Universidad de Oviedo

Programa de Doctorado en Economía y Empresa

Análisis y tecnología blockchain para la industria/ Blockchain analysis and technology for the industry

Tesis Doctoral

Autor: Simón Fernández Vázquez

Directores:
David de la Fuente García
Rafael Rosillo Camblor

Noviembre, 2022

Agradecimientos

Me gustaría expresar mi agradecimiento a todas las personas e instituciones que han hecho posible la realización de esta tesis doctoral.

A mis directores, David de la Fuente y Rafael Rosillo, tanto por su apoyo desde el primer día como su implicación en el proceso de investigación a lo largo de estos años y por la confianza para la consecución de los objetivos propuestos.

A los componentes del Grupo de Ingeniería de Organización (GIO) de la Universidad de Oviedo, por su predisposición para ayudarme tanto en la investigación como en los diversos congresos a los que he podido asistir. También a los demás miembros de todo Departamento de Administración de Empresas de la Universidad de Oviedo con los que he tenido la oportunidad de coincidir y colaborar, así como a la Universidad de Luxemburgo, al Instituto Universitario de Tecnología Industrial de Asturias (IUTA) y al Centro Tecnológico de la Información y la Comunicación (CTIC), por su incalculable ayuda durante estos años.

A mis amigos, en especial a Juan Martínez, sin el cual posiblemente esta tesis doctoral nunca se hubiera llevado a cabo.

Por último a mi familia, por su apoyo diario y fuente inagotable de paciencia.

A todos ellos, gracias.

Universidad de Oviedo

RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis	
Español/Otro Idioma: Análisis y tecnología Blockchain para la industria	Inglés: Blockchain analysis and technology for the industry

2.- Autor	
Nombre: Simón Fernández Vázquez	DNI/Pasaporte/NIE: 7
Programa de Doctorado: Economía y Empresa	
Órgano responsable: CIP y Comisión académica del programa de doctorado en Economía y Empresa	

RESUMEN (en español)

En los últimos años, hemos presenciado el advenimiento de una ola innovadora de tecnología transformadora distribuida a través de múltiples industrias, conocida como Industria 4.0 Este término se introdujo por primera vez en 2011, en referencia a cómo los avances tecnológicos cambiarían profundamente la organización de las cadenas globales de suministro. Aunque la Industria 4.0 ha sido generalmente aceptada por el ámbito académico y profesional, también se han desarrollado otros conceptos en este período de tiempo que se refieren al uso de tecnologías digitales en la producción. En este contexto, esta nueva industria representa un cambio desde una producción planificada y centralizada a una producción dinámica y descentralizada, diseñada para mejorar la calidad de los bienes, los procesos a medida y la flexibilidad de los sistemas.

Mediante el uso de un novedoso marco tecnológico como en el caso de blockchain, se pueden resolver muchos de los principales retos de la industria en cuanto a seguridad o monitoreo de productos durante toda la cadena de suministro. Blockchain proporciona un marco abierto y compartido entre sus usuarios. Las características innatas de esta tecnología hacen que la confianza de todas las partes involucradas aumente, a través de una mayor claridad en la trazabilidad de las transacciones. El objetivo en el medio plazo es permitir que máquinas, como las computadoras, desarrollen e interpreten conceptos como los de la mente humana.

Esta investigación trata de enfatizar, por un lado, los efectos favorables de la adopción de esta tecnología desde el prisma de la industria. Partiendo del desarrollo de un marco teórico acerca del uso de la tecnología blockchain en la gestión de la cadena de suministro, se analizan las principales ventajas y retos de la adopción de esta tecnología. Derivado de este desarrollo, se investigan las implicaciones que la implementación de blockchain puede tener en empresas del sector de tecnología financiera (*fintech*), un sector vanguardista en el uso de nuevas tecnologías. La investigación continúa con la exploración y comparación desde una perspectiva técnica de las tres mayores redes blockchain por capitalización de mercado: Bitcoin, Ethereum y Ripple. Esta investigación servirá como base a las empresas que adopten la tecnología blockchain, ayudándoles a escoger la red que mejor se adecúe a sus características. Esta tesis doctoral se completa con el análisis de una cadena de suministro habilitada para blockchain y sus implicaciones en la sostenibilidad en el largo plazo, en comparación con con las cadenas de suministro tradicionales, mediante el uso de la metodología de proceso de jerarquía analítica (AHP). Las conclusiones de este estudio son aplicables a las principales empresas industriales a lo largo de sus operaciones de cadena de suministro, como por ejemplo los sectores de logística, médico, de seguros y o el sector público en general.

Tanto la comunidad científica como la industria están cada vez más interesadas tanto en blockchain como en su aplicación. No obstante, esta tecnología se enfrenta obstáculos que deben superarse antes de poder expandirse aún más. Las mejoras en sus funciones, como la privacidad o la latencia se beneficiarían de mayores recursos para la investigación de su aplicación y una mayor inversión promovida desde la óptica empresarial. Si bien todavía estamos muy lejos de usar blockchain para resolver muchos de los problemas actuales, sus características brindan motivos para el optimismo.

RESUMEN (en Inglés)

In recent years, the world has witnessed the advent of an innovative wave of transformative technology distributed across multiple industries, known as Industry 4.0. This term was first introduced in 2011, referring to how technological advances would profoundly change the organization of companies and global supply chains. Although Industry 4.0 has been generally accepted by the academic and professional areas, other concepts have also been developed in this time period that refer to the use of digital technologies in production. In this context, this new industry represents a shift from planned and centralized production to dynamic and decentralized production, designed to improve the quality of goods, tailor-made processes and the flexibility of systems.

Through the use of a new technological framework such as blockchain, many of the main challenges of the industry in terms of security or monitoring of products throughout the supply chain can be solved. Blockchain provides an open and shared framework among its users. The innate characteristics of this technology increase the trust of all parties involved, through greater clarity in the traceability of transactions. The goal in the medium term is to allow machines, such as computers, to develop and interpret concepts like those of the human mind.

This research tries to emphasize, on the one hand, the favorable effects of the adoption of this technology from the perspective of the industry. Starting from the development of a theoretical framework about the use of blockchain technology in supply chain management, the main advantages and challenges of adopting this technology are analyzed. Derived from this development, the implications that the implementation of blockchain can have on companies in the financial technology sector (fintech), an avant-garde sector in the use of new technologies, are investigated. The research continues with the exploration and comparison from a technical perspective of the three largest blockchain networks by market capitalization: Bitcoin, Ethereum and Ripple. This research will serve as a basis for companies that adopt blockchain technology, helping them choose the network that best suits their characteristics. This doctoral thesis is completed with the analysis of a blockchain-enabled supply chain and its implications for long-term sustainability, compared to traditional supply chains, through the use of the Analytical Hierarchy Process (AHP) methodology. The findings of this study are applicable to major industrial companies throughout their supply chain operations, such as the logistics, medical, insurance, and/or public sector in general.

Both the scientific community and industry are increasingly interested in both blockchain and its application. However, this technology faces obstacles that must be overcome before it can be expanded further. Improvements in its functions, such as privacy or latency, would benefit from more resources for the investigation of its application and a greater investment promoted from the business sectors. Although there is still a long way for the adoption of blockchain to solve many of today's problems, its features provide reason for optimism.

SR. PRESIDENTE DE LA COMISIÓN ACADÉMICA DEL PROGRAMA DE DOCTORADO EN ECONOMÍA Y EMPRESA

Índice de contenidos

1 Capítulo 1: Introducción

1.1. Motivación

1.1.1 Importancia tecnológica en entornos dinámicos

La innovación tecnológica es considerada como una importante fuente de ventaja competitiva, así como un importante motor de crecimiento para las empresas. La revolución de la tecnología que estamos presenciando a día de hoy, es posiblemente una de las mayores de la historia, al menos por su rapidez en el desarrollo. Desde la capacidad de desplegar nuevos productos, a la reducción de los tiempos de suministro o la rapidez en los pagos, estamos asistiendo a una mejora continua y una adaptación de las empresas al entorno cambiante sin precedentes.

Diversos ámbitos están experimentando además importantes cambios, como una nueva actitud de los consumidores. Éstos juegan un papel mucho más relevante en el proceso de compra, alejándose de los tradicionales intermediarios pasivos y convirtiéndose en compradores que demandan nuevas características de los productos. Estas exigencias no se centran solamente en las particularidades técnicas de los mismos, sino que afectan a toda la cadena de suministro, como por ejemplo la sostenibilidad (Nayal et al., 2021).

La demanda de productos inteligentes, individualizados y sostenibles conducen al surgimiento de nuevos paradigmas de fabricación inteligente (por ejemplo, sistemas de producción cibernéticos o modelos de fabricación en la nube) en el modelo de la Industria 4.0 (Schwab, 2017). En la visión de esta nueva industria, las máquinas con un cierto grado de capacidad de interacción pueden cooperar entre sí a través del llamado internet de las cosas (*internet of things*, o IoT por sus siglas en inglés). Los datos de fabricación a gran escala se intercambian constantemente. Las máquinas son capaces de tomar decisiones de forma autónoma, lo que tiene una influencia clara y notoria en los procesos de fabricación (Cunha et al., 2021).

Sin embargo, estos paradigmas emergentes de fabricación de la Industria 4.0 carecen de herramientas para manejar los desafíos de seguridad y fiabilidad. Los sistemas de control industrial actuales generalmente sufren problemas de seguridad en los que los datos de fabricación pueden ser atacados o alterados. Datos erróneos y manipulados conducen a controles y decisiones incorrectas, representando una amenaza significativa para los complejos sistemas de fabricación. En la actualidad, la gestión de estos sistemas generalmente se basa en una plataforma centralizada, que adolece de una trazabilidad inadecuada de la información y una débil solidez frente a fallas del sistema (Büchi et al., 2020).

Debido a estas carencias en la gestión de las cadenas de suministro, existe una necesidad de investigación en la implementación de tecnologías complementarias o alternativas que permitan una gestión más eficiente de los recursos y procesos en la industria.

1.1.2 Blockchain como herramienta para las empresas

En el corto plazo, las máquinas y los componentes en la fabricación no requerirán el control humano para comunicarse. Estos avances ayudan en la formación y unión de redes de desarrollo interactivas y colectivas que involucran a toda clase de agentes. En la fabricación distribuida, las redes de producción a menudo se configuran como una respuesta a la competitividad global, combinando tecnologías y técnicas informáticas innovadoras (Chang et al., 2019). Desarrollos tecnológicos como la realidad virtual o la realidad aumentada, permiten reuniones en tiempo real o el intercambio de datos en entornos interactivos, constituyendo estrategias prometedoras para la cooperación empresarial. El trabajo colaborativo con estos sistemas virtuales puede aumentar la estabilidad de la producción y la calidad de los productos.

En el contexto de la cuarta revolución industrial, diversos avances han creado un gran impacto en la gestión de operaciones. El IoT, el análisis de big data y la computación en la nube influyen en las fuerzas financieras, culturales y sociales causando un impacto global en las operaciones comerciales. Pero quizá ninguna pueda llegar a tener el impacto que blockchain promete tener, debido a las características de esta tecnología revolucionaria (Lim et al., 2021).

La investigación de la tecnología blockchain desde un punto de vista de desarrollo informático no es algo nuevo. De hecho, lleva años siendo desallorada desde la creación de este sistema de bloques en 2008 (Nakamoto, 2008). Sin embargo, su implementación práctica en el mundo industrial requiere de nuevos estudios, principalmente relacionados con su viabilidad económica ligados a la correcta identificación de las necesidades concretas para las empresas. Por esta razón, cada vez más grupos de investigación que tradicionalmente se especializaban en la gestión de la cadena de suministro han identificado la necesidad de desarrollar proyectos de investigación en esta línea, ya que las mejoras reales como consecuencia de la puesta en práctica de esta tecnología son muy elevadas.

La mayoría de las industrias y empresas dependen de plataformas centrales de administración de información para preservar y manejar datos, la mayoría de los cuales son vulnerables a diferentes tipos de ataques (Ferreira et al., 2020). Blockchain, una tecnología descentralizada, se encuentra entre las innovaciones que tienen la capacidad de causar un mayor impacto en las empresas, ya sea tanto en la gestión de sus operaciones como en la gestión de su cadena de suministro (Qu et al., 2020).

En su origen, uno de los principales objetivos de blockchain era el de establecer el origen del producto mediante una perfecta trazabilidad. Esto incluye monitorear los movimientos de productos a través de numerosas redes de distribución como carne, pescado o café. La integración de toda la cadena de suministro en una red de cadena de bloques (blockchain, en inglés), desde los fabricantes o distribuidores hasta los consumidores, ayudará a las empresas a obtener información sobre el diseño de sus cadenas de suministro o a la ubicación de las plantas de fabricación más eficientes.

Por lo tanto, la elección de esta línea de investigación está relacionada con la necesidad de nuevos enfoques para apoyar la introducción de blockchain en las empresas, que es particularmente compleja debido a la interacción de numerosos factores sociales, tecnológicos y económicos. Para llevar a cabo el desarrollo de esta novedosa tecnología en el ámbito empresarial, se requiere la aplicación de métodos de gestión innovadores que permitan superar las limitaciones de las tecnologías implementadas hasta el momento.

1.2. Objetivos

Con base en las necesidades de investigación que inspiran esta tesis doctoral, se ha definido el siguiente objetivo principal:

El estudio y análisis en el proceso de implantación por parte de las empresas de la tecnología blockchain, que permitan perfeccionar las herramientas de apoyo a las mismas con el fin último de derivar en una mejora en la productividad y competitividad empresarial en un contexto económico cambiante y de creciente complejidad e incertidumbre. Este objetivo forma parte de una línea de trabajo que propone metodologías y técnicas cada vez más sofisticadas y adaptadas a las realidades de las empresas de la industria.

A su vez, este objetivo general se puede descomponer en seis objetivos específicos más concretos, que servirán de guía para este estudio:

- Objetivo Específico 1: El estudio y la investigación para el acercamiento a los avances y desarrollos presenciados en el mundo académico desde un prisma teórico, con los retos más actuales de las empresas en la industria desde una aplicación práctica.
- Objetivo Específico 2: El estudio de la situación actual en torno a la implementación de blockchain en las empresas de base tecnológico-financieras (Fintech), siendo las más propensas a la implementación de blockchain, así como los problemas más importantes a los que enfrenta esta tecnología y las alternativas con las que cuenta actualmente, con el objetivo de servir de guía para el resto de industrias.
- Objetivo Específico 3: La identificación de las principales características de las redes blockchain más destacadas, con el objetivo de servir de guía a las empresas que deseen adoptar esta tecnología.
- Objetivo Específico 4: El estudio de los principales protocolos de consenso desarrollados en blockchain, basado en el análisis exhaustivo las principales redes que permita a las empresas utilizar una u otra en función de sus características y objetivos.
- Objetivo Específico 5: La evaluación de los efectos de la adopción de blockchain en la gestión de la cadena de suministro, frente al sistema actual utilizado por la mayoría de las empresas.
- Objetivo Específico 6: El diseño y la implementación de una metodología para blockchain en la gestión sostenible de la cadena de suministro, utilizando el

proceso de jerarquía analítica (AHP por sus siglas en inglés) para la evaluación de forma estructurada de la toma de decisiones complejas.

1.3. Estructura de la tesis

Esta tesis doctoral se presenta mediante un compendio de publicaciones científicas. La tesis se estructura en 6 capítulos. Este primer capítulo sirve a modo de introducción, centrándose en la motivación y en los objetivos, tanto el objetivo general como los objetivos específicos. A lo largo del mismo se pone de manifiesto la importancia de la tecnología en la industria así como las más actuales alternativas para la gestión de la cadena de suministro, introduciendo novedosos sistemas que serán analizados en detalle en los sucesivos capítulos.

El capítulo 2 aborda el objetivo específico número 1, el cual se corresponde con la primera publicación. Mediante este artículo se propone la creación de un marco teórico acerca del uso de la tecnología blockchain en la gestión de la cadena de suministro, así como la ilustración y ponderación de la ventajas de esta novedosa tecnología a través de una revisión de la literatura. Como parte de este proceso, se han identificado aspectos clave como la sostenibilidad, la descentralización, la inmutabilidad de datos y los beneficios en el uso de contratos inteligentes, que sentarán las bases para el resto de las publicaciones y capítulos de esta tesis. Además, este capítulo tiene como objetivo proporcionar a la comunidad científica y la industria las repercusiones de la adopción de esta novedosa tecnología.

El tercer capítulo nace tras una primera investigación centrada en las características de blockchain y su aplicación en la industria 4.0. Derivado de esta investigación, se detectó un campo de mejora en la penetración de esta tecnología específicamente para empresas pertenecientes al campo de la tecnología financiera o fintech. La particularidad de estas compañías reside en su propensión a la aplicación de nuevas tecnologías para actividades financieras y de inversión. Estas empresas tienen la capacidad de ser, a priori, las más receptivas al uso de nuevas tecnologías dada la naturaleza de las mismas. Dado que las características de blockchain se adaptan a la misión y visión de estas empresas con base tecnológica, se ha llevado a cabo un exhaustivo estudio del arte, reflejando las limitaciones, brechas y tendencias futuras de blockchain en empresas fintech, abordando así los objetivos específicos 1 y 2.

