockchain development, the challenging upgrades and transitional phases experienced across networks and the tribalism that may arise in a competitive global crypto market. Furthermore, blockchain interoperability only describes the technical dimension of building cross-chain platforms through the ways we integrate different coding languages and frameworks across networks. The second dimension is social: the ways we as humans collaborate and work together to solve complex network problems. Within the 225 research articles, industry documents and websites explored within this study, cross-chain collaboration has been identified as a growth and development priority for blockchain developers, community members and enthusiasts across the space. The following section will outline the background, methodology and rationale for the Research Guild's Cross-Chain Collaboration report.

2.2. BACKGROUND

This report has been funded through Fund 8 of Project Catalyst, 'a decentralized funding platform for the Cardano blockchain', which is described as 'an extension of the Cardano treasury and the testing ground for the future governance of Cardano' (Emurgo, 2022). The project is further described as a 'turbo-charged innovation engine and one of the largest decentralized innovation funds in the world' (Richmond, 2022) and it 'exists to ensure we can bring on-chain governance to the Cardano blockchain by allowing the community to self-determine priorities for growth' (Gregaard, 2022). The first public iteration of the fund was launched in August 2020 (Garbash, 2020) and it is currently in its tenth round. Each fund involves a batch of campaigns which are proposed and voted for by the community as priority areas for development on the blockchain. In Fund 8, which was launched in February 24 2022 (Baird, 2022), 33 campaigns were selected by the community which distributed $16M worth of the Cardano native crypto-currency ada amongst 368 winning proposals (Weru, 2022).

The Research Guild was initially formed from a small contingent of PhD candidates whose studies straddled blockchain applications in land management, intellectual property and peer production; with expertise in law and international relations, research, project management, community development, governance, teaching, license compliance and auditing. It was identified that the Cardano blockchain was founded on 'the highest principles of academic rigour and evidence-based software development' (IOHK, n.d.-a) that includes a current research repository of 162 papers (IOHK, n.d.-b). With the development of Project Catalyst as an emergent crowd governance platform, a problem arose: Cardano values academic rigor; however, the Catalyst community lacks a coordinated research approach to community campaign problems. The Research Guild was formed to address this research gap by using a two-prong approach to campaign problem-solving: 1) Building the Research Guild as a coordinated network of skilled researchers and resource for the Catalyst community, and 2) Tailoring research reports to campaign or proposal briefs.

In Project Catalyst Fund 8, the Cross-Chain Collaboration campaign question asks: *How might we create connections and collaboration between Cardano and other blockchains in the next six months?* (About F8: Cross-Chain Collaboration, n.d.). With a lack of coordinated community-driven research that strategizes cross-chain collaboration, the Research Guild proposed a report to the Catalyst community to investigate opportunities and strategies that support cross-chain collaboration on Cardano (Research Guild, 2022). Our aim is to investigate cross-chain collaboration by conducting a scoping exercise in the form of a comprehensive literature review that targets collaboration challenges and solutions across blockchains, and within Cardano and Project Catalyst. To do so, this project will be delivered in the form of a public report with key research insights and recommendations that can be implemented by the community immediately, or pursued through future Project Catalyst funding proposals.

Although this project is funded by the Cardano community, in whom this project team holds as our primary stakeholder, the following research will be conducted from a relatively agnostic position on blockchain development, so as to support collaborative research and practices across the entire blockchain ecosystem.

2.3. METHODOLOGY

As a qualitative study, this report draws on a wide range of literature, and leverages plural research methods to match the complexity of the research topic. Our primary approach for academic studies (such as journal articles, white papers, and documentation) is to apply Mayring's (2005) systematic literature review framework. We have applied this framework to a sample of 40 academic texts, and an analytical process was then applied (as expanded below). For our review of industry "grey" papers (such as blockchain repositories, industry reports, and media articles), we have applied Stebbin's (2001) exploratory methodology. This approach enables a broader exploration of discussion documents in a way conducive to emergent industries, while employing abductive reasoning as 'an accepted social scientific procedure for both producing descriptions and generating understanding and explanation' (Blaikie, 2019, p. 2). This dual research approach will integrate both document types, which serve as a bridge between global best-in-class theories, and tangible real-world implementations in the blockchain industry.

Our research project involved seven stages: Project Proposal, Project Planning, Literature Review, Literature Analysis, Report Drafting, Report Finalisation and Report Dissemination. Our project plan would build upon the projects funding proposal, which highlighted a Problem and Solution statement, team outline and project Impact, Feasibility and Auditability descriptions as part of the funding proposal criteria. The plan would also highlight key project working documents, document locations as well as time and financial brackets for each project stage, with the project timeframe initially projected at four months duration. However, this timeline was extended to account for greater literature breadth, project administration set-up (financial systems, documentation, recruitment and onboarding processes), and to capture relevant Project Catalyst Fund 9 voting data released in late September. The full project duration ran from May (Q2 2022) to December (Q4 2022).

Initially this report was intended as a cross-chain "snapshot" of approximately 20-30 pages length, however, it became apparent that there was a dearth of academic literature exploring cross-chain collaboration, with most exploring blockchain interoperability. Furthermore, the majority of the practical literature would be found in industry blog-posts, websites, reports, white papers or project proposals, with less academic coverage. As such, it was decided to expand the size of our literature review from an initial 60 documents to 225; from a total document collation pool of 263. It is hoped that this report may contribute to the emerging body of cross-chain collaboration research, from both industry and academic sources.

By pivoting toward a more comprehensive literature review, the majority of project time was spent at the literature collation and analysis phase. The process for this stage would involve: a) Repository identification through general online key-word searches; b) Repository specific searches conducted using a PRISMA tool to outline keywords used and to document repository search hit-rates, as well as documents identified for further investigation; c) Identification and download of relevant documents into a team repository folder; d) Decomposition of relevant documents into Summary Tables to collate document citations, research themes arising (if any), and any applicable quotes or links; e) Sorting of Summary Tables into Group Documents by theme and repository; f) Conducting a staged literature analysis of Group Documents to determine keyword frequencies and key themes arising.

This report employs four analytic stages: firstly, a descriptive analysis is employed to identify, describe, explore, and understand initial patterns of data emerging. We then drew results obtained from the analysis stage to group these studies according to themes. Next, we conducted a content analysis to expand on insights, identify gaps and explore future directions. Here, word clusters are identified with the assistance of software tools. A further analysis was carried out to identify problems, illustrate existing solutions and address gaps. Finally, we use the method of consolidation to synthesize the findings and explore opportunities for future research. For the purposes of this project, primary keywords used included "Cross-Chain", "Collaboration", "Communication" "Blockchain" and "Interoperability", as well as secondary, blockchain specific keywords such as "Avalanche" or "Hyperledger". These keywords were chosen for their applicability to the research question, and to obtain search results specific to both technical and social innovations across chains.

The report drafting and finalising stage would involve sorting key data into a reporting template that forms the basis of this report's structure. The final phases of the project would be dissemination of the report, and a project close-out report delivered back to the Project Catalyst community. Instead of storing the final report on existing web 2.0 portals, it was decided that the report would be minted and accessible on the Cardano blockchain as a non-fungible token. This genesis NFT would be held indefinitely in a standalone Research Guild "report wallet", with a link to a downloadable pdf stored on IPFS. The link to this minted asset would be embedded in the projects close-out report, and distributed through the Research Guild's social channels and blockchain research networks. Five report NFT's will be minted in total, including one distributed to each of the three primary research team members, and the remaining one stored in the RG002 project wallet, with future distribution decided at the Guild's discretion. The report pdf will be freely accessible to the public.

2.4 RATIONALE

Research and development go hand-in-hand. In the excitement of experimentation, it can be easy to overlook or underestimate the value of founding a project on a sound research base. Effective research helps to scope the lay of the land, and analyse the strengths, weaknesses, opportunities and threats (SWOT) that impact a project. It also removes the guesswork, identifies knowledge gaps, builds future funding cases and supports sound decision-making by challenging false assumptions, misinformation or speculation. To continue Cardano's research-driven ethos, the Project Catalyst community has chosen to invest in community-driven research that provides coordinated research insights into cross-chain collaboration issues and problems. The Research Guild's customised reports are positioned to meet community-driven blockchain research needs across Project Catalyst campaigns.

2.5 SECTION SUMMARY

Building upon the work of the Fund 8 cross-chain collaboration challenge team (About F8: Cross-Chain Collaboration, n.d.), this project will seek to directly address the challenge question by conducting a professional community-driven research project, and drafting a report that scopes cross-chain collaboration strategies across the blockchain space, including developments within the Cardano and Project Catalyst network. A list of recommendations will be drawn from the report's findings, and these will be disseminated publicly so that the community can initiate actions immediately, or use the findings to support or merge future Catalyst funding proposals. The final report will be stored on-chain and disseminated via social channels and networks.

3.0 LITERATURE REVIEW

3.1 SECTION OVERVIEW

This literature review has been compiled from 225 sources, the purpose of which is to provide a general snapshot of the state of cross-chain collaboration at the time of writing. More specifically, this section's aim is to provide a descriptive analysis of three key themes collated in the literature: key problems, key solutions and key opportunities. The 225 documents are drawn from four main research areas: Industry Sources, Academic Papers, General Blockchain repositories and Cardano-specific Blockchain repositories. (Note: repository in this sense refers to research directories or databases, or general stores of information, as opposed to developer-specific repos). As outlined in the methodology section, repository searches are conducted using a PRISMA tool to identify key repositories, to outline keywords used, and to document repository search hit-rates as well as documents identified for further investigation. Once key documents are identified, they are then collated into a repository folder where they are decomposed into Summary Tables. These tables collate the document citation, key research themes arising, and any applicable quotes or links.

Five industry sources were identified as returning cross-chain specific content, including Blocknomi, Cointelegraph, Daily Hodl, The Block and the World Economic Forum; with a total of 19 documents analysed. Seven academic repositories were searched including Web of Science, ProQuest, Scopus, Google Scholar, ACM Digital Library, CiteSeer, ARVIX; with a total of 40 documents analysed in this group. Eight general blockchain repositories were searched including company websites, whitepapers and blogs specific to Avalanche, Binance, Ethereum, Hyperledger, Polkadot, Solana, Tezos and a general "Other Blockchain" category. A total of 69 documents were analysed from this group. Finally, three Cardano-specific blockchain repositories were searched including Project Catalyst: Fund 8 and Fund 9 Cross-Chain Collaboration proposals, IOHK research and a general "Other" category. 57 documents were analysed from this group. 185 summary tables were completed with an additional 40 supplementary sources accessed in relation to the study. The following section will include a descriptive analysis of the key themes arising from the literature review.

3.2 GLOBAL BLOCKCHAIN RESEARCH

In the aftermath of the Covid-19 global pandemic and the consequent realization that forms of socio-economic disempowerment emerge from civil fragmentation and isolation, the ideas pervading Satoshi Nakamoto's formative paper *Bitcoin: A peer-to-peer electronic cash system* (2008) have become all the more relevant. In particular, how can global citizens better leverage distributed ledger technologies (DLT) to advance socio-economic outcomes in remote, autonomous or heterarchical ways? Pivotal to such questions are the roles of cross-chain communication and interoperability, expressed through the ways different DLT and blockchain networks, coding languages and communities work together to develop a more integrated and user-friendly ecosystem. Like society itself, blockchains and blockchain communities need to learn ways to interact and collaborate with each other for their mutual enrichment and sustained growth. Assets need to move freely yet securely across eco-systems. DeFi builders recognize this need and thereby leverage multi-chain interoperability to transform traditional lending models to wider participants. Some protocols utilize non-custodial smart contracts and synthetic assets to facilitate cross-chain communication, while cross-chain bridges and atomic swaps provide another means to interoperability. These technologies allow lenders and borrowers to transfer assets across blockchains in real-time, which substantially broadens their access to liquidity (Gaur, 2021). Here, the key distinction arising is the need to understand the roles society (people) and technology (tools) have to play in this emergent landscape.

Blockchain research interest has seen dramatic growth in recent years with a number of academic publications, conference proceedings, research seminars, and industry reports arising. Among blockchain research in general, research on cross-chain communication and collaboration started receiving further attention alongside concerns for capacity and scalability (Malavolta et al., 2019; Abuidris et al., 2022). So too has research into integration of blockchain technology or principles by legacy (centralised finance) systems. For instance, on a global scale central banks are collaborating on the Multiple Central Bank Digital Currency (m-CBDC) Bridge Project to allow cross-border transactions. Current pilots of this project include: 1) DC/EP - PBOC, China; 2) e-krona - Riksbank, Sweden, and; 3) Bank of Thailand CBDC. Visa has proposed the offline payment system (OPS) protocol to avoid double payments occurring in the event there is no intermediary in CBDC transactions. From the DLT industry, we find examples of stablecoin interoperability solutions including Canton, ChainBridge, Cosmos, Hyperledger Cactus, Interledger Protocol (ILP), Liquality, Optics, Polkadot, and Syscoin. Examples of standard-setting initiatives include the Global Standards Mapping Initiative, Interwork Alliance, Global Digital Finance, and Digital Currency Global Initiative (DCGI), covering multiple standards-setting for different functions (Warren et al., 2021). Understanding the ways that a) legacy systems are integrating DLT, b) DLT systems are solving legacy problems, or c) the direction that DLT standards mapping and policy-making is being developed, are all beneficial avenues to explore future cross-chain innovation and collaborative opportunity.

In this report, we will explore cross-chain research that has been carried out in both academia and industry. Analysing these existing studies will enable us to draw themes from the current cross-chain research by summarizing key concepts; understanding outstanding problems and solutions offered; and examining opportunities arising for future study and innovation.

3.2.1 CROSS-CHAIN RESEARCH: ACADEMIC

Focusing on the ways blockchain technology is integrated with off-chain data systems, Calderelli (2022) conducted an overview of blockchain oracle research. This study highlighted that there were 'only 162 publications in all six years of academic production' on the subject, and that 'this is still a niche subject' (p. 10). Coincidentally, as of writing, this was the same quantity of papers stored on the IOHK blockchain research library (IOHK, n.d.-b). These results support the view that blockchain research is generally still in its infancy. In this section, the first step for investigations on cross-chain collaboration is a descriptive analysis of data obtained from existing academic research. Here, descriptive analysis is used to describe and summarize our collected data points to view where critical patterns might emerge.

For data collection, we began by conducting search queries in academic databases including Web of Science, ProQuest, Scopus, Google Scholar, ACM Digital Library, CiteSeer and ARVIX. The search strings were designed to search for the exact terms: "cross-chain" (and) "collaboration" (or) "communication", as well as "blockchain" (and) "interoperability". This setting assisted us to focus on cross-chain research but not blockchain in general. We then filtered the unqualified studies using several criteria such as number of citations, reputation of published sources, and relevance of topics. In addition, to avoid missing critical research, we included the keyword "interoperability" to the search string and added these relevant studies to the selection list. Following the below search procedure, we were able to obtain 40 academic articles that are most relevant to our report's objectives. We visualize our results in Figure 1 (below). It can be seen from this sample of academic publications on cross-chain research, that there has been a significant increase in the last four years, peaking in 2020.

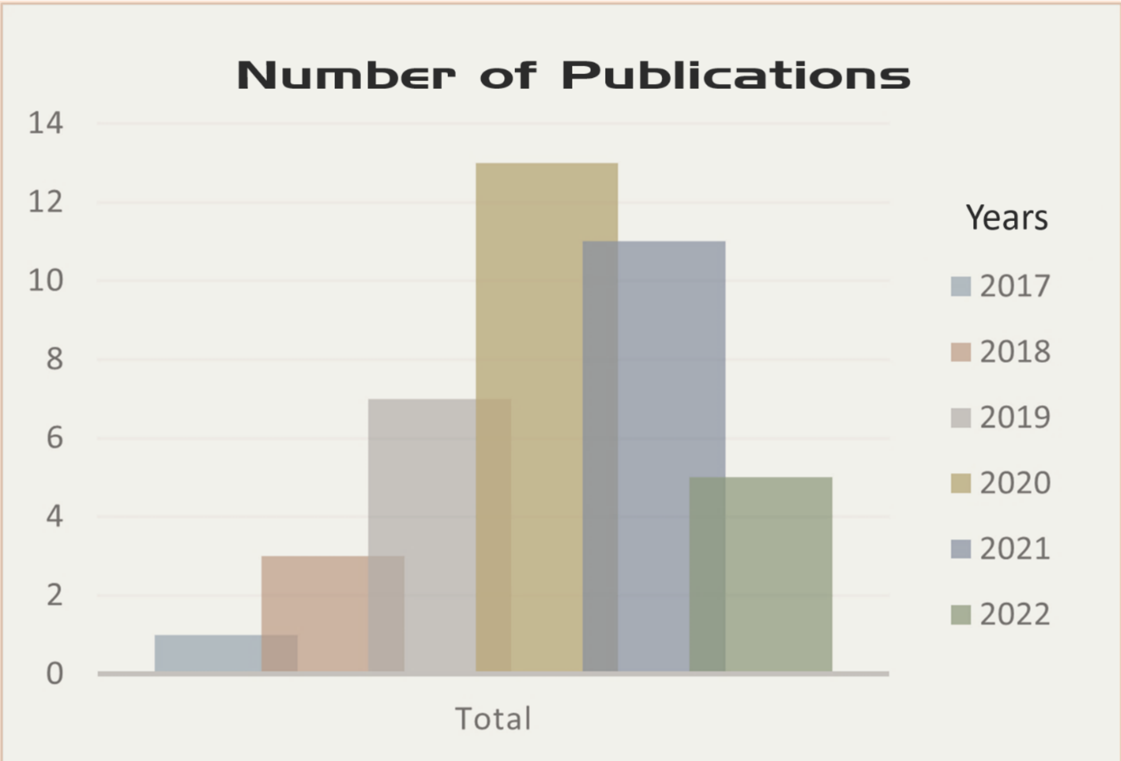

Figure 1. Number of academic publications throughout years.

Existing cross-chain collaboration research across academic databases include:

No.	Author	Year	Title
1	Yin et al.	2022	Interopera: An Efficient Cross-Chain Trading Protocol
2	Jin et al.	2018	Towards A Novel Architecture for Enabling Interoperability Amongst Multiple Blockchains
3	Belchior et al.	2021	A Survey on Blockchain Interoperability: Past, Present, and Future Trends
4	Kan et al.	2018	A Multiple Blockchains Architecture On Inter-Blockchain Communication
5	Pang	2020	A New Consensus Protocol for Blockchain Interoperability Architecture
6	Košt'ál	2020	Multi-Chain Architecture for Blockchain Networks
7	Pillai et al.	2022	Cross-blockchain technology: integration framework and security assumptions
8	Poly Team	2020	PolyNetwork: An Interoperability Protocol for Heterogeneous Blockchains
9	Ali et al.	2019	Blockchain and the future of the internet: A comprehensive review
10	Wang et al.	2017	Blockchain router: a cross-chain communication protocol
11	Wang	2021	SoK: Exploring Blockchains Interoperability
12	Herlihy	2018	Atomic Cross-Chain Swaps
13	Qasse et al.	2019	Inter Blockchain Communication: A Survey
14	Yang et al.	2020	A Review on Scalability of Blockchain
15	Caldarelli	2020	Overview of Blockchain Oracle Research
16	Flood and McCullagh	2020	Blockchain's future: can the decentralized blockchain community succeed in creating standards?
17	Pillai et al.	2020	Cross-chain interoperability among blockchain-based systems using transactions
18	Siris et al.	2019	Interledger Approaches
19	Robinson	2021	Survey of crosschain communications protocols
20	Kannengießer et al.	2020	Bridges Between Islands: Cross-Chain Technology for Distributed Ledger Technology
21	Johnson et al.	2019	Sidechains and interoperability
22	Garoffolo et al.	2020	Zendoo: a zk-SNARK Verifiable Cross-Chain Transfer Protocol Enabling Decoupled and Decentralized Sidechains
23	Sanchez et al.	2020	Bridging Sapling: Private Cross-Chain Transfers
24	Michelson et al.	2022	Accumulate: An identity-based blockchain protocol with cross-chain support, human-readable addresses, and key management capabilities
25	Lin et al.	2022	BcMON: Blockchain Middleware for Offline Networks
26	Narayanam et al.	2022	Atomic cross-chain exchanges of shared assets
27	Zarick et al.	2021	LayerZero: Trustless Omnichain Interoperability Protocol
28	Caldarelli	2021	Wrapping trust for interoperability. A study of wrapped tokens
29	Y. Lan et al.	2021	TrustCross: Enabling Confidential Interoperability across Blockchains Using Trusted Hardware
30	Eizinger et al.	2021	Open problems in cross-chain protocols
31	R. Lan et al.	2021	Horizon: A Gas-Efficient, Trustless Bridge for Cross-Chain Transactions

32	Liu and Ohsawa	2020	Improving Blockchain scalability based on one-time cross-chain contract and gossip network
33	Nissl et al.	2021	Towards Cross-Blockchain Smart Contracts
34	Hardjono et al.	2021	A Contract Service Provider Model for Virtual Assets and VASPs
35	Shlomovits and Leiba	2020	JugglingSwap: Scriptless Atomic Cross-Chain Swaps
36	Li et al.	2020	Cost-Effective Data Feeds to Blockchains via Workload-Adaptive Data Replication
37	Dinh et al.	2019	A Blueprint for Interoperable Blockchains
38	Liu et al.	2019	HyperService: Interoperability and Programmability Across Heterogeneous Blockchains
39	Miraz and Donald	2019	Atomic Cross-chain Swaps: Development, Trajectory and Potential of Non-monetary Digital Token Swap Facilities
40	Henry et al.	2021	Cross-collaboration processes based on blockchain and IoT: a survey

Table 1. Academic research on cross-chain collaboration.

The next step is to use our selected article list to generate a word cloud, which shows the most frequent keywords in the cross-chain academic literature (see Figure 2. below). While "interoperability" is the most popular keyword, "atomic cross", "chain swap", "interoperability protocol", and "heterogeneous blockchains" also received more attention. Based on this initial finding, we group academic studies on cross-chain collaboration under three main groups:

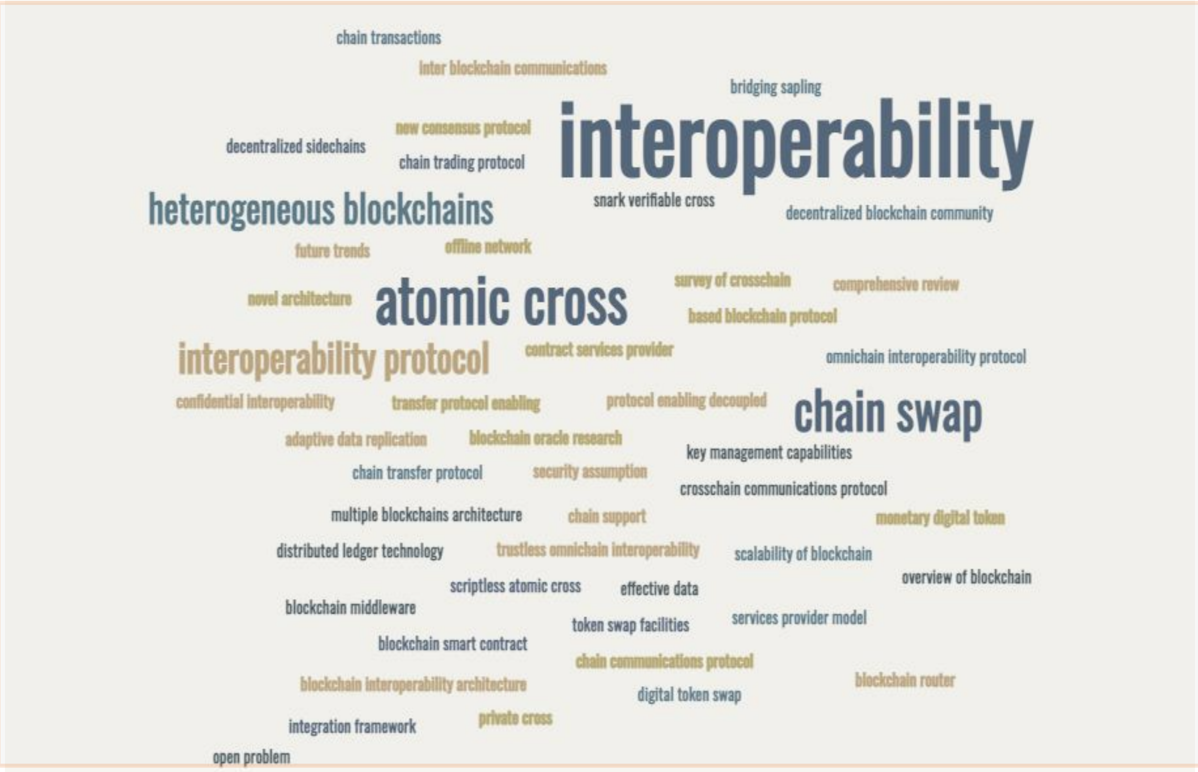

Figure 2. Word cloud of topics in blockchain academic studies.

