Chapter 6
Interoperability Among Heterogeneous Blockchains: A Systematic Literature Review

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6.1 Introduction

Blockchain technology has gained a great deal of attention in both industry and analysis in recent years. The rapid growth of this technology has led to the development of numerous different blockchain platforms and decentralized applications which serve not only cryptocurrency domains but also fields such as banking, supply chain management, healthcare, and other fields [64]. However, some concerns prevent the potential mass adoption of blockchain applications. The most common issue is the lack of interoperability. As many blockchain networks exist as isolated systems enabling all operations to be conducted locally, their structures and policies prevent communication between different blockchains, limiting their ability to transfer to and from various blockchains regardless of differences in language, interface, and execution platform. This issue attracted the attention of many researchers and blockchain application developers. They proposed and designed many different solutions to overcome this incompatibility problem and provide interoperability to blockchain systems.

We include the following definition of an "interoperable blockchain architecture" using the NIST [80] definition of blockchain to explain the importance of interoperability for blockchain systems. Interoperable blockchain architecture is a group of distinguishable blockchain systems, each representing a specific distributed data ledger, where multiple heterogeneous or homogeneous blockchains can execute atomic transactions and where data recorded in one blockchain ledger is available, verifiable, and referenced by another foreign transaction in a semantically

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compatible nature. In another definition of interoperable blockchain proposed by P. Lafourcade and M. Lombard-Platet [47], interoperability is the ability of two blockchains to work together by executing and validating transactions, sending assets from one participant to another in different chains, or invoking and executing smart contracts. Blockchain interoperability solutions can be categorized into four main types [64]:

- **Sidechain or relay chain solution** A separate blockchain system connected to the main blockchain (mainchain/parent chain) which has the main functionality of verifying and reading data for another blockchain. The blockchains are interconnected through a two-way peg mechanism. The two-way peg mechanism allows digital assets to transfer from a mainchain to a sidechain and vice versa at a fixed or otherwise deterministic exchange rate [2]. Another term, *Federated Peg*, was introduced by the authors of "Enabling Blockchain Innovations with Pegged Sidechains" [2], referring to a mechanism that uses functionaries to validate and sign the data blocks by Block signers and the pegs by Watchmen. This network acquires the property of being secure. However, sidechains are limited to homogeneous blockchain systems [64].
- **Blockchain router solution** This technique involves some blockchain entities or nodes to serve as routers for transmitting transactions across various blockchain networks [47]. The design concept of this solution is derived from the routing architecture of the Internet.
- **Smart contracts** This approach uses a smart contract or a set of smart contracts to create a kind of inter-communication protocol among multiple different blockchain networks [7, 20, 48]. This method provides interoperable and secure data sharing and access control [20].
- **Industrial solutions** This category uses a collection of trusted validators to validate and confirm transactions. Many modern industrial projects use validators to ensure and guarantee the state of the node and its integrity [64].

Our Contributions:

The primary purpose of this study is to provide a systematic review and conduct a comprehensive study of existing solutions for the creation of interoperable blockchains. Also, this review examines the methodologies used in the available solutions to reach blockchain interoperability and compares them in terms of several factors, including performance (throughput, average block confirmation time), the method used to achieve interoperability, strengths, challenges, and possible future directions. We expect that this study will allow researchers to have a clearer understanding of the various existing interoperable blockchain mechanisms and to situate them about the recent research carried out on this topic. Furthermore, we will present the projects currently implementing these protocols.

The rest of the chapter is organized as follows: In Sect. 6.2, we discuss the literature review. Section 6.3 illustrates the methodology used to conduct the systematic literature review (SLR), which consists of planning and conducting the research. In Sect. 6.4, we discuss the results and analysis. Finally, Sects. 6.5 and 6.6 present the conclusion, the limitations of this review, and directions for future works.

6.2 Literature Review

Currently, blockchain technology operates as a series of stand-alone networks without the ability to communicate with other blockchain networks, exchange external data, or autonomously perform transactions. Thus, the interoperability of blockchain is one of the most critical and challenging aspects of blockchain technologies. Motivated by this challenging aspect, we studied reviews that discussed innovation in interoperable blockchain. For example, Ilham et al. [64] provided an overall study of inter-blockchain communication. They reviewed all available inter-blockchain communication solutions and classified the available solutions into four main types: blockchain routers, sidechains, industrial solutions, and smart contracts. Furthermore, they provided a comparison where they discussed the weaknesses and strengths of each type. In another example, Rafael et al. [6] presented an extensive survey on all aspects of blockchain interoperability. They introduced the area of interoperability research, delved into the background of the domain, and defined and discussed various architectures and standards. Moreover, they presented existing solutions in three main categories: cryptocurrency-directed approaches, blockchain engines, and blockchain connectors. Additionally, they presented the advantages of a multiple-blockchain approach through a case study. They showed the various challenges related to the development of interoperable blockchain.

On the other hand, Stefan et al. [69] mentioned the need for blockchain interoperability and its benefits in improving the paradigm from current blockchain technology to an open system that allows different blockchain systems to communicate with one another. They review the aspects of cross-blockchain token transfers and smart contract invocation and interaction. Furthermore, Liping Deng et al. [21] presented a paper that outlines the importance of cross-blockchain and details multi-signature wallet concepts. Furthermore, they concentrate on the study of the latest relevant cross-chain technologies and active ventures. Peter Robinson [65] raised a review that looks at cross-chain communication usage scenarios, and specifically at atomic swaps, values transfers, and reading and writing state pinning. Additionally, he presents key cross-chain classification techniques, which include locked hash time contracts, block header relaying, relay chains and threshold structures, and communication chains. Moreover, Babu et al. [59] presented a paper that classifies digital crypto-assets for interoperable deployment. The authors categorized crypto-assets based on their features and purpose and provided an interoperability scenario for specified crypto-asset classes. In another paper, Richard Barnes [5] surveyed existing architecture for interoperability and smart contract language. Barnes also described variables that impact tokenized asset portability. Finally, he suggested a maturity model for portability that can be used to determine the existing state of technology and business infrastructure support.

In this systematic literature review, we have provided analyses that are different from those in the surveys mentioned above. Our study differs in various aspects from the related work in that we provide a full review of all proposed methods and solutions related to inter-blockchain communication and a precision comparison of each solution with its strengths and limitations. We also discuss the performance and evaluation metrics applied to each method and the applications and contexts of use. Finally, we present future directions related to inter-blockchain communication.

6.3 Methodology

We conducted a systematic literature review (SLR) based on Kitchenham and Charters' methodology [44]. This method consists of three main stages: planning, conduction, and reporting. In each stage, there are several processes and steps involved. In the planning stage, the following six steps are included: (I) identify your research questions based on the objectives you are planning to achieve in your study, (II) define your search strategy, (III) create criteria for your selection, (IV) set up your quality assessment rules, (V) define your techniques for data extraction, and (VI) specify how you will synthesize extracted data. Furthermore, the following subsection will include a detailed description of the steps mentioned. Figure 6.1 illustrates the search methodology applied in this research.