Durante el trascurso de la tesis, se ha tenido oportunidad de colaborar con un centro de investigación especializado en el desarrollo de la tecnología blockchain para la industria. En concreto se trata de un centro de investigación en el que se asiste a empresas a aplicar técnicas de blockchain para el desarrollo y la implementación de soluciones que tienen como objetivo la descentralización de sus procesos. Como resultado de esta estrecha colaboración nació el cuarto capítulo, dedicado a explorar y comparar desde una perspectiva técnica las tres mayores redes blockchain por capitalización de mercado: Bitcoin, Ethereum y Ripple. Se trata de un estudio comparativo mediante el cual se espera que sirva como guía, tanto para académicos como para profesionales, hacia una mayor comprensión de las diferentes redes de blockchain y sus características a la hora de adoptar dicha tecnología. La interpretación y el entendimiento de las particularidades de cada red es un primer paso fundamental para la correcta implementación y desarrollo de esta tecnología en las empresas. Es por esto por lo que esta publicación adquiere una gran relevancia. Mediante este capítulo se pretenden abordar los objetivos específicos 3 y 4 de esta tesis.

El quinto capítulo de esta tesis se centra en la cadena de suministro de las empresas. Sin importar el tamaño de la misma, la gestión de la cadena de suministro es una prioridad para todos los gerentes y directivos. La gestión de esta cadena engloba todos los procesos tanto directos como indirectos que satisfacen las necesidades de suministro, desde proveedores, almacenes de materias primas, canales de distribución o clientes finales. Debido a la importancia capital para las empresas de una correcta gestión de su cadena de suministro, siendo este un punto fundamental en el buen funcionamiento de las mismas, este capítulo introduce, mediante la conocida metodología de proceso de jerarquía analítica (AHP), el estudio de una cadena de suministro sostenible aplicando la tecnología blockchain. Mediante este análisis, se pone fin al objetivo principal de la investigación, así como a los objetivos específicos 5 y 6.

Finalmente, el sexto capítulo aborda las conclusiones de la presente tesis doctoral, así como extensiones y futuras líneas de trabajo.

2 Capítulo 2: The application of distributed ledger technology in Industry 4.0

Este primer capítulo se centra simultáneamente en los dos primeros objetivos de la tesis doctoral. Se propone un acercamiento hacia a la industria 4.0 desde el prisma de blockchain. Además se realiza un análisis de las implicaciones de la combinación de blockchain con el IoT, mediante la conectividad de dispositivos y sensores. Esta combinación está demostrando ser un enfoque que ahorra tiempo y dinero a las empresas, además de generar una gran cantidad de datos. Sin embargo, solo un pequeño porcentaje de los actores en la industria utilizan blockchain.

En el presente artículo se pone de manifiesto la capacidad de blockchain para rastrear un bien a lo largo de toda la cadena de suministro, siendo esta una de sus mayores virtudes. El hecho de que el libro mayor distribuido de blockchain sea casi imposible de alterar sirve como la herramienta perfecta para mantener un registro completo del intercambio de propiedad que ocurre a lo largo de, por ejemplo, las cadenas de suministro. Las ventajas de la tecnología blockchain han atraído a la comunidad científica para determinar sus posibles usos en la industria en general, y en el campo de la cadena de suministro en particular. Esta tecnología permite controlar y monitorear los esfuerzos de mitigación de riesgos y fortalecer a las empresas, resultando muy útil para, por ejemplo, prevenir fallas en la seguridad.

La segunda parte del trabajo se centra en los llamados contratos inteligentes. Estos contratos son un sistema inherente a blockchain, completamente independiente y autónomo que está codificado para realizar una serie de transacciones sin la intervención de un ser humano. Para que un contrato ejecute las transacciones, se debe incluir la programación de un código que tiene como objetivo la realización de una acción específica si se cumplen una serie de requisitos. La incorporación de los contratos inteligentes se basa principalmente en la seguridad de su aplicación y la reducción de, por ejemplo, el riesgo financiero.

Este estudio concluye que el uso emergente y la implementación de blockchain en la Industria 4.0 se encuentra en una fase preliminar. Algunos estudios demuestran que la mayoría de las técnicas relacionadas con blockchain se adaptan a sistemas particulares y puntuales en comparación con el conjunto de la empresa. Como consecuencia, para una transformación vertical, se requiere aún mayor investigación para poder culminar con éxito esta implementación. Avances en sectores como el alquiler de coches, repostaje de combustible o micropagos son solo algunos ejemplos de aplicaciones reales que se han implementado. Sin embargo, aún queda un largo camino por recorrer antes de que la tecnología blockchain se utilice en el día a día.

The application of distributed ledger technology in Industry 4.0

Fernández-Vázquez S[1], Rosillo R[2], Priore P[3], Puente J[4]

[1] Business Management Department, University of Oviedo
[2] Business Management Department, University of Oviedo
[3] Business Management Department, University of Oviedo
[4] Business Management Department, University of Oviedo

Abstract. Distributed ledger technology, also commonly known as Blockchain, is conceptualized as a form of transformative technology and is today considered to be one of the leading tools of the famously known Industry 4.0. The diverse features of Blockchain, such as smart contract, decentralization, openness, traceability, data immutability and data protection, together with a consensus framework, make it suitable for use in today's dynamic worldwide industries. As a result, companies should assess and analyse the importance of the conventional supply chain and the new Blockchain-based chains which introduce features such as transparency into the equation. The goal of this paper is to illustrate the advantages of Blockchain in the management of the supply chain through a literature review, identifying key aspects such as sustainability, decentralization, data immutability and the use of smart contracts. It also aims to provide professionals with constructive repercussions so that appropriate actions can be implemented to adopt this technology.

Keywords: Blockchain, Smart Contracts, Industry 4.0.

1 Introduction

At the Hannover Fair in 2011, the term Industry 4.0 was first introduced, referring to how advances in technology would profoundly change the organization of global value chains. Although Industry 4.0 has generally been accepted by the community, other concepts have also developed in this time period which refer to the use of digital technologies in production (SCH 17).

Lately, our society has seen the advent of an innovative wave of transformative technology distributed through multiple industries called Industry 4.0 (CHA 19). The industrial sector was responsible for the term known as Industry 4.0. Nevertheless, many industries have undergone an increase in their production by using disruptive technologies (SKI 17). This has led, for instance, in an increase in the use of these new technologies in sectors such as banking or telecommunications (BUC 20).

Currently, these service companies either use or test these innovations to modify the way they conduct business. The spectrum of the Industry 4.0 revolution involves a broad variety of innovations such as cloud computing, the Internet of Things (IoT), artificial intelligence (AI) or Blockchain (CHA 20). In today's world, incorrect and corrupted data can lead to inaccurate choices and become a major challenge to connected, dynamic development processes. The present manufacturing management typically depends on a centralized network, with limited data traceability and fragile to failure in processes (LEN 21).

In evolving conditions, the benefit of these technologies remains in their ability to learn through AI, their highly secured processes and their capability to predict. Customer knowledge and data can be combined through the use of cloud computing (LAR 16).

Through the use of Blockchain's groundbreaking technological framework that has recently revolutionized the industry in device protection and performance, security issues can be solved (AHR 17). An open and shared framework for rendering transactions in both enterprise and industry fields is provided by the Blockchain as a basis for distributed ledgers. Blockchain's innate features increase trust through clearness and traceability of transactions (ABE 16). The final aim is to enable machines such as computers to develop and interpret concepts such as those of the human mind (QU 20).

Industry 4.0 is a shift from a centralized planned production to a dynamic and decentralized production in order to improve the quality of goods, tailor-made processes and the flexibility of systems (ZAR 19). In order to make collaboration choices, a centrally controlled platform cannot prevent data privacy from other users, as it is essential to know one another's capacities and condition. Manufacturing companies also have to resolve the low robustness of centralized systems from a single key node, leading to unreliable networking and data service (SHE 02).

2 Blockchain

The Blockchain is a distributed public database that can be configured for data sharing and storage. Commonly defined as a distributed ledger, it consists of a chain of blocks and is built around a peer-to-peer (P2P) or shared network (WAN 20).

It is composed, amongst others, by consensus protocols, methods of cryptography, as well as smart contracts. It comprises modified blocks of data that are decentralized. A timestamp along with a connection to a previous block is included in each block of data. In order to trace each transaction in the database back to the source, a Blockchain includes full historical records. Blockchain is a modern secure and publicly available computer model (ALJ 19). Its main characteristics can be seen in Figure 1.

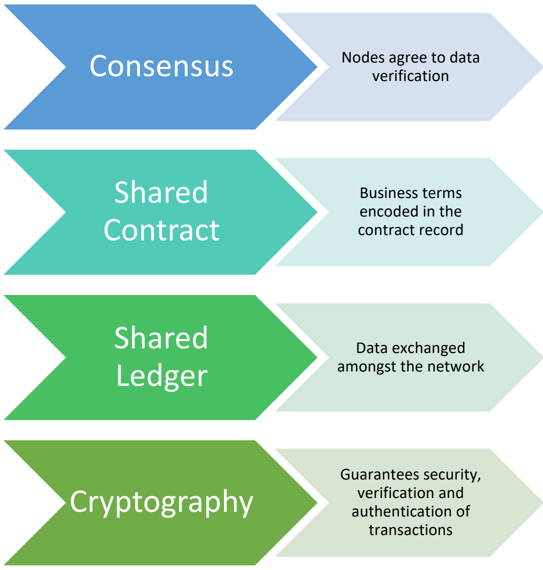

Fig. 1. Main characteristics of Blockchain technology.

Its applications are typically built based on the technology offered by mainstream Blockchain networks, such as Ethereum, EOS, Cardano, Hyperledger Fabric or Stellar. It is worth pointing out that different networks use different consensus algorithms. This is the way in which the users in a specific Blockchain reach an agreement. Below are some of the most important consensus algorithms and their principles (FU 20):

- Proof of Work (PoW): Consensus through mining by adding directly blocks to the Blockchain.
- Proof of Stake (PoS): The higher the stake the nodes have the more chances they will have in being accountants.
- Delegated Proof of Stake (DPoS): Nodes vote by the stake they hold.
- Notaries: Certifies that, for a particular transaction, no other transactions have already been signed that consume all of the input states of the proposed transaction.
- Orderer: Through transaction ordering, alongside other orderer nodes forms an ordering service.
- NeoScrypt: A PoW mining algorithm which has to be mined with graphics cards.

- Tangle : Miners do not validate transactions. Network participants jointly go through the validation process.
- Stellar: Nodes go through rounds of federated voting.

A list of the main networks and its consensus algorithms can be seen in Table 1.

Table 1. Record of some of the main Blockchain networks and their consensus algorithms.

Networks	Consensus algorithm
Bitcoin	PoW
Bitcore	Timetravel 10
Cardano	Ouroboros
Corda	Notaries
EOS	DPoS
Ethereum	PoW
Fabric	Orderer
Feathercoin	NeoScrypt
IOTA	Tangle
Qtum	PoS
Stellar	Stellar
Tezos	PoS
Wanchain	PoS

3 Smart Contract Implementations

Smart contracts convey an independent, autonomous system which is encoded to carry out a series of transactions without the intervention of a human being. In order for this contract to execute the transactions, a code needs to be embedded in the smart contract to perform a specific action if a series of requirements are met (GUA 19).

The incorporation of smart contracts arrived in IoT, mainly due to the security of its application and the reduction of, for example, financial risk. This inclusion allows transactions to be payed automatically or fully dedicated payment schemes. For instance, in industries such as agriculture, farmers can use a more efficient systems in which the payments made to farmers are made in a different scheme than the traditional fixed rate systems (LIM 21). Smart contracts are nowadays included in many Blockchain implementations. Some of those networks in which the deployment of smart contracts are allowed include Ethereum or Hyperledger Fabric.

The integration of Blockchain and IoT into today's payment system in the transportation industry, means having autonomous scenarios which are traceable and secure. In case of car rental, for instance, through the use of an application in the user's smartphone, a secure and transparent payment system can be deployed through the use of smart contracts. Another sector in which smart contracts can be introduced is fuel payment. In traditional mechanisms, the interaction between the user's credit card and the petrol pump takes place. On contrast, when using smart contracts, there is no need for a central authority. In this case the vehicle, which is running a decentralized application (dApp) on the Blockchain, sends its cryptocurrency to the smart contracts. The gas station communicates with the Blockchain explicitly to assess if the car has charged and tracks how much gas has been bought (FER 20).

Another area related to IoT (Internet of Things) in which this technology can excel are micropayments. Traditional payment systems are not the best method for a great deal of huge micro-payments. The reasons being are their high transactional costs and their limited capacity. Moreover, our credit card information when making micro-payments is shared between other devises (STJ 15). In order to implement smart contract systems in micro-payments, current issues with more traditional methods must be identified. Examples of these issues are:

- High transaction fees;
- High transaction timeframes; and
- A distribution system which lack of transparency

The use of Blockchain could help tackle these issues, as some of Blockchain's characteristics are (MUS 19):

- Low processing fees: through the use of Blockchain third-party fees are avoided. Payments are done in tokens and other users receive these tokens. The fees for transactions in cryptocurrencies are extremely low in comparison to traditional methods.
- Instant payment: When sending money, for instance, the transaction is completed within a few seconds. This contrasts with the hours or days that it might take to send money from one country to another (even more when it is done in different currencies).
- Transparent distribution: Smart contracts hold in place the transaction and the release of currency is automatic.

When using Blockchain technology in IoT, the system shifts towards a greater control in trade processes without human interference. The devices could be authenticated to ensure the security of the data transmitted and to deter unauthorized users. Blockchain could improve the IoT by offering immutability to apps, redundancy, openness, traceability and durability of operations (HAS 19).

Industry 4.0 includes the smooth convergence of processes through all elements. The production operations handled in the distributed shared ledger should be organized and reconciled between the separate nodes on the Blockchain (ANG 18). The middleware is essential to the incorporation of blockchain services in order to provide stability, traceability and decentralized manufacturing implementations between participating nodes. It is important to define the interface framework of blockchain-driven manufacturers, to design the operating principles of the blockchain manufacturing partnership specifically, and to create an adaptive blockchain logical structures for the manufacturing services (MOH 19).

4 Conclusion

The emerging use and implementation of Blockchain in Industry 4.0 is at a preliminary phase, as this is a field that has a lot to explore. Some methods demonstrate that most of the techniques are tailored for particular systems in which they aim to simplify horizontal integration. Consequently, strategies for vertical transformation of manufacturing do require practice to go forward. Advances in sectors such as car rental, fuel or micro-payments are just some examples of real applications in today's world that have been implemented. Nevertheless, there is still a long way to go before these and other Blockchain are used worldwide on a daily basis.