3.3.1 INTEROPERABILITY

No.	Author	Year	Title
1	Yin et al.	2022	Interopera: An Efficient Cross-Chain Trading Protocol
2	Jin et al.	2018	Towards A Novel Architecture for Enabling Interoperability Amongst Multiple Blockchains
3	Belchior et al.	2021	A Survey on Blockchain Interoperability: Past, Present, and Future Trends
5	Pang	2020	A New Consensus Protocol for Blockchain Interoperability Architecture
8	Poly Team	2020	PolyNetwork: An Interoperability Protocol for Heterogeneous Blockchains
11	Wang	2021	SoK: Exploring Blockchains Interoperability
17	Pillai et al.	2020	Cross-chain interoperability among blockchain-based systems using transactions
21	Johnson et al.	2019	Sidechains and interoperability
27	Zarick et al.	2021	LayerZero: Trustless Omnichain Interoperability Protocol
28	Caldarelli	2021	Wrapping trust for interoperability. A study of wrapped tokens
29	Y. Lan et al.	2021	TrustCross: Enabling Confidential Interoperability across Blockchains Using Trusted Hardware
37	Dinh et al.	2019	A Blueprint for Interoperable Blockchains
38	Liu et al.	2019	HyperService: Interoperability and Programmability Across Heterogeneous Blockchains

Table 1.1 Interoperability research papers.

INTEROPERABILITY DEFINITIONS

Interoperability is the first thematic group, appearing in 13 papers from our academic sample (see table 1.1). Amongst the literature surveyed, and across general blockchain sources, interoperability is becoming defined in more nuanced and context dependent ways. Beyond a dictionary etymology that describes interoperability as the ability to operate between or across states, Vernadat (2006) defines interoperability among enterprise systems as 'a measure of the ability of performing interoperation between two or more different entities (be they software, processes, systems, business units...) […] The challenge relies on facilitating communication, cooperation, and coordination among these processes and units' (p. 14). The National Institute of Standards and Technology (NIST) describe interoperability as:

> 'a composition of distinguishable blockchain systems, each representing a unique distributed data ledger, where transaction execution may span multiple blockchain systems, and where data recorded in one blockchain is reachable, verifiable, and referenceable by another possibly foreign transaction in a semantically compatible manner' (2018, as cited in Mohanty et al., 2022, p. 2).

In the World Economic Forum's whitepaper *Inclusive Deployment of Blockchain for Supply Chains: Part 6 – A Framework for Blockchain Interoperability* (Hewett et al., 2020), interoperability is described as an established set of computing technologies that ensure users see what others see within a single platform as well as across platforms and build trust in the ecosystem (p. 4). Blockchain interoperability supports ‘a) the capacity of computer systems to exchange and make use of information; and b) the capacity to transfer an asset between two or more systems while keeping the state and uniqueness of the asset consistent’ (p. 6). There are two types of blockchain-to-blockchain interoperability not found in traditional centralized computing systems, including digital asset exchange and arbitrary data exchange. Digital asset exchange allows users to send and swap assets between different blockchains without a centralized exchange such as spending bitcoin on an Ethereum application (p. 8). Arbitrary data exchange does not necessarily relate to an item of value being transferred but rather information relating to an event on one blockchain being shared with another blockchain, such as confirmation of an item being shipped (p. 9). Overall, key factors arising in these definitions include the performance of blockchain-based operations across different blockchain environments; a measure or composition of these performance types; and the presence of such functions as communicability, cooperation, coordination, compatibility, consistency, verifiability, referenceability, trust-worthiness and transferability. These descriptions serve as a starting point for investigating blockchain interoperability as a technological practice, as well as collaborative values as a social one. Interoperability may function at the granular level of coding languages, and how these operate across different platforms; or at the level of crypto-currency wallets that enable the transaction of tokens from across networks. At a macro-level, interoperability concerns the protocols and architectures that compose the global cross-chain ecosystem.

INTEROPERABILITY PROTOCOLS

Protocols are sets of rules that enable the governance of systems, and interoperability protocols are rules governing the ways different blockchain systems interact. From the literature, Abebe et al. (2019) propose a general communication protocol as an alternative approach to the “point-to-point” blockchain interoperability approach. For them, interoperability is defined as ‘the semantic dependence between distinct ledgers for the purpose of transferring or exchanging data or value, with assurances of validity or verifiability’ (p. 2). Pang (2020) proposes ‘a new consensus protocol, Multi-tokens Proof of Stake (MPoS) for a blockchain interoperability architecture. The MPoS protocol is able to strengthen the token network effects in a cross-chain ecosystem and grow the user base of blockchain systems dramatically. We also provide an analytical model to analyze and prove that the MPoS protocol can offer better security than traditional single-token PoS consensus protocols’ (p. 153719). Alternatively, Zarick et al. (2021) present

> ‘LayerZero, the first trustless omnichain interoperability protocol, which provides a powerful, low level communication primitive upon which a diverse set of cross-chain applications can be built. Using this new primitive, developers can implement seamless inter-chain applications like a cross-chain DEX or multi-chain yield aggregator without having to rely on a trusted custodian or intermediate transactions. Simply put, LayerZero is the first system to trustlessly

> enable direct transactions across all chains and does not involve any intermediate transactions' (p. 1).

One Cointelegraph article explains that '[t]he cross-chain protocol permits data sharing across many blockchain networks and streamlines interoperability between various blockchain networks. Users can communicate with one another directly using the cross-chain protocol. As a result, blockchains with comparable networks can exchange value and information' (What is blockchain interoperability, n.d., para. 12). Jin et al. (2018) state that '[a] reliable cross-chain consensus protocol should be available to support the diversification of blockchains. In other words, no or few modifications to the existing protocol of each system will be needed when a new blockchain joins the ecosystem' (p. 1206). Whereas, Yin et al. (2022) propose the 'Interopera protocol to achieve efficient cross-chain trades among multiple PoW blockchains with fewer transactions and low bandwidth and storage overheads' (p. 7). This project aims to enhance cross-chain communication via Partitioned-FlyClient and Tx-FlyClient, and by atomically processing each cross-chain trade faster and more cheaply with fewer transactions by a two-phase lock/unlock process (p. 1). Protocols for communication, consensus, trustlessness, data-sharing, composability, seamlessness, cross-chain processing and trading are some examples of cross-chain protocol development that touch on what is possible when it comes to the formalization of cross-network standards.

INTEROPERABILITY ARCHITECTURE

Along with the protocols used to govern and standardise a system, the literature also explores proposed and functioning frameworks and models that comprise network architectures. Where protocols dictate the road rules, so to speak, architectures describe the buildings and components of the cityscape that are bridged and connected by the road-network itself. Pillai, Biswas & Muthukkumarasamy (2020), and with the addition of Hóu (2022a, 2022b) discuss cross-chain interoperability through transactions, integration frameworks and conceptual models, respectively. They propose a cross-communication framework that works on the application layer, with 'a simplified solution to address cross communication between blockchain-based systems without an intermediary. Being user-driven and transaction based, this model ensures the authenticity of the information generated and will not alter the heterogeneous nature of the blockchain system' (p. 2). In their paper *Sidechains and interoperability*, Johnson et al. (2019) review 'the strategies that some key players in the blockchain ecosystem have implemented, or are proposing to develop, to satisfy the increasing demand for cross-chain communication and transactions between sidechains. Interoperability presents a complex and challenging stumbling block to the wider uptake of blockchain technology' (p. 1). This paper reviews the many techniques and initiatives vested in sidechain communication, including Ethereum Private Sidechains; Plasma; Polkadot; Ethereum 2.0 Sharding; Blockchain Router; Clearmatics, Metronome; NEC Blockchain; and Token Atomic Swap Tech. The authors describe sidechains as 'various "flavours'" of blockchains with a steady stream still entering the market. Despite individual variations in setting up and running sidechains, the overarching concepts are very similar (p. 6). In the vein of different blockchain 'flavours', Y. Lan et al. (2021) present 'TrustCross, a privacy-focused cross-chain platform to enable confidential interoperability across blockchains. The key insight behind TrustCross is to encrypt cross-chain communication data on the relay chain with the assistance of trusted execution environment and employ fine grained access control to protect user privacy' (p. 1). This paper proposes 'a novel cross-chain architecture that enhances confidentiality' as well as 'a cross-chain interoperability protocol to unify the standards of cross-chain transactions to transfer messages between different blockchains' (p. 1); as well as access control mechanisms and security key exchanges to support data security.

HyperService is described by Liu et al. (2019) as 'the first platform that delivers interoperability and programmability across heterogeneous blockchains' (p. 1). Their paper focuses on three proposals: a) developing HSL as 'the first programming framework for developing cross-chain dApps' (p. 2); b) creating 'UIP (short for universal inter-blockchain protocol)' (p. 2) which is described as being a generic, secure and financially atomic interoperability protocol; and c) a HyperService prototype and evaluation. In *A Blueprint for Interoperable Blockchains,* Dinh et al. (2019) describe their 'vision of interoperable blockchains. [They] argue that supporting interaction among different blockchains requires overcoming challenges that go beyond data standardization. The underlying problem is to allow smart contracts running in different blockchains to communicate' (p. 1). The three problems the authors identify include 'access control, general cross-chain transactions, and cross-chain communication', as well as discussing partial solutions and 'a novel design to overcome these challenges' (p. 1). Wang (2021) presents a Systematization of Knowledge model for existing efforts in blockchain interoperability. This model focuses on several key categories, 'namely chain-based interoperability, bridge-based interoperability, and dApp-based interoperability' (p. 2). Each category is reviewed and studied as a state-of-the-art solution with detailed analysis outlining advantages and disadvantages. In their whitepaper *PolyNetwork: An Interoperability Protocol for Heterogeneous Blockchains* (2020), the Poly Team describe their infrastructure proposal as follows:

> 'To build a better next-generation internet infrastructure, [the authors] have launched a new cross-chain technology, the Poly Network. Poly Network is based on the side-chain/relay mode and adopts a two-layer architecture. It employs the Poly chain as a cross-chain coordinator, multiple homogeneous chains as cross-chain transaction executors, and Relayer as a cross-chain information porter. By resolving issues such as trust, security and transaction issues of chain data, authors have realized a safe, easy-to-use, and efficient cross-chain system' (Poly Team, 2020, p. 1).

Their protocol involves both an interoperation solution and 'two-phase commit protocol for atomic cross chain transactions' (p. 1) whose functions are described as versatile, supportive of atomic transactions, cross-chain information and multi-chain ecosystems (BTC, ETH, NEO, Ontology and Cosmos), versatile, easy to join, secure and eco-friendly (p. 2). Finally, Hardjono et al. (2018) discuss 'a design philosophy for interoperable blockchain systems, using the design philosophy of the Internet architecture as the basis to identify key design principles' (p. 1); of which the authors find some similarity. Ultimately, their paper concludes that interoperability at the 'mechanical level plays a crucial role in providing technological solutions that can help humans in quantifying risk through the use of a more measurable notion of technical-trust. Human agreements (i.e. legal contracts) must be used at the value level to provide semantically compatible meanings to the constructs (e.g. coins, tokens) that circulate in the blockchain system' (p. 23). This reiterates the idea that cross-chain collaboration is both a technological (mechanical) and social (human) endeavour.

3.3.2. ATOMIC CROSS-CHAIN SWAPS & CROSS-CHAIN COMMUNICATION

No.	Author	Year	Title
6	Košťál	2020	Multi-Chain Architecture for Blockchain Networks
7	Pillai et al.	2022	Cross-blockchain technology: integration framework and security assumptions
10	Wang et al.	2017	Blockchain router: a cross-chain communication protocol
12	Herlihy	2018	Atomic Cross-Chain Swaps
19	Robinson	2021	Survey of crosschain communications protocols
20	Kannengießer et al.	2020	Bridges Between Islands: Cross-Chain Technology for Distributed Ledger Technology
22	Garoffolo et al.	2020	Zendoo: a zk-SNARK Verifiable Cross-Chain Transfer Protocol Enabling Decoupled and Decentralized Sidechains
23	Sanchez et al.	2020	Bridging Sapling: Private Cross-Chain Transfers
24	Michelson et al.	2022	Accumulate: An identity-based blockchain protocol with cross-chain support, human-readable addresses, and key management capabilities
26	Narayanam et al.	2022	Atomic cross-chain exchanges of shared assets
31	R. Lan et al.	2021	Horizon: A Gas-Efficient, Trustless Bridge for Cross-Chain Transactions
32	Liu and Ohsawa	2020	Improving Blockchain scalability based on one-time cross-chain contract and gossip network
33	Nissl et al.	2021	Towards Cross-Blockchain Smart Contracts
35	Shlomovits and Leiba	2020	JugglingSwap: Scriptless Atomic Cross-Chain Swaps
39	Miraz and Donald	2019	Atomic Cross-chain Swaps: Development, Trajectory and Potential of Non-monetary Digital Token Swap Facilities
40	Henry et al.	2021	Cross-collaboration processes based on blockchain and IoT: a survey

Table 1.2 Atomic cross and cross-chain collaboration research.

Atomic cross-chain swaps and cross-chain communication is a second interconnected thematic group arising from 15 papers in our academic sample. To address issues of trust in cross-chain interoperability, Herlihy (2018) explains that '[a]n atomic swap protocol guarantees (1) if all parties conform to the protocol, then all swaps take place, (2) if some coalition deviates from the protocol, then no conforming party ends up worse off, and (3) no coalition has an incentive to deviate from the protocol' (p. 1). Generally, cross-chain communication allows information to be communicated between blockchains, while protocols introduce rules-based processes or systems to that communication. In his *Survey of Crosschain Communications Protocols* (2021), Robinson informs that:

> '[C]onsensus in the context of cross-chain communications relates to how participants on one blockchain are convinced of the state of a remote blockchain. It describes how parties associated with a source blockchain come to agreement and communicate with a destination blockchain such that information from the source blockchain can be trusted' (p. 1).

Examples discussed include 'value swapping, cross-chain messaging, and blockchain pinning' (p. 1); while consensus issues arising include 'how each protocol achieves cross-chain consensus, what trust assumptions are made, their ability to operate successfully in permissionless and permissioned blockchains contexts, and whether the protocol delivers atomic updates across blockchains' (p. 1).

Pegging sidechains was a concept first proposed by Back et.al. (2014), that allows one to work around the constraints of a single decentralized blockchain. The idea is to create a separate blockchain, with whatever functionality is required, then provide a way to communicate with the mainchain. Communication here provides the ability to transfer a mainchain native asset to and from a sidechain. However, some of the early drawbacks of this model include layers of network and asset level complexity (p. 11); security concerns around fraudulent activity (p. 12); and risks associated with centralised mining (p. 12) which could lead to soft-forking; since majority-node rather than full-node consensus is possible (p. 13). Flood & McCullagh (2020) describe the 'essential property [of sidechains] is that they are separate blockchains linked to parent blockchains via a two-way pegs that permit digital tokens to be interchangeable and moved across chains at fixed deterministic exchange rates and operate by using simple payment verification proofs' (p. 9). On the other hand, R. Lan et al. (2021) describe '[c]ross-chain bridges are protocols that allow on-chain exchange of cryptocurrencies, on-chain transfer of assets to sidechains, and cross-shard verification of events in sharded blockchains, many of which rely on Byzantine fault tolerance (BFT) for scalability' (p. 1). However, bridging has arisen as one of blockchain's highest security risks (Chainalysis Team, 2022) with recent exploits affecting chains as large as Binance (Shukla & Irrera, 2022). Furthermore, 'existing bridge protocols that can transfer funds from a BFT blockchain incur significant computation overhead on the destination blockchain, resulting in a high gas cost for smart contract verification of events' (R. Lan et al., 2021, p. 1).

Added to pegging sidechains and cross-chain bridges, Košt'ál (2020) adds Notary Schemes, Sidechains/Relays and Hash-locking as predominant cross-chain communication techniques. Four use-case definitions he describes are: 'Asset portability' where assets are transferred from one block-chain to another; 'Atomic swaps' where assets are swapped between two blockchains in a granular way; 'Cross-chain oracles' which are used to read and activate off-chain data; and 'Cross-chain asset encumbrance [which] lock up assets within one ledger based on locking conditions dependent on another ledger' (p. 9). Finally, with regard to atomic swaps, Miraz & Donald (2019) provide a robust description:

> 'Atomic swaps, also known as atomic cross-chain swaps or atomic cross-chain trades, are tête-à-tête cross-chain smart transactions which can arise between two nodes. They enable secure peer-to-peer interchange of two different cryptos without involving any broker or centralised intermediary, such as legacy crypto exchanges, for establishing enforceability. The term "atomic" has been borrowed from database systems terminology, where atomicity or an atomic transaction is limited to a set of binary outputs: guaranteed to occur either completely or not at all. Atomic swap thus eliminates the need for legacy exchange without the risk of one party defaulting on the trade. Atomic swap – being a cryptographically powered smart contract technology – enables peer-to-peer exchange of cryptos directly between two users while both of them having complete control and ownership of their old crypto until the transaction actually happens' (p. 44).

3.3.3. INTER BLOCKCHAIN COMMUNICATION

No.	Author	Year	Title
4	Kan et al.	2018	A Multiple Blockchains Architecture On Inter-Blockchain Communication
9	Ali et al.	2019	Blockchain and the future of the internet: A comprehensive review
13	Qasse et al.	2019	Inter Blockchain Communication: A Survey
14	Yang et al.	2020	A Review on Scalability of Blockchain
15	Caldarelli	2020	Overview of Blockchain Oracle Research
16	Flood and McCullagh	2020	Blockchain's future: can the decentralized blockchain community succeed in creating standards?
18	Siris et al.	2019	Interledger Approaches
25	Lin et al.	2020	BcMON: Blockchain Middleware for Offline Networks
30	Eizinger et al.	2021	Open problems in cross-chain protocols
34	Hardjono et al.	2018	A Contract Service Provider Model for Virtual Assets and VASPs
36	Li et al.	2019	Cost-Effective Data Feeds to Blockchains via Workload-Adaptive Data Replication

Table 1.3 Inter Blockchain Communication research.

Inter Blockchain Communication is the third thematic group arising from 11 papers in our academic sample. In their survey of *Interledger Approaches* (2019), Siris et al. explain that a 'shared motivation for all of the discussed interledger solutions is to move away from the "one chain rules them all'' model to one that allows the interconnection of multiple ledgers, with different features and advantages, while also supporting innovation' (p. 89948). In this paper, the authors discuss '1) atomic cross-chain transactions, 2) transactions across a network of payment channels, 3) the W3C Interledger Protocol (ILP), 4) bridging, 5) sidechains, and 6) ledger-of-ledgers. The approaches are compared according to whether they support the transfer or the exchange of value, their interconnection trust mechanism, complexity, scalability, and transaction cost' (p. 89948). Such issues as trust, complexity, scalability, cost and security all make for challenging technological problems. Flood & McCullagh (2020) add that 'Interoperability is not simple because it will depend on how data are stored on blockchains. Further, interoperability will need to contend with off-chain data sources and will be subjected to data ownership and access policies invoked by owners of data sets' (p. 7). We will address further challenges and solutions to cross-chain collaboration later. For now, we shall explore key themes arising in industry based cross-chain initiatives.

3.2.2 CROSS-CHAIN RESEARCH: INDUSTRY

Since the development of distributed ledger technologies over the last decade and a half, there have been a number of cross-chain initiatives and projects that provide rich and practical insights for the blockchain community. As opposed to academic oriented research papers, this section will provide a review of existing projects and studies in the industry collected from multiple blockchain repositories, including grey and white paper sources. We find that two topics are prevalent: approaches to interoperability and cross-chain bridges.

AVALANCHE

Going live in September 2020, the Avalanche blockchain is described by Sekniqi et al. (2020) as being 'designed to be a universal and flexible infrastructure for a multitude of blockchains/assets [...and] is intended to support, in a value-neutral fashion, many blockchains to be built on top' (p. 2). They aim to do so by making it 'easy to port existing blockchains onto it, to import balances, to support multiple scripting languages and virtual machines, and to meaningfully support multiple deployment scenarios.' (p. 2). Rock (n.d.) notes that one of the main approaches employed by Avalanche is bridging, which

> 'makes use of Intel SGX to create a quick, secure, and low-cost bridge between the Avalanche and Ethereum Networks. It consists of a secure SGX enclave and a collection of trusted partners running Bridge Nodes. The design enables the Bridge to reduce the on-chain requirements to a single action (smart contract call or ERC20 transfer) without sacrificing security. As a result, the Avalanche Bridge provides one of the cheapest, fastest and easiest to use cross-chain transfer processes available today' (para. 14).

The Avalanche bridge is described in 'two main parts: the SGX application and a set of third-party indexers and verifiers called "Bridge Nodes" [which] are responsible for indexing the Avalanche and Ethereum blockchains and submitting eligible transactions to the enclave for processing' (para. 1). Along with its cross-chain bridging solution, 'Avalanche has taken a unique approach with the use of three separate blockchains in its primary platform' (Binance Academy, 2022b, para. 3). These include an asset exchange (X-chain); a smart contract (C-chain) for DApp development; and a platform focused (P-chain) which 'coordinates network validators, tracks active Subnets, and allows for the creation of new Subnets' (para. 10). Subnets feature 'as a novel method of horizontal scaling, allowing for the creation of customizable, interoperable blockchains. There's no limit on the number of Subnets possible' (para. 2). This provides a wealth of cross-chain collaboration opportunities.

DEBRIDGE

One initiative connecting to the Avalanche bridge is deBridge, described as a '[g]eneric messaging and cross-chain interoperability protocol that enables decentralized transfers of data and assets between blockchains' (deBridge, 2021a). This project is distinct from the platform DeBridges (2022) which aims to be a blockchain bridges aggregator. In a Coingecko interview with deBridge co-founder Alex Smirnov, bridges are described as falling into two types: (i) cross-chain value transfers including B2C, swaps or liquidity locking; and (ii) generic messaging protocols that can be composable with other defi projects (Coingecko, 2022); with a case for promoting more of the latter. To employ the Cosmos network slogan, 'deBridge is an internet of blockchains, a cross-chain infrastructure, that has been created to unite all blockchain ecosystems and provide freedom to users and protocols that now can easily decide what blockchain or L2 they want to operate in and easily move between ecosystems' (deBridge, 2022a, para. 2). Since winning the Chainlink Global Hackathon in 2021, DeBridge has incorporated 'a multi-chain world with more than 100 public blockchain networks available. Some of these blockchains solve specific problems like scaling or privacy. Some are just forks of others with their own communities, but we can certainly assume that the number of blockchains will only grow' (deBridge, 2021b, para. 1).

After launching its testnet 2.0 in early 2022, deBridge 'will allow users and protocols to transfer assets and data between all blockchain networks, starting with Ethereum, Binance Smart Chain, Huobi Eco Chain, Arbitrum, and Polygon (Maas, 2022, para. 1). As noted previously, bridges suffer from security vulnerabilities that have led to hacking exploit estimates ranging from $1.4B (Browne & Sigalos, 2022) to $2.9B (Locke, 2022) in losses this year alone. The Avalanche bridge has been no exception. Smirnov states that some of these vulnerabilities occur through poor decentralisation, poor key management and social engineering (Coingecko, 2022). Since 'deBridge's goal is to be the standard for cross-chain interoperability and liquidity transfers to interconnect the industry's innovations, making the crypto world more united' (Maas, 2022, para. 2), the project 'has been audited by Halborn, Zokyo, and Ackee Blockchain and maintains an ongoing bug bounty program on Immunefi' (para. 3). In addition, 'a technical multisig has been set up to decentralize protocol control before handing it over to governance' (deBridge, 2022a, para. 14). Avalanche and deBridge provide relatively untapped opportunity for Cardano and Catalyst community collaboration, but the problem of bridging exploits seems far from over.