6.3.1 Research Questions

In this study, our main objective is to review blockchain interoperability research area. The following research questions are raised to achieve this objective (Sect. 6.2):

3.1.1 RQ1: What is the methodology used to create inter-blockchain communication?
RQ1 aims to identify the methods and solutions applied by researchers to achieve blockchain interoperability.
3.1.2 RQ2: What are the strength and limitations of interoperable blockchain?
RQ2 aims at presenting the advantages and disadvantages of the methodologies proposed by researchers.
3.1.3 RQ3: What are the performance and evaluation metrics?
RQ3 aims to show the performance metrics used in evaluating the methods and solutions.
3.1.4 RQ4: What is the application and context of usage of inter-blockchain?
RQ4 is concerned with the application and context of the blockchain interoperable blockchain solution.
3.1.5 RQ5: What are the future directions of inter-blockchain?
RQ5 aims to present future direction for blockchain interoperability.

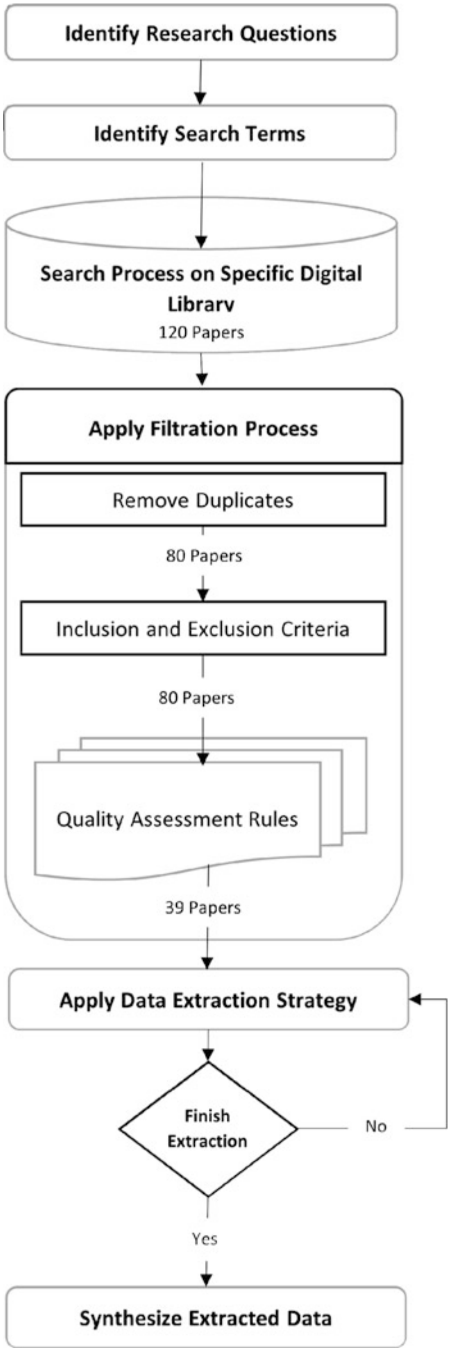

Fig. 6.1 Applied research methodologies

6.3.2 Search Strategy

The process for choosing the search term was as follows:

3.1.1. The research questions identified the main search terms.
3.1.2. Additional search terms were derived with the same meanings of the main search terms such as blockchain interoperability, cross-blockchain communication, multi-blockchain, and heterogeneous blockchain communication.
3.1.3. The search findings are constrained by Boolean operators (ANDs and ORs).
3.1.4. The search words used in this study refer to interoperable blockchain communications.

The digital libraries (journals and conference papers) used are listed as follows: GoogleScholar, Elsevier, Springer, the Association for Computing Machinery (ACM) Digital Library, and the Institute of Electrical and Electronics Engineers (IEEE) Library. Moreover, we found that the Cornell University journal includes several research papers that met our selection criteria.

Following our inclusion/exclusion criteria, we collected 39 scientific papers and 37 projects. The scientific papers included 24 conference papers and 15 journal papers.

6.3.3 Study Selection

Our initial search produced a collection of 90 scientific papers based on our search terms. Moving on, we filtered the results to verify that we included papers related to our subject. In our scheduled daily meetings, the filtration mechanism was addressed by the coauthors. The following table explains the filtration and selection processes:

Stage 1: Delete all duplicated papers from various digital collections.
Stage 2: Eliminate irrelevant papers by applying inclusion and exclusion criteria.
Stage 3: Remove review and survey papers from the collection.
Stage 4: Apply quality assessment rules that allow only qualified papers to be included.
Stage 5: Search for more papers from the sources mentioned in selected papers and repeat the processes for the newly added papers.

Table 6.1 addresses the inclusion and exclusion criteria that were applied in this study to provide the best possible answers for the proposed research questions. Finally, 39 papers were selected after the filtration stages.

6.3.4 Quality Assessment Rules (QARs)

This is the final step in determining the finalized list of papers to be included in the SLR. This is an important stage that aims to determine the quality of the collected research papers. Thus, 10 QARs are determined and marks are given to each paper

Table 6.1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Include only journals and conference papers	Exclude papers with no clear publication information
Include inter-blockchain communication solutions	Exclude non-refereed articles
Include studies that discuss solutions for communication in heterogenous blockchain	Exclude articles that include blockchain and it is not related to interoperability
	Exclude all digital resources, which do not discuss inter-blockchain

out of a total value of 10. Scores for each QAR are applied as follows: "fully answered" = 1, "above average" = 0.75, "average" = 0.5, "below average" = 0.25, and "not answered" = 0. The summation of the marks achieved for the 10 QARs is the paper's total ranking. Finally, we chose to retain only papers assigned a score of 5 or higher; otherwise, we excluded the paper from the SLR collection.

QAR1: Are the study objectives recognized?
QAR2: Are inter-blockchain backgrounds well defined?
QAR3: Are the specific context and usage of blockchain clearly defined?
QAR4: Are the strengths of the proposed methods well explained?
QAR5: Are the limitations of the proposed methods well explained?
QAR6: Are the methods well designed and justifiable?
QAR7: Are the evaluation metrics reported?
QAR8: Are the evaluation metrics compared to those of other methods?
QAR9: Are the evaluation metrics of the proposed methods suitable?
QAR10: Overall, does the study enrich the academic community or industry?

6.3.5 Data Extraction Strategy

In this stage, the final list of papers was analyzed to extract the necessary information to answer the set of research questions. The information extracted from each paper included information such as the authors, year of publication, the title of the paper, type of paper (whether it is from a conference or a journal), methodology applied for blockchain interoperability communication, and this methodology's strengths and limitations, contexts in which it can be applied, and future directions. It is important to note that not all papers collected were able to answer all the research questions.