References

1. Abeyratne, Saveen & Monfared, Radmehr. (2016). Blockchain Ready Manufacturing Supply Chain Using Distributed Ledger. International Journal of Research in Engineering and Technology.
2. Ahram, Tareq & Sargolzaei, Arman & Sargolzaei, Saman & Daniels, Jeff & Amaba, Ben. (2017). Blockchain technology innovations. 137-141. 10.1109/TEMSCON.2017.7998367.
3. Al-Jaroodi, Jameela & Mohamed, Nader. (2019). Blockchain in Industries: A Survey. IEEE Access. PP. 1-1. 10.1109/ACCESS.2019.2903554.
4. Angrish, A., Craver, B., Hasan, M., Starly, B. (2018). A Case Study for Blockchain in Manufacturing: "FabRec": A Prototype for Peer-to-Peer Network of Manufacturing Nodes. Procedia Manufacturing. 26. 10.1016/j.promfg.2018.07.154.
5. Büchi, G., Cugno, M., Castagnoli, R., (2020). "Smart factory performance and Industry 4.0". Technological Forecast & Social Change. https://doi.org/10.1016/j.techfore.2019.119790.
6. Chang, Shuchih Ernest & Chen, Yi-Chian & Lu, Ming-Fang. (2019). Supply chain re-engineering using Blockchain technology: A case of smart contract based tracking process. Technological Forecasting and Social Change. 144. 1-11. 10.1016/j.techfore.2019.03.015.
7. Chang, V., Wang, Y., Wills, G., (2020). Research investigations on the use or non-use of hearing aids in the smart cities. Technol. Forecast. Soc. Change. https://doi.org/ 10.1016/j.techfore.2018.03.002.
8. Ferreira, Celio & Rabelo, Ricardo & Sá Silva, Jorge & Cavalcanti, Carlos. (2020). Blockchain for Machine to Machine Interaction in Industry 4.0. In book: Blockchain Technology for Industry 4.0, Secure, Decentralized, Distributed and Trusted Industry Environment (pp.99-116), Springer. 10.1007/978-981-15-1137-0_5.
9. Fu, X., Wang, H., & Shi, P. (2020). A survey of Blockchain consensus algorithms: mechanism, design and applications. Science China Information Sciences, 64(2). doi:10.1007/s11432-019-2790-1

10. Garg, P., Gupta, B., Chauhan, A. K., Sivarajah, U., Gupta, S., & Modgil, S. (2020). Measuring the perceived benefits of implementing Blockchain technology in the banking sector. Technological Forecasting and Social Change, 120407. doi:10.1016/j.techfore.2020.120407
11. Guadamuz, Andrés. (2019). All watched over by machines of loving grace: A critical look at smart contracts. Computer Law & Security Review. 35. 105338. 10.1016/j.clsr.2019.105338.
12. Hassan, M., Rehmani, M., Chen, J. (2019). Privacy preservation in blockchain based IoT systems: Integration issues, prospects, challenges, and future research directions. Future Generation Computer Systems. 97. 10.1016/j.future.2019.02.060.
13. Larson, Deanne & Chang, Victor. (2016). A review and future direction of agile, business intelligence, analytics and data science. International Journal of Information Management. 36. 700-710. 10.1016/j.ijinfomgt.2016.04.013.
14. Leng, Jiewu & Ye, Shide & Zhou, Man & Zhao, J. & Liu, Qiang & Guo, Wei & Cao, Wei & Fu, Leijie. (2021). Blockchain-Secured Smart Manufacturing in Industry 4.0: A Survey. IEEE Transactions on Systems, Man, and Cybernetics: Systems. 51. 10.1109/TSMC.2020.3040789.
15. Lim, C. H., Lim, S., How, B. S., Ng, W. P. Q., Ngan, S. L., Leong, W. D., & Lam, H. L. (2021). A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach. Renewable and Sustainable Energy Reviews, 135, 110223. doi:10.1016/j.rser.2020.110223
16. Mohamed, N., Al-Jaroodi, J. (2019). Applying Blockchain in Industry 4.0 Applications. 0852-0858. Proceedings IEEE 9th Annual Computing and Communication Workshop Conference, Las Vegas, NV, USA, Jan. 2019 10.1109/CCWC.2019.8666558.
17. Mushtaq, Anum & Haq, Irfan. (2019). Implications of Blockchain in Industry 4.0. 1-5. 10.1109/CEET1.2019.8711819.
18. Qu, Y., Pokhrel, S. R., Garg, S., Gao, L., & Xiang, Y. (2020). A Blockchained Federated Learning Framework for Cognitive Computing in Industry 4.0 Networks. IEEE Transactions on Industrial Informatics, 1–1. doi:10.1109/tii.2020.3007817
19. Schwab K. (2017) The fourth industrial revolution. Crown Publishing Group, New York
20. Shen, Weiming. (2002). Shen, W.: Distributed Manufacturing Scheduling Using Intelligent Agents. IEEE Intelligent Systems 17(1), 88-94. Intelligent Systems, IEEE. 17. 88 - 94. 10.1109/5254.988492.
21. Skilton, M., Hovsepian, F. (2017) The 4th industrial revolution: Responding to the impact of artificial intelligence on business. Springer International Publishing, AG, Cham.
22. Stjepandic J., Wognum N., & Verhagen W. (2015) Concurrent engineering in the 21st century. Foundations, developments and challenges. Springer.
23. Wang, Michael & Wu, Yong & Chen, Bruce & Evans, Melissa. (2020). Blockchain and Supply Chain Management: A New Paradigm for Supply Chain Integration and Collaboration. Operations and Supply Chain Management: An International Journal. 111-122. 10.31387/oscm0440290.
24. Zarreh, Alireza & Wan, Hung-da & Lee, Yooneun & Saygin, Can & al Janahi, Rafid. (2019). Risk Assessment for Cyber Security of Manufacturing Systems: A Game Theory Approach. 10.31224/osf.io/mb5t9.

From: **LUIS RODRIGO IZQUIERDO MILLAN** lrizquierdo@ubu.es
Subject: Re: CIO 2021 paper accepted to be published in LNMIE, Congratulations!
Date: 17 September 2021 at 13:52
To: LUIS RODRIGO IZQUIERDO MILLAN lrizquierdo@ubu.es
Cc: JOSE IGNACIO SANTOS MARTIN jisantos@ubu.es, JUAN JOSE LAVIOS VILLAHOZ jjlavios@ubu.es, VIRGINIA AHEDO GARCIA vahedo@ubu.es

Dear CIO 2021 Author,

We resend the email below, as some people told us that they had not received it. Instead of including an attachment, you can download the files at http://luis.izqui.org/cio/for-authors.zip
All the best,
Luis

> On Sep 15, 2021, at 10:27, LUIS RODRIGO IZQUIERDO MILLAN <lrizquierdo@ubu.es> wrote:
>
> Dear CIO 2021 author,
>
> The scientific committee of the CIO 2021 has been discussing the assignment of the papers to the different publication channels. We are writing to you because you are listed as corresponding author of a paper that has been accepted to be published as a chapter in the book of the Springer series “Lecture Notes in Management and Industrial Engineering (LNMIE)” (https://www.springer.com/series/11786). The IDs of the accepted papers are:
>
> 005,006,007,019,021,022,024,028,031,032,038,039,043,051,073,074,081,090,095,096,098,099,102,103,104,109,110,112,116,130.
>
> Titles are included at the end of this email.
>
> First of all, congratulations. There are no fees to publish in this book. If you accept this invitation, you will have to send us the publishing agreement signed and the final version of your paper by the end of November 2021. If any changes are necessary, we will contact you and ask you to submit the corrected version by the end of January 2022. Below we provide detailed instructions on how to format your paper and the different files you must provide.
>
> We would be grateful if you could inform us of your intention (or not) to publish your work in this book, which will also serve as an acknowledgement of receipt of this message.
>
> Thank you very much,
>
> Kind regards,
>
> The scientific committee of the CIO 2021
>
> **IMPORTANT INSTRUCTIONS**
>
> **Checklist of items to be sent directly to us (Luis R. Izquierdo <lrizquierdo@ubu.es>, JOSE IGNACIO SANTOS MARTIN <jisantos@ubu.es>, JUAN JOSE LAVIOS VILLAHOZ <jjlavios@ubu.es>, VIRGINIA AHEDO GARCIA <vahedo@ubu.es>) by the end of November 2021:**
>
> - The final source files, **including the images**. We attach the word templates again and some formatting instructions (Springer_Guidelines_for_Authors_of_Proceedings). **Please, follow the instructions very closely**, as Springer is very strict with this. Not complying fully with the format will most likely imply that your work will not be published.
>
> - A final PDF file corresponding exactly to the final source files.
>
> - The copyright form (i.e. 15th_ICIEIM_CIO2021__copyrightform_v1.docx), **signed by hand** by one author on behalf of all of the authors of the paper. Please note that e-signatures are not allowed. You should print, sign by hand, scan and send back the form to us. We are sorry for this inconvenience, but Springer did not give us any other option.
>
> - The name and e-mail address of the contact author who will check the proof of the paper.
>
> - A suggestion for an abbreviated running head, if appropriate.
>
> - Information about correct representation of authors’ names, where necessary.
>
> **Important notes**
>
> It is sufficient that only the corresponding author signs the publishing agreement (i.e. 15th_ICIEIM_CIO2021__copyrightform_v1.docx) on behalf of all of the authors of the paper, but it is very important to include the name of all paper authors in the agreement.
>
> We strongly recommend that all paper authors include their affiliation and e-mail address in the manuscript. Your e-mail addresses (also published in the chapters) will be used by SpringerNature to provide you with a personal MySpringer account where you can download **a free copy of the eBook**. In addition, all authors will be offered a 40% discount on any eBook or print book order from our web shop. Both the free eBook and the author discount will be activated on MySpringer.

The corresponding author will receive a free printed copy of the book at the indicated postal address.

Finally, we kindly ask you to bear in mind the following important issues:

a. **Any research involving humans** requires approval from the appropriate IRB (Institutional Review Board) or an explicit waiver. This applies even to something as apparently inoffensive as answering a questionnaire.

Such permission should be stated explicitly in the paper, either as part of the methods or as a separate “Ethical Statement” at the end of the paper. This should contain the name of the ethical body authorizing the study; the reference number of the permission to carry out the study; a statement that the subjects' consent was given for the study, including publication; and the fact that results are suitably anonymized or that consent for publication of identifying details has been obtained (contributors may be asked to produce this).

If a waiver has been granted, that fact should be recorded in place of the permission along with the identity of the party granting the waiver.

b. **If photos are included as figures in a paper and those photos contain images of people from which they could be identified** by themselves or others, the consent of those individuals for publication must be obtained. We recommend not putting people or parts of people in figures when this can be avoided.

c. **Permission for the reuse of third-party copyright materials should be obtained and acknowledged appropriately in the manuscript**, using the attached form (Permission Request Form (Springer).docx).

d. All contributions will go through two plagiarism checker programs: iThenticate and Turnitin. **If any plagiarism is detected, the paper will be withdrawn from the process**.

Thank you very much for reading all the important notes!

List of Papers:

005 Industry 4.0 and Airspace Operations Research with EU financial contribution
006 The potential of Industry 4.0 in Lean Supply Chain Management
007 Fostering industrial symbiosis. Potential drivers and barriers
019 Digital twin enabling intelligent scheduling in ZDM environments: an overview
021 Dealing with the externalities of the sharing economy: effect of Airbnb in long-term rental prices in the city of Madrid
022 The application of distributed ledger technology in Industry 4.0
024 Enablers and barriers to Industry 4.0 implementation
028 PROTOCOL- Assessing the transversal competence of teamwork in bachelor's and master's degree by means the competency-based interview
031 Overview of lean manufacturing under uncertainty
032 How does blockchain impact on supply chains?
038 Proposal of a methodology and associated techniques for the design and management of the global supply chain operations strategy according to a circular economy criterion
039 A bibliometric analysis of the Time Driven Activity Based Costing system. The power of cost accounting in organisations
043 Industry 4.0 practices in pharma sector supply chain
051 A conceptual framework of a blockchain application in a manufacturing supply chain
073 Design of a simulation environment for training or testing algorithms to solve the job shop scheduling problem
074 Advanced methods and models of optimization and data visualization for the management, monitoring and control of operations in companies working in collaborative manufacturing environments
081 A framework for Production Planning in Additive Manufacturing
090 Digital twin for a zero-defect operations planning in supply chain 4.0
095 Annualized hours, multiskilling and overtime on annual staffing problem: an uncertainty approach.
096 Cognitive Ergonomics Perspective to boost Human-centred Innovations in Industry 4.0
098 Business model archetypes: A systematic literature review
099 Project management methodologies and efficiency. An analysis of international development cooperation projects
102 Approach to Artificial Intelligence for Production Scheduling
103 Design and implementation of an Experimentation Service of the Production Scheduling Algorithms
104 Systematic mapping study sobre métodos de previsión e inteligencia artificial aplicados en la investigación sobre marketing online
109 A Maturity Model for Industry 4.0 Manufacturing Execution Systems
110 Modelo de programación matemática para el abastecimiento colaborativo entre cadenas de suministro competitivas del sector del calzado
112 Green Aspects on Value Stream Mapping
116 Model Experimentation Environment for Production Planning
130 Hacia la Internet Física: un modelo que afianza la sostenibilidad con un necesario enfoque de transformación industrial

<for-authors.zip>

3 Capítulo 3: Blockchain in FinTech: A Mapping Study

Tras la investigación realizada para el artículo expuesto en el Capítulo 2, se detectaron industrias con una mayor propensión para la adopción de la tecnología blockchain. Este es el caso de empresas en sectores de tecnología financiera, o *fintech*. Para el estudio de limitaciones, brechas y tendencias futuras de blockchain, una de las tendencias más habituales es el empleo de un estudio de mapeo, o *mapping study* en inglés. En concreto, para la realización de este estudio, se utilizó una metodología ampliamente utilizada en el mundo académico como es la metodología PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*, por sus siglas en inglés).

El estudio de mapeo sistemático se caracteriza por proporcionar un esquema o una visión general del alcance de la investigación. Es un eslabón crucial en la cadena de evidencia que se extiende desde la literatura de investigación académica hasta su aplicación práctica, considerando que tanto los profesionales como los académicos utilizan las revistas de alto impacto como fuente de información. Un estudio de mapeo científicamente preciso y bien ejecutado sobre un tema claramente definido es de gran utilidad, ya que describe la investigación actual, define los límites de lo que se ha investigado y lo que no se ha investigado. Este ángulo analítico es extremadamente importante y sirve como punto culminante de los hallazgos de las principales brechas en la investigación.

El estudio responde a cinco cuestiones principales de investigación: i) ¿qué tendencias por año de publicación se pueden observar?; ii) ¿qué tipos de documentos (artículos, capítulos de libros, reseñas) se publican sobre blockchain?; iii) ¿cuáles son los principales temas de investigación abordados en la investigación actual de blockchain?; iv) ¿cuáles son los principales desafíos/limitaciones en la investigación actual de blockchain? y; v) ¿cuáles son las principales brechas en la investigación en blockchain?

En relación con las preguntas de investigación especificadas, el presente estudio de mapeo tiene como objetivo identificar principales áreas de investigación de blockchain en el sector FinTech, las principales tendencias de publicación y las principales brechas en la literatura académica. Este estudio de mapeo ofrece además una amplia comprensión de blockchain en el sector de la tecnología financiera. Para ello se revisaron un total de 49 artículos de la base de datos *Web of Science Core Collection*. Los resultados muestran un enfoque profundo en desafíos como seguridad, escalabilidad, legal y regulatorio, privacidad, latencia, riesgos cibernéticos o desarrollo tecnológico. Si bien se consiguieron identificar estos problemas, las soluciones propuestas aún parecen estar lejos de ser efectivas.

sustainability

MDPI

Review

Blockchain in FinTech: A Mapping Study

Simon Fernandez-Vazquez †, Rafael Rosillo *,†, David De La Fuente † and Paolo Priore †

Business Management Department, University of Oviedo, 33003 Asturias, Spain; fernandezvazquez.simon@gmail.com (S.F.-V.); david@uniovi.es (D.D.L.F.); priore@uniovi.es (P.P.)
* Correspondence: rosillo@uniovi.es; Tel.: +34-985-18-26-57
† These authors contributed equally to this work.

Received: 13 October 2019; Accepted: 6 November 2019; Published: 13 November 2019

Abstract: Blockchain is currently one of the most important topics in both the academia and industry world, mainly due to the possible effects that the continuing application of this new technology could have. The adoption of this technology by FinTech companies constitutes the next step towards the expansion of blockchain and its sustainability. The paper conducts a mapping study on the research topics, limitations, gaps and future trends of blockchain in FinTech companies. A total of 49 papers from a scientific database (Web of Science Core Collection) have been analyzed. The results show a deep focus in challenges such as security, scalability, legal and regulatory, privacy or latency, with proposed solutions still to be far from being effective. A vast majority of the research is focused into finance and banking sector, obviating other industries that could play a crucial role in the further expansion of blockchain. This study can contribute to researchers as a starting point for their investigation, as well as a source for recommendations on future investigation directions regarding blockchain in the FinTech sector.

Keywords: blockchain; FinTech; mapping study; technological challenges; cryptocurrency

1. Introduction

Blockchain is one of the most talked-about topics in the business and academic world. It was presented for the first time with Bitcoin in 2008, as a peer-to-peer payment system for electronic transactions which allowed different financial actors to send payments to one another without the intermediation of a central agent (for example a central bank), preventing the double-spending problem [1].

The chain of blocks, or blockchain, is a peer-to-peer network, connected by its nodes that form the chain. Its properties are that of a distributed, transactional database. Once each node in the network verifies the information, it is sent via their public keys to the rest of the nodes [2]. As shown in Figure 1, each block has a unique identification hash that makes reference to its preceding block. Any user with a public or private key can enter the network and have access to the information exchanged in the system network.

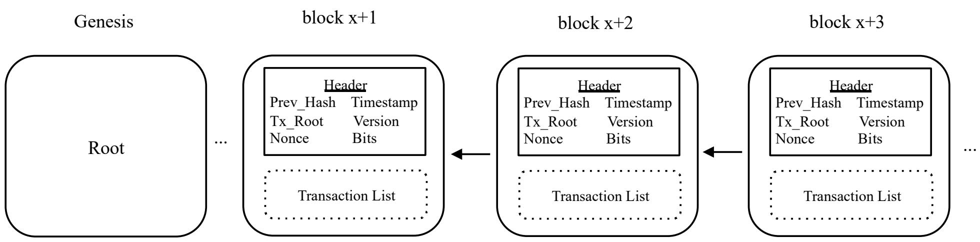

Figure 1. Blockchain network.

Public and private key systems have been developed way before blockchain. In 1976, Diffie and Hellman developed asymmetric cryptography, the first milestone into the development of the key system. In a public key system, two parties are able to send information via a public network, with public techniques and establish a connection that is secure. It works when one party sends the other information enciphered in their respective public keys. In order to decipher the message, the counterparty would use its private deciphering key [3].