BINANCE

Beginning as an ERC token in July 2017, Binance (BNB) would launch its own smart chain in September 2020. Since then, the Binance Bridge Project was launched as 'a cross-chain bridging service that aims to increase interoperability between different blockchains', and that enables users to 'convert selected coins into wrapped tokens (or "pegged tokens") to be used on Binance Chain and Binance Smart Chain. This brings digital assets such as BTC, ETH, USDT, LTC, XRP, LINK, ATOM, DOT, XTZ, ONT, and more to the Binance Chain ecosystem' (Binance Academy, 2020b, para 5). Binance commenced their interoperability rollout with the Binance Chain and the Binance Smart Chain (BSC), describing the latter as 'a blockchain that runs in parallel to the Binance Chain. Unlike Binance Chain, BSC boasts smart contract functionality and compatibility with the Ethereum Virtual Machine (EVM). The design goal here was to leave the high throughput of Binance Chain intact while introducing smart contracts into its ecosystem' (Binance Academy, 2020a, para. 6). Gkritski (2022) discusses the recent rebranding of the bridge project as the BNB Chain, where '[t]he BNB Chain will be made up of two parts: BNB Beacon Chain, previously Binance Chain; and BNB Smart Chain, formerly BSC. BSC is compatible with the Ethereum Virtual Machine (EVM), where smart contracts are executed, and serves as a hub to access other blockchains' (para. 3); while noting problems around centralisation of the system. The draw of EVM compatibility provides 'support for the rich universe of Ethereum tools and DApps. In theory, this makes it easy for developers to port their projects over from Ethereum. For users, it means that applications like MetaMask can be easily configured to work with BSC' (Binance Academy, 2020a, para. 8). As one of many Layer 1 blockchain innovators in the space, there has been an industry-wide trend toward EVM development, since it provides a means to interoperate with the one of the largest smart-contract enabled blockchain networks and userships.

ETHEREUM

Although second to Bitcoin in market cap, and USD Coin (USDC) as a multichain bridging asset (Sopov, 2021), Ethereum (ETH) is arguably the industry leader in cross-chain technology development by volume. Research regarding cross-chain collaboration, in both theoretical and practical aspects, have been made viable by multiple reports and articles provided by the Ethereum community, particularly the Enterprise Ethereum Alliance (EEA) Crosschain Interoperability Working Group (Enterprise Ethereum Alliance, n.d.). Since the formal inception of Ethereum introduced by Vitalik Buterin (2014) and the networks original co-founders, 'demands for cross-chain transactions between Ethereum and other blockchains have been soaring in the enterprise space' (Yoshida, 2022, para. 1). Smith et al. (2022) explain that '[w]ith the proliferation of L1 blockchains and L2 scaling solutions, alongside an ever-growing number of decentralized applications going cross-chain, the need for communication and asset movement across chains has become an essential part of network infrastructure' (para. 1). Alongside bridges, multiple concepts have been proposed to advance cross-chain collaboration pathways and technologies. Bhuptani unpacks some of these proposals in the context of *The Interoperability Trilemma* (2021). Like the scalability trilemma (Buterin, 2021) that impacts the degrees of scalability, decentralisation and security of a network, Bhuptani notes that 'there exists an Interoperability Trilemma in the Ethereum ecosystem. Interop protocols can only have two of the following three properties: Trustlessness: having equivalent security to the underlying domains; Extensibility: able to be supported on any domain; Generalizeability: capable of handling arbitrary cross-domain data' (p. 9-10). Bhuptani proposes applying a similar solution as Ethereum's scalability trilemma, by prioritising two factors at layer 1, and the third at layer 2. In this case 'the interoperability system with the most longevity, utility, and adoptability in the Ethereum ecosystem will be one that is maximally trustless and extensible' (p. 10). Generalizability will then be approached 'by plugging in natively verified protocols on top of NXTP (as a "Layer 2" of our interop network!)' (p. 10). However, in social media posts from January 2022, Buterin outlined his 'argument for why the future will be *multi-chain*, but it will not be *cross-chain* [since] there are fundamental limits to the security of bridges that hop across multiple "zones of sovereignty"' (Sun, 2022). With bridges as a predominant yet problematic cross-chain solution, it is important to explore further options if we are to indeed see a secure and sustainable cross-chain future on our horizon.

HYPERLEDGER

Hyperledger Foundation is the core of Hyperledger, which 'was founded in 2015 to bring transparency and efficiency to the enterprise market by fostering a thriving ecosystem around open source blockchain software technologies' (Hyperledger Foundation, 2021b, p. 2). Furthermore, Hyperledger Foundation is 'part of the Linux Foundation, [and] is a neutral home for developers to collaborate, contribute, and maintain open source software' (p. 4). According to Datachain (2020), Hyperledger's '[c]ross framework, which enables the interoperability of blockchains, is currently available in Hyperledger Fabric, Corda, Hyperledger Besu and Tendermint [now Ignite]' (p. 1), and has been explored as a strategy to improve supply chain transparency (Chou et al., 2022). In terms of interoperability, the Hyperledger Cactus, Hyperledger FireFly and Hyperledger Labs communities (2022) have emphasised that 'Blockchain interoperability is one of the crucial features of blockchain technology, operating in three main vectors: enabling scalability, diminishing risks and eliminating silos' (para. 1). Solutions they identify include following 'guidelines from standardization bodies for seamless integration' (para. 2); following Cosmos and Polkadot sidechain development where 'the common chain serves as an interoperation medium, offering decentralised trust guarantees to the sidechains for the settlement of crosschain transactions' (para. 3); augmenting (typically enterprise) blockchain networks 'with modules and capabilities that allow it to interoperate directly with another network without depending on third-party infrastructure' (para. 4). Hyperledger also offer a suite of interoperability initiatives including Hyperledger Cactus as 'a pluggable enterprise-grade framework to transact on multiple distributed ledgers' (para. 6) and Hyperledger Firefly as 'an API orchestration layer over multiple blockchain ledgers, fostering interoperability in the application tier' (para. 8). Weaver is 'a framework with a family of protocols to enable interoperation for data sharing and asset movements between independent networks built on heterogeneous DLTs in a manner that preserves the core blockchain tenets of decentralization and security' and that 'does not rely on trusted mediators' (para. 9). Further initiatives include a Cross-Ledger Interbank Settlement; the Digital Green Bond Project; Interoperable platform for international exchange of CBDC's; and Multichain Trade Settlement (Hyperledger, 2022). Daml as 'a multi-party application platform […] that deliver[s] portability across a number of blockchain platforms' (Hyperledger, 2021a, para. 3); Project Starling is designed 'to help empower organizations to securely capture, store, and verify human history' (para. 5); and YUI is 'a project to achieve interoperability between multiple heterogeneous ledgers' (Kimura, 2021, para. 4). These initiatives provide ample opportunity for exploring cross-chain collaboration pathways (Pellerin, 2020).

POLKADOT

Polkadot is described as 'a Nominated Proof-of-Stake (NPoS) blockchain network designed to support various interconnected, application-specific Layer-1 chains known as parachains' (Garcia et al., 2022a, p. 3). Using a blockchain development framework called Substrate, the ecosystem is designed to be composable, 'which allows developers to select specific components that best suit their application-specific chain' (p. 3). Parachains and the Cross-Consensus Message Format (XCM) are key features of Polkadot's cross-chain roll-out. A Kraken (n.d.) explainer describes parachains as 'custom, project-specific blockchains that […] can be customized for any number of use cases and feed into the main blockchain, called the Relay Chain […which] is responsible for the network's shared security, consensus and transaction settlements' (para. 1-3). In his whitepaper *Polkadot: Vision for a Heterogeneous Multi-Chain Framework* (2016), Polkadot founder Gavin Wood describes an early vision for cross-chain interoperability:

> 'We see conservative, high-value chains similar to Bitcoin or Z-cash co-existing alongside lower-value "theme-chains" and test-nets with zero or near-zero fees. We see fully-encrypted, "dark", consortium chains operating alongside—and even providing services to—highly functional and open chains such as those like Ethereum. We see experimental new VM-based chains such as a subjective time-charged wasm chain being used as a means of outsourcing difficult compute problems from a more mature Ethereum-like chain or a more restricted Bitcoin-like chain' (p. 4).

Wood argues that '[t]he critical final ingredient of Polkadot is interchain communication. Since parachains can have some sort of information channel between them, we allow ourselves to consider Polkadot a scalable multi-chain' (p. 7). Shirazi et al. (2020) state that the 'Cross-Chain Message Passing (XCMP) scheme is a subset of the Polkadot protocol. It defines how messages can be passed among parachains with no additional trust assumptions beyond the economic security of the relay chain' (para. 2). Cross-chain collaboration opportunities on Polkadot include work with Osmosis, a 'Cosmos-based interchain automatic market maker (AMM), […that integrates] with Axelar and Moonbeam to enable one-click swaps between Cosmos, Polkadot, and Ethereum-based tokens. Axelar's cross-chain infrastructure provides the secure transport layer to make liquidity from the Polkadot ecosystem available on Osmosis' (Osmosis, 2022, p. 1). Since 'Moonbeam is a smart contract platform for building cross-chain connected applications that can access users, assets, and services on any chain' and 'Axelar delivers secure cross-chain communication' (p. 3), then each of these platforms are forming a strong cross-chain collaborative position.

In a Polkadot decoded 2022 presentation, Moonbeam Founder Derek Yoo addresses migration barriers and the 'fragmentation of the user experience' (2022, 04:57) that can occur when independent parachain and smart contract deployments occur. Initiatives such as the

OAK Network can be employed as '[a] hub for cross-chain automation, enabling multichain applications to schedule and automate any substrate extrinsic or EVM smart contract function' (Garcia et al., 2022b, p. 7). The idea of a 'central hub that now has visibility into what's happening across all of the chains right into this kind of universal scope of visibility' (Yoo, 2022, 09:11) appeals to the need for having clearer 'big picture' views a around cross-chain strategies. Yoo states that user adoption is enhanced by utilising 'cross-chain messaging to power superior user experiences by hiding away complexity from the users' (11:00). This provides an opportunity for the Cross-Consensus Message Format (XCM) V3 and Cross-Chain Message Passing (XCMP) channels to 'further drive adoption in an increasingly competitive market, a developing Polkadot needs to birth powerful cross-chain applications that excite the community and attract new users to the platform.' (Garcia et al., 2022b, p. 11). This appears to be a sound aim for any blockchain cross-chain collaboration strategy.

SOLANA

Trautman and Kremer (2022) describe Solana as 'a public, open-source blockchain that aims to deliver scalability and support smart contracts without sacrificing decentralization and security. It accomplishes this through a novel timestamp mechanism called Proof-of-History (PoH). Using PoH, the network can order and batch transactions before they're processed through a Proof-of-Stake (PoS) mechanism' (p. ii). The blockchain uses a relatively centralised network model when compared to other chains. It is argued that a centralized database can 'process 710,000 transactions per second on a standard gigabit network if the transactions are, on average, no more than 176 bytes […and] can also replicate itself and maintain high availability without significantly compromising that transaction rate using the distributed system technique known as Optimistic Concurrency Control' (Solana, 2022, para. 1-2). Solana's co-founder Anatoly Yakovenko first proposed a PoH consensus model in his 2018 whitepaper:

> 'This paper proposes a new blockchain architecture based on Proof of History (PoH) - a proof for verifying order and passage of time between events. PoH is used to encode trustless passage of time into a ledger - an append only data structure. When used alongside a consensus algorithm such as Proof of Work (PoW) or Proof of Stake (PoS), PoH can reduce messaging overhead in a Byzantine Fault Tolerant replicated state machine, resulting in sub-second finality times' (p. 1)

Using time to establish a trustless form of verification is a key feature of Solana's blockchain system, since 'introducing a decentralized clock to a cryptocurrency blockchain makes it more efficient' (Krupka, 2021, para. 2). One cross-chain application is Allbridge, described as 'a simple, modern, and reliable way to transfer assets between different networks. It is a bridge between both EVM (Like Ethereum, Polygon, BSC) and non-EVM compatible (like Solana, Terra) blockchains, that aims to cover L2 (like Arbitrum, Optimism) solutions and NFT transfers in the future' (Allbridge, n.d., para. 3). Another project called Wormhole 'is a communication bridge between Solana and other top decentralized finance (DeFi) networks' (Solana, 2020, para. 1) which aim to include 'Ethereum, Solana, Terra, Binance Smart Chain, Polygon, Avalanche, Oasis, Fantom, Karura, Celo, Acala and Aurora' (Wormhole, n.d., para. 1). This is achieved by:

> '[…] emitting messages from one chain which are observed by a Guardian network of nodes and verified. After verification, this message is submitted to the target chain for processing. This simple message passing primitive enables cross chain functionality. Users interact with xDapps (cross chain decentralized applications) to transfer xAssets (cross chain assets) between networks or access their xData (cross chain data) to provide them services on their current network' (para. 2-3).

It is of note that 'Wormhole is a popular Ethereum-Solana bridge championed by Jump Crypto and Sam FTX's Bankman-Fried' (Protos Staff, 2022, para. 1), for whom the latter is currently involved in a 'high level of media interest in the solvency of FTX' (para. 2). Wormhole, for whom the FTX contagion is yet to be fully played out, acts as a framework for Portal Bridge.

TEZOS

Tezos is described by their community as 'an open-source, community-governed, blockchain network capable of running complex smart contracts for asset settlement and decentralized applications (dApps) which benefit from censorship resistance, decentralization, and user-control' (Tezos Wiki, n.d., para. 1). This is achieved through on-chain governance, a model of decentralised innovation and formal verification processes including Proof-of-Stake (PoS) "baking" and delegation. Cross-chain interoperability and collaborative opportunities arise through cross-chain swaps via Atomex, StakerBridge and TEZEX (Nomadic, 2022, para. 9) to name a few. StakerBridge is described by its community as '[a]n open-source, trustless, method for transferring a token from one chain to another. The StakerBridge process modifies the TokenSwap open-source algorithm so that a single party is both the transmitter and receiver of their token, enabling a seamless transfer of tokens from one chain to another' (StakerDAO, 2021, para. 1). Atomex (2021) describe its protocol as 'a modified cross-chain atomic swap scheme adapted for use as an exchange backend' (para. 4). Service features include '(i) smart contracts/bitcoin scripts for each supported chain that implement a modified atomic swap protocol; (ii) A backend service responsible for order matching and monitoring transactions [exchange]; (iii) Desktop/web/mobile wallets with a builtin support for Atomex protocol and exchange API' (para. 1). Mehrabi (2021) describes TEZEX Bridge as 'a non-custodial cross-chain token bridge for Tezos, that runs on the basis of atomic swaps through a double-sided marketplace. At first, TEZEX Bridge will enable swaps to/from the Ethereum blockchain (ERC-20 tokens), to the Tezos blockchain (FA-1.2, FA-2.0)' (para. 1). This project's aim – like many cross-chain bridges – is to establish it's pairing network, starting with USDCm USDT, ETH and WBTC (para. 2). Tezos provides bridging opportunities with cross-chain potential.

CARDANO

Cardano is described as 'a proof-of-stake blockchain platform: the first to be founded on peer-reviewed research and developed through evidence-based methods' (Cardano.org, n.d.-c, para. 2). Built on a proof-of-stake consensus mechanism, Cardano's roadmap is not only focused on decentralised financial systems, but on governance: 'a decentralised future without intermediaries, in which power is returned to the individual' (para. 10). To so do, Fitzi (2022) notes that the 'recent enabling of smart contracts on Cardano has led to a significant increase in user activity […] To keep up with this elevated demand, the system's current transaction throughput must be increased' (para. 1). This growth is part of the Cardano's vision to build a global decentralised 'economy of the future' that is built on principles of 'scalability, interoperability, and sustainability needed for real-world applications' (Cardano.org, n.d.-b), para. 1). Hryniuk (2022b) affirms that '[s]idechains and layer 2 solutions are key to increasing scalability for projects building on Cardano' (para. 2) which will include further research by the blockchain's builder Input Output Global (Sanchez, 2022). Discussions covering cross-chain collaboration in this area include Gaži et al, (2019), Garoffolo et al. (2020), Input Output (2021, 2022), Cardano Catalyst Women (2022) and Needham (2022).

In terms of interoperability, Cardano has been exploring 'blockchain bridges, sidechains, and the role of the AGIX ERC20 converter. These are the core elements that enable communication between blockchains to ensure greater scalability, technology adoption, and ease of use' (Hryniuk, 2022a, para. 3). Hryniuk noted in 2021 that 'IOHK announced a collaboration with Cardano, Ergo, Nervos, and Topl and Komodo to create the UTXO alliance' (2021a, para. 1) and a collaborative project to support UTXO standardisation across ecosystems, amongst other things. Hryniuk explains that '[t]he UTXO alliance will facilitate cross-ecosystem initiatives to extend the capabilities of UTXO in terms of smart contract functionality. Teaming up with other blockchain industry projects, the shared objective is to foster and support further research, development, and education across the entire space' (para. 4-5). Zhang and Louie (2022) discuss how '[t]eams from IOG, Wanchain and MLabs […] collaborated to design an actionable plan to make Cardano interoperable' (para. 6). According to Newsfile Corp. (2022), '[t]hese efforts will see the teams deploy decentralised, non-custodial, bi-directional crosschain bridges connecting Cardano to other Layer 1 blockchains. Wanchain bridge nodes will also be upgraded to peg the Wanchain and Cardano networks to further secure Cardano's crosschain bridges and transactions. In other words, Wanchain will become an EVM-compatible sidechain to Cardano' (para. 1). In a collaboration with Emurgo, Cardano's commercial adoption arm, 'Partisia's development team will develop customized smart contracts for Cardano developers to utilize when applicable to their dApp's use case […] It is the first demonstration of Partisia Blockchain's layer 1 blockchain delivering cross chain privacy smart contracts that partner ecosystems can benefit from' (Partisia Blockchain Foundation, 2022, para. 2). In the Cardano ecosystem, Milkomeda C1 sidechain is also a significant initiative building bringing infrastructure across Cardano, Solana and Algorand.

However, with an emphasis on technical interoperability, one core feature missing from formal research is the social role of collaboration in the cross-chain domain. Kathryn Stacy notes in a Cardano360 overview of EVM sidechains, that 'connection extends beyond merely the technological aspects of a network. We must also cultivate an ecosystem where it is rewarding and welcoming for all of the new users who will be joining the network over the coming years' (Input Output, 2022, 11:00). A community discussion on cross-chain collaboration also identified a need to collaborate between technology people and the rest of the world, such as those involved in business, marketing or sales (Cardano Catalyst Women, 2022, 07:37); along with a need to find mutual topics to collaborate on with other communities (08:32). In 2020, IOHK CTO Romain Pellerin articulated such sentiments when he discussed the importance of collaboration:

> 'A community's overall success largely depends on its ability to collaborate. How its members interact with each other, how they share knowledge to find new avenues of development, and how open they are to embrace innovation and novel technologies will determine the community's long-term viability. One of IOHK's founding principles is its belief in nurturing a collaborative ecosystem for blockchain development. Our commitment to knowledge-sharing and to our deeply-held principles of open-source serves as the rationale behind becoming a member of the Hyperledger community' (Pellerin, 2020, para. 1-2).

3.5 SECTION SUMMARY

Unfortunately, due to the size and scope of this study, the list of blockchains discussed is inexhaustive. With an estimated one thousand blockchains in current operation (McGovern, 2022), there are many instances of cross-chain collaboration that we are unable to capture. Notable mentions include 'Cosmos and their "internet of blockchains" vision through the Inter-Blockchain Communication Protocol (IBC), where messages can travel between different blockchains that have implemented the protocol' (Binance Academy, 2021, para. 3). Chainlink's 'cross-chain interoperability protocol (CCIP), which provides a standard of communication between blockchains' (Locke, 2022, para. 10). Lafourcade and Lombard-Platet (2020) note that 'interoperable blockchains exist, such as Kadena' (p. 7) among others. And Harmony One's Horizon bridge has a 'unifying vision […] to connect multiple distributed systems together' (R. Lan et al., 2021, para. 1) while navigating an environment where 'cross-chain bridges have been susceptible to a number of hacks so far, the cross-chain availability of some of these tokens opens up a number of compounding technical risks' (Tse, 2022, para. 54). The essence of this study is to extract a broad range of themes around key problems, solutions and opportunities evident in cross-chain collaboration, for the purposes of prompting further research, discussion and innovations amongst collaborative communities, including those not covered here. To begin, we will commence by exploring some of the problems arising.

4.0 LITERATURE ANALYSIS

4.1 SECTION OVERVIEW

The following section will explore key themes drawn from the comprehensive literature review. These themes are grouped into Problems, Solutions and Opportunities arising from cross-chain research and development. The section will be followed by Report Findings and Recommendations drawn from these findings. The aim of this section is to distil valuable research insights to support further cross-chain research and industry development.

4.2 PROBLEMS

In this section, we will investigate and analyse collaboration, communication and interoperability problems across blockchains. Results from an initial descriptive analysis taken from academic and industry sources reveal that the major problems arise in the areas of blockchain networks, interoperability protocols, scalability, security, technological constraints, and users.

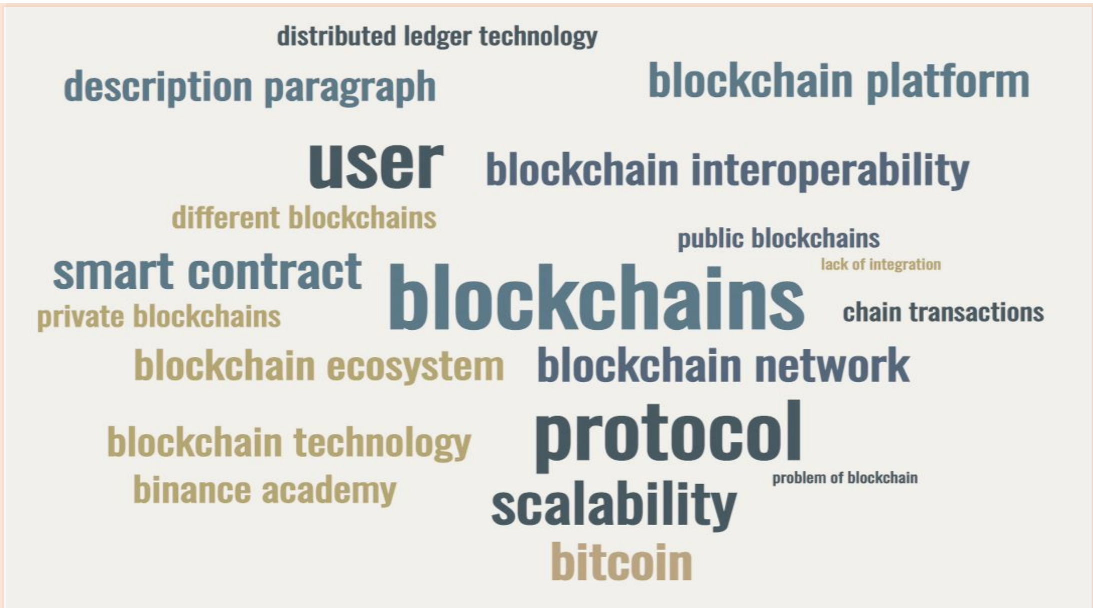

Figure 3. Problems associated with cross-chain collaboration.