6.3.6 Synthesis of Extracted Data

In this stage, we employed numerous processes to gather evidence to answer the research questions to synthesize the information obtained from selected papers. Furthermore, we utilized the narrative synthesis method to answer all research questions. Narrative synthesis refers to the method used to tabulate and visualize the findings of the research questions through pie charts, bar charts, and diagrams.

6.4 Results and Analysis

We analyze the findings of this study in this segment. This subsection describes the selected scientific papers and projects collected to answer the research questions stated above. In the following five parts, the findings of each research question are explored in detail. A total of 39 scientific papers and 37 projects that carried out inter-blockchain communication were selected. Furthermore, according to Figs. 6.4 and 6.5, the collected scientific papers were published between 2016 and 2020, while the projects had taken place between 2015 and 2020. As mentioned above, a quality assessment rule criterion was applied and the scores of the selected papers and projects are shown in Tables 6.12 and 6.13. The list is presented in Appendix A, Table 6.14. Furthermore, the full table of the quality assessment rule is in Table 6.15 in Appendix A.

6.4.1 Design and Implementation Methods

In this section, we address RQ1, which aims to find the methods and solutions raised in scientific papers for heterogeneous blockchain interoperability.

6.4.1.1 Scientific Papers

Depending on the type of interoperable solution used, a portion of platforms and protocols has been developed. The inter-blockchain protocol consists of the rules programmed to define intercommunication policies between blockchains. A blockchain platform is a group of interoperable blockchain technologies that are used as a base to create communication with other blockchain networks. In this part, we discuss the types of inter-blockchain proposed by selected scientific papers. Figure 6.2 shows that the proportion of inter-blockchain platforms and protocols studied in the selected articles was approximately equal, recorded at 46% and 39%, respectively. However, for the remaining 15%, we could not define the solution type.

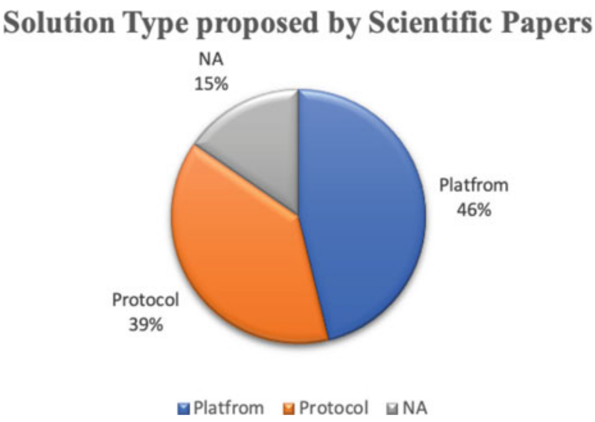

Fig. 6.2 Solution type in scientific papers

Table 6.2 Methodologies proposed by scientific papers

Inter-blockchain Solution	Description	Paper ID	Freq.
Router	Some blockchain entities or nodes serve as routers to send requests between different blockchain networks	A1, A2, A3,A4, A9, A21, A30	7
Sidechain	The main blockchain is linked to the independent blockchains (sidechains) The asset may be transferred using a two-way peg process	A8, A10, A17, A19, A20, A23, A33, A34, A37	9
Smart contract	To build interoperable protocols between independent blockchain networks, a smart contract or a series of smart contracts is used	A5, A6, A7, A11, A12, A25, A29, A35, A39	9
Atomic cross-chain swap	This approach utilizes the following basic mechanisms: • Multi-signatures • Hash-locks • Time-locks • Basic scripting	A15, A18, A22, A24, A28, A31, A32, A36	8
Multi-tokens Proof of Stake (MPoS) consensus protocols	MPoS modified version of PoS It supports the staking mechanism with multiple tokens in a cross-chain ecosystem	A14	1

As shown in Table 6.2, we identified five techniques that had been applied by researchers in the development of inter-blockchain communication.

In this review, the most frequent approaches used to create inter-blockchain communication are the sidechain, smart contract, atomic cross-chain swap, and router methods.

Sidechains are emerging mechanisms that allow one chain to safely use tokens and digital assets on a different chain. A two-way peg, also known as a bridge, allows the transfer of assets.

Atomic swaps are based on **Hashed Time-Lock Contracts (HTLCs)**, which utilize the following basic mechanisms [72]:

- Multi-signatures: a signature-based condition where transactions must be signed by two or more entities, thereby confirming and accounting for multi-signature transactions by signing parties.
- Hash-locks: used on two blockchains for linking transactions. Both locks are designed with the same hash function and are programmed with the same hash, so the password unlocking one hash-lock releases the password used to open the hash-lock on the other chain.
- Time-locks: a time-based condition restricts a transaction from being returned after a particular amount of time has passed. The period can be proportional to the publishing time of the transaction on the blockchain, or it can be an absolute time.
- Basic scripting: the purpose of basic scripting is to ensure that a transaction is initiated only if multiple (or committed) conditions are met. For example, the conditions may include the expiration of the period defined by the time-lock and the provision of a specific signature, or the release of both passwords to unlock a hash-lock.

Blockchain router is another approach that can connect various network blockchains in the same manner as the Internet network. In the blockchain router network, a blockchain plays the function of a router that analyzes and transmits connection requests according to the communication protocol, retaining a dynamic communication layout of the blockchain network.

6.4.1.2 Projects

The Fig. 6.3 below shows the percentage of inter-blockchain projects developed in one of the two types: platform or protocol. The review reveals that, with a percentage of 57%, the most frequent inter-blockchain implementations are the platform type, while inter-blockchain protocols were used in 40% of the projects. For the remaining 3% of the projects, the solution type was not specified.

According to Table 6.3, we have identified eight inter-blockchain project solutions. Most of the projects use the sidechain structure and atomic cross-chain swap technique as a solution for blockchain interoperability. However, some projects developed their internal architecture to achieve blockchain interoperability.

The ICON [37] project aims to link numerous blockchain communities across its platforms. Nexus and ICON Republic are part of the ICON structure. A Nexus is a collection of separate independent blockchains that are connected through the ICON Republic.