The public and private pair of keys are interrelated, meaning that they can only be used in combination. This is obtained through a mathematical algorithm that sets the exclusive relationship between this pair of keys. Public keys can be shared with unlimited parties, whilst private keys must be kept safe and secret [4].

One of the most important players in the blockchain technology are its miners. Miners validate the information in the network by solving cryptographic puzzles and attaining agreement. This procedure makes the chain of blocks secure [5]. Every time one of the miners deciphers the puzzle, a transaction is documented. Due to the reward approach of the blockchain and to incentivize its miners, every time a puzzle is solved Bitcoins are earned. Miners with the greatest resources will be more likely to solve the puzzle first, thus earning the reward. The decentralized environment of Bitcoin is possible due to this structure [6].

When a new miner has access for the first time to a blockchain, it has access to the whole chain, from the genesis to the ultimate validated block [7]. The genesis, also known as the first block or root of the chain, is hard-coded into the client software that supports the valid blockchain. Due to the fact that miners need to solve puzzles, also called proof-of-work (PoW), a new transaction will only be valid once a new block is created and added into the existing blockchain [8]. Blockchain is an asset-agnostic technology. It is capable of storing, record-keeping and transferring all types of assets [9].

This paper introduces a mapping study which aims at comprehending the research topics, limitations, gaps and future trends of blockchain technology in FinTech companies. It can serve researchers as a starting point for their investigation, or as a source of information on future trends regarding blockchain in the FinTech sector. The rest of the paper is organized as follows: Section 2 provides a background on FinTech and smart contracts; Section 3 presents the materials and methods used to conduct this study; Section 4 presents the results of the study; Section 5 discusses the limitations of a systematic mapping study; and Section 6 presents the conclusions and recommendations derived from this study.

2. Background

2.1. FinTech

Financial technology, also known as 'FinTech', denotes the use of computer programs or other technology to assist the financial industry. The term was used for the first time at the beginning of the 1990s [10] and what started as a word related solely to the financial industry, it soon expanded into other very diverse sectors. Since early 2014, the sector has started attracting the attention of regulators, industry members, customers, and academics [11]. Blockchain in FinTech appeared for the first time as the distributed ledgers of Bitcoin, but has recently attracted consideration from practitioners and researchers [12]. Today, financial institutions and other market participants, mainly due to the development of the blockchain technology, are approving the nature of FinTech and the necessity for research in the academic world given the implications of this technology. Financial innovation is not something new, as it has an extensive history. The development of FinTech throughout history can be divided into three main eras [11].

i. Fintech 1.0 (1866–1967): In this early stage, finance started developing in agricultural states. The use of money, with its main advantage being the transfer of its value, started facilitating financial transactions. Developments in the 19th century of railroads and the invention of the telegraph facilitated connections across borders. After the Great War, technology started quickly developing, laying the foundations of the next FinTech era.

ii. Fintech 2.0 (1967−2008): This era is characterized by the rapid expansion of electronic payment systems. In 1968, the Inter-Bank Computer Bureau was founded in the United Kingdom, cementing what today is known as the Bankers' Automated Clearing Services. Regulations in the FinTech world started taking place, mainly due to the collapse in 1974 of Herstatt Bank. The effects of the collapse of the stock market in 1987 (also known as Black Monday), confirmed the suspicion that global markets were technologically linked. Throughout the 1990s, technological advances were made in risk management systems and the development of online consumer banking. The creation of digital banking (back then banks were the sole authorized monetary institutions) attracted more attention by regulators as it created new risks.

iii. Fintech 3.0 (2008–present): The beginning of this era was characterized by the financial turmoil of the years 2007–2008. Trust in the banking system started to be lost, and technological firms started to operate through peer-to-peer networks outside the regulatory framework (in China alone over 2000 platforms were developed). Today, these technological firms and many start-ups are displacing banks at a pace never seen before. Flexible regulations that stimulate entrepreneurship [13] are beginning to be adopted by some countries.

2.2. Smart Contracts

The introduction of smart contracts has been key in the development of FinTech. During the last decade, blockchain technology has been constantly evolving. Some of the most relevant products of this evolution are smart contracts. These are not something new, as Nick Szabo introduced the concept in 1994. Smart contracts can be defined as a computerized transaction procedure that performs the terms of a contract. This means that all the contractual clauses are embedded in the computer of the individuals performing the transactions [14]. As these contracts are automatically executed when certain conditions are met (the codes in the algorithm that conform the smart contracts specify these conditions), there is no need for a central authority or third-party support these transactions. As shown in Figure 2, the blockchain is represented on the lower part. Parties involved in the transaction (for example Party A sends units of currency Y to Party B and obtains units of currency Z) are represented in the upper part. Parties exchange this information through their keys (public and private), and consensus of this transaction is reached through mining. The transaction can only be completed with the creation of a new block.

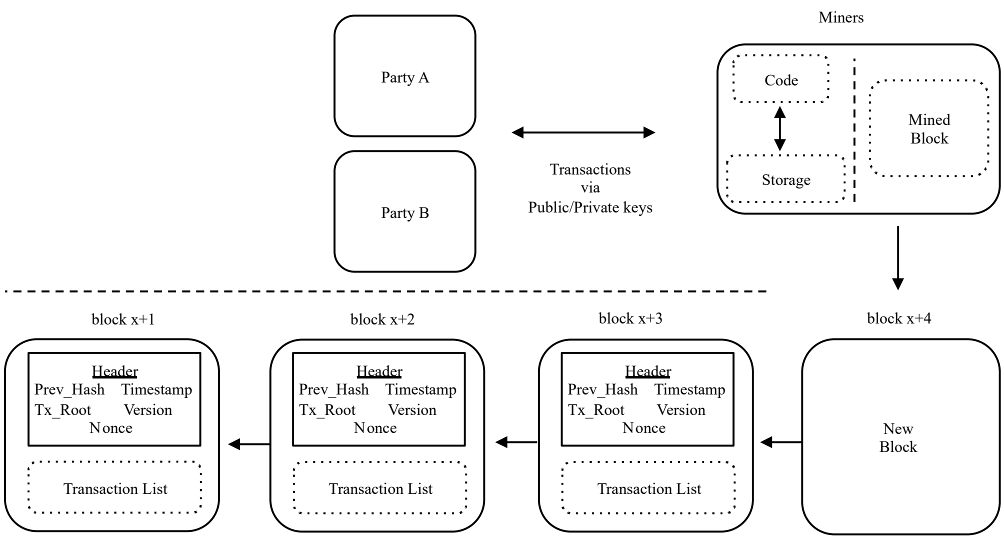

Figure 2. Smart contract system.

There are many different languages in which smart contracts can be coded, Ethereum being one of the most relevant to date. Ethereum has been proven to be extremely reliable when preventing the double spending problem, although, in order to attain this, a high level of difficulty is added [15]. Currently, the platforms that support blockchain's smart contract are Ethereum and Hyperledger [16].

Ethereum uses its own language, just as any other computer program. It has a consensus procedure that details the way in which the nodes forming the network extend the blockchain. A particularity of Ethereum is that blocks are added based on the strength of the nodes that form the network, through what is called a lottery. This means that nodes with a higher degree of computational strength have more chances of winning this lottery than the ones with less computational strength. Malicious nodes, which could access to win this lottery and add improper contract executions, are automatically removed from the blockchain [17].

3. Materials and Methods

A systematic mapping study was the research method used to conduct this study. The objective of a systematic mapping study is to present an outline on an investigated area, establishing and quantifying research evidence on a subject. By performing a mapping study, gaps in the research on a certain topic come to light, which could be considered as weak areas or areas of future study. In order to perform this mapping study, the processes outlined by Petersen [18] and Kitchenham [19] have been followed. The objective of this investigation is to carry out an investigation related to blockchain technology in FinTech. This study provides an indication of the area of research of blockchain technology in FinTech as of today. The Prisma Checklist is provided in Appendix A. Figure 3 shows the systematic mapping study process. It is comprised of five process steps (in the upper part) with their respective five outcomes (in the lower part).

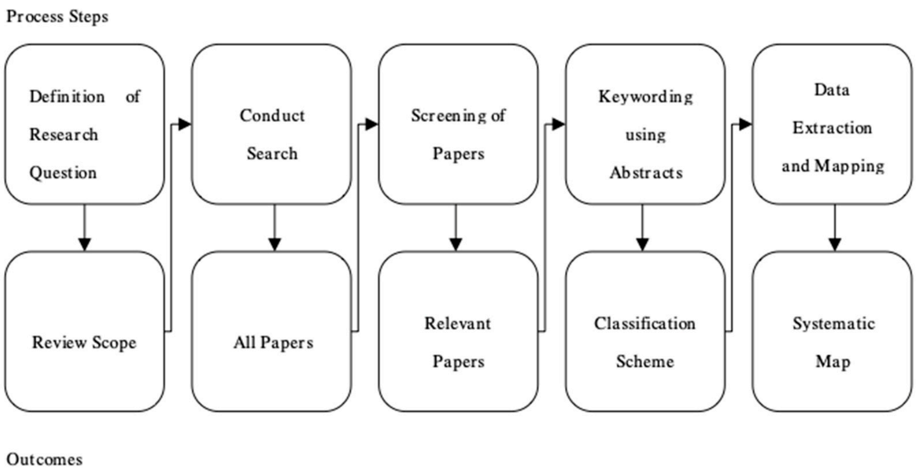

Figure 3. Systematic mapping process.

3.1. Definition of Research Questions

A systematic mapping study is characterized by providing an outline or overview of the research scope. It is a crucial link in the chain of evidence that extends from the academic research literature to the practical application, considering that both practitioners and academics use journals as a source of information [20]. A well-executed, scientifically accurate mapping study on a clearly defined topic is invaluable as it outlines current research, defines the limits of what has and has not been investigated and shows the main gaps in the literature research. This analytical angle is extremely important and serves as a highlight of relevant additional issues [21]. This study helps identify the amount and types or research that have been done within the industry. Diverse attributes can be mapped, such as publication date trends or the specific topics within the explored area. Research questions (RQs) can help outline these topics more easily.

RQ1: What trends by publication year can be observed?

In order to analyze the trends of blockchain in the academic world, a study of the publication year for the research papers is performed.

RQ2: What types of documents (articles, book chapter, reviews) are being published in blockchain?

Publication channels as a target of research give an idea of the kind of investigation that is being developed within blockchain.

RQ3: What are the main research topics addressed in the current blockchain research?

In order to explore the main topics that have been studied in blockchain, a categorization has to be made. This is one of the most important questions throughout the systematic mapping study carried out, as it serves as a basis to create an overall understanding of the current areas of research. This mapping study will assist researchers to have a wider understanding of this area and serve as a milestone for further investigation.

RQ4: What are the main challenges/limitations in the current blockchain research?

In order to explore the problems and challenges that the development of blockchain in FinTech is experimenting, the main issues will be categorized. By mapping the limitations of the technology, further research can be conducted in a specific area of importance.

RQ5: What are the main gaps in the research in blockchain?

The identification of gaps can help investigators explore areas that have not yet been explored. This will help find answers to questions that have not yet been solved regarding the blockchain technology. Thus, a systematic mapping study provides information on research areas but also on existing research gaps.

RQ6: Where is the blockchain technology moving in the near future?

The above five questions set the groundwork to establish possible future research directions. It is of high importance to address this question in order to lay the groundwork for future research in blockchain and the applications of this technology in the years to come.

3.2. Conducting the Research

The second stage after the definition of the research questions is to conduct the search. A search protocol, which will be followed, specifies the approaches that will be taken into account when performing this systematic review. This protocol helps to mitigate the probability of researcher bias. Without this protocol, for instance, it could be probable that the researcher expectations or pre-defined conclusions would drive the selection of individual studies and not the other way around [19]. By this means, an independent third-party (i.e., an independent peer reviewer) could follow this protocol and achieve identical or very similar results.

This search has been performed during the January–March 2019 period. Once the protocol was designed and tested, the search engine/database used was the Web of Science Core Collection (Clarivate Analytics, Philadelphia, USA), which comprises over 1 billion cited reference indexed from journals, books, and proceedings and 21,000 unique global journals covering 254 disciplines. This database contains only high-quality, peer-reviewed papers from different sources.

Within the Web of Science Core Collection, the keyword 'blockchain' was used in the search engine. Since the goal of this mapping study is to map papers related to the blockchain technology in FinTech, no searches for specific terms such as Bitcoin or smart contracts were made. Within the Core Collection, a search was firstly conducted for publications with the word 'FinTech' (or 'financial technology') in the title, abstract or keyword. Also, in order to withdraw subjectivity from the search, there was no manual search involved to retrieve papers or literature that were not contained in the Web of Science Core Collection database (i.e., grey literature such as unpublished papers, Master's or PhD theses, documents not published as a scientific work, or Google Scholar).

3.3. Screening of Relevant Papers for Inclusion or Exclusion

In order to perform a screening for the relevant papers to be included in the systematic map, the protocol defined by Dyba [22] was adopted. During the first screening phase, papers were screened based on their titles and abstracts. Papers that did not have appropriate titles for the study were excluded. In circumstances where it was not clear whether the title was appropriate, it was passed on to the next phase for further reading. During the second phase, the abstracts of all the papers that passed the first screening phase were read. In this phase, papers with the following characteristics were rejected:

i. Papers where the full text was not available;
ii. Papers written in any other language than English; and
iii. Papers that had other relevance different from blockchain applications in FinTech.

Papers that fulfilled the criteria in both phases passed on to the next stage.

3.4. Abstract Keywording

Keywording search is a very useful way to reduce time needed when classifying the results performed and certifying that all studies have been taken into account. In order to perform a keyword search, two steps must be performed. The first one is the reading of the abstract and the identification of key concepts that reveal the contribution of the paper [18]. Once this was completed, a combination of keywords from different papers was performed in order to acquire an understanding of the nature of the search. These keywords were used to form a set of categories in the mapping study. After the categories were shaped, the selected papers were read. Then, if a paper that was initially clustered under a specific category was more relevant under a new category, it was updated accordingly, as it can be seen in Figure 4.

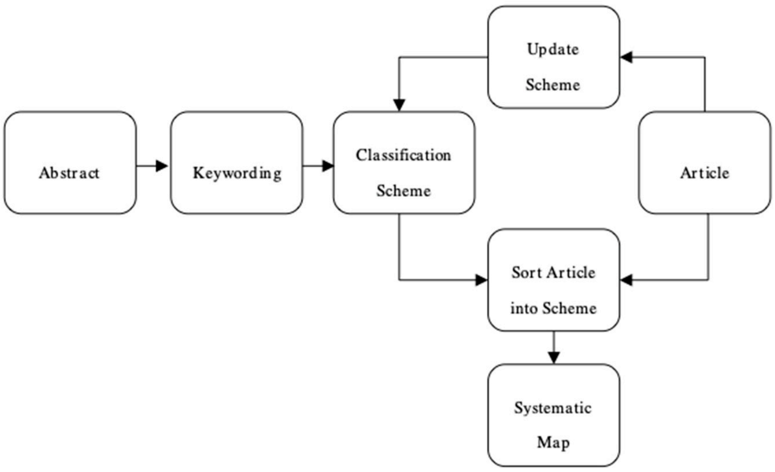

Figure 4. Protocol for building the classification scheme.

3.5. Data Extraction and Mapping of Papers

Once the data was obtained from the Web of Science Core Collection database, as previously described, it was sorted in an Excel spreadsheet with the following headers: author(s) name(s), title, source (article, review, book), abstract, and publication year.

3.6. Paper Information

The search of results can be seen through the PRISMA diagram in Appendix B. The initial search of the term blockchain in the Web of Science database gave 1,786 results. As it has been previously described, the title and abstract keywording led to the selection of 52 papers. The reason for the exclusion of a high number of papers was the absence of correlation between blockchain and Fintech. A vast majority of the papers related to other scientific domains.

After this initial selection of 52 papers, the guidelines for the inclusion of the relevant papers (Section 3.3) were followed. One paper was found to be duplicate, and two papers were eliminated due to the low correlation to the study of blockchain from a FinTech perspective. This process resulted in the final selection of 49 papers. The full list of the selected papers can be seen in Table 1.