4.2.1 BLOCKCHAIN NETWORKS

The proliferation of blockchains and decentralisation in recent years has dawned a new era of collaboration. However, a consequence of this rapid technological and social emergence has led to severe fragmentation between blockchain communities. Currently, many blockchains are designed to operate as isolated entities (Liu et al., 2019; Zarick et al., 2021), establishing walled ecosystems that inhibit cross-chain communication and interoperability solutions (Sanchez et al., 2022, p. 1). To stimulate network growth, platforms tend to silo their liquidity, and limitations are imposed on users seeking to move liquidity outside of the network. Even though improvements in the adoption and interoperability of Ethereum and similar blockchains has increased collaborative opportunities, the inherent limitations of cross-chain communication affect throughput, latency, and create challenges for scaling, functionality and user experiences (Garoffolo et al., 2020, p.1). Despite several large blockchains such as Ethereum or Hyperledger Fabric developing interoperable standards, there is a considerable number of other blockchains that have been designed for specific applications and do not communicate with each other accordingly (Dinh et al., 2019, p.1). Due to sizeable industry blockchain investment, and the desire to increase user adoption and retail engagement, the issue of fragmentation may arise from a continuation of competitive legacy market practices. These points are reiterated by deBridge (2021b):

> 'The major problem is that these chains are evolved independently and are not interconnected with each other or interconnected through some narrow and specific channels that are often centralized and different for each specific blockchain. This leads to vital problems of ecosystem fragmentation, such as fragmentation of technologies, liquidity, and even competitive environments. Today, the problem is currently not solved since there's no unified standard of interconnection between various blockchain networks leading to (i) Fragmentation of technologies; (ii) Fragmentation of liquidity; and (iii) Fragmentation of competitive environments' (para. 2).

Another major challenge is that, since there are multiple decision-making participants within decentralised ecosystems, it can be difficult to update the system thoroughly. Even a small protocol change may require community consensus, involving cumbersome or iterative processes that slow the introduction of new features in the face of swift market competition. Furthermore, blockchain communities have been looking for effective protocol design solutions to improve data storage and management, with a high level of security and efficiency. The Poly Team (2020) also note that '[i]nformation exchange and asset replacement between blockchain ecosystems is also limited' (p.1). Michelson et al. (2022) suggest that an ideal solution would be a platform that has integrated 'fast read/write speeds (low block and transaction times), low transaction costs, scalability, security, pathways for migrations of legacy systems, and easy management of data access and authorizations' (p.2). It may be argued that some blockchains have achieved these ends, to a degree. However, achieving these goals via cross-chain collaboration is difficult.

With current constraints in cross-chain smart-contract communication, and the lack of efficiencies and security in scaling, there are obstacles when seeking to incorporate existing blockchain protocols. Blockchain, as a new generation of information infrastructure (Lin et al., 2022, p.1), also rely on continuous network connectivity that may impact user adoption for remote or poorer communities with limited internet access or data storage. Satellite technology may be employed to forward offline transactions on chain. However, this may contribute to further interoperability issues and extensive user costs. Calderelli (2021) explains that 'there is no one-size-fits-all solution for blockchains because each distinct ecosystem consists of discrepancies in scalability, security, programmability, and privacy. The needs of each chain's users are also varied justifying the heterogeneity of coexisting separate platforms. From a financial perspective, this inability to collaborate or communicate means that the related capital is not completely exploitable for DeFi purposes' (p.1). Hence the desire for a blockchain ecosystem where users across all blockchains can interact with each other becomes more urgent. Unfortunately, today's blockchain landscape is relatively fragmented and heterogeneous (Nissl et al., 2020, p.1), a situation potentially confounding attempts for blockchain contributors seeking to forge cross-chain collaboration.

As outlined above, another important consideration for blockchain interoperability is cost. Builders and users must consider suitable costs and pricing models for cross-chain development and participation (Hardjono, 2021, p.1). Even though digital assets and messages can be transferred securely without an intermediary, the work of integrating blockchain networks is complex and accompanied with the competitive costs of developer recruitment and onboarding and solution development (Poly Network, 2022).

4.2.2 INTEROPERABILITY PROTOCOLS

Interoperability protocols facilitate token transfers between blockchains. Eizinger et al., (2021) note that some practical propositions in recent years have included 'hash-based locks, Scriptless Scripts, and other more complex signature-based protocols' (p. 1). However, the authors further describe 'a whole new dimension of hardly studied and completely unsolved problems, which lies in between theoretical work and practical cross-chain product development' with a call for 'anyone working in this field to collaborate on possible solutions' (p. 1). These include the need for cryptographic protocol applications in the domain for crypto wallets, blockchain monitoring and interaction, fees, testing and the economics of atomic swaps. Liu et al. (2019) confirm that 'the scope of blockchain interoperability goes beyond just token exchange' (p. 1) and they address two problem areas for interoperability programming: a fragmented programming model for cross-chain dApps and interoperability protocols, and token-exchange protocols are not generic enough to be applicable beyond their native environment (p.1).

On the other hand, there are multiple thoughts on the disproof of Interoperability. Lafourcade and Lombard-Platet (2020) argue that, at a base theoretical level, interoperability is a contradiction of fundamental blockchain characteristics (p. 6) which asserts that no blockchain is able to rely on external data (including another blockchain) to assert the validity of a transaction. Mohanty et al. (2022) argue that 'cross-blockchain protocol design is difficult as both the source and target of blockchain systems may differ in the hashing scheme, consensus algorithm, block size, execution environment, and network design' (p. 2). Thus, it is hard to 'identify and verify data recorded in one chain from another chain just by examining the information exchanged between them' (p. 2). DeBridge (2021b) point out that a '[l]ack of interoperability solutions leads to the situation where all the projects have to compete locally […] But what if users could perform their swaps with PancakeSwap or Raydium simultaneously and be able to decide which DEX provides the better rates? That's what we will have in the near future when we have cross-chain interoperability' (para. 5).

Another challenge in this space is the need for consolidated interoperability standards (Karacaoglu et al., 2021, p. 11). Liao (2020) notes that, unlike other technology standards, it is difficult to achieve 'consolidation around dominant blockchain protocols that have the primary burden to become interoperable' (para. 3). This is because 'convergence around a protocol is absolutely no guarantee that the blockchain networks that use that protocol can readably communicate with one another' (para. 3). Liao states that the problem of interoperability via Web APIs also involves (i) high cost for one-to-one integration between blockchains, and (ii) unverified authentication of data exchange between blockchains due to a lack of a cross-platform consensus mechanisms. Lacking adequate cross-chain governance structures, that enable the flexible and secure expedition of API's, will also produce adverse effects on cross-chain operations (para. 9).

Finally, Herlihy (2018) raises the issue of trust within interoperability protocols. He considers how it is possible to devise a protocol that ensures that – in the event that users behave irrationally – then no rational party will end up worse off (p. 1). Varying solutions have been proposed to tackle this issue, such as atomic swap protocols, sidechains, cross-chain projects on Polkadot, Cosmos and TrustCross (Y. Lan et al., 2021). Although these solutions have taken into account the needs of cross-chain interaction, data privacy issues remain uncertain (Herlihy, 2018, p. 10). This may pose a threat to enterprise as well as individual usership.

4.2.3 SCALABILITY

Along with decentralization and security, scalability is a key component of the blockchain trilemma (Buterin, 2021). Growing a network's size and capacity, in the hopes of generating greater usership, is therefore inhibited by the degrees to which that network is interoperable and secure. Qasse et al. (2019) argue that, since most existing blockchain networks are operating in standalone environments, scalability and connectivity within blockchain platforms are affected, thus limiting broader adoption within the industry (p. 1). According to Yang et al. (2020), the current blockchain ecosystem evidences scalability bottlenecks through low transaction efficiency, high confirmation latency, function extension requirements and lack of mutual trust (p.1). These problems have stifled cross-chain interaction, and their capacity has amounted to a LAN-like architecture. The inability to scale has been a problem popular with layer-1 networks (Binance Academy, 2022c, para. 5). This problem is explicit in the way Proof-of-Work (PoW) transactions are processed, affecting applicable crypto-currencies. While PoW aims to assure decentralization and security, its networks also tend to have latency and high-cost during times of network congestion (para. 6), and may sacrifice decentralization through an oligopoly of miners. Bhuptani (2021) explains that to build truly decentralized and non-censored transactions, we need to protect blockchain systems from attack by prioritising security, such as through Ethereum's L2 solution. However, in the context of the trilemma, this may serve to compromise interoperability. Chainwire (2022) identified that token swapping in Defi gaming is often slow and unreliable because of the complexity involved with current applications and the lack of scaling solutions. In the Polkadot ecosystem, the cross-consensus message format (XCMP) was established to allow 'otherwise isolated parachains [to] send messages between each other with guarantees and in a secure and trust-free manner' (Shirazi et al., 2020, para. 4). To do so, 'each parachain has a limit on the total size of messages that can be sent to other parachains. The gossiping protocol has been using a bounding delivery to avoid large overhead' (para. 31). Adding exponential parachains to the relay chain, may provide a secure and scalable solution through XCMP.

4.2.4 SECURITY

Among the blockchain trilemma, security has received additional attention recently, 'aggravated by the problem of incompatibility between systems' (Dionysopoulos, 2022, p. 105). Security issues for cross-chain bridges have been reported in multiple aspects (Browne & Sigalos, 2022; Chainalysis, 2022; Locke, 2022; Shukla & Irrera, 2022; Tse, 2022). Suffice it to say, cross-chain bridges are highly vulnerable to hacks, which range from poor decentralisation, poor key management that is targeted through social engineering (Coingecko, 2022), or 'vulnerabilities in their underlying code' (Browne, 2022, para. 1). Furthermore, vulnerabilities can also arise through a lack of clarity around which bridging mechanisms are secure and which are not (Bhuptani, 2021, para. 3), which results in significant disadvantage and loss of confidence in the blockchain community (Say, 2022b). Despite their promise, some decentralised applications (dApps), which require off-chain data to operate, have created a greater attack surface for hackers (Dale, 2021).

With so much vulnerability, security is considered the first priority for bridges that support many cross-chain assets. At the current rate, cross-chain development between EVM-compatible chains is certainly mature. However, there are challenges regarding security for asset transfer between PoW and Proof-of-Stake (PoS), or non-EVM compatible chains and EVM-compatible ones (Microchains, 2022, p.7). In terms of attack, Sekniqi et al. (2020) describe that '[c]lassical consensus protocols are designed to withstand up to f attackers, and fail completely when faced with an attacker size of $f + 1$ or larger, and Nakamoto consensus provides no security when 51% of the miners are Byzantine' (p. 2). This reiterates the dangers of miner concentration in so-called decentralized networks. On a broader scale, the make-up of a blockchain and its constituents – be they public, permissioned or hybrid – may also carry their own security complications for future builders (Johnson et al., 2019; Geroni, 2021).

4.2.5 TECHNOLOGICAL CONSTRAINTS

Technological constraints within cross-chain research are another recurring issue, particularly impacting interoperability and network latency (Miraz & Donald, 2019, p.42). A well-known cross-chain solution – sidechains, have also received criticism that they lack decentralized architectures that stifle collaboration between proof-of-work blockchains. Kiayias & Zindros (2019) explain that more generic architectures are needed to enable greater operability between chains (p. 1). Fitzi (2022) discusses technical limitations, such as transaction throughput being squeezed by increased user demand, or limits on block sizes needed to 'achieve high throughput without compromising the security of the system' (para. 2). Decentralized systems can also be difficult to update because of the emergent nature of distributed decision-making models (Garoffolo et al., 2020). Liu & Ohsawa (2020) argue that maintaining consistency is the most difficult part if a cross-chain system aims to advance performance and scalability at the same time. The reason being that such a system needs to achieve consistency between all nodes in a very limited time to achieve higher performance (p. 1). On the other hand, a lack of connectivity between blockchains may also impact communication and consensus costs (p. 2). Wang et al. (2017) note that a comprehensive blockchain architecture that can deliver high-traffic, regulation, privacy, and scalability is still missing (p. 97), although there have since been many inroads made by blockchain communities discussed in this study. Wang (2021) notes that '[t]he development of independent and incompatible blockchain technologies has caused significant fragmentation of the research' (p. 1) while 'research on cross-blockchain token transfer is still limited' (p. 5). Wang also suggests the need for 'a generic framework to cover most existing blockchain systems' (pp. 1-2) since 'the standardization of blockchain interoperability still has a long way to go' (p. 5). Other issues that arise regarding blockchain security issues include, but are not limited to: the non-trivial undertaking of "two-way peg" security (Garcia et al., 2022, p. 12); difficulties around liquidity spread across L1 and L2 dApp protocols that affect economies of scale (Osmosis, 2022, para. 3); a lack of integration between traditional computing systems (such as those that issue credit score information) and blockchains (Orcutt, 2020), potentially resulting in a need to overhaul infrastructure and expenditure over time (Blekinsop, 2020). Also, there are integration hurdles between public and enterprise blockchains (such as centralised cloud services or data-feed provision) that generate security, throughput, governance, cost and legal issues (World Economic Forum, n.d.; Li et al., 2020). These latter issues signal the hidden control that cloud providers, or other centralised entities, may have on deployment solutions, thus restraining interoperability. One cross-chain collaboration approach may be for private and public blockchain participants to have forums to discuss terms that establish and promote mutual outcomes.

4.2.6 USERSHIP

A further issue affecting cross-chain collaboration is around the impacts on blockchain usership. Currently, centralization leads to key parties dominating exchange market share and imposing controls over fund custody. This places greater liability upon exchange users if the exchange should collapse, as is currently being experienced with FTX and its market contagion, as well as other historic precedents such as Mt. Gox or Quadriga. In the transition between traditional (TradFi or CeFi) market practices, and decentralised financial services (DeFi), there remains a challenge in the domain of cross-chain protocol design and its implications for users. It has been argued that, without a single point of failure, such as a "trusted" third party, the decentralization of fund custody should provide users with greater flexibility and control of their assets (Shlomovits & Leiba, 2020, p. 2). Luo et al. (2018) raise the concern that 'high barriers between heterogeneous blockchain systems' (p. 139) include a lack of trust, communication and secure exchange between one another; issues which could potentially be addressed through collaborative engagement with network participants. Although asset and information exchange between ledgers is convenient and meaningful for users, there are also 'high barriers to entry for creating new connections' (p. 1) between ledgers. The catch is that the speed of 'global consensus mechanism[s] in blockchain [...] cannot be improved by adding extra nodes' while 'a single blockchain has limited performance [...] unable to meet the requirements of large-scale applications' (p. 139). In defi, many users found that current solutions for cross-chain token transfers and trading are too complicated, leading to poor user experiences and accessibility, and producing negative impacts on blockchain asset market dynamics (Gaur, 2021).

A lack of generic messaging protocols and convoluted UX design contributes to user struggles with cross-chain bridging and swapping mechanisms, and asset migration issues. For potential users, these issues provide extra layers of complexity for cross-chain interactions and collaboration, as users have to a perform sequential transactions across chains to achieve the desired results. This problem could be minimised if there were a collaborative platform that streamlines cross-chain transactions for varying grades of blockchain users, projects, and developers (DeBridge, 2022b). Users may also want to better understand the cost accrual across chains when assets are wrapped and unwrapped, or minted and burned, depending on the types and frequency of bridging protocols used.

Although blockchain aims to address core problems around trust, transparency and the distribution of decision-making power, the social dimension of these issues often become subsumed by the technical. The complex nature of social issues and roles requires further discussion and understanding in order to better inform how communities collaborate. This is especially so if the operational mechanisms driving inter-chain applications require users to trust in them, even though there are vulnerabilities evident with little protection from unexpected loss (Hyperledger Foundation, 2021b, p. 5). Defi users have reflected on the lack of trusted sources for lending, causing inconvenience in obtaining collateralised loans (Say, 2022a). At the moment, one of the driving forces behind cross-chain interoperability is the generation of robust machine consensus protocols. Anatoly Yakovenko (2018) described a prior machine consensus protocol issue that affected blockchain timestamping, which lead him to found Solana. However, there is a human dimension that machine consensus is currently unable to address: in a collaborative setting that is dependent on nuanced and intrinsic social protocols, a different set of challenges face participants seeking to reach group consensus, particularly if a network is built on decentralised forms of social governance. Along with the development of decentralised governance (or what we shall call dGov), Moonbeam founder Derek Yoo states that '[t]he biggest challenge for broader end user adoption of web3 apps is the end user experience' (Osmosis, 2022, para. 5).

4.2.7 PROBLEMS: IMPLICATIONS

Although these implications will focus primarily on the Cardano community, this report encourages consideration of impacts affecting other blockchain communities as well. Cardano, like many blockchain networks, is increasing expansion to a larger community of developers and blockchain users. To date, there are approximately '4.5 million native tokens, over 5,000 NFT projects, and more than 900 overall projects building on Cardano' (Hryniuk, 2022a). To stimulate further network growth, Cardano seeks to support wider user adoption. Along with the above findings, it is clear that interoperability is essential for blockchain network growth in general, and Cardano in particular. To do so, blockchain users need to have the ability to transact seamlessly across networks. This includes smart contracts that are compatible and communicable across different blockchains with reduced limitations. Cross-chain UI may also need to be more user-friendly to unlock the full potential of these networks (Camps, 2022). Cross-chain integration is also a complex endeavour, requiring substantial development, resources, time and collaborative effort. There is also a lack of research around social collaboration initiatives that can stimulate growth between blockchain communities. Specific implications that impact Cardano, and other networks seeking to improve cross-chain collaborations and user adoption, include the following Project Catalyst F8 funded proposals:

- Hashed public key-based wallet addresses are not human-readable and do not offer personalization (Camps, 2022);
- Sending and receiving crypto currency payments, including ADA, may still be seen as a barrier to entry into the crypto world (Camps, 2022);
- Fees for sending payments across different networks remains complicated, uncertain or costly (Sieber, 2022);
- A lack of general public awareness around Cardano (or other) projects and lack of ease to locate them, in an open access database, with other projects (Raz, 2022a);
- Difficulties in identifying and following the development of projects leveraging Cardano technologies in the areas of social and environmental goods;
- Challenges in determining projects, asset integration, and finding correct verified APIs, processes, and contacts on Cardano (Securities & Commerce Institute, 2022);
- Collaboration between Cardano and other chains may be seen as relatively limited (Raz, 2022a);
- Negative perceptions of NFTs in the general public due to the evolvement of siloed NFT spaces and a lack of exchanges between different chains (Gentner, 2022);

- A need for clearer Wed 3.0 and Metaverse definitions and cross-chain interoperability solutions (Gassner, 2022);
- Multiple FT and NFT bridging opportunities yet to be explored, including with Filecoin as a perpetual storage option (Kiriakos, 2022), or between Cardano and the Polkadot/Kusama communities (Mohan, 2022);
- Cross-chain collaboration is under-utilised as a cross-blockchain education pathway (Oliver, 2022);
- An ongoing need for cross-chain interaction and collaboration standards around NFT data (Feghaly, 2022);
- An ongoing need for cross-chain collaboration research, particularly at the sociological level (Research Guild, 2022);
- A lack of clear innovation pathways (and coordinated macro-planning) that link and unify them blockchain communities to support mass adoption (Cohen, 2022);
- A need for Cardano, and other blockchain communities, to accelerate the experimentation of cross-chain services to catch up with multi-chain trends (Wolfram Blockchain Labs, 2022a).

4.3 SOLUTIONS

Kathyrn Stacy, technical product marketer for IOHK, stated in a recent overview of EVM sidechains that 'if you want to build a smart contract platform of the future, you must be able to transcend the capabilities of a single programming language' (Input Output, 2022b, 7:35). This statement frames the key themes and approaches arising in this section, including novel solutions; atomic swaps and protocols; the interledger protocol; novel solutions via Polkadot and Cosmos; sidechains and bridging solutions. The section will then conclude with a review of solution-based implications for Cardano and other blockchains.

4.3.1 NOVEL SOLUTIONS

At a base level, blockchain incorporates ubiquitous products and features that provide cross-chain interoperability solutions. These are evident in multi-token crypto-currency wallets. Takahashi & Lakhani (2019) describe how the multi-chain components of crypto-wallets incorporate different software that provides access to applicable blockchain data and operations, such as viewing crypto-currency balances and transactions per token-type, key management, anonymous or know-your-customer (KYC) processes, and integration with crypto exchanges or dApps (pp. 2-3). To that extent, crypto exchanges and defi platforms also act as aggregators for various blockchain tokens and protocols, whether in centralised or decentralised ways. Technical applications such as anchoring (or hashing) is the process of inserting data into a blockchain, usually in the form of a transaction (Konashevych & Poblet, 2019, p. 317). This process may provide interoperability in the form of linking cross-chain data, or off-chain data using blockchain oracles. Pang (2020) proposes a novel consensus algorithm through Multi-token Proof of Stake (MPoS) to support a blockchain interoperability architecture. Compared to traditional PoS consensus protocols that involve single token staking, MPoS facilitates the staking process with multiple crypto tokens in a cross-chain ecosystem, that the author argues, may be more secure than the single-token PoS model (p. 153720). Regarding optimistic rollups, Richards et al. (2022) explain that the architecture consists of two components: firstly, the on-chain smart contracts which store rollup blocks, monitor state updates on the rollup, and track user deposits. Here, the blockchain (acting as a distributed "server") provides the base layer (L1) for optimistic rollups. Secondly, the off-chain virtual machine (VM), where applications and state changes are executed, serve as the upper layer (L2) for optimistic rollups. Due to blockchains having a limit on the amount of data blocks can hold (and which are administered through network "gas" fees), it then becomes desirable to reduce the amount transaction-related data. Optimistic rollups serve to increase network scalability, but they may also be an area to consider how Layer architecture design occurs between different chains, including searching for elegant and concise cross-chain coding solutions that different communities can use together.

Another approach to consider are the blockchain accounting models used, whether that be account-based, Unspent Transaction Output (UTXO)-based or Extended UTXO (eUTXO)-based. Account-based models provide 'a balance management system that works in a similar way to the traditional bank account. Unlike UTXOs, value in an account-based balance can be partially spent' (Crypto APIs Team, 2022). Generally, the trade-offs between an account-based model such as Ethereum, and a UTXO-based model such as Bitcoin, is the degree of expressiveness or simplicity the model provides. This prompts the question: 'is it possible to have expressive smart contracts, while keeping the semantic simplicity of the UTXO model' (Chakravarty et al., 2020, p. 1). Cardano.org (n.d.-a) released an EUTXO handbook that argues that 'Cardano's ledger model extends the UTXO model to support multi-assets and smart contracts without compromising the core advantages of a UTXO model. Our innovative research enables functionality beyond what is supported in any other UTXO ledger' (p. 31). This approach may potentially enable multi cross-chain assets, but will require collaboration in the form of accounting model design with other blockchain communities. Hryniuk (2021b) discusses Alephium as 'the first operational sharded blockchain bringing scalability, ETH-inspired smart contracts, and DApp capabilities to Bitcoin's proven core technologies' (para. 5). Unpacking the benefits and opportunities of cross-chain collaboration with other UTXO-based ecosystems is advantageous, as is explored through the UTXO alliance (Hryniuk, 2021a).

Licorish (2022) discusses Chainlink's 'CCIP as a landmark innovation in the development of Web3)' (para. 5). This protocol is 'Chainlink's highly secure consensus mechanism to cross-chain communication, enabling not only token movement but messaging between distinct blockchains (para. 3), and aims to allow for composable smart contracts and coding languages across chains. In *A Review of Scalability of Blockchain* (2020) Yang et al. believe that cross-chain collaboration can be improved through the use of multiple cross-chain communication technologies such as Side Chain or Relay Chain Technology, Hash Locking, Distributed Private

Key Control and Sharding mechanisms, Directed Acyclic Graph (DAG)-based architectures, and off-chain payment networks including Lightning, Raiden, Sprites, Plasma or TrueBit.

4.3.2 ATOMIC SWAPS AND PROTOCOLS

A well-known cross-chain solution is found in cross-chain atomic swaps. This solution allows users to directly exchange multiple ledger-based assets with reduced intermediaries. This type of exchange 'derives from the term "atomic state" in which a state has no substates; it either happens or it doesn't—there is no other alternative [...] In this case, the conditions are that each party agrees to the transaction before a timer runs out' (Frankenfeild, 2022, para. 2-3). They can be created when funds from two chains are initially deposited in hashed time-locked smart contracts (HTLCs), which can only be unlocked using a special key that combines a key and a code (Dionysopoulos, 2022, p. 107). This setting ensures a scenario in which a single party cannot control both assets at the same time, including through manipulation or human error. In doing so, atomic swaps provide an effective form of security for trustless forms of cross-chain token exchange.