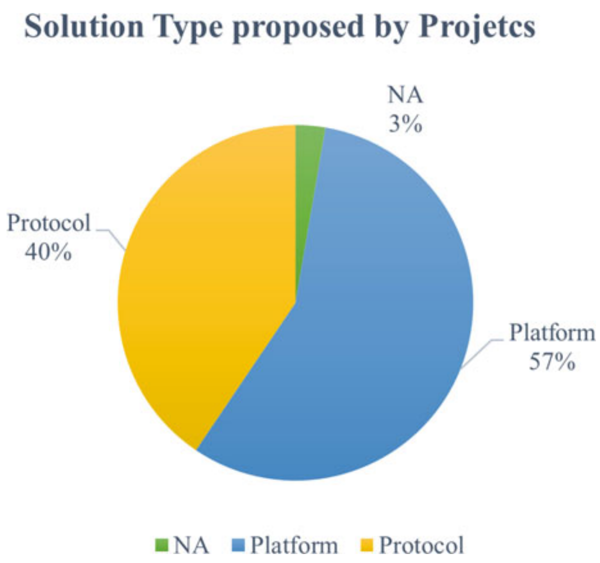

Fig. 6.3 Solution type by projects

The ArcBlock [51] project provides an environment for open blockchain applications to be developed and implemented. The project consists of three key components: Open Chain Access Protocol, Chain Adapter, and Blocklet. Open Chain Access Protocol provides an abstract layer for accessing different blockchain underlayers. Chain Adapter acts as a converter for switching blockchain underlayer protocols into the shared APIs specified in the Open Chain Access Layer protocol. Blocklet manages smart contracts, oracles, management of capital, and business logic off-chain. Blocklet interacts with blockchains through ArcBlock Open Chain Protocol.

The Cosmos [56] project is based on an Inter-Blockchain Communication (IBC) protocol. The architecture of the project consists of two major elements: center hubs and zones. The individual blockchains are zones, while the hubs allow for connections between various zones.

6.4.2 *Strengths and Limitations*

In this section, we address RQ2, which concerns the strengths and limitations of the solutions and methods raised in the previous subsection.

6.4.2.1 Scientific Papers

Table 6.4 presents the strengths and limitations of the collected research articles. Please note that not all research articles are included in this research question.

Table 6.3 Methodologies proposed by projects

Inter-blockchain solution	Description	Project ID	Freq.
Atomic cross-chain swap	This approach utilizes the following basic mechanisms: multi-signatures, hash-locks, time-locks, and basic scripting	P11, P13, P15, P20, P26, P27, P29, P30, P31, P35	10
Sidechain	The main blockchain is linked to independent blockchains (sidechains) and the asset may be transferred using a two-way peg process	P1, P2, P3, P4, P12, P18, P19, P21, P22, P23, P34	12
Router	Blockchain entities or nodes serve as routers, sending requests between different blockchain networks	P5	1
Atomic cross-chain swap	This approach utilizes the basic mechanisms: multi-signatures, hash-locks, time-locks, and basic scripting	A15, A18, A22, A24, A28, A31, A32, A36	8
Smart Contract	To build interoperable protocols between independent blockchain networks, a smart contract or a series of smart contracts is used	P16, P17, P24, P28, P32	5
Bringing	A specially programmed component enables the intercommunication between different blockchains and controls the validation of the transactions	P8, P10, P14	2
Nexus and ICON Republic	A Nexus is a collection of multiple blockchain networks ICON Republic portal is the link connecting independent blockchains (Nexus)	P9	1
Open Chain Access Protocol, Chain Adapter, Blocklet	Open Chain Access Protocol: enables different blockchains to interact with one another by assessing blockchains underlayers. Chain Adapter: converts the blockchain into the standardized APIs specified in the Open Chain Access Layer under layer protocols. Blocklet: manages different types of applications (smart contracts, oracles, management of capital and properties, and business logic off-chain)	P36	1
Zones, Hub, IBC protocol	Zones are different separate blockchains connected to Hub through IBC protocol	P7	1

Moreover, we found that most of the limitations related to inter-blockchain communication fall into the categories of security, privacy, lack of control, scalability, and lack of support for hybrid systems. This allows us to surmise that those limitations will open the gate for researchers to think of them as future directions to solve those challenges for inter-blockchain communication. On the other hand, most of the strengths found in the proposed methods involved achieving communication between different chains, allowing scalability for any interoperable blockchain network, and building securable, cheap, and fast solutions. Furthermore, scientific papers focused on the efficiency, feasibility, and flexibility of their solutions.

Table 6.4 Strengths and weaknesses of scientific papers

Strength	Paper ID	Limitation	Paper ID
Enable communication between blockchain systems	A1, A2, A6, A9, A10, A31	Privacy	A1, A3, A16, A20
No third party needed	A2, A4	Security	A2, A7, A16, A20, A24
High throughput	A5, A17	Scalability	A7, A26
Efficiency, feasibility, flexibility	A8, A11, A17, A21, A26, A27, A35, A37	Need an efficient consensus algorithm	A13, A16
Support heterogeneous consensus protocol	A5	Efficiency	A10
Atomic cross-chain compatibility	A7, A8, A11, A18	Throughput affected	A4
Scalability	A3, A13, A15, A17, A32	Lack of control	A19
Security	A10, A11, A13, A14, A17, A27, A31, A32, A33, A34, A37	Data store is in the provider's local database	A6, A10
Support multi-token users	A14	Does not support token transfer	A18
Low overhead, latency	A17	Exchange crypto assets in a seamless manner	A29, A18
Improve access control	A20	Lack of trust	A35
Ease of use and adoption	A27	Long lag for reconciliation	A36
No single point of failure	A34	Slow access time	A38
Improve data storage	A20	Restricted by latency and gas fee cost of the other blockchain platform	A39

6.4.2.2 Projects

In this section, we address the strengths and limitations of the collected projects that apply and achieve interoperability between blockchain networks. Table 6.5 presents each project's strengths and weaknesses in their ability to provide solutions and methods for inter-blockchain communication. According to Table 6.5, the strengths of most of the collected projects involved achieving interoperable connections and communications between two blockchain networks. Furthermore, most projects were able to achieve high scalability and security and to reduce the transaction costs of their solutions. On the other hand, some interesting limitations were revealed by the Plasma project, which addressed the issue of mass exit. This project demonstrated a situation where several users simultaneously attempted to release their Plasma chains, flooding the root chain and leading to network congestion.

Table 6.5 Strengths and limitations of projects collected

Strength	Project ID	Limitation	Project ID
Successful communicating and interoperable connection	P5, P7, P10, P11, P14, P15, P18, P23, P33, P34, P35	Compatibility	P37
High scalability	P1, P3, P7, P8, P9, P13, P14, P36	Relies on PoW, which is inefficient	P1
Secure	P1, P2, P14, P18, P24, P25, P31, P34	Network congestion (mass exit problem)	P3
Reduce transaction cost	P1, P4, P13, P31, P36	Geographic concentration	P4
Fast	P9, P13, P18, P19	Low TPS rate	P6
Easily adaptable	P8, P9, P14, P25	Gets slower with an increase in validators	P7
Confidential transaction	P2, P18, P27	Focused and designed for Korea	P9
Efficient and decentralized	P22, P26, P24	Scaling	P10
Trustless reutilization	P12, P24, P28	Not completely decentralized	P11
Compatible with scaling solution	P3, P8	Limited to digital assets	P12
Coin interchangeable with other units of the same coin	P6, P24	Uses a large amount of processing power	P14
Optimization	P12, P36	No rigorous technical documents	P19
High performance	P9, P36	Support interaction between a maximum of two blockchains networks	P23
Real-time value exchange	P29	Strict requirement	P27
Full control of assets	P31	No instant atomic swap	P28
Encryption algorithms supported	P34	The sender and receiver must know the private asset transfer key	P29
Cloud supported	P36	Does not support negotiation protocol	P31
Increasing bitcoin utilization	P1	…	…
Enable payment across different networks	P15	…	…
Asset issuance, flexible configuration	P2	…	…

Table 6.6 Performance metrics frequencies among scientific papers

Scientific papers	Quantity
Cost (computational cost and monetary cost)	6
I/O overhead	4
Process time	4
Transaction per second	3
Gas per transaction	3
Latency	3
Security risk	2
Scalability	2
Throughput	1
Speed	1
CPU utility	1
Query time	1

6.4.3 Performance and Evaluation Metrics

In this section, we present the performance and evaluation metrics applied to test the quality of the methods and solutions proposed by the researchers. Moreover, we determine which metrics have been applied most and discuss the metrics in greater detail.