Table 1. Publication channels

Journal	Author(s)
IEICE Transactions on Fundamentals of Electronics Communications and Computer Sciences	[23]
Electrical Engineering in Japan	[24]
Software Engineering and Algorithms in Intelligent Systems	[25]
Accounting and Finance	[26]
Journal of Economics and Business	[27]
Production and Operations Management	[28]
Quality-Access to Success	[29,30]
European Business Organization Law Review	[31]
NMIMS Management Review	[9]
Strategic Change-Briefings in Entrepreneurial Finance	[32]
International Journal of Environmental Research and Public Health	[33]
Proceedings of The International Conference on Business Excellence	[34]
Technological Forecasting and Social Change	[35]
2018 IEEE International Conference on Intelligence and Security Informatics (ISI)	[36]
Journal of Investment Management	[37]
Blockchain Technology: Platforms, Tools and Use Cases	[38]
Handbook of Blockchain, Digital Finance, and Inclusion, Vol 1: Cryptocurrency, Fintech, Insurtech, and Regulation	[39]
2018 9th IFIP International Conference on New Technologies, Mobility, and Security (NTMS)	[40]
Journal of Money Laundering Control	[41]
Australian Feminist Studies	[42]
Internet Science, INSCI 2017	[43]
Emerging Markets Finance and Trade	[44]
Financial and Credit Activity-Problems of Theory and Practice	[45]
2018 6th International Symposium on Digital Forensics and Security (ISDFS)	[46]
Journal of Management Information Systems	[47]
Journal of Risk Finance	[48,49]
Review of International Business and Strategy	[50]
International Journal	[51]
Financial Innovation	[52]
Business Horizons	[53]
Enfoque UTE	[54]
Computer	[55]
Symmetry-Basel	[56]

Table 1. *Cont.*

Journal	Author(s)
Electronic Commerce Research and Applications	[57]
2017 ITU Kaleidoscope: Challenges for a Data-Driven Society (ITU K)	[58]
2017 IEEE II International Conference on Control in Technical Systems (CTS)	[59]
2017 IEEE 1st International Conference on Cognitive Computing (ICCC 2017)	[60]
2017 AEIT International Annual Conference	[61]
Geoforum	[62]
2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking, and Communications (WIMOB)	[63]
2017 13th European Dependable Computing Conference (EDCC 2017)	[64]
Enterprise Applications, Markets and Services in the Finance Industry, Financecom 2016	[65]
Proceedings of The 6th International Conference on Computing and Informatics: Embracing Eco-Friendly Computing	[66]
2017 IEEE 13th International Symposium on Autonomous Decentralized Systems (ISADS 2017)	[67]
2017 19th International Conference on Advanced Communications Technology (ICACT)—Opening New Era Of Smart Society	[68]
Recent Developments in Intelligent Systems and Interactive Applications (IISA 2016)	[69]
Banking Beyond Banks and Money: A Guide To Banking Services in the 21st Century	[70]

4. Results

4.1. RQ1

4.1.1. Year of Publication

Figure 5 shows the year of publication of the selected articles. Due to the fact that FinTech in academia is a rather new subject (blockchain was introduced in 2008), it is not a surprise that only 2.0% of the selected articles were from the year 2016. The core of the academic publications are found in the years 2017 (38.8%) and 2018 (53.1%). Finally, 6.1% of the selected articles in 2019 (as of march) discussed blockchain in FinTech. If this rate keeps steady, the number of publications in 2018 will be surpassed. This shows that blockchain in FinTech is a very recent research are and that it is quickly expanding. This increase in the publications shows a deep interest in the matter.

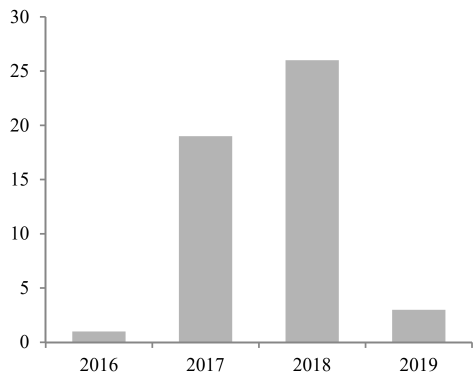

Figure 5. Selected articles published by year.

4.1.2. Geographical Distribution

Regarding the geographical distribution for the selected papers, the main country of publication was the USA with 21 papers (42.9%), followed by the UK with 11 papers (22.4%) and Switzerland with 6 papers (12.2%). The rest of the countries had two or less papers published (Figure 6). This distribution shows that, although the publications are mainly concentrated in three countries, there is a high diversification amongst continents that are presently researching blockchain applications in FinTech around the globe.

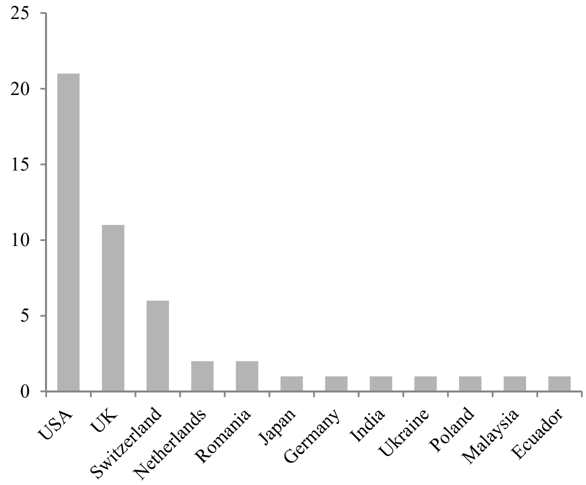

Figure 6. Selected papers geographical distribution.

4.2. RQ2

Source of Publication

Figure 7 shows the publication source for the selected papers. The results from the search show that 55.1% of the selected papers were articles (27), 34.7% were proceedings papers (from conferences and symposiums) (17), only 6.1% of the papers being book chapters (3) and 4.1% reviews (2).

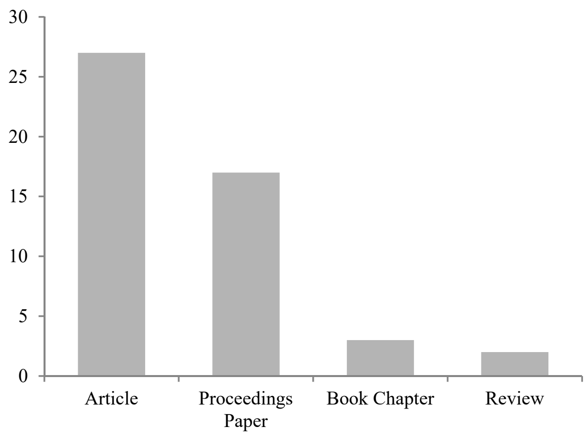

Figure 7. Selected papers source of publication.

Table 1 shows the publication channels for the selected papers.

4.3. RQ3

Summary of the Topics

Figure 8 shows the topics identified through the review of the final selected papers.

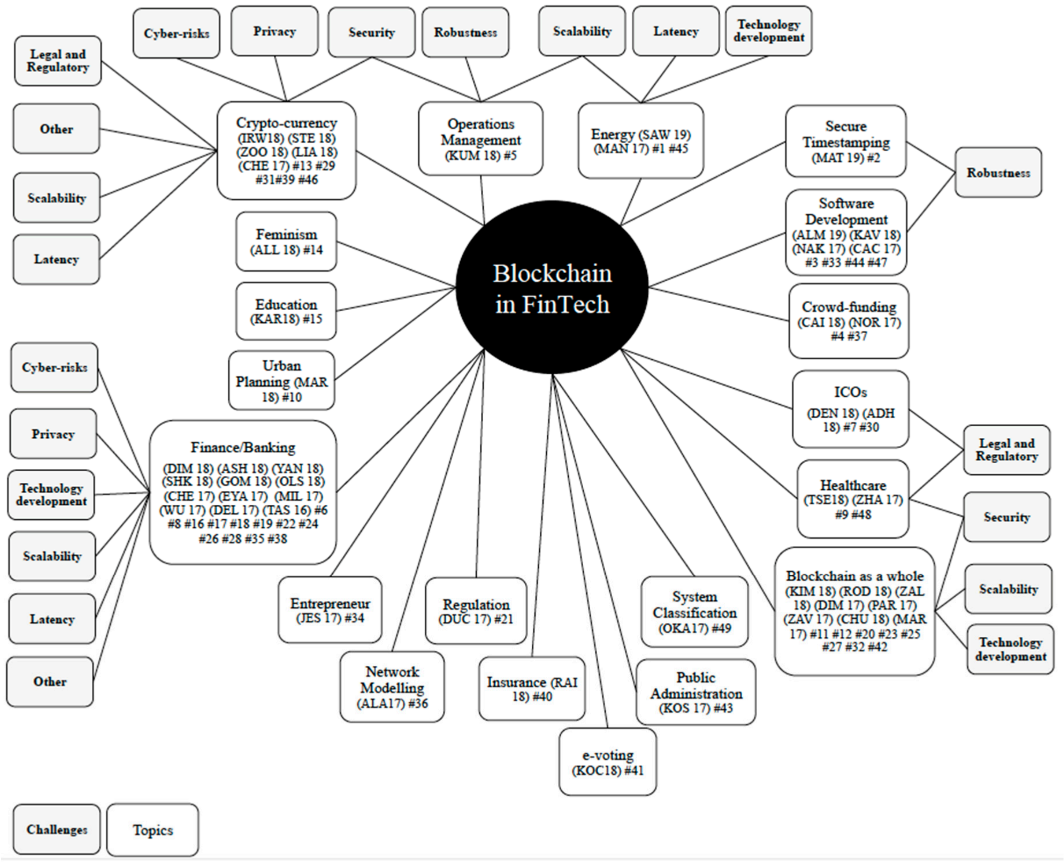

Figure 8. Summary of the main topics and key challenges of the selected papers.

The results of the search performed show that banking and finance are the main topics of the current research in blockchain applied to FinTech, being in 24.5% the main topic (12 papers). It is not surprising that a wide spectrum of academic research has focused on the banking and finance sector, as blockchain started precisely in these areas. The second most talked-about subject is blockchain and its applications in a wide manner, from the introduction of the technology to the application of the ledger technology to FinTech companies, with 16.3% (8 papers). The third and fourth topics with the highest amount of interest are cryptocurrencies with 10.2% (5 papers) and blockchain software development, with 8.2% (4 papers).

4.4. RQ4

4.4.1. Classification of the Main Challenges for the Selected Papers

This section presents the classification of the selected papers. Once the papers were read, a classification based on the findings was made. Due to the fact that most of the challenges represented in the papers were related to the classification presented by Treiblmaier [71], this classification was used. The challenges included were: scalability, robustness, latency, legal and regulatory, cyber-risks, security, and privacy. Additionally, a new classification type was identified: technology development. This is a very important attribute as blockchain is a rather new technology and presents development challenges. Finally, a classification under the name of 'others' was also used. It comprises all the elements that cannot be classified in the aforementioned categories. The classification is shown in Figure 9.

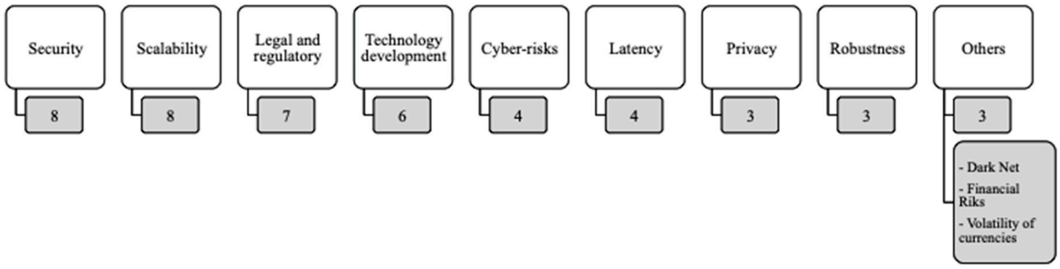

Figure 9. Classification of the main challenges for the selected papers.

4.4.2. Security

Security was one of the most talked-about challenges in the selected papers, with eight papers addressing this issue. Different topics inside security were identified, such as 51% attack, wallet security, cryptographic security, and other issues.

- 51% attack: One of the most recurrent topics identified related to security has been the 51% attack to the network. This arises when an attacker has more than 50% of the mining capability, meaning full control of the blockchain. Whenever there is a fork in the blockchain (two different miners answering the puzzle at the same time), the block that is not selected by the rest of the peers in the network will become worthless. If an attacker has 51% of the mining capacity in a network, and therefore full control, false transactions can be included in the blockchain. There are five main steps that create the 51% attack: (i) publication of a mining software with bigger expected value; (ii) creation of a pool with stickiness (Ponzi scheme); (iii) creation of unwanted coalitions; (iv) assault of other pools with cannibalized pools; and (v) an eventual switch to members only [56]. Consensuses of the nodes regarding the transactions are also concepts addressed by other authors [34].
- Wallet security: Regarding Bitcoin, there are numerous security issues that are addressed. Transactions in the Bitcoin world are created using scripts, which are codes in a programming language. An extensively used method that includes a multiple signature process is called 'multisig'. Even though the creation of scripts helps to solve a wide variety of problems, there is a possibility that a transaction is not correctly configured as the complexity of the script rises. When this occurs, the Bitcoin that uses an incorrectly configured script would be discarded, as it would have no use since the unlocking script will not be able to be generated [56]. Humans that run the mining nodes are responsible for choosing which network they want to join, affecting the security of the blockchain. The bigger the amount of nodes in the network, the more secure it will be. The decision to run a specific form of code, or the shifts in the changes in the performance of the systems, have real-world outcomes, i.e. higher expenses on energy and CPU sequences committed to solve proof-of-work encryptions [62].
- Cryptography: Key cryptography is another major topic within security. In the Bitcoin wallet, information such as the personal key of the address used to generate the unlocking script is stored. Having access to this information would mean leading to a potential loss of Bitcoins, as this information plays a crucial part in the system. Consequently, the Bitcoin wallet is one of the central issues when regarding hacking attacks on Bitcoin. One way to tackle this problem is by using multisig for multiple signatures. Because of the particularities of multisig, which only allows a transaction to be executed with multiple signatures, it can be used to configure the signature of the Bitcoin owner in addition to the signature of the online wallet site. In the event of an attack,

withdrawal can be avoided since the owner's personal key is not kept, even when the online wallet site is being hacked [56]. Security breaches when using cryptographic tools, intrinsic to the concept of blockchain could have a high operational impact. These same breaches could increase costs for users in the network. For instance, arrangements in certain blockchain networks can lead to alterations in the cost allocation amongst users. In a ledger where users contribute through the maintenance and update of the network, some users, by operating certain nodes in an arranged way, could contribute to a cost increase in the network derived from this arrangement [54].

- Other security threats: Some authors point out that operations through blockchain can lead to high overhead traffic [38]. Other authors identify managed monitory services related to cybersecurity. The main idea behind this is that processes are supervised in real-time and attacks are tackled before they can make much damage. Nevertheless, since these monitoring resources are scarce, it is necessary to sacrifice these resources to process those with the higher possibility of being damaged [28]. For other authors, security improvements in the blockchain, especially those between the participants in the logistics supply chain, would result in less cost (i.e., medicines) [33].

4.4.3. Scalability

One of the most important challenges concerning blockchain is its scalability. Today, improving the network's scale is not considered itself as a goal, but as a moving target. One of the main objectives of cryptocurrencies is to be able to attain a similar rate of transactions per second as a centralize system does while maintaining the core of its technology unchanged [38].

Some authors point out that the restrictions on a block's data volume limit the amount of transactions performed [24]. Because of its incapability of acting as an exchange mechanism, due mainly to scalability (and speed), cryptocurrencies have been viewed as a source speculative trading [62].

In Bitcoin, another point of view regarding scalability is related to the technical extension of the system. The non-scalable technical extension of the design of Bitcoin does not allow other features or applications to be incorporated. For example, creators that want to incorporate the Bitcoin system to smart contracts, find it extremely complicated. This is how other systems were born, Ethereum being one of the most relevant examples today [63].

In the near future, blockchain can have an issue regarding storage capacity as transactional histories are constantly added onto one another [54]. A solution to this could be the limitation in the access to write information, and only grant permission to a central intermediary, which would diminish consensus needs [9]. Other authors reflect on the necessity of designing a blockchain that can cope with scalability and coming up with a number of computers, which would be necessary to confirm each transaction [28].

Some of the papers that include scalability problems relate it with another common challenge that will be later discussed: latency. In an experiment conducted by Raikwar et al. [40], the parameters when creating a blockchain should be cautiously selected, as they have a direct impact on the network's latency.

4.4.4. Legal and Regulatory

Throughout history, there has been a delay between early implementation and regulatory acknowledgment when dealing with important market innovations. Legal compliance and regulation by the authorities in each jurisdiction is a key requirement if blockchain wants to make its way into the financial system. One of the common denominators after any financial crisis is regulatory belief on stable and optimal rules. However, this framework, which relies on stable and predictable rules, could be inadequate in many cases, especially when introducing a disruptive technology such as blockchain in the equation. The proper nature of FinTech, which has diminished barriers to entry, increased access to financial services and challenged the nature of the financial system, needs a regulation that adapts accordingly. Some authors propose regulatory frameworks, whilst others explore the implications that an unregulated system would have.

Regulators face a series of dilemmas when addressing blockchain law enforcements. On one hand, the risks for policymakers for not incentivizing innovation through the adequate development of an adapted regulation could mean a loss of a country's competitive advantage. Some FinTech start-ups may even end up moving to more favorable jurisdictions in other parts of the globe. On the other hand, an unregulated situation may boost the creation of criminal organizations that would profit from the lack of laws that govern these activities [51]. This deregulation and its consequences is precisely what has been criticized by Stephan C. [34].