A number of atomic swap solutions have been proposed. Herlihy (2018) proposes an Atomic Swap Protocol that use motivation-based modelling, swap digraph's, game theory, smart contracts, hashlocks and hashkeys. Shlomovits & Leiba (2020) present JugglingSwap as 'a scriptless atomic cross-chain swap protocol towards a higher level of interoperability and cross-chain collaboration' (p.1). Zarick et al. (2021) propose LayerZero as 'the first system to trustlessly allow direct transactions across all blockchains without involving any intermediaries' (p. 1). Y. Lan et al. (2021) designed the TrustCross protocol, which includes a novel cross-chain architecture that improves confidentiality, and allows information and asset transfer between different blockchains via the integration of cross-chain transaction standards (p. 9). Calderelli (2021) believe wrapped tokens provide a practical solution for cross-chain interoperability (p. 10), with collaborative potential. Belchor et al. (2021) use a novel blockchain interoperability approach called Hybrid Connectors. These involve trusted relays, blockchain-agnostic protocols and blockchain migrators. Hashflow proposes bridgeless cross-chain swaps using a request-for-quote model (Chung, 2022). Sanchez et al. (2022) concur that a protocol that allows private transactions across blockchains is possible to construct, and will enable trustless cross-chain transfers with high user privacy (p. 8).

Maas (2022) notes that bridges provide an in-road that enables existing cross-chain protocols and applications to apply across ecosystems. The author cites deBridge as one such initiative, where a 'permissionless, decentralized design of the protocol will allow users and protocols to transfer assets and data between all blockchain networks, starting with Ethereum, Binance Smart Chain, Huobi Eco Chain, Arbitrum, and Polygon' (para. 1). The protocol design uses a lock and mint approach that instantly validates the current state of the protocol and checks if the total supply of the wrapped asset is entirely backed by its collateral. Collaborating projects can then 'tap into the various cross-chain opportunities the protocol enables, such as asset swaps and transfers, governance voting, farming strategies, NFTs, oracle data, and much more (para. 3). DeBridge (2022) believes that their cross-chain interoperability protocol would become 'the first generic exchange protocol that allows passing arbitrary data and liquidity in one single transaction between various chains' (para. 6). Composability is described as one of the core features of the protocol design, enabling compatibility with DeFi systems (para. 6). Such architecture will enable collaborative cross-chain bridging development and opportunities.

Use cases carried out by institutions such as the central bank of Singapore (Khatri, 2020) have looked at improving settlement efficiencies for various cross-chain transactions, with the aim of promoting commercial adoption of their service (para. 3). Project Ubin was a collaborative venture with Temasek Holdings and JP Morgan, using 'JP Morgan's Quorum blockchain protocol as the base infrastructure' (para. 6). While:

> 'The first two phases of Project Ubin focused on building technology capabilities in the context of a domestic payments network. The next two phases focused on the interoperability of blockchain-based networks for Delivery-versus-Payment (DvP) and cross-border Payment-versus-Payment (PvP)' (para. 4).

However, as a decentralized and trustless interoperability protocol for heterogenous blockchains, Poly Network (2022) provide interoperability between different classes of applications, assets, and consensus via its Poly Relay Chain, as well as a systematic development framework for infrastructure, smart contracts, applications, and others to participate in the establishment of such ecosystem. The solution provided by Poly Network includes a cross-chain bridge and an interoperability service. This interoperability design will help move assets between blockchains easily, provide effective support for interoperation via a class of service APIs, and include advanced security features.

As an additional solution, Interledger refers to an outstanding open protocol that enables an exchange of assets across multiple distributed payment networks and ledgers. A revised and open-source implementation of cross-chain atomic swap protocols, Interledger operates on a stack of four layers: (i) application layer (responsible for coordinating the atomic swap sender and destination addresses), (ii) the transport layer (an end-to-end protocol between the sender and receiver of value), (iii) Interledger layer (that handles the transaction data), and (iv) the ledger (or payment settlement) layer (Dionysopoulos, 2022, p. 111).

4.3.3 HYPERLEDGER PROTOCOLS

Liao (2020) recommends that 'the best way to foster interoperability for those industries where blockchains remain largely fragmented is to work on a data standard as soon as possible' (para. 11). This might include the need for best practices around cross-chain collaboration. The author recommends that industry data standards for the blockchain industry should include: (i) a set of standards issued by the banking and trade associations that involve distributed ledger payments, (ii) potentially blending proprietary and non-proprietary technologies (such as SkuChain Popcodes technology for traceability in the mining industry), and (iii) incorporation of Hyperledger Fabric services, such as Corda (para. 11-12). Hyperledger Foundation (2021a, 2021b, 2022) and the Hyperledger Community (2022) introduces a series of legacy system interoperability collaborations on Hyperledger including:

- The Cross-Ledger Interbank Settlement project launched by the French Central Bank to complete cross-ledger interbank settlement transactions in a multi-blockchain ecosystem;
- The Digital Green Bond Project carried out by The Bank for International Settlements (BIS) Innovation Hub to develop digital platforms that enables investors to buy and sell bonds that support green projects. This project aims to improve green bond distributions while producing more insightful reporting on the environmental impact. It has achieved real-time synchronization across Hyperledger Besu and Hyperledger Fabric blockchain while preserving the level of privacy demanded by regulated bodies;
- An interoperable platform for the international exchange of Central Bank Digital Currencies (CBDCs) that has been successfully incorporated the participation of BIS Innovation Hub, Hong Kong Monetary Authority, Bank of Thailand, People's Bank of China, and Central Bank of the United Arab Emirates;
- Multichain Trade Settlement has carried out the simultaneous transfer of digital assets and digital currencies via Datachain. Two assets were exchanged simultaneously through delivery versus payment (DVP) settlement via Hyperledger Fabric;
- The use of Daml as a smart contract coding language to enable composable applications across centralised and distributed ledger technologies. This flexible language supports cross-chain communication and collaboration through blockchains such as Hyperledger Besu, Fabric, and Sawtooth;
- Project Starling supports the collection, storage, and verification of human history across blockchains. This novel methodology is also expected to be effective in fighting against misinformation and fake news threats;
- Hyperledger Cactus is described as a pluggable enterprise-grade framework to transact across several distributed ledgers. Hyperledger Cactus targets a decentralized, adaptable, and secured integration of blockchain networks. The number of protocols to be integrated by Hyperledger Cactus is unlimited using an extensible plugin architecture where new protocols can be included as new plugins;
- Hyperledger FireFly provides an API orchestration layer that connects multiple blockchain ledgers, and fosters interoperability and collaborative opportunities at the application level;
- Weaver is a Hyperledger Lab that is described as 'a general-purpose interoperability framework that provides a common set of capabilities for trustworthy information communication across ledgers, whether they belong to the same network or different networks running on different DLT stacks' (Ramakrishna, 2021, para. 5);

- YUI is also a Hyperledger Lab that supports communication between multiple heterogeneous blockchains. YUI lab contains modules and middleware for cross-chain communication and application development. In term of cross-chain communication, YUI uses inter blockchain communication (IBC) protocol provided by Cosmos project, which consists of multiple extensions to support various Hyperledger projects (Hyperledger Community, 2022).

As a further solution, Datachain (2020) proposes the Cross Framework 'which enables the interoperability of blockchains. Cross Framework is currently available in Hyperledger Fabric, Corda, Hyperledger Besu and Tendermint' (para. 1). The Cross Framework contains potential mechanisms that facilitate the development of a system where data integrity in token exchange and distributed transactions can be established via smart contracts deployed on multiple blockchains. The project was 'developed as a mechanism to connect blockchains and realize cross-chain smart contracts' (para. 5). This, and the Hyperledger projects outlined above, provide ample opportunity to explore cross collaborations between chains.

4.3.4 POLKADOT SOLUTIONS

Polkadot is recognised as a promising cross-chain collaboration solution, and is described by Dionysopoulos (2022) as 'one of the most ambitious interoperable projects' (p. 109). To achieve this purpose, Polkadot has set out its core infrastructure to include three main elements: a relay chain, parachain, and bridge chain. The relay chain is the main blockchain (or hub) of the ecosystem, where all parachains (or sidechains) connect to each other. The relay chain will enable consensus, security and data transfer between parachains. A parachain may include any public or permissioned blockchain or data structures that acts as connectors to the relay chain. The bridge chain is responsible for connecting additional blockchains that do not comply with Polkadot's governance protocols (p. 109-110).

Polkadot and Kusama provide cross-chain collaboration solutions that enable information and token transfers between blockchains. In contrast to Ethereum, where decentralized applications predominantly function on one main chain, Polkadot and Kusama enable developers to develop independent blockchains. This mechanism allows each parachain to set their parameters per se, including block times, transaction fees, governance mechanisms and mining rewards. While parachains require a dedicated slot to append to the relay chain, Polkadot and Kusama consensus mechanisms have successfully developed parachain auctions to distribute the available slots, and network security, in an equitable manner (Kraken, n.d., para. 10). The ecosystem also applies a messaging process called egress and ingress cueing, for outgoing and incoming messages between parachains and validators (Shirazi et al., 2020).

Garcia et al. (2022a) discuss parathreads as 'pay-as-you-go' parachains that aim to support equitable flexible and robust treasury models on the network. The authors explain that 'parathreads pay for the Relay Chain's security and interoperability as needed. Parathreads are useful for projects that do not wish to acquire a full parachain slot and/or existing parachains that no longer require a dedicated parachain slot' (p. 13). This may be advantageous for cross-chain projects looking for cost-effective ways to seed development on the network. Further developments on Polkadot include GOV V2, which is the rollout of Polkadot Governance V2: a decentralized governance model that removes the Polkadot Council and Technical Committee. The transition supports an increasing the number of governance proposals that can be voted on at once, and reduces the proposal submission threshold. Also, the Cross-Consensus Message Format (XCM) is a communication language that allows parachains to exchange messages with other parachains (like Inter-Blockchain Communication on Cosmos). This language will enable parachains to open multiple communication channels with other parachains (p. 12), and may provide a standardisation model for projects and communities seeking to further develop cross-chain collaboration.

On a conceptual-level, Wood (2016) conceived the Parity Polkadot Platform as a stack that incorporates a number of functional components and developments. It has a number of significant landmarks in its roadmap including: developing a networking subsystem, consensus mechanism, proof-of-stake chain, parachain implementation, transaction processing subsystem, transaction-routing subsystem, relay chain, independent collators, network dynamics modelling and research, network intelligence, information publication platform, Javascript interaction bindings, governance, interaction platform, light clients, Parachain UI, On-chain Dapp services, Application development tools, Ethereum-as-a-parachain, Bitcoin-RPC compatibility layer, web 2.0 bindings, zk-SNARK parachain example, trust-free Bitcoin bridge, abstract/low-level decentralised applications, contract language, and integrated development environments (IDE) for smart contracts. Understanding the ways in which ecosystem and project roadmaps intersect with other ecosystems is critical for determining the collaborative possibilities available.

4.3.5 COSMOS SOLUTIONS

One of the core features of Cosmos is the Inter-Blockchain Communication (IBC) protocol, which supports a cross-chain asset management ecosystem. The network involves 262 apps and services to date, which includes the Binance Chain, Terra, Crypto.org and Cosmos Hub. The platform states: 'We believe in interoperability and autonomy over siloes and monopolies, collaboration and innovation over competition and status quo' (Interchain Foundation, n.d., para. 3). Wood (2016) described Cosmos early proposal as involving 'multiple chains (operating in zones) each using individual instances of Tendermint [algorithm], together with a means for trust-free communication via a master hub chain. This interchain communication is limited to the transfer of digital assets […] however such interchain communication does have a return path for data' (p. 3).

While Cosmos is a Tendermint-based framework, it is similar to Polkadot in terms of seeking cross-chain communication standards toward interoperable and collaborative ends. Cosmos and Polkadot are alike in terms of parachain utilisation, using 'zones' that connect to the Hub, and validators to commit blocks originating from zones to the Hub (Dionysopoulos, 2022, p. 110-111). Chawla (2022) states that multiple solutions have been deployed on Cosmos and these could be integrated on via EVM. Evmos is one example that partners with existing blockchain bridges and applications such as Connext, Celer, Nomad and others. Hence, transfers of tokens and assets can be made between the two chains. Evmos announces that it will expand such cross-chain collaboration method by using the Inter-Blockchain Communication (IBC) protocol for data and assets sharing with members of the Cosmos blockchain as a whole.

4.3.6 SIDECHAINS

To scale the blockchain network to millions or billions of users, developers need to build more advanced cross-chain collaboration systems. Pegged sidechain are a solution that enables ledger-based assets of one blockchain to be freely transferred to and from another blockchain (Kiayias & Zindros, 2019). On the other hand, the secondary chain (or sidechain) has no impact on the main or original chain as it is a fully independent (Dionysopoulos, 2022, p. 106). In the case of Ethereum, Tarcan et al. (2022) explain that '[s]idechains are independent blockchains, with different histories, development roadmaps, and design considerations' (para. 3). The authors argue that, although sidechains hold similar surface features to the mainchain, they are distinguished by several unique features: Firstly, sidechains can select alternative consensus protocols that suit demand, such as proof-of-authority, delegated proof-of-stake or Byzantine fault tolerance. Secondly, while Ethereum places limits on block times and block sizes, sidechains use different parameters, such as faster block times and higher gas limits to achieve higher throughput, faster transactions, and lower fees. Thirdly, the Ethereum Virtual Machine (EVM) enables compatibility between chains to execute contracts and EVM-compatible languages. Thirdly, blockchain bridges enable interoperable asset migration between chains, again through the use of smart contracts.

Qasse et al. (2019) carried out a comprehensive survey of all the available cross communication solutions and classified them into categories such as Sidechains, Blockchain Router, Inter-Blockchain Communication (IBC), Cosmos blockchain (Atom), Polkadot project, ICON project and Aion project. There are several existing sidechain initiatives currently being developed or implemented, including Federated Pegs, Ethereum's Plasma, Cardano's EVM sidechain, Blockstream's Elements and Liquid, Bitcoin's Merged Mining and Rootstock, amongst others. Smart contract implementations include Polygon POS, Skale, Gnosis Chain and Loom Network. Garoffolo et al. (2020) proposed Horizen's Zendoo, a blockchain system that supports the creation, communication, and collaboration with different sidechains. The relationship between the mainchain and sidechains is conceived as a parent-child. In this architecture, sidechain nodes can observe the mainchain while mainchain nodes can only observe cryptographically authenticated certificates from sidechain maintainers. Latus is a specific sidechain construction that was built to realize a decentralized verifiable blockchain system. In addition, many techniques and solutions have been proposed for communicating between sidechains, the more popular being Ethereum's Private Sidechains, Plasma, Polkadot and Ethereum 2.0 Sharding. Other historic implementations include Blockchain Routers, Clearmatics, Metronome and NEC Blockchain (Johnson et al., 2019). These solutions hold potential for collaboration across networks.

4.3.7 BRIDGES

Blockchain bridges are a recurring interoperability solution that connects different blockchains to enable communication in the form of data and asset transfer, payments, and dApp interaction (Vasquez, 2022; Chand, 2022). Because each blockchain has its own data protocols, rules, governance mechanisms, and native assets, bridges can help mitigate siloes by enabling users to send tokens between incompatible chains (Browne, 2022, para. 5). Bridges are generally managed through trusted or trustless mechanisms. Trusted bridges use a central authority for their operations, so users must entrust a third party to hold their funds. Trustless bridges, on the other hand, are operated by smart contracts and algorithms without the need for a trusted third party, so users are responsible for the security of their funds.

Bridges can also be classified based on their function, such as chain-to-chain bridges, multi-chain bridges, specialized bridges, wrapped asset bridges, data-specific bridges, and dApp-specific bridges (Chand, 2022). They can be classified by type, such as lock and mint (bridges that lock assets on the source chain and mint assets on the destination chain), burn and mint (bridges that burn assets on the source chain and mint assets on the destination chain), or atomic swaps (bridges that swap assets on the source chain for assets on the destination chain) (R. Lan et al., 2021; Browne, 2022). They can appear in three types, including i) centralized bridges (bridges that are owned and fully controlled by a single party such as a company) that can validate all bridge operations, ii) permissioned (federated) bridges, which are operated by multiple parties and thus are more decentralized but will require an entity to be a validator to validate bridge operations, and iii) permissionless (trustless) bridges, which perform as a fully decentralized system, i.e., anyone can help validating bridge operations (Hryniuk, 2022a).

Examples of popular cross-chain bridges include Binance Bridge, which allows users to convert crypto assets between the native blockchain and Binance Chain/Binance Smart Chain (Binance Academy, 2020b), and Wormhole, which allows users to swap ERC20 tokens from the Ethereum network for Solana's SPL tokens (Orcutt, 2020). Tezos is another example of a bridge that incorporates cross-chain swaps, including Atomex (an atomic swap cross-chain DEX with Tezos using FA 1.2 tokens), StakerBridge by StakerDAO (an open-source, trustless method of bi-directional transfer of tokens between Ethereum and Tezos), and TEZEX (which enables cross-chain swaps between Ethereum and Tezos) (Mehrabi, 2021; Zonda, 2022). On Ethereum, MetaMask is also launching a bridging aggregator service called MetaMask Bridges which includes third-party vetting of bridging protocols (Jagdev, 2022)

Interchain Foundation (2022) states that the Inter-Blockchain Communication (IBC) protocol is more advanced than regular bridges that support token movements, as it facilitates general-purpose message passing. IBC provides an ecosystem where any form of data can be compatible with each other, achieving all interoperability requirements for enterprise use cases of blockchains (Datachain, 2022). Nomic is a bridge built for communicating with Bitcoin, and is expected to connect Cosmos and BTC, Cosmos to Polkadot and Kusama, interoperability between Celo and Cosmos, interoperability with Hyperledger, Mainnet Ethereum applications, and Avalanche (Cosmos, 2021). Rainbow Bridge is an application on the NEAR Protocol that enables users to transfer tokens and NFTs between Ethereum and NEAR blockchains. Aurora is a layer-2 solution on the NEAR Protocol blockchain that supports developers expanding their apps on an Ethereum-compatible platform, reducing tx costs.

4.3.8 SOLUTIONS: IMPLICATIONS

In May 2022, the Project Catalyst community funded approximately 379 out of 1088 proposals in Fund 8, 17 of which focused specifically on cross-chain collaboration. This was from a total of 52 proposals in that campaign, 25 of which were over budget and 10 did not meet the approval threshold (Project Catalyst, 2022a). The funded projects fells into two main categories: technical and social solutions. Technical solutions included three of nineteen proposed Adatar.me cross-token integrations for ATOM, BTC and XRP (Sieber, 2022); a Cross-Chain Connector Search engine (Securities & Commerce Institute, 2022); ERC721 & ERC-1155 for Milkomeda (DC Spark, 2022); a bridge for Filecoin (Kiriakos, 2022); a dDataStorage solution (Feghaly, 2022); a cross-chain framework, and Cardano-DESO blockchain webtool integration (Camps, 2022). Socially oriented solutions include the creation of a Cardano impact project directory (Raz, 2022a); a cross-chain impact lead generator (Raz, 2022); an OnChainUniversity education platform (Oliver, 2022); a cross-community caricature art project (Cohen, 2022); a cross-chain NFT conference (Gentner, 2022); DLT business services (Gassner, 2022); KILT events for Cardano (Mohan, 2022); and a cross-chain collaboration research report (Research Guild, 2022). We will briefly discuss some of these proposals and their implications.

Solutions for Cardano blockchain collaboration has received increasing attention. Camps (2022) aims to support Cardano integration for end-solutions utilising the DESO Blockchain's open-source web-templates to develop projects with customizable tools and user interfaces. These tools can be used to test solutions on an easier, cheaper, faster, and larger scale compared to existing solutions. The current DESO model consists of a node, which is an open-source 3.0 web-app template, that can integrate into a friendly user interface with customizable blockchain tools. These tools are able to encrypt and store artworks and content as NFTs, launch Creator Coins to raise capital and invest in each other, gain royalties related to NFTs and Creator Coins, tip micro-monetization, and diverse DAO Coin capabilities. By December 2022, DESO 3.0 social tools are expected to be integrated into Cardano dApps.

Licorish (2021) defines a decentralized mega network as one that should empower cross-chain collaboration, using DeFi or Chainlink to deliver a growing range of decentralized transactional services on and off-chain. There are potential collaboration opportunities between Chainlink and Cardano through the Cross-Chain Interoperability Protocol (CCIP) that can communicate with Cardano sidechains. Communication integration between Cardano readable addresses and other tokens (including BTC and ATOM) have been proposed and funded (Sieber, 2022). There is a Cardano-based community network of 25+ professionals focused on connecting the world to Africa using blockchain and AI (Securities & Commerce Institute, 2022). Raz (2022a) aims to support the porting of Cardano projects into the open access Positiveblockchain database and platform. A cross-chain project contact, API, and integration directory engine have been proposed. Raz (2022b) also argues that modeling interoperability in the Cardano Impact Community to generate multi-chain collaborations is key to cross-chain collaboration.

The Cardano user community have been actively involved in cross-chain collaborations, as seen in the multiple proposals and initiatives in social collaboration, lead incentivization, and research sharing and model creation. Some notable proposals for cross-chain collaboration include OxBAT – Oxford Blockchain, Art, Technology by Gentner (2022), an Interoperability Research approach by Gassner (2022), NFTs or ERC1155-compatible assets between Cardano and Milkomeda by Spark (2022), bridges to create storage contracts for IPFS objects in Filecoin from inside Cardano dApps by Kiriakos (2022), and Kusama parachain in the Dotsama ecosystem for Cardano developers by Mohan (2022). Other proposals include multi-chain courses exploring current and future use-cases for collaborating cross-chain by Oliver (2022), open-source tools, standards and utilities for projects to integrate NFT technology by Feghaly (2022), and a report to investigate opportunities and strategies that support cross-chain collaboration on Cardano by the Research Guild (2022). Wolfram Blockchain Labs (2022a, 2022b) have also introduced several use cases such as NFT Import/Export, Tokens Import/Export, Cross-chain Transactions, and Cross-chain Oracles. Wanchain and MLabs collaboration has focused on developing the first foundational block for Cardano cross-chain bridges. This bridge will be decentralized, non-custodial, and bi-directional, connecting Cardano and other L1 blockchains (Zhang & Louie, 2022).

Bridging and sidechain development is seen as a key to network expansion and scalability. Cardano's IELE compiler, for instance, offers support for a range of programming languages including Solidity, Java, C plus, Rust and Scala (Input Output, 2021). Like many open-source initiatives in the space, the EVM source code is open to individuals, teams, and organizations to enable Cardano EVM sidechain development. This model has delivered an outstanding, affordable, and high security solution for cross-chain collaboration as it supports Cardano in achieving faster transaction confirmation, better usability, and lower congestion through EVM model Sidechains. Protocols on Binance and Polygon have also helped reduce the load.

4.4 OPPORTUNITIES

According to Pillai et al. (2022a), cross-chain technologies have enormous potential for supporting global GDP creation. According to a PWC (2020) report projection, blockchain technology is estimated to boost global GDP by US$1.76 trillion over the next decade. Another estimation by a Gartner report (n.d.). shows that blockchain will reach the $2 trillion worth of goods and services in 2023. This trend is based on the increasing interest in blockchain technology, which is recognised as a technology that incorporates trust into operational processes without depending on intermediaries or third parties (p. 41257). Key themes and approaches arising in the area of cross-chain opportunities relate to blockchain 3.0 networks; enhanced atomic transactions; privacy networks; multi-bridge infrastructures; Industry 4.0 integration and Project Catalyst cross-chain proposals. This section will then conclude with a review of opportunity implications for Cardano, and other blockchains.

4.4.1 BLOCKCHAIN 3.0 NETWORKS

Blockchain 3.0 is a general term that is used to refer to the third generation of blockchain technology, which is characterized by the integration of advanced technologies such as artificial intelligence, cloud computing, and the Internet of Things with blockchain. This allows for the creation of more complex and sophisticated decentralized applications and services, and enables the development of new use cases for blockchain technology beyond the traditional applications in finance and supply chain management. Blockchain 3.0 is also often associated with an emphasis on scalability, interoperability, and security, with the goal of making blockchain technology more accessible and user-friendly for a wider range of applications and industries (Di Francesco Maesano & Mori, 2020). In the context of problems, gaps, and trends in cross-chain collaboration, there are a number of development opportunities in the blockchain 3.0 space. G. Yang et al. (2022) propose a distributed fusion cross-chain model and architecture which supports a large-scale high-performance P2P network, security cryptography protocols, and high-performance computing engine. Datachain (2022) describe the opportunity to support IBC transactions on public chains (para. 2). Johnson et al. (2019) identify how the rapid growth of public and permissioned blockchains will drive urgency for cross-chain transactions and communications amongst disconnected parties (p. 6). Hence, blockchain communities should develop and support reliable cross-chain communication (including UX) design solutions to support ecosystem collaboration and adoption. The optimal interoperability solution is achieved with the cooperation of participating blockchain providers (Qasse et al., 2019, p. 5).