6.4.3.1 Scientific Papers

In this section, we discuss the performance metrics most applied by the selected scientific papers. Table 6.6 presents the metrics and the frequency of each metric applied in the collected scientific papers. Please note that most of the papers applied more than one performance metric to evaluate the performance of their proposed solution. On the other hand, some papers did not apply any experiments to their solutions. Moreover, the most frequently used performance metrics applied were solution cost, I/O overhead, and processing time.

6.4.3.2 Projects

In this section, we present the performance metrics used by the projects that implement cross-blockchain. Table 6.7 lists the metrics applied and presents the frequency of their application in the collected projects. The most frequently applied performance metric was transaction per second, with 14 projects applying this performance to test the quality of their projects. Block time, cost, and block confirmation were also applied by several projects each. Please note that some of the projects applied several performance metrics.

Table 6.7 Performance metrics frequencies among projects

Projects	Quantity
Cost (computational cost and monetary cost)	6
Transaction per second	14
Block time	5
Cost	5
Block confirmation	4
Block size	2
Process time	1
Gas limit	1
Latency	1
Transaction confirmation	1
Transaction per block	1
Throughput	1

6.4.4 Application and Context of Usage of Inter-blockchain

In this section, we aim to identify the applications and use cases of inter-blockchain to address RQ4. Inter-blockchain is an evolving technology that enhances multiple structures in different areas and applications. In this regard, the applications that implement this technology must give independent blockchains the ability to connect and communicate with one another. Inter-blockchain can be used in a wide variety of applications. In this review, we defined multiple distinct applications in the selected papers and projects

6.4.4.1 Scientific Papers

Table 6.8 represents the list of inter-blockchain applications discussed in scientific papers. Moreover, the tables provide detailed information on the frequency with which a given inter-blockchain application is used in the selected papers.

As shown in Table 6.8, the review indicates that healthcare and finance and payment are the applications that most often implement inter-blockchain in the selected documents, with a percentage of 15% and 17%, respectively. However, it is obvious from the review that inter-blockchain can be applied in a variety of fields.

6.4.4.2 Projects

In this subsection, we discuss the applications used in the selected projects integrating blockchain interoperability. In Table 6.9, it can be seen that inter-blockchain communication was frequently integrated in decentralized exchange and finance and payment applications, with proportions of 12% and 21%, respectively. Business

Table 6.8 Inter-blockchain applications among scientific papers

Application	Paper ID	Freq.	Percentage
Arbitrary blockchain system	A2	1	2%
Asset transfer application	A5, A15	2	4%
Can be applied in many fields	A1, A3, A10, A11, A16, A24, A28, A29, A31, A32, A35	11	23%
Chain communication	A14, A17	2	4%
Cloud computing	A15	1	2%
Decentralized exchange	A7, A21, A34	3	6%
Finance and payment applications	A5, A8, A12, A13, A15, A26, A27, A34	8	17%
Gaming	A19, A39	2	4%
Healthcare	A6, A20, A22, A23, A33, A36, A37	7	15%
N/A	A4, A9, A38	3	3%
Retail services	A5	1	2%
Security systems	A18	1	2%
Smart contract applications	A25	1	2%
Storage services	A34	1	2%
Supply chain system	A5, A27, A30	3	6%

and supply chain systems are also applications that quite often implement inter-blockchain communication, with a percentage of 8%.

6.4.5 *Future Direction of Inter-blockchain*

In this section, we present future directions for innovation in inter-blockchain communication. Generally, it seems clear that more blockchain technology will be adopted in the ecosystems over time. There is currently a lack of interoperable and scalable solutions available to develop decentralized applications. Furthermore, there is a continuing gap between theoretical and practical applications, since much of the work currently underway is mostly conceptual. Recent developments in this field make interoperability a fact that needs to be addressed.

6.4.5.1 Scientific Papers

Table 6.10 shows the future directions for blockchain interoperability discussed in the selected scientific papers. As shown in Table 6.10, most of the researchers' future directions involve improving the security and privacy of their proposed solutions. Moreover, many researchers in the field plan to verify connections with formal methods, implement different network topologies, and improve efficiency and performance.

Table 6.9 Inter-blockchain applications among projects

Application	Project ID	Freq.	Percentage
Artificial intelligence systems	P35, P36	2	2%
Asset transfer applications	P13, P16, P18, P25, P33	6	5%
Business applications	P9, P10, P11, P13, P14, P32, P33, P36	9	8%
Can be applied in many fields	P11	1	1%
Chain communication	P8, P14, P21, P23, P25	5	4%
Cloud computing	P36	1	1%
Cyber-physical systems	P36	1	1%
Decentralized asset trading	P11, P17, P25, P30, P35	5	4%
Decentralized exchange	P1, P4, P11, P13, P14, P20, P23, P25, P26, P29, P31, P34, P35	14	12%
Development of commercial applications	P13, P19, P28, P30, P36	5	4%
Finance and payment applications	P1, P3, P4, P5, P6, P7, P8, P9, P11, P13, P14, P15, P16, P18, P21, P24, P26, P28, P29, P30, P32, P33, P35, P36, P37	25	21%
Gaming	P1, P4, P8, P14, P19, P21, P36	7	6%
Government organizations	P9, P36	2	2%
Healthcare	P5, P9, P25	3	3%
Internet of Things	P8, P11, P14, P15, P32	5	4%
N/A	P2, P22, P27	3	3%
Retail services	P1, P15	2	2%
Security systems	P9	1	1%
Smart contract applications	P8, P24, P32, P34	4	3%
Storage services	P8, P12, P16, P35	4	3%
Supply chain system	P1, P5, P8, P11, P14, P15, P21, P29, P32, P33	10	8%
Voting Systems	P1, P4, P26	3	3%

6.4.5.2 Projects

In this part, we present the future directions of the projects that currently implement cross-blockchain communication. Table 6.11 shows the future directions discussed in the project documentation. Various projects are planning to form more strategic partnerships and providers, to develop and consider more protocols, to generalize recursive SNARKs/STARKs to boost the security of the project, and to upgrade the consensus engine and smart contract system.