Some authors propose data monitoring as a technology driven regulation, which would make financial systems more efficient and effective, protecting the end users' rights. A dynamic and flexible integration with access to the blockchain by the parties involved (i.e., institutions and regulators), would improve real time oversight. This contrasts with the reforms introduced after the financial crisis in 2008 (the *Dodd–Frank Wall Street Reform and Consumer Protection Act* in the US), at levels that were not attained since the New Deal [44].

The appearance of initial coin offerings (ICOs), a means by which capitalists raise money in the form of cryptocurrencies which can be then bought and sold to obtain services in exchange, is a subject which has attracted the attention of many researchers. Due to the recent widespread increase of cryptocurrencies, ICOs have become very relevant in the blockchain world. Deng et al. [31] suggest that regulation for ICOs in China is necessary, but not to be banned. The authors explore the regulations that have taken place in other countries and jurisdictions—such as the US, Australia, Canada, Singapore, or Hong Kong—where ICOs have been regulated under the securities law. Adhami et al. [27], suggest that ICOs favors innovation and could have substantial significance when funding decentralized groups of developers.

In line with the need for regulation of ICOs, Gomber et al. [47] suggest that it is key for governments and financial institutions to regulate electronic payment systems (i.e., transfer of funds) that are today the leading target of the FinTech revolution. Regulation in other areas, such as in the supply chain of medicines via blockchain when using the Gcoin system, is suggested by Tseng et al. [33].

4.4.5. Technology Development

Blockchain technology is far from having reached its maturity, with the technical implications that this may have. Mills et al. [9], for instance, point out that although the blockchain system is regarded with optimism, there is still a lot of room for the development of its applications as the technology is still at an early stage. Although many industry actors are suggesting applications for this technology, the idea is years ahead of the actual technological development.

In order for the distributed ledger technology to be implemented, widespread participation is needed for it to be successful. Every time a new user is included, the whole community benefits. In this case, and because of the characteristics intrinsic to blockchain, early adopters can be penalized from the use of the technology without sufficient participants, which could lead to a withdrawal in the use of blockchain [54].

Rodrigues et al. [38] warn about the possible consequences of investing in blockchain-based start-ups. They point out that investors need to be sure that the technology used to develop the applications is relevant in order to prevent financial losses. The challenges come from developing a system that maintains the blockchain's original properties (transparency and decentralization) without diminishing others (i.e., performance or confidentiality).

Some authors have investigated into the application of the blockchain technology in sectors such as energy and electric power. Through experiments, Sawa, T. [24] demonstrates that the use of this technology remains limited in these areas. Nevertheless, these experiments may help others solve issues relative to energy and provide new solutions that would help companies and customers integrate their needs through blockchain.

Some authors have also addressed waste of resources connected to the early stage of the technology development. One main problem of the proof-of-work system is that it serves no other purpose than assuring the security inside the network. A higher computational power is needed when mining takes place, which results in high-energy expenditure. Some studies suggest that by the end of 2020, the energy consumption in assuring the blockchain's PoW will be equivalent to that of Denmark. Some recent attempts to reduce the energy consumed by the PoW (through the recycling of energy) are far from solving this issue [55].

Today, some development models (Standards Development Organizations and National Standards Organizations) are only open to users who have paid a subscription. This limits the number of users that can make developments into a specific area. In order to overcome this situation, Marsal-Llacuna et al. present a blockchain model for drafting with a token to administer open to sharing [35].

4.4.6. Cyber-Risks

Blockchain's permissionless public systems can be used for unlawful purposes. This is due to the fact that the system enables (occasionally completely anonymous) transactions across the globe without the intervention of a central authority. The particularities of the permissionless public systems, which cannot impose rules or obligations to its users in order to verify their identity, foster the development of illegal activities [51].

In recent years, cryptocurrencies have gathered attention for being linked to the drug business, money laundering, and financing of terrorism. These new currencies allow users to purchase any kind of malicious items using, for example, Bitcoins. Ransomware attacks have also taken place, such as WannaCry, which affected more than 300,000 computers in 150 countries. Users with infected computers were asked to pay the sum of $300 in Bitcoins to be able to have access to their computers. Investigating the traces of these attacks is a very complex and difficult assignment. Also, users in the blockchain can undergo financial losses if their cryptographic keys or identifications are lost or stolen. These losses are in most cases instant and irreversible without recourse [9].

Irwin et al. [41] point out that a solution could come from policies that would support data sharing between different members from the law enforcement, intelligence entities, and organizations dealing with cyber-security as well as the FinTech industry. The result would be the creation of behavioral models and threat landscapes that could help recognize the identities behind the attacks. Other authors point out for the need for a regulation in order to prevent fraud and money laundering activities [34].

4.4.7. Latency

Today, it takes around 10 minutes to create a new block using PoW. Roughly, seven transactions are processed per second, which seems very far away compared to the performance of credit cards, which perform around 2,500 transactions per second on average, peaking at 4,000 and even reaching 45,000 at its maximum (SAW 19) with only a fraction of the electrical power used by Bitcoin. The reasons for this latency are mainly due to cryptographic verification and blockchain's consensus algorithms, which delay the amount of transfers that some systems need to function correctly [54].

Nowadays, Bitcoin block puzzles are solved at a minimum time of three seconds and a maximum of more than 50 minutes. Decreasing the complexity of PoW would diminish the time spent, but could lead up to blockchain forks if the block generation timeframe is very narrow [52]. Zook et al. [62] point out that one of the solutions that some cryptocurrency exchanges and miners are coming up with is to charge higher fees in order to process the transactions quicker, and even include charges to cover risks that embrace slow exchange.

4.4.8. Privacy

One of the most important challenges of blockchain is privacy. Blockchain's transparency, which is one of the main assets of this technology, could turn to be a major issue. For instance, two companies which have transactions with one another, could be reluctant to have this information tracked by a third party, due to the commercial and client privacy implications that this may have [55]. Holders of Bitcoin can be tracked by analyzing the transactions they perform, mainly through the use of the public keys related to their payments. After the identification of a certain subject, a software tool can be used to create a behavioral map based on the gathered information to have an idea of where that person shopped, the amount spent and the frequency of the transactions. Even external third parties can have access to and analyze this information.

Solutions to privacy issues are proposed by Del Rio, C. [54], where the author reflects on a notary based blockchain system, in which no node in the system has the complete set of information, could allow higher privacy as a trusted third party would assist in validating the transactions. The downturn is that if the information in one or more nodes was fraudulent, the system would collapse as nobody would have a full copy of the ledger and verification would not be possible. Bitcoin Fog or Dark Wallet, which foster anonymity through a series of scripts, could be used as an alternative [41].

4.4.9. Robustness

When, after the aforementioned challenges, the blockchain network will display similar characteristics to traditional economic networks, it will mean that the system has achieved its robustness. Nevertheless, today, this technology confronts problems that need to be addressed. Robustness looks precisely into higher availability (meaning no downtime) and a 24/7 service available for transactions.

Some authors, like Matsuura [47], point out that many FinTech and emerging blockchain-based applications lack of a solid service quality. Research is made towards the stabilization of the applications with the help of token valuation interpretation function. The main challenge is to comprehend the new necessities regarding blockchain's software development products that startups need in order to develop their business. Improvement in the software's capacity for decision-making, allowing a higher degree of automation, and even evolving traditional software engineering concepts to make them adaptable to blockchain, are the key factors pointed out by Almeida et al. [25]. In line with this, the optimization of smart contracts in the blockchain would certainly help the network achieve its robustness [28].

4.4.10. Others

Other topics that have been found relevant when researching blockchain in FinTech are the dark net, financial risks, and cryptocurrency volatility. We have previously analyzed some of the risks associated with cyber-security, and talked about the problem of users being able to buy illicit items with cryptocurrencies. However, the darknet goes beyond common users, as it has been estimated that only one out of 3,000 web pages are visible to everyday search engines, and between 80% to 98% of the information on the Internet resides in the darknet. The degree of security of this net, accessible using, for example, a Tor Browser, is extremely high, and recurrent changes in the codes and the use of techniques of indexing of search engines create a place for any kind of illegal activity [41].

In the blockchain, and when dealing with transactions between financial institutions, another challenge that comes up is how the autonomous system would manage financial risks, such as credit or liquidity risks. How the system handles these risks will have a direct impact on the counterpart's liquidity needs [9]. In line with this, financial players also need to address the handling of variables such as the volatility of cryptocurrencies, which has experience in the last two years huge growth accompanied with violent volatility [34]. The sophistication of the designed scripts in the network is key when tackling these issues and will contribute to the expansion of blockchain in FinTech.

4.5. RQ5: What Are the Main Gaps in the Research in Blockchain?

By doing this mapping study, some major research gaps were identified. First of all, most of the research is being done in sectors related to banking and finance. There is very little current research in the application of blockchain for FinTech companies that do not relate to these sectors. For instance, investigation of blockchain in sectors such as durable and non-durable manufacturing, retail and wholesale trade, real estate, construction or utilities, is necessary as they represent the biggest industries in the economy. Also, a more detailed focus on how blockchain technology could help FinTech's supply chain is needed.

A second major gap is the only focus on Bitcoin when exploring cryptocurrencies and its uses. There are numerous other currencies, for instance, Ethereum, which has the importance of being used in smart contracts. Another research gap can be found in these types of contracts, since they serve as the basis for most of the transactions that will take place in the future of blockchain. If correctly programmed, smart contracts will be able to execute thousands of transactions in an autonomous way. Throughout the selected papers, there were no specific proposals of application development from a smart contract perspective.

The third research gap was the absence of a technical literature. There were no mathematical models for applications related to FinTech. Papers were mostly descriptive and lacked a technical approach in the sense of developing real tools that would help the major challenges brought into light to be overcome. A more thorough investigation is needed to be able to come up with solutions that would help companies in the FinTech sector that want to start using blockchain technology.

4.6. RQ6: Where is Blockchain Technology Moving in the Near Future?

It is not clear where the future research of blockchain in the FinTech is going. Cryptocurrencies such as Bitcoin have attracted interest in recent years, and platforms that trade these currencies are growing in users every day. It is very probable that Bitcoin will continue to be one of the most researched topics in the near future, from both business and technical perspectives. As we have pointed out in the current research gaps, other currencies, such as Ethereum, will probably be of interest as well, largely due to the application in smart contracts. Nevertheless, it seems that Bitcoin has taken the lead in the research and we will have to wait for the irruption of other competitors in academic papers.

As more and more users in the real world start to make use of this technology, researchers will start drawing their attention to these uses and applications. An increase in users means that challenges, such as scalability or security, will have greater importance, and the development of applications that tackle these and other issues will be subject of literature review. Even though blockchain has not reached its maturity, we can observe a growth in the interest that will presumably continue until this technology reaches its full capacity.

5. Discussion

5.1. Limitations of a Systematic Mapping Study

The most common limitations of systematic mapping studies are publication and selection bias, inaccuracy in data collection and misclassification [72]. Publication bias refers to the issue that negative results are less likely to be published, because it takes longer or are less cited, than positive results. This issue was addressed by the use of the Web of Science Core Collection, which only contains high-quality, peer-reviewed papers. Grey literature (i.e., unpublished papers, Master's or PhD theses, documents not published as a scientific work, or Google Scholar) was not considered as part of the search. This could, to an extent, affect the validity of the findings. However, using a reputable database ensures that the results of the study are of high quality.

Selection bias refers to the misrepresentation of a statistical analysis owing to the criteria used to select publications. This issue was addressed by a careful design of a search protocol. Inclusion and exclusion criteria were rigorously applied, and each selected paper answered the research questions. Nevertheless, there is a possibility that papers that addresses the applications of blockchain in the FinTech sector have been left out if they made little reference to the subject, and the terms FinTech (or financial technology) was not included in the title, abstract or keyword. Based on pilot searches carried out prior to the final search, we believe that the majority of relevant papers discussing the subject have been included. Inaccuracy in data selection and misclassification refer to the possibility of a study's information being extracted in different ways by different reviewers. This issue was addressed by asking three authors in the paper to extract and classify the results obtained. When discrepancies arose, discussions were solved by consensus. This resulted in the final 49 papers that were selected.

Additionally, according to Centobelli [73] this mapping study is conducted using manual screening and is based on the researcher's analysis and interpretation of the literature. Their critical perspectives unavoidably influence this process. This fact represents, without a doubt, the main strengths and limitations of literature reviews. As a matter of fact, a certain degree of subjectivity is an essential requirement to develop a mapping study and provide thorough understanding of qualitative aspects.

5.2. Future Research

The findings of this paper may be useful for future research. The gaps that have emerged from this mapping study highlight that, although in recent years there is an increasing number of articles published on blockchain, the knowledge framework in the discipline is still scattered and a vast majority of subjects and research directions are still substantially unexplored. Nonetheless, the principal outcomes of the mapping study show that interest in the topic is mounting and its framework is in expansion. Since this mapping study provides a conceptual framework, it sets the grounds to future empirical research and improves the awareness in the field of blockchain in the FinTech sector. Recommendations on the research directions of this technology would comprise:

- Further investigation from a technical perspective to attain solutions to the main challenges and limitations that have been identified. If the issues are tackled in the blockchain network as a whole, FinTech companies will soon be able to adapt and take onboard these solutions to today's problems. The recent interest in the technology (mainly since 2016) comprises many papers dedicated to the explanation of blockchain in a broad manner, but there is a lack investigations tackling its limitations with real solutions.
- Further research on issues such as privacy or latency. These are key issues that have not attracted as much interest as security or scalability but that are fundamental to the development of blockchain technology.
- Further development of smart contracts. If FinTech companies want to succeed in the adoption of blockchain technology, smart contracts are the key to further unleashing its potential.
- Development of applications for FinTech companies outside the banking sector. Other industries such as manufacturing, trade, real estate, construction, or utilities have the capacity to take blockchain technology onboard and apply it for many uses. The introduction of blockchain in the supply chain of these industries could foster even more the attention and interest towards blockchain and help further investigate solutions to its main challenges.

6. Conclusions

Blockchain is a decentralized network environment with a shared ledger, in which all transactions are publicly available to its users. Throughout a set of protocols and cryptographic techniques, it provides privacy, security, transparency, and anonymity. Nevertheless, these benefits also set up a list of challenges and limitations that need to be explored. In order to comprehend the academic literature available on blockchain, a systematic mapping study was carried out. The objective of this mapping study was to scrutinize the current status, topics and challenges and limitation of blockchain technology in FinTech companies. A total of 49 papers from the Web of Science Core Collection database were examined. The results show a deep focus in challenges such as security, scalability, legal and regulatory, privacy, latency, cyber-risks, or technology development. Although these issues are identified, the proposed solutions are still far from being effective.

In relation to the specified research questions, the present mapping study aims to pinpoint the main research areas of blockchain in the FinTech sector, the main publication trends and the main gaps in academic literature. This mapping study also offers an extensive understanding of blockchain in the financial technology sector. It highlights that companies willing to adopt this technology should deal with upcoming challenges and shows the importance of the efforts in understanding and tackling the aforementioned issues. Although blockchain is currently far from being the solution to problems in numerous sectors, its characteristics set hopes for a greater importance in forthcoming years.

Author Contributions: Conceptualization, S.F.-V., R.R., D.D.L.F., and P.P.; Methodology, S.F.-V., R.R., D.D.L.F., and P.P.; Formal analysis, S.F.-V., R.R., D.D.L.F., and P.P.; Investigation, S.F.-V., R.R., D.D.L.F., and P.P.; Resources, S.F.-V., R.R., D.D.L.F., and P.P.; Data curation, S.F.-V., R.R., D.D.L.F., and P.P.; Writing—original draft preparation, S.F.-V., R.R., D.D.L.F., and P.P.; Writing—review and editing, S.F.-V., R.R., D.D.L.F., and P.P.; Supervision, S.F.-V., R.R., D.D.L.F., and P.P.; Project administration, S.F.-V., R.R., D.D.L.F., and P.P.; Validation, S.F.-V., R.R., D.D.L.F., and P.P.; The authors contributed equally to this work.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. PRISMA checklist.

Section/Topic	#	Checklist Item	Reported on Page No.
		TITLE	
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
		ABSTRACT	
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	1
		INTRODUCTION	
Rationale	3	Describe the rationale for the review in the context of what is already known.	1–4
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	4–8
		METHODS	
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., web address), and, if available, provide registration information including registration number.	4–8
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	4–8
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	4–8
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	4–8
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4–8
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	4–8
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	4–8
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	4–8

Table A1. *Cont.*

Section/Topic	**#**	**Checklist Item**	**Reported on Page No.**
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	-
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	4–8
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	18
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	-
		RESULTS	
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	6–8
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	6–8
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	18
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	4–18
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	4–18
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	18
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression (see item 16)).	-
		DISCUSSION	
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	18–19
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	18
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	18–19
		FUNDING	
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	-

From: [74].