Opportunities for future research are found in sidechain construction (Garoffolo et al., 2020, p. 36). There is a need for human-readable ADIs that involve W3C standards and integration of blockchain technology through distributed servers and applications (Michelson et al., 2022). There are also opportunities around the modification of network protocols to provide more efficient offline experiences for blockchain usership (Lin et al., 2022, p. 10). On the other hand, since there is a need to establish international standards regarding blockchain technology and terminology, future research and development can focus on cross-chain collaboration enhancement in terms of interoperability (between blockchain systems), user privacy, security, user identity, governance, risks, and services (Ali et al., 2019, p.15), and more notably, through sociological research integration.

Cross-chain collaboration may also unlock opportunities in Web 3 through cryptocurrencies, smart contract computing, decentralized hardware infrastructure, NFT's (including digital identity and property rights), the metaverse and community governance (including DAO's) (Tse, 2022). Karacaoglu et al. (2021) cite opportunities around digital identification (DID's) that 'cannot be locked in one platform – it needs interoperability across multiple platforms, and provide more choice to the end-user' (p. 8). In terms of supply chains, the authors identify advantages for a large-scale traceability supply chain environment, that would help tackle key supply chain challenges including the lack of interoperability between siloed data systems of supply chains. In the healthcare sector, cross-chain collaboration may support information systems management amongst a complex network of vendors, providers, policy makers, and users in information exchange, which is equally applicable across other sectors.

Another opportunity is the development of inter-ledger approaches that show high promise (Siris et al., 2019; Pillai et al., 2020). Luo et al. (2018) propose an inter-blockchain connection model as routing management for heterogeneous blockchain systems, will be a potential area that communities should focus on (p. 139). Blockchain router's (H. Wang et al., 2017; Shahzad, 2022) are touted as providing cross-chain opportunities in the realm of the decentralized internet (Zarrin et al., 2021) and blockchain-enabled wireless communications (J. Wang et al., 2021). Multiple novel types of blockchain technologies such as Optimistic and Zero Knowledge Rollups, are still in the development phase, which will enable opportunities for new initiatives, use cases and consensus approaches (Robinson, 2021). Interoperability will be a potential area that communities should focus on in regards to the development of inter-ledger approaches and blockchain router's that provide cross-chain opportunities in the realm of the decentralized internet and blockchain-enabled wireless communications.

4.4.2 ENHANCED ATOMIC TRANSACTIONS

For improved performance of the process of atomic cross-chain transactions, Herlihy (2018) suggests that an atomic 'swap protocol can be modified to provide better privacy (p. 10). This has been proven with the expansion of the usage with multi-asset shielded pool such as ZCLAIM and a more recent Orchard version of the Zcash protocol (Sánchez et al., 2022, p. 8). The improvement of atomic transactions will be an opportunity for cross-chain solutions.

Cross-chain collaboration protocols such as HTLC and MPHTLC (Multi-Party Hash Time Locked Contracts) are also able to be applied to multiple blockchains (Narayanam et al., 2022, p. 13). Additionally, decentralized exchanges such as LayerZero have implemented cross-chain bridges that operate exclusively with their native assets. Multi-chain yield aggregators can also deploy LayerZero for cross-chain transactions. These aggregators consist of strategies that evaluate the best opportunities across blockchain ecosystems, thereby increasing access to high yield opportunities. Users can take advantage of market inefficiencies or carry out arbitrage activities. Multi-chain lending via LayerZero has also enabled a secure pathway for lending assets (Zarick et al., 2021, p. 8-9). Furthermore, the CSP model offers an effective path for data distribution and low transactional costs for end-users (Hardjono et al., 2021). These existing atomic swap protocols provide a solid foundation for future development and cross-chain collaboration.

Another area of protocol development that offers opportunities for future exploration is a protocol that allows users to participate without assumptions while trading. Specifically, there would be no switching back and forth between general transactions while funds are locked. The blockchain would use a time lock mechanism to approve transactions (Shlomovits & Leiba, 2020, p. 19-20). Additionally, the extension of the UIP protocol to improve the dynamic transaction graph is a promising opportunity. This is because with these extensions, users can monitor operational flows and control HSL through active verification that guarantees the precise performance of dApps (Liu et al., 2019, p. 13). However, there are technical problems associated with on-chain atomic swaps, such as transactional latency and time-lock errors. This presents an opportunity to develop solutions such as Lightning Network atomic swaps in the near future.

Mohanty et al. (2022) believe that there is a lot of research potential in the domain of atomic swapping protocol generalization for P2P crypto exchanges. Therefore, it is important to develop a blockchain interoperability mechanism that adheres to the essential system architecture, ecosystems, operations, interoperability principles, standards, and best practices (p. 3). The transfer of assets, although not new, also requires further work to address how to expand existing cross-chain collaboration protocols to achieve the transfer of data, such as general information, across blockchains (Yin et al., 2022, p. 11). Some solutions have been proposed. Jin et al. (2018) seek to advance the current Interopera protocol to achieve efficient cross-chain trading via multiple PoW blockchains with higher storage and cheaper costs. The potential application for non-PoW consensus models appears untapped.

Coingecko (2022) points out the need for a foundational layer of DeFi for all existing blockchain ecosystems, including a lending protocol such as L2s. However, existing solutions for this need are still in progress and may only be available in the near future. Further efforts are needed to work on complete trustless wrapped token minting and redemption, as well as reducing costs (Binance Academy, 2021). Cosmos and the Interchain Foundation both highlight the opportunity to develop inter-blockchain applications and protocols for more intuitive interfaces and enhanced user experiences that benefits for the entire ecosystem.

4.4.3 PRIVACY NETWORKS

Privacy, idea protection and trust can be major collaborative issues, especially in the domain of enterprise and IP protection. How do blockchain communities collaborate with one another if projects aim to be proprietary in nature? Besides permissioned or hybrid block-chains, there are opportunities to explore privacy protocols for cross-chain collaboration. Such options are not new, and have been spearheaded by such chains as Monero and ZCash. Freuden (2019) identifies two subsets of privacy chains: opt-in (where privacy is an elected option) and opt-out (where privacy is the standard). Recently, Secret Network – touted as the first blockchain with customizable privacy in the Web3 domain, promotes privacy in the form of smart contracts, defi or NFT metadata. Aleph Zero is a hybrid option, TrustCross promotes privacy preservation, while Cardano is developing Midnight as a data protection-based sidechain 'protecting fundamental freedoms of association, commerce, and expression for developers, companies, and individuals' (Midnight, 2022). There are also alternative P2P protocols that aim to disrupt conventional file-sharing, such as the launch of the BitTorrent chain to support file storage fees through BTFS, BTFS mining and increasing download speeds of the BitTorrent protocol (BitTorrent Inc., 2021). In this regard, protocols to address privacy issues in enterprise and IP domains provide new opportunities for cross-chain collaboration.

4.4.4 MULTI-BRIDGE INFRASTRUCTURES

With existing bridges, a significant opportunity for future development is the integration of collaborative approaches for improved cross-chain bridging (Maas, 2022, p. 1). This idea has been presented by deBridge's infrastructure, which claims that integration will enable various cross-chain collaboration opportunities (DeBridge, 2021b). Protocols and applications can already start integrating with the deBridge infrastructure, for instance, users from other blockchain ecosystems can now use their protocols without switching wallets, scale up to other ecosystems and exchange information and assets on different blockchains. This includes enabling protocols from other ecosystems, preserving the internal logic of bridge NFTs, and providing interoperability with digital metaverses. The emergence of such protocols (including user-friendly universal wallets) provides a better framework for swapping assets between blockchains. However, it still requires multiple steps that might be confusing to users, providing education opportunities. Another project is the Binance Bridge Project, which provides an essential way to improve cross-compatibility and cross-chain collaboration on the Binance blockchain (Binance Academy, 2020a & 2020b).

The process of bridging assets and constructing the best abstraction and aggregation solutions for cross-chain collaboration is ongoing, bringing multiple opportunities to the market (Chand, 2022). The StakerBridge protocol allows any party to be an operator. This means that the participant is able to successfully bridge tokens via the deployment of StakerBridge's open-source software (StakerDao, n.d., p. 3). Chawla (2022) suggests that instead of each blockchain constructing their independent solution, blockchain providers should partner with existing bridges to improve the collaboration of blockchain networks as a whole. This will bring the opportunity to achieve faster speed and lower costs. Future development opportunities can be seen in the applications that leverage token transfers, such as the establishment of reliable decentralized exchanges and marketplaces for NFTs. A consolidated bridge solution, such as the Ethereum bridge, will also potentially help blockchain networks connect their markets with faster and cheaper processing of smart contracts and multiple backup solutions (Orcutt, 2020).

The World Economic Forum (2021) supports the development of greater interoperability with qualified technical standards across multiple cross-chain collaboration activities such as messaging, privacy, anti-money laundering, combating financing of terrorism, identity and authentication, DLT protocols, certification of interoperability for CBDC and stablecoins, and developing inter-currency exchange rate standards. These provide opportunities for future research and development. Berenzon (2021) concurs that these options provide several interesting directions for bridge integration across all bridge types, namely, (i) decreasing costs of block header verification (for lowering costs for light clients) such as Tendermint light client on zkSync, (ii) moving from trusted to bonded models (referring to bonded validators for a better capital efficiency), (iii) Scaling liquidity for liquidity networks (refers to the construction of the fastest bridge for asset movement and liquidity), and (iv) Bridge aggregation for the improvement of user experiences (para. 18). The range of bridging projects, along with security risks posed, provides an opportunity for a more in-depth stocktake of approaches in this area.

4.4.5 INDUSTRY 4.0 INTEGRATION

Beyond the first three industrial revolutions, which drove production through mechanization, steam and electrical energy and computer technologies, Industry 4.0 incorporates a convergence of new technologies such as Internet of Things (IoT), Artificial Intelligence (AI), robotics and blockchain (IBM, n.d.). Industry 4.0 promises to create a multitude of new and hyper-efficient services, business opportunities, and employment (Bellavista et al., 2021). Industry 4.0 supports a totally integrated smart manufacturing apparatus, that provides potential for cross-chain collaboration development. Of the convergent set of Industry 4.0 technologies, AI is at a disruptive tipping point. The increasing capability of AI provides prime opportunity for developing effective, secure, and scalable interoperable blockchains and internet-native tokenization for cross-chain collaboration (Dionysopoulos, 2022). Multiple emergent scenarios may arise where human-users are incentivised to trade data with AI learning models for digital assets, or where open-source AI projects such as OpenAI or SingularityNET may be employed to drive Human-AI creative economies or community problem-solving ecosystems. In addition, AI machine learning agents might be able to continuously learn and update their knowledge, which could support the optimization of cross-chain collaboration protocols and networks via statistical data analytics. The operational manner of AI-integration into a cross-chain collaboration platform would also act as blackbox testing. Cross-chain collaboration security could be improved accordingly. The integration of AI into cross-chain collaboration could also unleash the potential of IoT systems consisting of multimillion devices around the globe. This would open up a new level of collaborative potential. Dionysopoulos concludes that ‘blockchain-backed AI could unleash the full potential of IoT devices. Billions of connected devices around the world record our universe of data, serving as a nervous system for a distributed on-chain *master brain* that would process this wealth of information’ (p. 113).

Another opportunity that can be foreseen is the integration of IoT systems with blockchain-based business process management systems (BPMS) (Henry et al., 2021). These innovations may arise in the forms of (i) Use cases for trustworthy data platforms that deliver an immutable public ledger. This allows for commonly agreed-mechanisms instead of a single source of truth in several processes such as monitoring, auditing, and dispute resolution; (ii) The development of the IoT-aware blockchains – blockchains that allow to share agreement executions; (iii) Protecting data and digital identity privacy using the multiparty key management encryption techniques, in which companies avoid the surveillance of trusted third parties (p. 4291-4292). Research directions suggested for the development of blockchain-based systems in the era of Industry 4.0 include a focus on advanced tools that are adaptive to data-centric processes and applications; for example, an IoT system for continuous tracking and monitoring in a smart factory. The implementation of IoT systems should also pay attention to the model-driven, data centric, and declarative-based BPMS. With hybrid blockchains, devices and nodes might be implemented in a private network with limited access, that is, partial systems can be made public while maintaining privacy and security issues (Geroni, 2021, p. 1). A cross-chain collaboration platform with an Industry 4.0-based approach will also provide a direction for future research. Belchor et al. (2021) believe that use cases with multiple blockchains and cross-chain collaboration can be achieved with more advanced, innovative, and disruptive solution in the future (p. 28).

4.4.6 PROJECT CATALYST PROPOSALS

In September 2022, the Project Catalyst community funded 205 proposals out of approximately 1500 in Fund 9, 15 of which focused specifically on cross-chain collaboration. This was from a total of 80 proposals in that campaign, 20 of which were over budget and 45 did not meet the approval threshold (Project Catalyst, 2022b). Outstanding problems mentioned in the Fund 9 proposals include a lack of interoperability (Tran, 2022), no direct access to the liquidity of other blockchains for dApps (Black, 2022), and a lack of coordination, communication and collaboration between Cardano and other Communities (Catalyst Swarm, 2022; Kwananda, 2022) making adoption and cross-chain collaborations more difficult (Innovatio, 2022). In addition, detailed information on cross-chain solutions, DAO enabling tools, and other technologies are difficult to reach (Littlefish Foundation, 2022). UTXO chains need to accelerate their collaborative efforts and remember their common origins (Wolfram Blockchain Labs, 2022). However, there is also a need for skilled developers to build Cardano sidechains (Mikushin, 2022) while many valuable resources such as Gimbalabs' Plutus PBL are only available in English (Pabon, 2022; Ungar, 2022). Cardano's NFT ecosystem is starting to experience more of a lack of trust due to plagiarism, counterfeits, and scams (Brerranbbit3, 2022). Cardano also doesn't have a real marketplace for Gamefi on Cardano (DareNFT, 2022). Multiple bridges for Cardano which fragment liquidity and impact UX in protocols (Arqueros, 2022). Finally, real world businesses have no easy access to Crypto Funding Capital (Token Allies, 2022) while the SSI community needs to know about Cardano identity (RootsID, 2022a).

There are several problems facing the Cardano community, including a lack of interoperability (Tran, 2022), no direct access to liquidity from other blockchains for dApps (Black, 2022), and a lack of coordination and communication between communities (Catalyst Swarm, 2022; Kwananda, 2022). This makes adoption and cross-chain collaboration more difficult (Innovatio, 2022). In addition, there is a lack of information on cross-chain solutions and technologies, and a shortage of skilled developers to build a Cardano sidechain. The Cardano ecosystem is also experiencing a lack of trust due to plagiarism and scams, and there is no real marketplace for Gamefi on Cardano. Real-world businesses also have no easy access to crypto funding capital, and there is misinformation and disinformation in Ethereum communities about Cardano identity (Ungar, 2022).

To address the barriers hindering cross-chain collaboration in the Cardano community, several solutions have been proposed. These include the use of Camenisch-Lysyanskaya signatures and anonymous credentials to enable zero-knowledge proofs, a Layer 2 DeFi scaling solution to solve cross-chain interoperability problems, Catalyst Swarm strategies for community coordination and engagement, a cross-chain AI/ML-powered asset and IP protection service for Cardano and Ethereum NFTs, and regular AMAs with crypto and cross-chain communities in Indonesia. Other proposed solutions include the Ocean Map to collect information on space projects, the Oneiron SDK as an open-source JVM-based Cardano sidechain SDK, a canonical smart contract for whitelisted assets and bridges, the DarePlay platform for onboarding traditional games to blockchain games, and the Innovatio community of entrepreneurs, developers, and early adopters. Additionally, the Everscale blockchain and the Japanese Cardano community are working on common projects, and there is a focus on Key Event Receipt Infrastructure as a decentralized identity system. RootsID has also been funded to engage SSI working groups, and there are plans to provide crowdfunding for all, as well as a significant list of "active" and "historical" UTXO blockchains. It is also proposed that Cardano needs to collaborate with KERI as a first truly decentralized identity system that is ledger-portable (RootsID, 2022b).

There are several gaps in the funded proposals, including a lack of focus on AI and blockchain integration, as well as a lack of proposals related to cross-chain collaboration within DAOs. In terms of trends, the F9 funded proposals tend to focus on novel architectures with a high volume of design, programming, and technical approaches. Most of the approved proposals explore the technical aspects of cross-chain protocols, smart contracts, and bridges. There is a focus on adding value to Cardano specifically, and the funded proposals tend to take one of two approaches: either focusing on architecture or on the community. There is also some focus on niche areas such as stand-alone game projects and ocean apps, but the number of approvals in these areas are limited. There are several emergent and novel opportunities in the area of cross-chain collaboration. There is also potential for future funding, such as for projects focused on collaborative approaches to AI, DAO's and blockchain.

From the above evaluation of recent Project Catalyst funded projects that focus on cross-chain collaboration, key opportunities arising from recently funded, as well as unfunded and potentially overlooked cross-collaboration solutions, commence with a community call to identify, support and leverage existing opportunities happening in the field. Along with Fund8 proposals (see section 4.3.8), cross-chain collaboration initiatives building on Cardano in the next 6-9 months include:

- Use of Camenisch-Lysyanskaya signatures and anonymous credentials to enable zero-knowledge proofs for improved security and trust in cross-chain collaboration;
- Implement a Layer 2 DeFi scaling solution to solve cross-chain interoperability problems and improve access to liquidity for dApps;
- Engage the Catalyst Swarm community of experienced members to improve coordination and communication between communities;
- Develop a cross-chain AI/ML-powered asset and IP protection service for Cardano and Ethereum NFTs to address issues of plagiarism, counterfeits, and scams;
- Conduct regular AMAs with crypto and cross-chain communities in Indonesia to increase engagement and share knowledge;
- Use the Ocean Map to collect information on space projects and improve access to detailed information on cross-chain solutions and technologies;
- Develop the Oneiron SDK as an open-source JVM-based Cardano sidechain SDK to enable skilled developers to build Cardano sidechains;
- Create a canonical smart contract for whitelisted assets and bridges to improve liquidity and user experience in protocols;
- Launching and supporting the DarePlay platform to onboard traditional games onto the blockchain and create a real marketplace for Gamefi on Cardano;
- Establish and support the Innovatio community of entrepreneurs, developers, and early adopters to foster collaboration and innovation in the Cardano ecosystem;
- Collaborate with the Everscale blockchain and Japanese (and global) Cardano community on common projects to accelerate cross-chain collaboration efforts;
- Focus on Key Event Receipt Infrastructure as a decentralized identity system to improve trust and accessibility for real-world businesses;
- Engage RootsID to work with SSI working groups and address misinformation and disinformation in Ethereum communities about Cardano identity;

- Provide crowdfunding opportunities for all members of the community to support the development of cross-chain collaboration projects;
- Create a significant listing of cross-chain projects, solutions, and technologies to improve access to information and facilitate collaboration.

4.4.7 OPPORTUNITIES: IMPLICATIONS

In terms of opportunities, the implications for Cardano (and other blockchain communities) include the potential for Cardano to contribute to a standardisation initiative across different cross-chain collaboration protocol. The need for general standards for cross-chain collaboration protocols is urgent but remains mammoth in scale and incomplete. Further standards are required to test the efficiency of bridges (Hyperledger Community, 2022) and NFT standardisation protocols. Standardization will also put forward opportunities for operational normalization across interoperability layers for cross-chain collaboration. Some examples of ongoing standards coordination include the Open Digital Asset Protocol (ODAP) from IETF, the interoperability working group in Digital Currency Global Initiative (DCGI) at ITU, the subgroup 7 (ISO/TC/SG7) from ISO Technical Committee 307, and the Cross-Chain Interoperability working group at the Ethereum Enterprise Alliance. Arqueros (2022) argues for the 'creation of a canonical smart contract where whitelisted assets (and bridges) can exchange their bridged asset by a canonical version that will be used by the Cardano ecosystem' (para. 2). There then arises an opportunity for greater community input into Cardano Improvement Proposals (CIPs), as well as awareness and collaboration on such proposals on other ecosystems (including Polkadot PSPs, Bitcoin BIPs or Ethereum EIPs), that support cross-chain collaboration and interoperability; as well as the inclusion of coordinated efforts and discussion amongst community members at the global standards group level.

There are ample opportunities to map, identify and strategically align with interoperability and collaboration focused platforms on other ecosystems, including (but not limited to) deBridge, Hyperledger, Polkadot, Interledger or Alexar (Osmosis, 2022). For example, Axelar provides an interoperability mechanism that facilitates the linkage of different infrastructures such as Osmosis and Moonbeam and brings the isolated blockchains together as an interconnected network. Blockchain communities have also raised the need for better user experiences with cross-chain collaboration. Camps (2022) believes that there are plenty of opportunities and integrations with web3 social platforms (para. 3). Future work might also look at cross-chain initiatives as a methodological path into community-led cross-chain development (Yoo, 2022). Hryniuk (2022b) discusses plans to establish a series of sidechains for greater communication, scalability, interoperability, and collaborations on Cardano. Sidechains will enable participants to create novel smart contracts, dapps and token swaps beyond the current methods of remote ICOs or atomic swaps (Kiayias & Zindros, 2019, p. 15).

For Zhang & Louie (2022), full interoperability and collaboration between the Cardano mainnet, Cardano sidechains and other heterogeneous blockchain networks are part of a long-term roadmap. This roadmap, like those of other ecosystems, both ends and begins at the point of decentralised governance, a place where understanding issues around trust, communication, collective intelligence, distributed decision-making and collaboration are a must. Alongside such a long-term vision and development goals, contributors will have opportunities for iteration and incremental improvements. Future cross-chain collaborations will require more connectivity between Cardano and other blockchain networks. This approach will also need to consider strategies for engaging diverse populations. For instance, Catalyst Swarm has organised localised townhall's for global participants, while Cardano Catalyst Women (2022) seek to promote the participation of women in blockchain through multiple networks, workshops, and scholarships, to advance female blockchain contribution around the world. Such initiatives are vital to achieve a rich collaborative environment.

4.5 SECTION SUMMARY

The integration of advanced technologies such as artificial intelligence, cloud computing, and the Internet of Things with blockchain 3.0 technology presents opportunities for the development of more complex and sophisticated decentralized applications and services, and the expansion of blockchain technology to new use cases and industries through an emphasis on scalability, interoperability, and security. The development of optimal atomic swap protocols and other solutions that address issues such as transactional latency and time-lock errors presents opportunities for improving cross-chain collaboration protocols and expanding their applications to multiple domains, including the transfer of data across blockchains. The development of privacy protocols for cross-chain collaboration, such as customizable (opt-in, opt-out) privacy in smart contracts, helps to mitigate trust and legal issues within proprietary or private networks. Collaborative approaches to bridge integration are providing opportunities for cross-chain collaboration, including the use of protocols and universal wallets, the development of security and reliability for cross-chain bridges, and the establishment of decentralized exchanges and marketplaces for NFTs. The development of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and blockchain in the era of Industry 4.0 promises to create new and hyper-efficient services, business opportunities, and employment, and supports the integration of smart manufacturing with the potential for cross-chain collaboration.

Finally, the Cardano community is facing a number of challenges in terms of cross-chain collaboration, including challenges around interoperability and direct access to liquidity from other blockchains for dApps, as well as a lack of coordination and communication between communities. Proposed solutions to these challenges include the use of zero-knowledge proofs, a Layer 2 DeFi scaling solution, and engagement with experienced community members. Additionally, there are efforts to build a cross-chain AI/ML-powered asset and IP protection service, regular AMAs with crypto and cross-chain communities, and the development of platforms to collect information and onboard traditional games to blockchain games. Calderelli (2022) points to the necessity of more active cooperation between practitioners and academia Collaborative approaches to bridge integration, including the use of protocols and universal wallets, the development of security and reliability for cross-chain bridges, and the establishment of decentralized exchanges and marketplaces for NFTs, are providing new opportunities for cross-chain collaboration. However, even with these technical solutions on offer, there is a gap in social research around cross-chain collaboration, how this contributes to gaps in interoperability research (Lafourcade & Lombard-Platet, 2020), and the ways in which Industry 4.0 technologies such as the Internet of Things, artificial intelligence, and robotics are applied. Also, more is needed to understand Industry 4.0 collaboration practices, the social implications of these developments and their potential impact on society. To unpack some of these ideas further, the following sections will conclude with this report's literature findings and overall recommendations.