Table 6.10 Future direction of scientific papers

Future Direction	Paper ID
Improve security and privacy	A2, A3, A5, A16, A18, A21, A31, A34
Verify connection with formal methods	A2, A4, A24, A37
Discuss different network topologies	A4, A27, A28, A36
Improve efficiency and performance	A10, A25, A30, A38
Design an efficient consensus algorithm or improve it	A3, A27, A32
Add access control	A2, A30, A31
Add cloud computing platform	A22, A36
Add encryption	A2
Improve adaptability, scalability	A6
Improve data storage	A10
Atomic swaps on other blockchains	A7
Transaction-related error handling	A21
Reduce cost and support token transfer	A25
Analysis of the behavior of dishonest trustee	A26
Analysis of the behavior of irrational observer	A26

Table 6.11 Future direction of projects

Future direction	Project ID
Generalize recursive SNARKs/STARKS to increase security	P3, P21
Form strategic partnerships and add more products and providers	P9, P14
Protocol consideration for development	P17, P36
Upgrade consensus engine and smart contract system	P19, P37
Enable trustless messaging	P8
Work on other Hyperledger projects	P15
Translate script operation onto discrete logarithm information	P6
Focus on the number of extensions	P8
Scaling to more bridged chains	P17
Increase scalability and usability and enable para threads	P8
Transaction and storage fees	P19
Release of public API facilitating automatic shifting	P20
Evolve more refined approaches for veto contrast	P27
Add more features and increase the number of governing members	P34
Implement chain adapter for bitcoin, Ethereum, and Hyperledger	P36
Support Windows Azure, Google Compute Engine, IBM Bluemix	P36

6.5 Limitation of This Review

This systematic literature review is restricted to journals, conference papers, and studies related to inter-blockchain. By applying our research strategy at the first stage of the review, we filtered out a significant number of research papers that were found to be irrelevant. This guaranteed that the selected research articles fulfilled the criteria of this review. However, we assume that this analysis may have been further improved by considering additional references. Our pool of data may have been constrained by our stringent quality assessment criteria, which included only relevant papers that could provide synthesized findings.

6.6 Conclusion

In this SLR, we analyzed and compared the methodologies used in the current solutions for achieving blockchain interoperability. We examined several factors such as performance metrics (throughput, transmission time, block confirmation time), the strengths and limitations of the proposed solutions, and potential future directions. Our conclusion is summarized as follows:

- RQ1 shows that approximately 46% implement platform-based inter-blockchain communication and 39% implement protocol-based solutions in scientific papers. Moreover, 5 approaches were identified and the most frequently used to create inter-blockchain communication in scientific papers are sidechain, smart contract, atomic cross-chain swap, and router methods. On the other hand, for projects collected, we found that with a percentage of 57%, the most frequent inter-blockchain implementations are implemented as a platform type, and with a percentage of 40%, inter-blockchain protocols were created. Adding more, most of the projects leverage from the sidechain structure and atomic cross-chain swap technique as a solution for blockchain interoperability.
- RQ2 found that most of the limitation of inter-blockchain communication falls into the category of security, privacy, lack of control, scalability, and not supporting hybrid systems, as well as most of the strengths that have been found in the proposed methods were achieving the communication between different chains, allowing scalability for any interoperable blockchain network, and building securable, cheap, and fast solutions. On the other hand, for projects, we found that they were able to achieve high scalability and security and reduce the transaction cost of their solutions.
- RQ3 discussed the most applied performance metrics in scientific papers and projects. We found that cost performance is the most applied metric in scientific papers, whereas transmission per second is applied the most by the projects.
- RQ4 mentioned the most applied application of inter-blockchain. The most applied context for scientific papers and projects is finance and payment applications. Adding more, most of the scientific paper's context can be applicable in many fields.
- RQ5 presented the future directions for the scientific papers and projects. We found that the most common future direction for scientific papers is improving the security and privacy of their proposed solutions. Alternatively, for projects,

we did not find a lot of similarities, but some of them were working with other network topologies such as Hyperledger (Tables 6.12 and 6.13).

As part of our future work, we intend to implement and develop some of the inter-blockchain solutions, and we plan to conduct some experiments to test and enhance some of the blockchain interoperability problems discussed in Sect. 6.4.2 and improve the performance of our solution. Moreover, providing a discussion of the technical background of our inter-blockchain approach will be a focus in our future work (Tables 6.14 and 6.15).

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Appendix

See Figs. 6.4 and 6.5 and Tables 6.12 to 6.15.

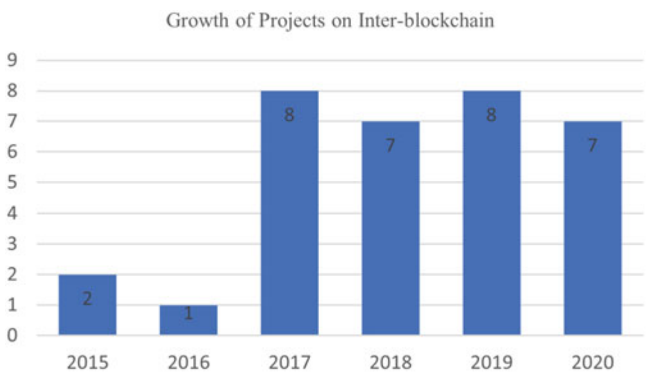

Fig. 6.4 Growth of projects based on years

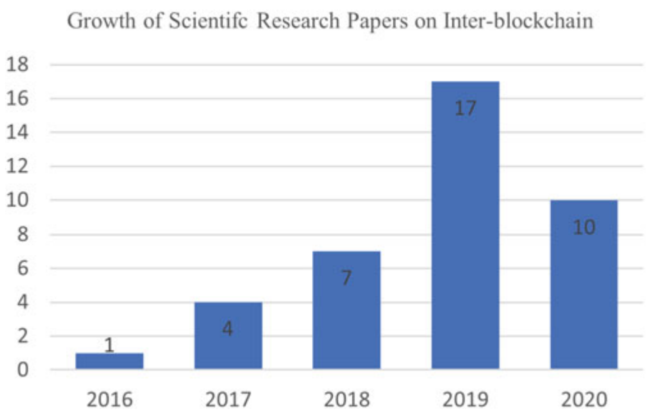

Fig. 6.5 Growth of scientific papers based on years

Table 6.12 QAR distribution among scientific papers

Result	No. of paper	Paper number
4	1	A39
5.5	1	A9
5.75	1	A12
6	2	A32, A36
6.75	1	A23
7	3	A34, A35, A22
7.25	1	A16
7.75	2	A27, A38
8.25	4	A3, A4, A19, A30
8.5	6	A1, A5, A6, A8, A18, A24, A31
8.75	2	A15, A29
9	4	A13, A17, A20, A25
9.25	1	A10
9.5	3	A7, A11, A28
9.75	4	A14, A21, A26, A37
10	2	A2, A33