Appendix B

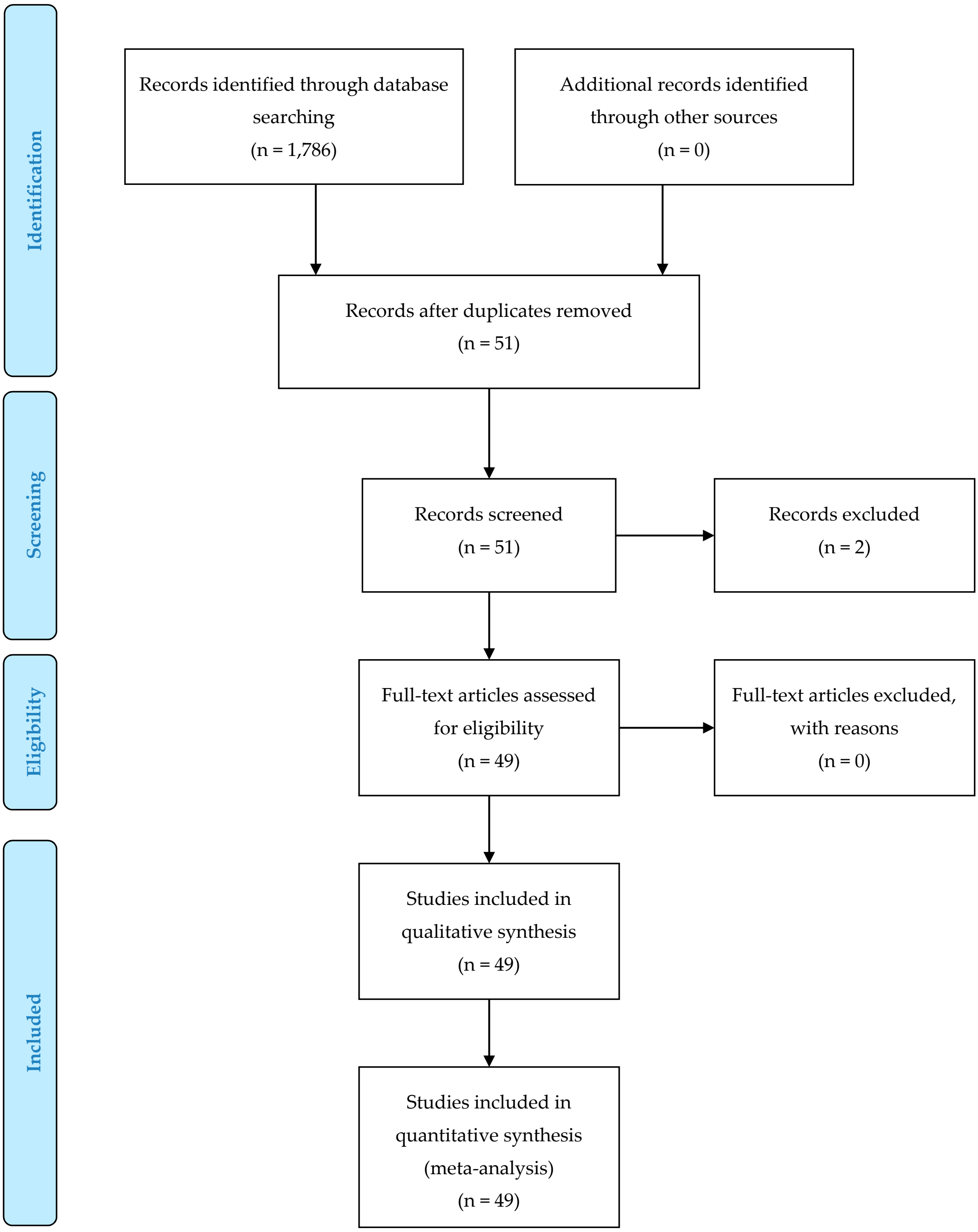

Figure A1. PRISMA Flow diagram. From: [74].

References

1. Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System. 2008. Available online: https://bitcoin.org/bitcoin.pdf (accessed on 25 February 2019).
2. Tschorsch, F.; Scheuermann, B. Bitcoin and beyond: A technical survey on decentralized digital currencies. *IEEE Commun. Surv. Tutor.* **2015**, *18*, 2084–2123. [CrossRef]
3. Diffie, W.; Hellman, M. New directions in cryptography. *IEEE Trans. Inf. Theory* **1976**, *22*, 644–654. [CrossRef]
4. Konashevych, O.; Poblet, M. Is Blockchain Hashing an Effective Method for Electronic Governance? *arXiv* **2018**, arXiv:1810.08783.
5. Macrinici, D.; Cartofeanu, C.; Gao, S. Smart contract applications within blockchain technology: A systematic mapping study. *Telemat. Inform.* **2018**, *35*, 2337–2354. [CrossRef]
6. Eyal, I.; Gencer, A.E.; Sirer, E.G.; Van Renesse, R. Bitcoin-NG: A Scalable Blockchain Protocol. In Proceedings of the 13th USENIX Symposium on Networked Systems Design and Implementation, Santa Clara, CA, USA, 16–18 March 2016; pp. 45–59.
7. Fanning, K.; Centers, D.P. Blockchain and Its Coming Impact on Financial Services. *J. Corp. Account. Financ.* **2016**, *27*, 53–57. [CrossRef]
8. Kiayias, A.; Lamprou, N.; Stouka, A.-P. Proofs of Proofs of Work with Sublinear Complexity. In *International Conference on Financial Cryptography and Data Security*; Springer: Berlin/Heidelberg, Germany, 2016; Volume 9604, pp. 61–78.
9. Mills, D.; Wang, K.; Malone, B.; Ravi, A.; Marquardt, J.; Chen, C.; Badev, A.; Brezinski, T.; Fahy, L.; Liao, K.; et al. Distributed Ledger Technology in Payments, Clearing, and Settlement. *Financ. Econ. Discuss. Ser.* **2016**, *2016*. [CrossRef]
10. Hochstein, M. Fintech (the word, that is) Evolves. *American Banker*. 2015. Available online: https://www.americanbanker.com/opinion/FinTech-the-word-that-is-evolves (accessed on 23 June 2019).
11. Arner, D.W.; Barberis, J.; Buckley, R.P. 150 Years of FinTech: An evolutionary analysis. *Finsia J. Appl. Financ.* **2016**, *3*, 22–29.
12. Du, W.; Pan, S.L.; Leidner, D.E.; Ying, W. Affordances, experimentation and actualization of FinTech: A blockchain implementation study. *J. Strateg. Inf. Syst.* **2019**, *28*, 50–65. [CrossRef]
13. Ramanathan, R.; Ramanathan, U.; Bentley, Y. The debate on flexibility of environmental regulations, innovation capabilities and financial performance—A novel use of DEA. *Omega* **2018**, *75*, 131–138. [CrossRef]
14. Szabo, N. Smart Contracts. Unpublished work. 1994.
15. Natoli, C.; Gramoli, V. The Blockchain Anomaly. In Proceedings of the IEEE 15th International Symposium on Network Computing and Applications (NCA), Cambridge, MA, USA, 31 October–2 November 2016; pp. 310–317.
16. Gu, Y.; Hou, D.D.; Wu, X.H.; Tao, J.; Zhang, Y.Q. Decentralized Transaction Mechanism Based on Smart Contract in Distributed Data Storage. *Information* **2018**, *9*, 286. [CrossRef]
17. Atzei, N.; Bartoletti, M.; Cimoli, T. *A Survey of Attacks on Ethereum Smart Contracts (SoK)*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2017; Volume 10204, pp. 164–186.
18. Petersen, K.; Feldt, R.; Mujtaba, S.; Mattsson, M. Systematic Mapping Studies in Software Engineering. In Proceedings of the 12th International Conference on Evaluation and Assessment in Software Engineering, EASE'08, Bari, Italy, 26–27 June 2008; pp. 68–77.
19. Kitchenham, B.; Brereton, O.P.; Budgen, D.; Turner, M.; Bailey, J.; Linkman, S. Systematic literature reviews in software engineering – A systematic literature review. *Inf. Softw. Technol.* **2009**, *51*, 7–15. [CrossRef]
20. Bharti, K.; Agrawal, R.; Sharma, V. Value co-creation: Literature review and proposed conceptual framework. *Int. J. Mark. Res.* **2015**, *57*, 571. [CrossRef]
21. Centobelli, P.; Cerchione, R.; Esposito, E. Shashi Exploration and exploitation in the development of more entrepreneurial universities: A twisting learning path model of ambidexterity. *Technol. Forecast. Soc. Chang.* **2019**, *141*, 172–194. [CrossRef]
22. Dybå, T.; Dingsøyr, T. Empirical studies of agile software development: A systematic review. *Inf. Softw. Technol.* **2008**, *50*, 833–859. [CrossRef]
23. Matsuura, K. Token Model and Interpretation Function for Blockchain-Based FinTech Applications. *IEICE T FUND ELECTR* **2019**, *E102.A*, 3–10. [CrossRef]

24. Sawa, T. Blockchain technology outline and its application to field of power and energy system. *Electr. Eng. Jpn.* **2019**, *206*, 11–15. [CrossRef]
25. Almeida, S.; Albuquerque, A.; Silva, A. An Approach to Develop Software that Uses Blockchain. *Softw. Eng. Algorithms Intell. Syst.* **2019**, *763*, 346–355. [CrossRef]
26. Cai, C.W. Disruption of financial intermediation by FinTech: A review on crowdfunding and blockchain. *Account. Financ.* **2018**, *58*, 965–992. [CrossRef]
27. Adhami, S.; Giudici, G.; Martinazzi, S. Why do businesses go crypto? An empirical analysis of initial coin offerings. *J. Econ. Bus.* **2018**, *100*, 64–75. [CrossRef]
28. Kumar, S.; Mookerjee, V.; Shubham, A. Research in Operations Management and Information Systems Interface. *Prod. Oper. Manag.* **2018**, *27*, 1893–1905. [CrossRef]
29. Dimbean-Creta, O. Fintech in Corporations. Transforming the Finance Function. *Qual. Access Success* **2018**, *19*, 21–28.
30. Dimbean-Creta, O. Fintech—Already New Fashion in Finance, but what about the Future? *Qual. Access Success* **2017**, *18*, 25–29.
31. Deng, H.; Huang, R.H.; Wu, Q. The Regulation of Initial Coin Offerings in China: Problems, Prognoses and Prospects. *Eur. Bus. Organ. Law Rev.* **2018**, *19*, 465–502. [CrossRef]
32. Ashta, A.; Biot-Paquerot, G. FinTech evolution: Strategic value management issues in a fast changing industry. *Strat. Chang.* **2018**, *27*, 301–311. [CrossRef]
33. Tseng, J.-H.; Liao, Y.-C.; Chong, B.; Liao, S.-W. Governance on the Drug Supply Chain via Gcoin Blockchain. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1055. [CrossRef]
34. Stefan, C. Tales from the crypt: Might cryptocurrencies spell the death of traditional money? A quantitative analysis. In Proceedings of the International Conference on Business Excellence, Bucharest, Romania, 15 Jun 2018; Volume 12, pp. 918–930.
35. Marsal-Llacuna, M.-L. Future living framework: Is blockchain the next enabling network? *Technol. Forecast. Soc. Chang.* **2018**, *128*, 226–234. [CrossRef]
36. Liang, J.; Li, L.; Zeng, D.; Zhao, Y. Correlation-based Dynamics and Systemic Risk Measures in the Cryptocurrency Market. In Proceedings of the IEEE International Conference on Intelligence and Security Informatics (ISI), Miami, FL, USA, 8–10 November 2018; pp. 43–48.
37. Kim, S.; Sarin, A. Distributed Ledger and Blockchain Technology: Framework and Use Cases. *SSRN Electron. J.* **2018**, *16*, 90–101. [CrossRef]
38. Rodrigues, B.; Bocek, T.; Stiller, B. The Use of Blockchains: Application-Driven Analysis of Applicability. *Blockchain Technol.* **2018**, *111*, 163–198. [CrossRef]
39. Chuen, D.L.K.; Deng, R. *Handbook of Blockchain, Digital Finance, and Inclusion: Cryptocurrency, FinTech, InsurTech, and Regulation Preface*, 1st ed.; Academic Press Ltd.: Cambridge, MA, USA; Elsevier Science Ltd.: Amsterdam, The Netherlands, 2017; Volume 1.
40. Raikwar, M.; Mazumdar, S.; Ruj, S.; Gupta, S.S.; Chattopadhyay, A.; Lam, K.-Y. A Blockchain Framework for Insurance Processes. In Proceedings of the 9th IFIP International Conference on New Technologies, Mobility and Security (NTMS), Paris, France, 26–28 February 2018; pp. 1–4.
41. Irwin, A.S.; Turner, A.B. Illicit Bitcoin transactions: Challenges in getting to the who, what, when and where. *J. Money Laund. Control* **2018**, *21*, 297–313. [CrossRef]
42. Allon, F. Money after Blockchain: Gold, Decentralised Politics and the New Libertarianism. *Aust. Fem. Stud.* **2018**, *33*, 223–243. [CrossRef]
43. Karkkainen, T.; Panos, G.A.; Broby, D.; Bracciali, A. On the Educational Curriculum in Finance and Technology. In *International Conference on Internet Science*; Springer: Berlin/Heidelberg, Germany, 2018; Volume 10750, pp. 7–20.
44. Yang, D.; Li, M. Evolutionary Approaches and the Construction of Technology-Driven Regulations. *Emerg. Mark. Financ. Trade* **2018**, *54*, 3256–3271. [CrossRef]
45. Shkodina, I.V.; Timoshenkov, I.V.; Nashchekina, O.N. The impact of financial technology on the transformation of the financial system. *Financ. Crédit. Act. Probl. Theory Pract.* **2018**, *1*, 417–424. [CrossRef]
46. Yavuz, E.; Koc, A.K.; Cabuk, U.C.; Dalkilic, G. Towards secure e-voting using ethereum blockchain. In Proceedings of the 6th International Symposium on Digital Forensic and Security (ISDFS), Antalya, Turkey, 22–25 March 2018; pp. 1–7.

47. Gomber, P.; Kauffman, R.J.; Parker, C.; Weber, B.W. On the Fintech Revolution: Interpreting the Forces of Innovation, Disruption, and Transformation in Financial Services. *J. Manag. Inf. Syst.* **2018**, *35*, 220–265. [CrossRef]
48. Olsen, R.; Battiston, S.; Caldarelli, G.; Golub, A.; Nikulin, M.; Ivliev, S.; Buchanan, B.; Tasca, P. Case study of Lykke exchange: Architecture and outlook. *J. Risk Financ.* **2018**, *19*, 26–38. [CrossRef]
49. Kavassalis, P.; Stieber, H.; Breymann, W.; Saxton, K.; Gross, F.J.; Buchanan, B.; Tasca, P. An innovative RegTech approach to financial risk monitoring and supervisory reporting. *J. Risk Financ.* **2018**, *19*, 39–55. [CrossRef]
50. Zalan, T. Born global on blockchain. *Rev. Int. Bus. Strat.* **2018**, *28*, 19–34. [CrossRef]
51. Ducas, E.; Wilner, A. The security and financial implications of blockchain technologies: Regulating emerging technologies in Canada. *Int. J. Can. J. Glob. Policy Anal.* **2017**, *72*, 538–562. [CrossRef]
52. Chen, Z.; Li, Y.; Wu, Y.; Luo, J. The transition from traditional banking to mobile internet finance: An organizational innovation perspective—A comparative study of Citibank and ICBC. *Financ. Innov.* **2017**, *3*, 12. [CrossRef]
53. Larios-Hernández, G.J. Blockchain entrepreneurship opportunity in the practices of the unbanked. *Bus. Horizons* **2017**, *60*, 865–874. [CrossRef]
54. Del Rio, C.A. Use of distributed ledger technology by central banks: A review. *Enfoque Ute* **2017**, *8*, 1–13. [CrossRef]
55. Eyal, I. Blockchain Technology: Transforming Libertarian Cryptocurrency Dreams to Finance and Banking Realities. *Computer* **2017**, *50*, 38–49. [CrossRef]
56. Park, J.H.; Park, J.H. Blockchain Security in Cloud Computing: Use Cases, Challenges, and Solutions. *Symmetry* **2017**, *9*, 164. [CrossRef]
57. Alabi, K. Digital blockchain networks appear to be following Metcalfe's Law. *Electron. Commer. Res. Appl.* **2017**, *24*, 23–29. [CrossRef]
58. Marsal-Llacuna, M.-L.; Oliver-Riera, M. The standards revolution: Who will first put this new kid on the blockchain? In Proceedings of the ITU Kaleidoscope: Challenges for a Data-Driven Society (ITU K), Nanjing, China, 27–29 November 2017.
59. Kostin, G.A.; Pokrovskaia, N.N.; Ababkova, M.U. Master-chain as an intellectual governing system for producing and transfer of knowledge. In Proceedings of the IEEE II International Conference on Control in Technical Systems (CTS), St. Petersburg, Russia, 25–27 October 2017; pp. 71–74.
60. Nakashima, H.; Aoyama, M. An Automation Method of SLA Contract of Web APIs and Its Platform Based on Blockchain Concept. In Proceedings of the IEEE International Conference on Cognitive Computing (ICCC), Honolulu, HI, USA, 25–30 June 2017; pp. 32–39.
61. Mannaro, K.; Pinna, A.; Marchesi, M. Crypto-trading: Blockchain-oriented energy market. In Proceedings of the AEIT International Annual Conference, Cagliari, Italy, 20–22 September 2017.
62. Zook, M.A.; Blankenship, J. New spaces of disruption? The failures of Bitcoin and the rhetorical power of algorithmic governance. *Geoforum* **2018**, *96*, 248–255. [CrossRef]
63. Chen, P.-W.; Jiang, B.-S.; Wang, C.-H. Blockchain-based payment collection supervision system using pervasive Bitcoin digital wallet. In Proceedings of the IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Rome, Italy, 9–11 October 2017; pp. 139–146.
64. Cachin, C. Blockchains and Consensus Protocols: Snake Oil Warning. In Proceedings of the 13th European Dependable Computing Conference (EDCC), Geneva, Switzerland, 4–8 September 2017; pp. 1–2.
65. Zavolokina, L.; Dolata, M.; Schwabe, G. FinTech Transformation: How IT-Enabled Innovations Shape the Financial Sector. In *Exploring Service Science*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2017; Volume 276, pp. 75–88.
66. Nor, R.M.; Rahman, M.M.H.; Rahman, T.; Abdullah, A. Blockchain Sadaqa Mechanism for Disaster Aid Crowd Funding. In Proceedings of the 6th International Conference on Computing and Informatics: Embracing Eco-Friendly Computing, Kuala Lumpur, 25–27 April 2017; pp. 400–405.
67. Zhao, H.; Zhang, Y.; Peng, Y.; Xu, R. Lightweight Backup and Efficient Recovery Scheme for Health Blockchain Keys. In Proceedings of the IEEE 13th International Symposium on Autonomous Decentralized System (ISADS), Bangkok, Thailand, 22–24 March 2017; pp. 229–234.
68. Yamasaki, S.; Okada, H.; Bracamonte, V. Proposed classification of blockchains based on authority and incentive dimensions. In Proceedings of the 19th International Conference on Advanced Communication Technology (ICACT), PyeongChang, Korea, 19–22 February 2017; pp. 593–597.