5.0 REPORT FINDINGS

5.1 SECTION OVERVIEW

Based upon the above literature review and subsequent analysis, we will now present the key findings from the literature. The findings section will be divided into our three research areas: problems, solutions and opportunities. Within each section, we will discuss general findings arising, and group them according to their applicable sub-section. These findings will inform the key recommendations section that will follow.

5.2 KEY FINDINGS

5.2.1 PROBLEMS: BLOCKCHAIN NETWORKS

Blockchain interoperability is a major challenge facing the industry today. Fragmentation between blockchain communities and limitations on liquidity movement have hindered network growth. While some larger blockchains, such as Ethereum and Hyperledger Fabric, have developed interoperable standards, many other blockchains have been designed for specific applications and do not communicate with each other (Dinh et al., 2019, p. 1). This fragmentation may stem from competitive legacy market practices and the difficulty of achieving community consensus for protocol changes. The Poly Team (2020) also notes that "information exchange and asset replacement between blockchain ecosystems is also limited" (p. 1). Michelson et al. (2022) suggest that an ideal solution would be a platform with fast read/write speeds, low transaction costs, scalability, security, and easy data access and authorization management (p.2). There are also challenges with incorporating existing blockchain protocols due to constraints in cross-chain smart contract communication and a lack of security and efficiency in scaling. These issues can impact user adoption, especially for communities with limited internet access or data storage. Additionally, the inability to collaborate or communicate can lead to missed opportunities for DeFi. Cost is also a major consideration, as integrating blockchain networks is complex and comes with competitive developer costs. There are also various technical challenges in implementing interoperability, including fragmented programming models and a lack of generic token exchange protocols. The lack of interoperability solutions also leads to competition and duplication of effort among projects. To address these issues, some solutions have been proposed, such as bridging, sidechains, and relays. However, these solutions come with their own limitations and trade-offs. Overall, there is a need for ongoing research and development in the area of blockchain interoperability.

5.2.2 PROBLEMS: SCALABILITY

Blockchain scalability is an ongoing issue for the technology. Bottlenecks in scalability, interoperability and security, low transaction efficiency, and high confirmation latency are all contributing factors to this issue. In addition, different consensus mechanisms may have an impact on interoperability and participants willingness to engage with certain blockchains. For instance, Proof-of-Work (PoW) consensus mechanisms have been shown to have latency and high-cost during times of network congestion and may result in an oligopoly of miners, sacrificing decentralization, while high energy usage may have significant environmental ramifications Proof of Stake (PoS) consensus may experience reduced throughput, storage limits or network congestion. These scalability limits have been identified as a problem in Defi gaming, where token swapping is often slow and unreliable. Some potential solutions to these issues include parachains and XCMP, as proposed by Polkadot. However, as Yang et al. (2020) noted, the current state of the blockchain ecosystem has stifled cross-chain interaction and its capacity is limited, resembling a LAN-like architecture.

5.2.3 PROBLEMS: SECURITY

Recently, security has received additional attention among the blockchain trilemma, as it is "aggravated by the problem of incompatibility between systems" (Dionysopoulos, 2022, p. 105). Cross-chain bridges are highly vulnerable to hacks, which can range from poor decentralization and poor key management that is targeted through social engineering (Coingecko, 2022), to "vulnerabilities in their underlying code" (Browne, 2022, para. 1). There can also be vulnerabilities arising from a lack of clarity around which bridging mechanisms are secure and which are not (Bhuptani, 2021, para. 3), leading to significant disadvantage and loss of confidence in the blockchain community (Say, 2022b). Some decentralized applications (dApps), which require off-chain data to operate, have created a larger attack surface for hackers (Dale, 2021). There are also challenges regarding security for asset transfer between PoW and Proof-of-Stake (PoS), or non-EVM compatible chains and EVM-compatible ones (Microchains, 2022, p.7). This highlights the dangers of miner concentration in so-called decentralized networks. Additionally, the make-up of a blockchain and its constituents – whether they are public, permissioned, or hybrid – may also carry their own security complications for future builders (Johnson et al., 2019; Geroni, 2021).

5.2.4 PROBLEMS: TECHNOLOGICAL CONSTRAINTS

Cross-chain integration is complex and requires significant development, resources, and collaboration. Research on social collaboration initiatives that can stimulate growth between blockchain communities is limited. There is a lack of generic messaging protocols and convoluted UX design, making cross-chain transactions difficult. The cost of sending payments across different networks is complicated, uncertain, or costly. There is a lack of general public awareness and ease of locating open access databases with other projects. Identifying and following the development of projects using Cardano technologies is difficult. Collaboration between Cardano and other chains is growing but still limited. Cross-blockchain education is under-utilised as a collaborative pathway. There is a need for clearer definitions and solutions for cross-chain interoperability. There is also a need for cross-chain interaction and collaboration standards around NFT data, and there is a lack of clear innovation pathways linking and unifying blockchain communities to support mass adoption. Cardano and other blockchain communities need to accelerate experimentation of cross-chain services.

5.2.5 PROBLEMS: USERSHIP

Centralization leads to key parties dominating exchange market share and imposing controls over fund custody. There is a challenge in the domain of cross-chain protocol design. Without a single point of failure, decentralization of fund custody should provide users with greater flexibility and control of their assets (Shlomovits & Leiba, 2020, p.2). There are high barriers between heterogeneous blockchain systems, including a lack of trust, communication and secure exchange between one another; high barriers to entry for creating new connections between ledgers; and a lack of generic messaging protocols and convoluted UX design that hinders user interaction with cross-chain bridging and swapping mechanisms, and asset migration (Luo et al. 2018, p. 139). Users may not understand the cost accrual across chains when assets are wrapped and unwrapped, or minted and burned (DeBridge, 2022b). Technical issues often subsume the social dimension of trust, transparency and distribution of decision-making power in blockchain systems. The human dimension of collaboration and social protocols require further discussion and understanding to inform how communities collaborate. Decentralized forms of social governance create challenges for participants seeking to reach group consensus. End user experience is the biggest challenge for broader adoption of web3 apps (Yoo, quoted in Osmosis, 2022, para. 5).

5.2.6 PROBLEMS: IMPLICATIONS

Overall, cross-chain integration presents significant challenges and opportunities for the blockchain community. Collaborative efforts are necessary to develop solutions that address the complexity of cross-chain integration and unlock its full potential. Research on social collaboration initiatives and human aspects of collaboration can help stimulate growth between blockchain communities. User-friendly interfaces and clearer definitions and solutions for interoperability are also needed. Ongoing research on cross-chain collaboration and experimentation with cross-chain services is crucial for advancing the field and supporting mass adoption. However, a lack of clear innovation pathways and limited collaboration between different blockchain networks currently hinders progress in this area.

5.2.7 SOLUTIONS: NOVEL SOLUTIONS

Multi-token crypto-wallets and crypto exchanges provide access to different blockchain data and operations, but true interoperability requires more than just access. Anchoring or hashing data into a blockchain can provide interoperability by linking cross-chain data. MPoS consensus protocols, which involve staking with multiple crypto tokens in a cross-chain ecosystem, can also provide interoperability. However, the use of optimistic rollups to increase network scalability raises questions about Layer architecture design between different chains. The trade-offs between account-based and UTXO-based models also need to be considered in cross-chain collaboration. In order to effectively address the challenges of cross-chain interoperability, a framework is needed to cover most existing blockchain systems. This framework must address security, throughput, governance, cost, and legal issues in order to facilitate successful cross-chain collaboration. Collaboration with other UTXO-based ecosystems may provide opportunities for multi-asset support and smart contract functionality. Overall, cross-chain collaboration is a crucial aspect of the development of blockchain technology and requires continued research and development to overcome the challenges and unlock its full potential.

5.2.8 SOLUTIONS: ATOMIC SWAPS AND PROTOCOLS

Cross-chain atomic swaps allow for direct exchange of multiple ledger-based assets with reduced intermediaries (Frankenfeild, 2022, para. 2-3). Cross-chain bridges and interoperability protocols enable compatibility with decentralized finance (DeFi) systems (Maas, 2022, para. 3; deBridge, 2022, para. 6). Wrapped tokens, hybrid connectors, and private transaction protocols provide solutions for cross-chain interoperability (Calderelli, 2021, p. 10; Belchor et al., 2021; Sanchez et al., 2022, p. 8). The development of standard protocols and cross-chain interfaces can improve collaboration between different blockchain communities (Konashevych & Poblet, 2019, p. 317; Pang, 2020, p. 153720). Collaborative ventures between institutions, such as Project Ubin, can promote the commercial adoption of cross-chain solutions (Khatri, 2020, para. 3). Cross-chain development communities, such as the Cosmos Network, can provide support and coordination for cross-chain projects (Hryniuk, 2021a, para. 2; Hryniuk, 2021b, para. 5). Cross-chain collaboration can facilitate the development of new blockchain technologies, such as sharding and rollups (Herlihy, 2018; Zarick et al., 2021). It can also support the creation of more user-friendly interfaces and human-readable wallet addresses (Camps, 2022).

5.2.9 SOLUTIONS: HYPERLEDGER PROTOCOLS

The blockchain industry needs a data standard to improve interoperability. Collaborations on Hyperledger can help legacy systems work together more easily and facilitate cross-chain collaboration through the use of best practices and common coding languages. The Cosmos Network provides support for cross-chain projects, which can lead to the development of new blockchain technologies and user-friendly interfaces. The Cross-Ledger Interbank Settlement project is working on completing cross-ledger interbank settlement transactions in a multi-blockchain ecosystem, while the Digital Green Bond Project is focused on improving green bond distributions and providing more insightful reporting on environmental impact. Project Starling is collecting, storing, and verifying human history across blockchains to combat misinformation. Hyperledger Cactus is a framework for transacting across multiple distributed ledgers, and YUI and Weaver are Hyperledger Labs that support communication between heterogeneous blockchains. Datachain proposes the Cross Function Pay as a solution for cross-chain interoperability.

5.2.10 SOLUTIONS: POLKADOT SOLUTIONS

Polkadot is a cross-chain collaboration solution that includes a relay chain, parachain, and bridge chain. The relay chain is the main blockchain where all parachains connect to each other, enabling consensus, security, and data transfer. Parachains are independent blockchains that can set their own parameters, including block times, transaction fees, governance mechanisms, and mining rewards. Parathreads are pay-as-you-go parachains that allow for flexible and cost-effective development on the network. The Parity Polkadot Platform includes a number of functional components and developments, such as a networking subsystem, consensus mechanism, proof-of-stake chain, and transaction processing subsystem. The Polkadot governance model has been updated with GOV V2, which increases the number of governance proposals that can be voted on and reduces the proposal submission threshold. The Cross-Consensus Message Format (XCM) allows parachains to exchange messages with other parachains, potentially providing a standardisation model for cross-chain collaboration.

5.2.11 SOLUTIONS: COSMOS SOLUTIONS

Cosmos has an Inter-Blockchain Communication (IBC) protocol that supports a cross-chain asset management ecosystem. The network includes 262 apps and services, such as Binance Chain, Terra, Crypto.org and Cosmos Hub. Cosmos and Polkadot share similarities in terms of parachain usage and seeking cross-chain communication standards. Solutions like Evmos have been deployed on Cosmos and can be integrated via the Ethereum Virtual Machine (EVM). Evmos plans to expand cross-chain collaboration by using the IBC protocol for data and asset sharing within the Cosmos blockchain.

5.2.12 SOLUTIONS: SIDECHAINS

Pegged sidechains enable the transfer of ledger-based assets between different blockchains. Sidechains can select alternative consensus protocols and have different block times and block sizes. Smart contracts enable compatibility between chains and facilitate asset migration. Several existing solutions and techniques have been proposed for communicating between sidechains, including Ethereum's Private Sidechains, Plasma, Polkadot, and Ethereum 2.0 Sharding.

5.2.13 SOLUTIONS: BRIDGES

Blockchain bridges act as an interoperability solution by connecting two different blockchains together to enable communication and data transfer. They can be classified into trusted and trustless, with the latter being operated by smart contracts and algorithms. In terms of function, bridges can be chain-to-chain, multi-chain, or specialized. Examples of bridges include Binance Bridge, Milkomeda C1 and TEZEX. IBC is a more advanced type of bridge that facilitates general-purpose message passing. Cosmos and Polkadot, similar to each other in their aim to establish cross-chain communication standards, utilize 'zones' that connect to the Hub and validators to commit blocks. Pegged sidechains enable the transfer of ledger-based assets between blockchains, while sidechain solutions such as Federated Pegs, Ethereum's Plasma, and Cardano's EVM sidechain have their own independent blockchains, consensus protocols, and design considerations. Other solutions for cross-chain communication include Ethereum's Private Sidechains, Plasma, and Ethereum 2.0 Sharding.

5.2.14 SOLUTIONS: IMPLICATIONS

Cross-chain collaboration is essential for the success of Cardano and the mass market adoption of blockchain technology. The Cardano user community has already been carrying out cross-chain collaborations through multiple proposals and initiatives, such as the IELE compiler, which offers support for a range of programming languages and enables EVM sidechain development. Notable proposals for cross-chain collaboration on Cardano include OxBAT, Interoperability Research and KILT seminars. Other proposals focus on social collaboration, lead incentivization, blockchain education and model creation. Wanchain and MLabs collaboration has been an actionable plan to make Cardano interoperable, with the Wanchain bridge emerging as a solution to connect Cardano and other L1s blockchains. This setting considers Wanchain as a Cardano sidechain for cross-chain collaboration. Elements for building Cardano's cross-chain interoperability solutions include decentralized, non-custodial, and bi-directional bridges. However, there are challenges to existing solutions for Cardano cross-chain collaboration, including fierce commitment to blockchain “tribes” and an increase in competitor-providers. The biggest challenge is to put multi-chain users in conversation with each other, which requires a common effort to connect communities and users with Cardano, and vice versa.

5.2.15 OPPORTUNITIES: BLOCKCHAIN 3.0 NETWORKS

Blockchain 3.0 is a term used to refer to the third generation of blockchain technology, which integrates advanced technologies such as artificial intelligence, cloud computing, and the Internet of Things with blockchain. This allows for the creation of more complex and sophisticated decentralized applications and services, and enables the development of new use cases for blockchain technology beyond finance and supply chain management. Blockchain 3.0 is also often associated with an emphasis on scalability, interoperability, and security. For the Cardano community, there are a number of cross-chain collaboration opportunities in the blockchain 3.0 space. For example, G. Yang et al. (2022) propose a distributed fusion cross-chain model and architecture that supports a high-performance P2P network, security cryptography protocols, and high-performance computing engine. Additionally, Datachain (2022) describes the opportunity to support IBC transactions on public chains. Furthermore, Johnson et al. (2019) identify how the rapid growth of public and permissioned blockchains will drive the need for cross-chain transactions and communications amongst disconnected parties. Therefore, the Cardano community should develop and support reliable cross-chain communication design solutions to support ecosystem collaboration and adoption.

5.2.16 ENHANCED ATOMIC TRANSACTIONS

The Cardano community has several opportunities for cross-chain collaboration. For improved performance of atomic cross-chain transactions, Herlihy (2018) suggests that an atomic 'swap protocol can be modified to provide better privacy' (p. 10). This has been proven with the expansion of the usage with multi-asset shielded pool such as ZCLAIM and a more recent Orchard version of the Zcash protocol (Sánchez et al., 2022, p. 8). The improvement of atomic cross-chain transactions will be a huge opportunity for the development of cross-chain collaboration solutions. Additionally, cross-chain decentralized exchanges such as LayerZero have implemented cross-chain bridges that operate exclusively with their native assets (Narayanam et al., 2022, p. 13). The CSP model also offers an effective path for data distribution and low transactional costs for end-users (Hardjono et al., 2021). Furthermore, Mohanty et al. (2022) believe that there is a lot of research potential in the domain of atomic swapping protocol generalization for P2P crypto exchanges (p. 3). These existing atomic swap protocols provide a solid foundation for future development of an optimal swapping protocol that supports cross-chain collaborations for the Cardano community.

5.2.17 PRIVACY NETWORKS

The Cardano community has several opportunities for cross-chain collaboration in the area of privacy. Freuden (2019) identifies opportunities to explore privacy protocols for cross-chain collaboration, citing the success of opt-in and opt-out privacy chains such as Monero and ZCash. Secret Network, the first blockchain with customizable privacy in the Web3 domain, promotes privacy through the use of smart contracts, defi, and NFT metadata (Freuden, 2019). Additionally, Cardano is developing Midnight, a data protection-based sidechain that aims to protect fundamental freedoms of association, commerce, and expression (Midnight, 2022). Alternative P2P protocols, such as the launch of the BitTorrent chain, also present opportunities to disrupt conventional file-sharing and support cross-chain collaboration (BitTorrent Inc., 2021). Protocols that address privacy issues in enterprise and IP domains provide additional opportunities for cross-chain collaboration (Freuden, 2019).

5.2.18 OPPORTUNITIES: MULTI-BRIDGE INFRASTRUCTURES

Several findings support the potential for cross-chain collaboration opportunities for the Cardano community. For instance, DeBridge's infrastructure claims that "integration will enable various cross-chain collaboration opportunities" (DeBridge, 2021b). The Binance Bridge Project, which improves cross-compatibility and collaboration on the Binance blockchain (Binance Academy, 2020a), and the StakerBridge protocol, which allows any party to be an operator and bridge tokens (StakerDao, n.d., p. 3), demonstrate the potential for such collaboration. Additionally, the need for improved security and reliability for cross-chain bridges (Say, 2022) and the opportunity for blockchain providers to partner with existing bridges to improve collaboration (Chawla, 2022) highlight the importance of these efforts. Future development opportunities also exist in applications that leverage token transfers, such as decentralized exchanges and NFT marketplaces (Orcutt, 2020), and in the development of greater interoperability with qualified technical standards, as supported by the World Economic Forum (2021). Overall, these findings suggest that there are many potential opportunities for cross-chain collaboration for the Cardano community.

5.2.19 OPPORTUNITIES: INDUSTRY 4.0 INTEGRATION

The convergence of Industry 4.0 technologies, including AI, robotics, and blockchain, presents opportunities for the development of integrated smart manufacturing and cross-chain collaboration (IBM, n.d.). The increasing capabilities of AI offer the potential for developing interoperable blockchains and internet-native tokenization for cross-chain collaboration, and the integration of AI into cross-chain collaboration could improve security and optimize protocols and networks through statistical data analytics (Dionysopoulos, 2022). Additionally, IoT systems integration with blockchain-based business process management systems presents opportunities for trustworthy data platforms and the protection of data and digital identity privacy (Henry et al., 2021). Advanced tools that are adaptive to data-centric processes and applications are also key to the development of blockchain-based systems in Industry 4.0 (Geroni, 2021). The integration of IoT and cross-chain collaboration could unlock the potential of Defi solutions (Say, 2022a), and use cases involving multiple blockchains and cross-chain collaboration can be achieved with innovative, adaptable, and interoperable solutions (Belchor et al., 2021). Furthermore, blockchain-based solutions for the sharing economy offer opportunities for cross-chain collaboration (Tschorsch et al., 2021), and an IoT-based approach to cross-chain collaboration could enable the integration of multiple platforms and the development of new business models (Simar et al., 2021). The combination of blockchain and IoT technologies could also enable new forms of cross-chain collaboration, such as decentralized supply chain management and digital twin systems (Delmolino et al., 2016). Overall, these findings suggest that there are many potential opportunities for cross-chain collaboration for the Cardano community in the era of Industry 4.0.

5.2.20 OPPORTUNITIES: PROJECT CATALYST PROPOSALS

In terms of opportunities, the implications for Cardano (and other blockchain communities) include the potential for Cardano to contribute to a standardisation initiative across different cross-chain collaboration protocols, including further standards required to test the efficiency of bridges (Hyperledger Community, 2022). By doing so, standardization will provide opportunities for operational normalization across interoperability layers for cross-chain collaboration. Next, Cardano has the potential to connect to other blockchain ecosystems via Alexar (Osmosis, 2022) and deBridge (DeBridge, 2022), amongst others. Opportunities and integrations with web3 social platforms exist, as well as enhancing user experiences (Camps, 2022). Developing multi-chain wallets integrated on Cardano would be advantageous for not only Cardano but also other blockchain users (Sieber, 2022). The Cardano NFT space is a promising area for research and solution development, while bridging assets will support a number of projects potentially migrating their assets to Cardano (DC Spark, 2022).

5.2.21 OPPORTUNITIES: IMPLICATIONS

The development of sidechains on Cardano could enable novel ecosystems and applications, and full interoperability and collaboration between Cardano and other heterogeneous blockchain networks is a long-term goal (Hryniuk, 2022b; Zhang & Louie, 2022). Engaging diverse populations through initiatives such as townhall meetings and scholarships is vital for achieving a collaborative environment (Catalyst Swarm, 2022; Cardano Catalyst Women, 2022), and the development of human-readable ADIs involving W3C standards and integration of blockchain technology is a potential area of focus for future research (Michelson et al., 2020). The security of Cardano bridges is also an important area for future research (Garoffolo et al., 2020). There is potential to expand the scope of the Cardano cross-chain project to collaboratively map all blockchains and their projects. Although a monumental task, it would require innovations in the area of collaboration.

5.3 SECTION SUMMARY

This section discusses several challenges facing blockchain collaboration, including fragmentation between blockchain networks, scalability issues, and security vulnerabilities. However, these challenges also present opportunities for innovation and growth. First, the need for interoperability solutions offers opportunities for the collective development of platforms and protocols that can overcome fragmentation and enable communication between different blockchain networks. Second, the scalability challenges can be addressed through the integration of extant technologies such as parachains and XCMP, which can improve transaction efficiency and confirmation latency. Third, security vulnerabilities can be addressed through improved decentralization and key management, as well as the development of formal verification techniques to ensure the security of cross-chain bridges and decentralized applications. Fourth, the ability to integrate existing blockchain protocols and overcome constraints in cross-chain communication can open up new opportunities for DeFi, Web3, Industry 4.0 and other decentralized applications. Finally, the ongoing research and development in the area of blockchain interoperability and collaboration can lead to new breakthroughs and innovations in the field. We will now conclude by proposing recommendations for further investigation and innovation.

6.0 RECOMMENDATIONS

6.1 SECTION OVERVIEW

Based upon the above literature review, analysis and findings, the report will conclude with a series of general recommendations for future research, development and collaboration. The recommendations section will be divided into our three research inquiries: problems, solutions and opportunities. Within each section, we will list general suggestions arising, and group them according to their applicable sub-section. At the end of each subsection, a recommendation will be recorded from those suggestions (boxed in grey). At the end of the three main sections, we will also record a broader section recommendation (boxed in orange), presenting three overarching approaches for increasing cross-chain collaboration. (These recommendations are suggested pathways of inquiry, and might not take into account projects current or in development that were not captured in the research):

6.2 GENERAL RECOMMENDATIONS

6.2.1 PROBLEMS: BLOCKCHAIN NETWORKS:

- Develop and adopt common standards and protocols for interoperability;
- Invest in research and development of secure, efficient, and scalable interoperability solutions;
- Find social and technical ways to encourage collaboration and communication between different blockchain communities;
- Invest in infrastructure and technology to improve network connectivity and accessibility;
- Encourage adoption of interoperability solutions and technologies among users and developers;

- Invest in education and training to improve understanding and adoption of interoperability solutions;
- Foster a collaborative and inclusive culture that values diversity and encourages participation from different blockchain communities.

RECOMMENDATION 1.1: The development of multi-chain wallets (like Lace) integrated with Cardano and other blockchain networks could address the challenges presented by fostering interoperability and collaboration across blockchain networks.