Table 6.13 QAR distribution among projects

Result	No. of Projects	Paper number
4	1	P29
4.25	1	P37
4.5	1	P15
5	1	P22
5.75	1	P2
6.25	1	P23
6.5	1	P24
7	4	P4, P10, P13, P26
7.25	3	P20, P31, P35
7.5	1	P27
7.75	2	P21, P30
8.25	2	P18, P7
8.5	4	P9, P11, P19, P34
8.75	5	P3, P5, P6, P8, P33
9	4	P1, P14, P25, P32
9.25	4	P12, P16, P28, P36
9.5	1	P17

Table 6.14 Selected scientific papers and projects

ID	Title	Type	Year	Ref
A1	"Blockchain Router: A Cross-Chain Communication Protocol"	Journal	2017	[75]
A2	"A Multiple Blockchains Architecture on Inter-Blockchain Communication"	Conference	2018	[42]
A3	"InterChain: A Framework to Support Blockchain Interoperability"	Conference	2018	[23]
A4	"Inter-Blockchain Communication"	Conference	2017	[18]
A5	"Towards Scalable and Private Industrial Blockchains"	Conference	2018	[48]
A6	"Towards Secure Interoperability between Heterogeneous Blockchains using Smart Contracts"	Conference	2017	[20]
A7	"An Analysis of Atomic Swaps on and between Ethereum Blockchains using Smart Contracts"	Journal	2018	[7]
A8	"XCLAIM: Trustless, Interoperable, Cryptocurrency-Backed Assets"	Conference	2019	[84]
A9	"Toward an Interoperability Architecture for Blockchain Autonomous Systems"	Journal	2019	[34]
A10	"A Multi-blockchain Architecture Supporting Cross-Blockchain Communication"	Conference	2020	[79]
A11	"Towards a Novel Architecture for Enabling Interoperability among Multiple Blockchains"	Conference	2018	[41]
A12	"Inter-Bank Payment System on Enterprise Blockchain Platform"	Conference	2018	[76]
A13	"Multi-Blockchain Model For Central Bank Digital Currency"	Conference	2017	[71]
A14	"A New Consensus Protocol for Blockchain Interoperability Architecture"	Journal	2020	[57]
A15	"HyperService: Interoperability and Programmability Across Heterogeneous Blockchains"	Conference	2019	[50]
A16	"SoK: Communication Across Distributed Ledgers"	Journal	2019	[83]
A17	"An Electricity Cross-Chain Platform Based on Sidechain Relay"	Journal	2020	[77]
A18	"Atomic Cross-Chain Swaps: Development, Trajectory and Potential of Non-Monetary Digital Token Swap Facilities"	Journal	2019	[53]
A19	"Towards Blockchain Interoperability: Improving Video Games Data Exchange"	Conference	2019	[8]
A20	"Interoperability and Synchronization Management of Blockchain-Based Decentralized e-Health Systems"	Journal	2020	[8, 9]
A21	"Bifröst: a Modular Blockchain Interoperability API"	Conference	2019	[68]
A22	"Blockchain-Based Interoperable Electronic Health Record Sharing Framework"	Conference	2019	[16]
A23	"CEPS: A Cross-Blockchain based Electronic Health Records Privacy-Preserving Scheme"	Conference	2020	[15]
A24	"Reliable inter-blockchain communication framework for improving scalability"	Journal	2020	[49]
A25	"Towards Blockchain Interoperability"	Report	2020	[69]
A26	"Disincentivizing Double Spend Attacks Across Interoperable Blockchains"	Conference	2019	[66]

(continued)

Table 6.14 (continued)

ID	Title	Type	Year	Ref
A27	"Enabling Enterprise Blockchain Interoperability with Trusted Data Transfer (Industry Track)"	Conference	2019	[1]
A28	"Dextt: Deterministic Cross-Blockchain Token Transfers"	Journal	2019	[12]
A29	"Cross-chain interoperability among blockchain-based systems using transactions"	Journal	2020	[60]
A30	"Toward a Policy-based Blockchain Agnostic Framework"	Conference	2019	[67]
A31	"A Blueprint for Interoperable Blockchains"	Journal	2019	[24]
A32	"CVEM: A Cross-chain Value Exchange Mechanism"	Conference	2018	[82]
A33	"Enhanced Decentralized Management of Patient-Driven Interoperability Based on Blockchain"	Conference	2019	[43]
A34	"Strong Federations: An Interoperable Blockchain Solution to Centralized Third-Party Risks"	Journal	2016	[22]
A35	"A Workflow Interoperability Approach Based on Blockchain"	Conference	2020	[28]
A36	"Blockchain-Based Interoperable Electronic Health Record Sharing Framework"	Conference	2019	[16]
A37	"Blockchain-based Interoperable Healthcare using Zero-Knowledge Proofs and Proxy Re-Encryption"	Conference	2020	[70]
A38	"A Framework for Blockchain Interoperability and Runtime Selection"	Journal	2019	[29]
A39	"Demo Abstract: An Interoperable Avatar Framework Across Multiple Games and Blockchains"	Conference	2019	[14]
P1	"RSK"	Project	2015	[55]
P2	"Elements Alpha"	Project	2015	[25]
P3	"Plasma"	Project	2017	[63]
P4	"POA Network"	Project	2017	[78]
P5	"Anlink Network"	Project	2017	[3]
P6	"Mimblewimble"	Project	2016	[56]
P7	"Cosmos "	Project	2019	[46]
P8	"Polkadot"	Project	2020	[61]
P9	"ICON"	Project	2019	[37]
P10	"AION"	Project	2017	[32]
P11	"Wanchain"	Project	2017	[74]
P12	"Blocknet"	Project	2018	[35]
P13	"Interledger"	Project	2017	[72]
P14	"ARK"	Project	2019	[4]
P15	"Hyperledger Quilt"	Project	2019	[39]
P16	"Metronome"	Project	2018	[52]
P17	"Block Collider"	Project	2018	[10]
P18	"Liquid"	Project	2018	[54]
P19	"Loom network"	Project	–	[40]
P20	"Pantos"	Project	2018	[27]
P21	"Zendoo"	Project	2020	[36]
P22	"Testimonium "	Project	2020	[30]

(continued)

Table 6.14 (continued)

ID	Title	Type	Year	Ref
P23	"Peace Relay"	Project	–	[58]
P24	"BTC Relay "	Project	2018	[77]
P25	"Hyperledger Cactus"	Project	2020	[13]
P26	"chainX"	Project	2020	[17]
P27	"DeXTT"	Project	2019	[11]
P28	"Fusion"	Project	2017	[31]
P29	"Tokrex"	Project	–	[73]
P30	"Komodo"	Project	2019	[45]
P31	"COMIT"	Project	2020	[19]
P32	"chainlink"	Project	2019	[26]
P33	"HyperExchange"	Project	2018	[38]
P34	"PolyNetwork"	Project	2020	[62]
P35	"Ferrum Network"	Project	2019	[81]
P36	"ArcBlock"	Project	2017	[51]
P37	"GOST Protocol"	Project	–	[33]

Table 6.15 QAR results

Number	QAR 1	QAR 2	QAR 3	QAR 4	QAR 5	QAR 6	QAR 7	QAR 8	QAR 9	QAR 10	Total
A1	1	1	0.75	0.75	0.5	1	0.75	0.75	1	1	8.5
A2	1	1	1	1	1	1	1	1	1	1	10
A3	1	1	1	1	1	1	0.5	0.5	0.25	1	8.25
A4	1	1	0	0.75	1	1	1	0.75	0.75	1	8.25
A5	1	1	0.25	1	0.25	1	1	1	1	1	8.5
A6	1	1	1	1	1	1	0.5	0.75	0.25	1	8.5
A7	1	0.5	1	1	1	1	1	1	1	1	9.5
A8	1	0.75	0.5	1	0.25	1	1	1	1	1	8.5
A9	1	1	0.75	0.5	0.25	1	0	0	0	1	5.5
A10	1	1	0.5	1	1	1	1	0.75	1	1	9.25
A11	1	1	0.5	1	1	1	1	1	1	1	9.5
A12	1	1	1	0.75	0.25	0.75	0	0	0	1	5.75
A13	1	1	1	0.75	0.25	1	1	1	1	1	9
A14	1	1	1	1	0.75	1	1	1	1	1	9.75
A15	1	0.75	1	1	0.25	1	1	0.75	1	1	8.75
A16	1	0.75	0.25	0.25	1	0.75	0.25	1	1	1	7.25
A17	1	1	0.75	1	0.25	1	1	1	1	1	9
A18	1	1	1	1	1	1	0.25	1	0.25	1	8.5
A19	1	1	1	1	1	1	0.25	0.75	0.25	1	8.25
A20	1		1	1	1	1	1	1	1	1	9
A21	1	1	0.75	1	1	1	1	1	1	1	9.75
A22	1	1	1	0.25	1	0.25	0.25	0.5	0.75	1	7
A23	1	1	1	0	0	0.25	1	0.5	1	1	6.75
A24	1	0.75	0.5	0.75	1	0.5	1	1	1	1	8.5
A25	1	1	0.25	1	0.75	1	1	1	1	1	9
A26	1	1	0.75	1	1	1	1	1	1	1	9.75
A27	1	1	1	1	1	1	0	0.25	0.5	1	7.75
A28	1	1	0.5	1	1	1	1	1	1	1	9.5
A29	1	1	0.5	0.5	1	1	1	0.75	1	1	8.75
A30	1	1	1	0.75	1	1	0.25	1	0.25	1	8.25
A31	1	1	1	1	1	1	0	0.75	0.75	1	8.5
A32	1	1	0.25	1	0.25	1	0	0.25	0.25	1	6
A33	1	1	1	1	1	1	1	1	1	1	10
A34	1	1	1	1	0.25	1	0.25	0.25	0.25	1	7
A35	1	1	0.25	1	1	1	0.25	0.25	0.35	1	7.1
A36	1	1	1	0.5	0.5	1	0	0	0	1	6
A37	1	1	1	1	0.75	1	1	1	1	1	9.75
A38	1	1	0.25	1	1	1	0.5	0.5	0.5	1	7.75
A39	0.5	0.25	1	0.25	0.25	0.75	0	0	0	1	4

(continued)

Table 6.15 (continued)

Number	QAR 1	QAR 2	QAR 3	QAR 4	QAR 5	QAR 6	QAR 7	QAR 8	QAR 9	QAR 10	Total
P1	1	1	1	1	0	1	1	1	1	1	9
P2	1	0.5	1	1	0.25	1	0	0	0	1	5.75
P3	1	1	1	1	1	1	0.75	0.25	0.75	1	8.75
P4	1	0.75	1	0.75	0.75	0.25	1	0.25	0.25	1	7
P5	1	1	1	1	1	1	0.75	0	1	1	8.75
P6	1	1	1	1	1	0.75	1	0	1	1	8.75
P7	1	1	1	1	0.5	1	1	0	0.75	1	8.25
P8	1	1	1	1	0	1	1	0.75	1	1	8.75
P9	1	1	1	1	0.5	1	1	0.25	0.75	1	8.5
P10	1	1	0.5	1	0	1	0.75	0	0.75	1	7
P11	1	1	1	1	0.75	1	0.75	0.25	0.75	1	8.5
P12	1	1	1	1	1	1	1	0.25	1	1	9.25
P13	1	1	1	1	0.25	1	0.25	0.25	0.25	1	7
P14	1	0.5	1	1	0.75	1	1	0.75	1	1	9
P15	0.5	0	1	1	0	1	0	0	0	1	4.5
P16	1	1	1	1	0.25	1	1	1	1	1	9.25
P17	1	1	1	1	1	1	1	0.5	1	1	9.5
P18	1	1	1	1	0.5	1	1	0	0.75	1	8.25
P19	1	0.5	1	1	1	1	1	0	1	1	8.5
P20	1	1	0.75	1	0.75	1	0.25	0	0.5	1	7.25
P21	1	1	0.75	1	1	1	0.25	0.25	0.5	1	7.75
P22	1	0.5	0	0.5	0.5	1	0.25	0	0.25	1	5
P23	1	0.5	1	0.75	0.75	0.75	0.25	0	0.25	1	6.25
P24	1	1	0.75	1	0	1	0.25	0	0.5	1	6.5
P25	1	1	1	1	1	1	1	0	1	1	9
P26	1	1	0.75	1	0.25	1	0.25	0	0.75	1	7
P27	1	1	0	1	1	1	0.75	0	0.75	1	7.5
P28	1	1	1	1	1	1	1	0.25	1	1	9.25
P29	1	0.25	0.25	0.5	0.5	0.25	0.25	0	0	1	4
P30	1	0.5	0.75	0.75	0.75	1	0.75	0.5	0.75	1	7.75
P31	1	1	1	1	0.5	1	0.25	0	0.5	1	7.25
P32	1	1	1	1	0	1	1	1	1	1	9
P33	1	0.75	1	1	0	1	1	1	1	1	8.75
P34	1	1	1	1	0.25	1	1	0.25	1	1	8.5
P35	1	1	1	1	0.25	0.75	0.5	0	0.75	1	7.25
P36	1	0.75	1	1	0.75	1	1	0.75	1	1	9.25
P37	1	0.25	0.25	0.5	0.25	0.5	0.25	0	0.25	1	4.25

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