6.2.2 PROBLEMS: SCALABILITY

- Collaborate with other blockchain communities to share scalability knowledge and expertise, and to identify and implement best practices for cross-chain collaboration and interoperability;
- Consider implementing scaling solutions (such as parachains and XCMP) to address bottlenecks in scalability and improve transaction efficiency and confirmation latency;
- Prioritize interoperability and security to facilitate cross-chain collaboration and prevent issues with trust and function extension requirements;
- Explore options for connecting blockchains composed of different consensus mechanisms to mitigate potential downsides;
- Monitor and address issues with Defi gaming and token swapping to improve reliability and user experience in emergent crypto industries.

RECOMMENDATION 1.2: The exploration of cross-chain collaboration approaches utilizing scaling solutions and alternative consensus mechanisms, prioritizing interoperability and security, and facilitating collaboration with other blockchain communities could address the challenges presented.

6.2.3 PROBLEMS: SECURITY

- Industry-wide prioritization of security design and implementation of cross-chain bridges to protect against hacks, social engineering, and vulnerabilities in the underlying code;
- Provide clear and accessible information about the security of different bridging mechanisms to promote confidence and trust within the blockchain community;
- Address the security challenges associated with dApps and off-chain data to reduce the attack surface for hackers;
- Develop solutions for secure asset transfer between PoW and PoS chains, as well as between EVM-compatible and non-EVM compatible chains;

- Monitor and address the potential security risks associated with miner concentration and the make-up of different blockchain networks;
- Collaborate with other blockchain communities to share knowledge and expertise, and to identify and implement best practices for cross-chain collaboration and interoperability.

RECOMMENDATION 1.3: The development of an industry-wide security monitoring framework for cross-chain bridges that prioritizes security, provides clear information about security, addresses security challenges, develops solutions for secure asset transfer, and monitors and addresses potential security risks could address the challenges presented by the security of cross-chain collaboration in the blockchain ecosystem.

6.2.4 PROBLEMS: TECHNOLOGICAL CONSTRAINTS

- Consider the impact of transaction throughput on network performance and security;
- Develop more generic cross-chain architectures to enable greater interoperability between chains;
- Address the challenges of maintaining consistency in cross-chain systems;
- Develop a comprehensive blockchain architecture that can deliver high-traffic, regulation, privacy, and scalability;
- Conduct further research on cross-blockchain token transfer and standardization of blockchain interoperability;
- Address non-trivial issues such as "two-way peg" security and liquidity spread across L1 and L2 dApp protocols;
- Improve integration between traditional computing systems and blockchains;
- Address integration hurdles between public and enterprise blockchains;
- Encourage private and public blockchain participants to have forums to discuss terms that establish and promote mutual outcomes.

RECOMMENDATION 1.4: Consider a comprehensive EVM-inspired peer-chain architecture that creates a network of Visitor sidechains off of Host mainchains, while external Hosts connect to their allocated Visitor sidechain. To enable interoperability, improve transaction throughput and connectivity, address consistency and security challenges, and facilitate integration with traditional computing systems and public and private blockchains.

6.2.5 PROBLEMS: USERSHIP

- Develop a cross-chain protocol that addresses the trust, communication, and secure exchange issues between different blockchain systems;

- Reduce barriers to entry for creating new connections between ledgers and improve the performance of global consensus mechanisms;
- Create a collaborative platform that streamlines cross-chain transactions for different users, projects, and developers;
- Provide better information and understanding of the cost accrual across chains when assets are wrapped, unwrapped, minted, or burned;
- Address the social dimension of trust, transparency, and decision-making power in cross-chain collaboration;
- Improve the end user experience of web3 apps to encourage broader adoption.

RECOMMENDATION 1.5: In collaboration with existing interchain protocols and standards working groups, develop a cross-chain protocol that streamlines trust, communication, and secure exchange between different blockchain systems, reduces barriers to entry for creating new connections, and provides better information and understanding of cost accrual across chains to improve the end user experience of web3 apps and adoption.

6.2.6 PROBLEMS: IMPLICATIONS

- Develop user-friendly cross-chain UI to improve accessibility and adoption of blockchain networks;
- Conduct more research on social collaboration initiatives to stimulate growth between blockchain communities;
- Work on creating more human-readable and personalized wallet addresses;
- Simplify the process of sending and receiving payments across networks;
- Increase public awareness of Cardano and other blockchain projects.
- Facilitate collaboration between Cardano and other chains;
- Explore NFT bridging opportunities with other blockchain communities;
- Utilize cross-chain collaboration as a pathway for education;
- Establish cross-chain interaction and collaboration standards for NFT data;
- Conduct more research on cross-chain collaboration at the sociological level;
- Encourage coordination and macro-planning among blockchain communities to support mass adoption;
- Accelerate experimentation with cross-chain services to keep up with multi-chain trends.

SECTION 1 RECOMMENDATION (1.6): Develop a collaborative platform to enhance Cross-Chain Community and End-User experiences. This platform should be designed to facilitate a coordinated approach to community collaboration and should include a user-friendly cross-chain UI for cross-chain collaboration and service development, as well as providing a platform to increase social research in blockchain collaboration.

6.2.7 SOLUTIONS: NOVEL SOLUTIONS

- Encourage the use of multi-token crypto wallets to provide access to blockchain data and operations across different token types;
- Explore the use of anchoring or hashing to insert data into a blockchain and link cross-chain data;
- Consider the use of Multi-token Proof of Stake (MPoS) consensus algorithms to support a blockchain interoperability architecture;
- Investigate the use of optimistic rollups to increase network scalability and facilitate cross-chain collaboration in Layer architecture design;
- Investigate the potential for using extended Unspent Transaction Output (eUTXO) ledger models to support multi-asset and smart contracts across different UTXO-based ecosystems;
- Collaborate with other blockchain communities to develop and share cross-chain coding solutions;
- Explore the potential for using cross-chain oracles and off-chain data sources to improve interoperability;
- Invest in research and development of cross-chain collaboration initiatives, including at the sociological level;
- Engage in forums and discussions with other blockchain communities to establish and promote mutual outcomes for cross-chain collaboration;
- Accelerate experimentation and adoption of cross-chain services to catch up with multi-chain trends.

RECOMMENDATION 2.1: To encourage further research into novel innovations such as anchoring applications, MPoS consensus algorithms, optimistic rollups, extended UTXO ledger models, and collaborate with other blockchain communities to develop and share cross-chain coding solutions, oracles, and off-chain data sources to accelerate experimentation and adoption of novel cross-chain services.

6.2.8 SOLUTIONS: ATOMIC SWAPS AND PROTOCOLS

- Implement multi-token crypto-wallets and exchanges to provide access to different blockchain data and operations;
- Explore the use of cross-chain atomic swaps to allow for direct exchange of multiple ledger-based assets with reduced intermediaries;
- Consider the development of cross-chain bridges and interoperability protocols to enable compatibility with decentralized finance (DeFi) systems;
- Investigate the potential of wrapped tokens, hybrid connectors, and private transaction protocols as solutions for cross-chain interoperability;
- Invest in the development of standard protocols and cross-chain interfaces to improve collaboration between different blockchain communities;

- Collaborate with institutions, such as The World Economic Forum, to promote the commercial adoption of cross-chain solutions;
- Join cross-chain development communities, such as the Cosmos Network, to receive support and coordination for cross-chain projects;
- Explore opportunities for cross-chain collaboration to facilitate the development of new blockchain technologies, such as sharding and rollups;
- Collaborate with other blockchain communities to create more user-friendly interfaces and human-readable wallet addresses.

RECOMMENDATION 2.2: Fund and implement multi-token crypto-wallets and exchanges that explore cross-chain atomic swaps and interoperability protocols for Defi, and join cross-chain development communities to receive project support and coordination.

6.2.9 SOLUTIONS: HYPERLEDGER PROTOCOLS

- One key recommendation is to prioritize the development of industry data standards for the blockchain industry, which can include a mix of proprietary and non-proprietary technologies;
- Collaborating with organizations such as the Hyperledger Foundation can provide access to proven interoperability solutions, such as the Cross-Ledger Interbank Settlement project and the Digital Green Bond Project;
- Using pluggable frameworks like Hyperledger Cactus and API orchestration layers like Hyperledger FireFly can enable the integration of multiple blockchain networks and support interoperability at the application level;
- Implementing smart contract languages like Daml and interoperability frameworks like Weaver and YUI can facilitate cross-chain communication and collaboration;
- Utilizing cross-chain communication protocols like IBC can enable the exchange of information and assets between different blockchains;
- Leveraging existing solutions, such as the Cross Fabric protocol and the DLT Interoperability Framework, can provide a framework for cross-chain interoperability and support collaboration between different blockchain communities;
- Addressing security, throughput, governance, cost, and legal issues is crucial for the successful implementation of cross-chain collaboration.

RECOMMENDATION 2.3: Prioritize the development of industry data standards for the blockchain industry, collaborating with organizations such as the Hyperledger Foundation, and implementing pluggable frameworks and smart contract languages to facilitate cross-chain communication and collaboration, leveraging existing solutions and addressing security, throughput, governance, cost, and legal issues.

6.2.10 SOLUTIONS: POLKADOT

- ollaborating with Polkadot and Kusama as cross-chain solutions that enable information and token transfer between different blockchains;
- Explore the use of parachains and parathreads as potential options for cost-effective development of cross-chain projects on the Polkadot and Kusama networks;
- Stay informed about the latest developments in the Polkadot ecosystem, such as GOV V2 and XCM, which can support decentralized governance and communication between parachains;
- Utilize the resources and tools provided by Polkadot and Kusama for developers looking to build cross-chain projects on their networks;
- Collaborate with other blockchain communities that are also using the Polkadot and Kusama ecosystems to develop cross-chain projects.

RECOMMENDATION 2.4: Explore Polkadot and Kusama as cross-chain solutions, explore the use of parachains and parathreads, stay informed about the latest developments in the Polkadot ecosystem, utilize the resources and tools provided by Polkadot and Kusama, and collaborate with other blockchain communities using the Polkadot and Kusama ecosystems to develop cross-chain projects.

6.2.11 SOLUTIONS: COSMOS

- Explore the potential of using Inter-Blockchain Communication (IBC) protocols, such as those used by Cosmos, to facilitate cross-chain collaboration and interoperability;
- Consider using EVM-compatible solutions, such as Evmos, to facilitate cross-chain transfers of tokens and assets;
- Collaborate with existing blockchain bridges and applications, such as Connext, Celer, and Nomad, to expand cross-chain collaboration capabilities;
- Utilize the Tendermint-based framework and concepts of parachains, as utilized by Cosmos and Polkadot, to support cross-chain communication and collaboration;
- Investigate the possibility of integrating existing solutions deployed on the Cosmos network into the Cardano ecosystem.

RECOMMENDATION 2.5: Explore the potential of using IBC protocols, such as Cosmos, Tendermint and EVM protocol solutions, and investigate the possibility of integrating existing solutions deployed on the Cosmos network into the Cardano ecosystem.

6.2.12 SOLUTIONS: SIDECHAINS

- Use pegged sidechains to transfer ledger-based assets between different networks;
- Consider alternative consensus protocols on sidechains to suit specific demands;

- Adjust block times and block sizes on sidechains to improve throughput, transaction speed, and reduce fees;
- Use blockchain bridges and smart contracts to enable interoperability and asset migration between chains;
- Explore existing cross-chain communication solutions, such as sidechains, blockchain routers, and inter-blockchain communication protocols;
- Consider implementing solutions such as Horizen's Zendoo or Latus for decentralized and verifiable sidechain systems;
- Research and utilize techniques for communication between sidechains, such as Ethereum's Private Sidechains, Plasma, Polkadot, and Ethereum 2.0 Sharding.

RECOMMENDATION 2.6: Research and utilize techniques and solutions for communication between sidechains, such as Ethereum's Private Sidechains, Plasma, Polkadot, and Ethereum 2.0 Sharding. This can enable interoperability and asset migration between different blockchain networks.

6.2.13 SOLUTIONS: BRIDGES

- Explore the collaborative potential of existing blockchain bridges to facilitate the transfer of assets between different blockchains;
- Consider implementing sidechain solutions, such as Federated Pegs and Ethereum's Plasma, to enable the transfer of ledger-based assets between different blockchains;
- Invest in blockchain systems that support cross-chain collaboration, such as Horizen's Zendoo and Latus, to facilitate decentralized communication and collaboration between different blockchains;
- Consider using validator bridges on Cardano that rely on external validation for cross-chain transactions;
- Investigate the use of generalized message passing bridges to transfer information and assets between Cardano and other networks;
- Utilize liquidity networks on Cardano to facilitate asset transfers with other networks via atomic swaps. This will help increase collaboration and interoperability within the Cardano community, as well as with other blockchain communities;
- Explore trustless bridges, which are operated by smart contracts and algorithms, as a decentralized option for cross-chain communication.

RECOMMENDATION 2.7: Further investigate the use of blockchain bridges and blockchain security, to facilitate the transfer of assets between different blockchains, and invest in blockchain projects and systems that support cross-chain collaboration.

6.2.14 SOLUTIONS: IMPLICATIONS

- Model interoperability in the Cardano Impact Community to generate multi-chain collaborations, such as with Wanchain;
- Develop cross-chain bridges to connect Cardano with other L1 blockchains;
- Evaluate integration potential for cross-chain protocols such as Chainlink's Cross-Chain Interoperability Protocol (CCIP) to communicate with Cardano sidechain;
- Explore potential collaboration opportunities with Binance and Polygon to reduce network congestion;
- Develop open-source tools and standards for projects to integrate NFT technology, and programmable functions to connect Cardano NFTs, tokens, transactions, and smart contracts to other blockchains;
- Invest in research and development of decentralized networks to empower cross-chain collaboration;
- Work towards creating a common effort to connect communities and users with Cardano to sustain cross-chain communication and collaborations.

SECTION 2 RECOMMENDATION (2.8): To address the need for cross-chain standardization, we recommend creating an open-source cross-chain standardization forum that connects to existing industry standardisation working groups (including Enterprise Ethereum Alliance). The forum can cover standardisation issues around coding languages, layer and architecture design, novel solutions, protocol design, and the incorporation of existing blockchain industry improvement processes (such as CIP, CCIP, EIP, BIP, UIP and PSP).

6.2.15 OPPORTUNITIES: BLOCKCHAIN 3.0 NETWORKS

- Develop and support reliable cross-chain communication design solutions to support ecosystem collaboration and adoption;
- Cooperate with participating blockchain providers to achieve optimal interoperability;
- Develop human-readable ADIs involving W3C standards and the integration of blockchain technology through distributed servers and applications;
- Modify network protocols to provide more efficient offline experiences for blockchain users;
- Focus on cross-chain collaboration enhancement in terms of interoperability, user privacy, security, user identity, governance, risks, and services;
- Investigate opportunities in Web 3 through cryptocurrencies, smart contract computing, decentralized hardware infrastructure, NFT's, the metaverse, and community governance;
- Investigate the use of digital identification (DID's) that can be interoperable across multiple platforms;

- Explore the advantages of a large-scale traceability supply chain environment;
- Investigate the potential of cross-chain collaboration in the healthcare sector and other industries;
- Explore the potential of the inter-blockchain connection model as routing management for cross-chain collaboration systems.

RECOMMENDATION 3.1: Investigate the potential of cross-chain collaboration across industries by developing and supporting reliable cross-chain communication design solutions, modifying network protocols to provide more efficient offline experiences for blockchain users, and focusing on cross-chain collaboration enhancement in terms of interoperability, user privacy, security, user identity, governance, risks, and services.

6.2.16 OPPORTUNITIES: ENHANCED ATOMIC TRANSACTIONS

- Modify atomic swap protocols to improve privacy;
- Implement cross-chain collaboration protocols such as HTLC and MPHTLC;
- Use cross-chain bridges to facilitate transactions with native assets;
- Utilize multi-chain yield aggregators to access high yield opportunities and enable cross-chain transactions;
- Adopt the CSP model for data distribution and low transactional costs;
- Develop protocols that allow for participation without assumptions while trading;
- Extend the UIP protocol to improve the dynamic transaction graph;
- Develop solutions to address technical issues with on-chain atomic swaps;
- Create a blockchain interoperability mechanism that adheres to essential system architecture, ecosystems, operations, interoperability principles, standards, and best practices;
- Invest in research and development for the transfer of data across blockchains;
- Implement a foundational layer of DeFi for all existing blockchain ecosystems;
- Adopt multi-chain governance frameworks to coordinate on-chain and off-chain activities across multiple blockchains.

RECOMMENDATION 3.2: Research and design protocols that allow for participation without assumptions while trading, utilizing multi-chain yield aggregators to access high yield opportunities and enable cross-chain transactions, and adopting the CSP model for data distribution and low transactional costs.

6.2.17 OPPORTUNITIES: PRIVACY NETWORKS

- Explore privacy protocols for cross-chain collaboration;
- Implement protocols that promote privacy in the form of smart contracts, Defi, or NFT metadata;

- Develop data protection-based sidechains to protect fundamental freedoms of association, commerce, and expression;
- Invest in alternative P2P protocols that aim to disrupt conventional file-sharing;
- Address privacy issues in enterprise and IP domains to facilitate cross-chain collaboration.

RECOMMENDATION 3.3: Explore privacy protocols for cross-chain collaboration, implement protocols that promote privacy in the form of smart contracts, DeFi, or NFT metadata, and develop data protection-based sidechains to protect fundamental freedoms of association, commerce, and expression.

6.2.18 OPPORTUNITIES: MULTI-BRIDGE INFRASTRUCTURES

- Integrate collaborative approaches for improved cross-chain bridging;
- Invest in the development of user-friendly universal wallets;
- Partner with existing bridges to improve the collaboration of blockchain networks;
- Focus on improving security and reliability for cross-chain bridges;
- Invest in applications that leverage token transfers, such as decentralized exchanges and NFT marketplaces;
- Participate in the development of greater interoperability with qualified technical standards;
- Explore opportunities for research and development on bridge integration, such as decreasing costs of header verification and improving user experiences through bridge aggregation.

RECOMMENDATION 3.4: integrate collaborative approaches for improved cross-chain bridging, invest in the development of user-friendly universal wallets, and focus on improving security and reliability for cross-chain bridges

6.2.19 OPPORTUNITIES: INDUSTRY 4.0 INTEGRATION

- Invest in the development of AI-powered interoperable blockchains and internet-native tokenization for cross-chain collaboration;
- Explore the integration of AI into cross-chain collaboration platforms to improve security and optimize protocols and networks;
- Invest in IoT systems integration with blockchain-based business process management systems;
- Focus on advanced tools that are adaptive to data-centric processes and applications;

- Invest in the integration of Industry 4.0 and cross-chain collaboration to unlock the potential of Defi and DGov solutions;
- Explore opportunities for cross-chain collaboration in blockchain-based solutions for the sharing economy.

RECOMMENDATION 3.5: Invest in the development of AI-powered interoperable blockchains and internet-native tokenization for cross-chain collaboration, and explore the integration of AI into cross-chain collaboration platforms to improve security and optimize protocols and networks.

6.2.20 OPPORTUNITIES: PROJECT CATALYST PROPOSALS

- Contribute to a standardization initiative across different cross-chain collaboration protocols;
- Explore opportunities for operational normalization and better user experiences through further standards and integrations with web3 social platforms;
- Consider expanding the scope of the project to include all blockchains and their projects;
- Develop multi-chain wallets integrated with Cardano to provide benefits for users of other blockchain networks;
- Invest in research and solution development in the Cardano NFT space;
- Invest in the bridging of assets on Cardano to attract more projects to the platform;
- Collaborate with other communities and protocols to explore and develop cross-chain use cases.

RECOMMENDATION 3.6: Create a community-driven cross-chain network that supports cross-chain initiative building through Project Catalyst. The network may be composed of existing community working groups or members, and may support campaign leaders and builders to ensure project accountabilities, resources and communication is available to ensure project success.

6.2.21 OPPORTUNITIES: IMPLICATIONS

- Standardization across cross-chain collaboration protocols is needed to facilitate interoperability between Cardano and other blockchain networks;
- Cardano has the potential to contribute to a standardization initiative and connect with other blockchain ecosystems;
- Operational normalization and improved user experiences can be achieved through further standardization and integration with web3 social platforms;

- The scope of the project could potentially be expanded to include all blockchains and their projects;
- The development of multi-chain wallets integrated with Cardano could provide benefits for users of other blockchain networks;
- The development of sidechains on Cardano could enable novel ecosystems and applications;
- Full interoperability and collaboration between Cardano and other heterogeneous blockchain networks is a long-term goal.

SECTION 3 RECOMMENDATION (3.7): It is recommended that an industry-wide Cross-Chain collaboration fund be established, including a pool of funds from participating blockchain communities. This fund could also support the launch of a Cross-Chain token to further incentivize cross-chain innovation and research. A Bounties system could also be implemented to enable payments to cross-network innovations, and a Cross-Chain Hackathon could be organized to promote collaboration and idea-sharing.

6.3 SECTION SUMMARY

The recommendations outlined in this section focus on actionable approaches when participating in the highly complex global blockchain environment. These recommendations include the development of a multi-chain wallet integrated with Cardano and other blockchain networks, a security framework for cross-chain bridges, a comprehensive EVM-inspired peer-chain architecture, as well as collaborating with existing interchain protocols and standards working groups. Other recommendations focus on encouraging the use and implementation of multi-token crypto-wallets and exchanges, prioritizing the development of industry data standards, exploring extant cross-chain solutions such as Polkadot, Cosmos and Interledger, and researching and utilizing techniques and protocols for cross-chain data sharing. The three key recommendations comprising our investigation of cross-chain collaboration problems, solutions and opportunities include Recommendation 1.6: developing a collaborative platform to enhance cross-chain community and end-user experiences; 2.8: creating an open-source cross-chain standardisation forum; and 3.7: establishing an industry wide cross-chain collaboration fund. It is proposed that an industry-wide macro-level approach to cross-chain standards, tools and resources will greatly advance the progress of interoperability and collaboration for Cardano and the industry as a whole.

In this report, we have discovered that one of the main gaps in cross-chain research relates to the lack of security solutions for effective and safe integration between different blockchain networks. Additionally, there is a lack of sociological studies of collaboration in the context of blockchain and distributed technologies, as well as research on cross-chain transactions and networks, both in terms of theoretical approaches and practical implementations. One challenge is that cryptocurrency communities and their users may be fiercely committed to their chosen blockchain (or crypto investments), making it difficult for new participants to join. Another challenge is the increasing market competition, which requires communities to innovate and develop new ways of engaging participation outside of legacy system thinking. Additionally, crypto and blockchain can be overwhelming for new users, so there is a need for user-friendly design and user experiences, as well as the simplification of concepts and use cases for Cardano. There is a need to facilitate conversations and collaboration between multi-chain users. Knowledge gaps in these areas hinders the development of effective solutions for cross-chain collaboration, and the adoption of such solutions by the broader blockchain community. However, what these and other gaps provide is the opportunity to use these insights to further ideate, investigate, plan, map, strategize, collaborate and build future solutions; something for which the blockchain and emergent technologies industries are built on.

To conclude, this research project has been funded by a blockchain community call to answer the question: How might we create connections and collaboration between Cardano and other blockchains in the next six months? To extend our Blockchain City analogy, we currently live in a sprawling and high-tech metropolis occupied by millions of distributed citizens. However, that city has grown in organic and ad hoc ways, with vibrant and unique communities building disparate architectures and building codes, and in some ways insular and speaking different languages; not unlike the world of the prior century. What our city currently lacks is a coordinated road-network between all communities; safe and reliable bridging infrastructures; citywide immigration, language and social services; and city-wide coordination bodies supporting transportation, communication and resourcing. What we do have, are parts of all of these solutions tucked within the communities themselves. Based on the findings of this report, the work required to achieve greater cross-chain collaboration within the industry is both sprawling, organic, chaotic and highly engaged. The Cardano roadmap, like those of other ecosystems, both ends and begins at the point of decentralised governance, a place where understanding issues around trust, communication, collective intelligence, distributed decision-making and collaboration are a must. It is from this position that the provision of tools and insight to better support how communities work together is essential. This is echoed in the words of one of many blockchain community groups around the world:

> *"If we collaborate, we can be so much more"* - Cardano Catalyst Women (2022, 1:02:24).

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