69. Wu, S.; Guo, D. Research into Information Security Strategy Practices for Commercial Banks in Taiwan. *Recent Dev. Intell. Syst. Interact. Appl.* **2017**, *541*, 182–187. [CrossRef]
70. Tasca, P.; Aste, T.; Pelizzon, L.; Perony, N. *Banking Beyond Banks and Money-A Guide to Banking Services in the Twenty-First Century Introduction*; Springer: New York, NY, USA, 2016. [CrossRef]
71. Treiblmaier, H.; Beck, R. *Business Transformation through Blockchain*; Palgrave Macmillan: Cham, Switzerland, 2019; Volume 1. [CrossRef]
72. Fernández, A.; Insfrán, E.; Abrahão, S. Usability evaluation methods for the web: A systematic mapping study. *Inf. Softw. Technol.* **2011**, *53*, 789–817. [CrossRef]
73. Centobelli, P.; Cerchione, R.; Esposito, E. Knowledge Management in Startups: Systematic Literature Review and Future Research Agenda. *Sustainability* **2017**, *9*, 361. [CrossRef]
74. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann. Intern. Med* **2009**, *151*, 264–269. [CrossRef]

4 Capítulo 4: A comparative study of blockchain's largest permissionless networks

Este capítulo corresponde con una publicación que busca comprender, desde un punto de vista técnico, las características de las principales redes blockchain. Este análisis y comprensión resultarán de gran valor para compañías que pretendan adoptar esta tecnología, ya que no todas las redes blockchain son iguales. Para llevar a cabo esta investigación, se contó con el apoyo de un centro tecnológico especializado en el desarrollo de aplicaciones blockchain, que otorgaron comentarios y propuestas de incalculable valor.

Para el análisis, se utilizó un método exploratorio de estudio de casos múltiples para comprender la lógica y las metodologías utilizadas por estas tres redes principales. Se usó un análisis comparativo, proceso que compara elementos entre sí distinguiendo sus similitudes y diferencias. Cuando una empresa quiere analizar una idea, un problema, una teoría o una pregunta, se realiza un análisis comparativo que le permite comprender mejor el problema y formar estrategias en respuesta. Dado el objetivos del estudio, se decidió centrar la investigación analítica en redes que tienen aplicaciones de mercado habilitadas para blockchain. La mayoría de los datos son de naturaleza cualitativa y se recopilaron de dos fuentes principales: la *Web of Science Core Collection* y la bases de datos estadística de *coinmarketcap.com*.

En este capítulo, se proporciona un análisis comparativo exhaustivo de las redes blockchain más relevantes por capitalización bursátil. Se exploran sus características, con énfasis en los algoritmos de consenso, incentivos o privacidad. A partir de una breve introducción a blockchain y sus aplicaciones, se ha construido un análisis en profundidad de las redes Bitcoin, Ethereum y Ripple desde un punto de vista técnico. Con base en el análisis integral de las redes y sus protocolos de consenso, se han establecido las bases para futuros estudios sobre las aplicaciones emergentes de blockchain en diferentes sectores. El foco de este estudio reside en el análisis de las características más relevantes de cada red. Mediante esta comparativa, se espera que el trabajo sirva como guía para una mayor comprensión de las diferentes redes de blockchain y la exploración de direcciones de investigación prometedoras que pueden conducir a resultados inspiradores en áreas relacionadas.

Technology Analysis & Strategic Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ctas20

A comparative study of blockchain's largest permissionless networks

Simon Fernandez-Vazquez, Rafael Rosillo, Luis Meijueiro, Raul Alonso Alvarez & David De La Fuente

TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT
https://doi.org/10.1080/09537325.2021.1976748

A comparative study of blockchain's largest permissionless networks

Simon Fernandez-Vazquez [a], Rafael Rosillo[a], Luis Meijueiro[b], Raul Alonso Alvarez[b] and David De La Fuente[a]

[a]Business Management Department, University of Oviedo, Spain; [b]CTIC Centro Tecnológico, Gijón, Spain

ABSTRACT
Blockchain is increasingly gaining interest in both the academic and professional worlds. The implementation of this decentralised and distributed network has started taking place, firstly in the financial world and in recent years reaching to other industries. Nevertheless, not all blockchain networks are the same, and choosing the right consensus algorithm is important for companies willing to invest in this technology. Companies eager to implement blockchain should understand the underlying architecture when selecting a particular network. Through an in-depth analysis, this paper aims to explore and compare from a technical perspective the three biggest permissionless blockchain networks by market capitalisation: Bitcoin, Ethereum and Ripple. Our research shows that Bitcoin gains a competitive advantage as a widely adopted means of payment, Ethereum excels in adopting a robust and flexible smart contract functionality whilst Ripple is most suitable for cross-border payments due to its scalability and fast processing speed. Based on the comprehensive analysis of the networks and their consensus protocols, this paper is designed to set the ground for further studies on the emerging applications of blockchain in numerous sectors.

ARTICLE HISTORY
Received 18 June 2021
Revised 16 August 2021
Accepted 20 August 2021

KEYWORDS
Blockchain; bitcoin; ethereum; ripple

1. Introduction

In the past years, the world has witnessed the emergence of distributed ledger technology (DLT). Blockchain is a distributed ledger shared amongst its nodes that enables trustless networks. As a form of DLT, blockchain emerged as a solution to the inefficiencies of the current financial system, quickly expanding to other sectors.

When created, blockchain was not intended to back cryptocurrencies. The gain in popularity through many industrial applications such as capital markets, agriculture or transportation is due to the characteristics of its underlying architecture (Christidis and Devetsikiotis 2016). These characteristics include anonymity, transparency, resilience and low transaction costs. In recent years, researchers and academics have been exploring blockchain's main strengths and weaknesses and developing diverse platforms that suit different purposes, through, for instance, the use of different consensus algorithms (Dennis and Disso 2019).

Blockchain technology offers multiples advantages such as time and cost reduction and faster reconciliation amongst transacting parties. This is achieved through the absence of a trusted intermediary or middleman. Blockchain uses different consensus mechanisms depending on the

CONTACT Simon Fernandez-Vazquez fernandezvazquez.simon@gmail.com Business Management Department, University of Oviedo, East Departmental Building, 1 Floor. Campus of Viesques s / n, 33204 Gijón, Spain

blockchain network to validate information through its nodes. Choosing the most appropriate consensus algorithm and network is key when implementing blockchain solutions (Chaudhry and Yousaf 2018). Likewise, the allowance of smart contracts, block generation time, block size or coin supply determine the performance of each network (Pinna et al. 2019). It is key to understand the implications and potential of the most appropriate platform for every specific application.

This paper examines the three biggest blockchain networks by market capitalisation[1] as of March 2021: Bitcoin, Ethereum and Ripple (Figure 1). These three networks account for more than 85% of the total market capitalisation of all blockchain networks. This paper takes into account only newly developed network algorithms and not forks or modifications of the original ones, such as Bitcoin Cash or Litecoin. These selected platforms embody the most well-known networks within public and private domains and cover a varied selection of application fields stretching from simple money transfers to complex financial environments.

The organisation of the paper is as follows: Section 2 outlines the literature review and related work. Section 3 provides the methodology. Section 4 presents the results. Section 5 details the discussion and Section 6 introduces the conclusion and future research.

2. Literature review and related work

2.1. Introduction

Over the past years, there have been several kinds of research directed to the study and review of blockchain networks. An overview of some of the recent researches carried out is provided in this section. Garcia (Garcia Ribera 2018), in his paper, focuses on the design and implementation of only the Proof-of-stake (PoS) consensus algorithm in the blockchain. Dai et al. (2017) conduct a thorough investigation on the application of blockchain limited to cybersecurity, providing a comparative study on the advantages that blockchain has brought to this specific area. Wang et al. (2019) provide a review of the state-of-the-art consensus protocols, delivering a comprehensive survey on blockchain emerging applications in the telecommunication industry. Wan et al. (2019) analyse the strengths and weaknesses of some of the main consensus algorithms without entering into further detail regarding the networks and their uses. Adefemi Alimi et al. (2020) explore the connectivity within networks, as well as security and privacy challenges to be addressed when implementing a low power wide area network (LPWAN). Kuo, Rojas, and Ohno-Machado (2019) provide a comparison on blockchain platforms focusing mainly on healthcare. While the paper presents blockchain's main features introducing the system to healthcare and biomedical applications, the study takes into account platforms that come from the same network (for instance Bitcoin and Litecoin) as a separate DLT.

2.2. Blockchain

The blockchain, also known as the chain of blocks, is a peer-to-peer network that is connected by its nodes to form a chain. It has the properties of a distributed, transactional database. Whenever a node

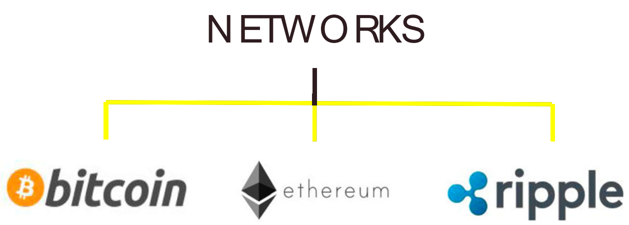

Figure 1. Blockchain networks are to be analysed in this paper.

in the network verifies the information that must be validated, it is sent through their respective public keys to the rest of the nodes in the network (Tschorsch and Scheuermann 2015). The data, stored in blocks, are linked to one another to form a chain. The sequence of the chain is conformed using a timestamp. The nodes in the network update and store a copy of the full ledger every time a new block is generated. This simplifies the tracking of tangible (house, car and land) and intangible (patents, brands, copyrights and stocks) assets (Chaudhry and Yousaf 2018). Figure 2 shows an illustration of a blockchain.

Blockchain relies heavily on cryptography in order to bring authentication to all interactions in the network. The verified information is sent to the other nodes via their public keys (Tschorsch and Scheuermann 2015). The public key system was invented in 1976 when Diffie and Hellman developed the idea of asymmetric cryptography (Fernandez-Vazquez et al. 2019). This resulted in the creation of public and private keys. Through public key systems, two users are able to engage in a secure connection and send information securely via a public network with public techniques. The sender would transmit a message enciphered in the receiver's public enciphering key (public key). To decipher the message, the receiver would use its own secret deciphering key (private key) (Diffie and Hellman 1976). Public and private keys can be combined only with the other key in the pair, making the relation between both keys exclusive (or interrelated). This is achieved through the mathematical computation in the algorithms of both keys. Private keys must be kept secret, whilst public keys can be shared unlimitedly amongst different users (Yu, Kang, and Park 2019).

2.3. Types of blockchains

There are two main types of blockchains, permissioned and permissionless.

- *Permissioned (private networks)*: These networks require permission to access the ledger. They are highly controlled by the owners, which might be desirable under certain situations. Examples of these networks are Hyperledger Fabric (2017) or Corda (Gendal Brown 2018).
- *Permissionless (public networks)*: These networks require no permission to access the ledger. Any user can become part of the network. The information, its transactions and the ledger state are transparent and accessible to all participants of the blockchain. All three networks analysed in this paper are permissionless networks.

3. Methodology

We used an explorative multiple case study method to further understand the range of value generation logic and value capture methods used by blockchain networks. Site selection for several case studies should be based on content rather than statistics to ensure that case firms are adequately representative of the target population (Greene and David 1984). Given our study goals (Seawright and Gerring 2008), we choose to focus our analytical research on networks that have blockchain-

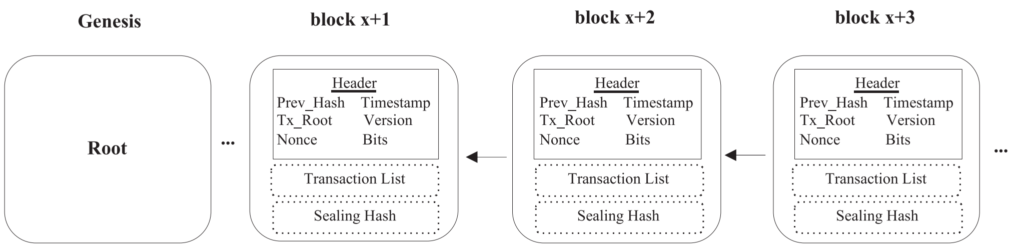

Figure 2. Blockchain. A new block is created on the chain with a header and a transaction list. Users with public or private keys have access to the information in the network.

enabled market applications. The majority of the data are qualitative in nature and was collected from two main sources: The web of Science Core Collection (WoS) database and from statistical databases such as coinmarketcap.com. The descriptive information was gathered from articles from journals in the WoS database. A manual review technique was used, which included a preliminary level of reading of titles and abstracts. Then, after reading the entire paper, irrelevant studies were eliminated (Golder, Loke, and Zorzela 2014). Furthermore, significant filtering methods were employed for each database to limit the research results. Our explorative data gathering methodology is particularly well-tailored to the open and competitive innovation environments under which blockchain networks currently operate (Adner and Kapoor 2010) (Iansiti and Levien 2004).

3.1. Selection of networks

To come up with a diverse range of blockchain networks, we started by approaching web pages with information from cryptocurrency prices, charts and markets that suggested the top three blockchain permissionless networks that met our requirements. The credibility of these networks was provided by their market capitalisation. This was used as a proxy for trust and worldwide adoption of the network. These case networks were purposefully chosen to represent a broad variety of large, blockchain networks that use open-source or self-developed technology to create enterprise applications for internal or external consumption. The networks of concern are: (i) Bitcoin; (ii) Ethereum; and (iii) Ripple.

3.2. Data gathering

Main and secondary sources were used to gather information on the three case networks. We gathered relevant information on these networks by reading widely available news stories and media releases. Data regarding market capitalisation was gathered from the website coinmarketcap.com.

Following a thorough examination of our primary and secondary evidence, concise case narratives were written to outline the business model that underpins each of the three blockchain networks, with a focus on their specific technical assets, value capture processes and the major challenges they face. This analysis is derived from the quantitative and qualitative assessments in Section 6.

4. Results

This section examines the different blockchain underlining their key features and uses.

4.1. Bitcoin

Bitcoin was introduced in 2008 (Nakamoto 2008) as a peer-to-peer system for electronic transactions. This system enables users to transfer digital payments from one entity to another through transactions. Without the involvement of central agents (i.e. central banks), the double-spending problem is prevented. Nakamoto proposed the first complete system for electronic transactions without relying on trust. Its architecture is designed to remove the central authority through a non-reversible, cash-like transaction system. The designed consensus algorithm is called Proof-of-Work (PoW). Nodes that engage in the network by solving cryptographic puzzles (or PoW) generating a cryptographic hash with specific properties are known as miners (Sun Yin et al. 2019).

4.1.1. Network

The first block in a chain, known as genesis or root, is coded into the user's software of the blockchain network. New transactions will only be effective with the creation of a new block into the existing blockchain.

4.1.2. Incentive

The Bitcoin system rewards miners by setting incentives for their computational power use. Miners seek profits and attempt to break even with their mining costs as soon as they can. Back in the day, an ordinary CPU could be used to solve PoW, but soon the speed was limited. Miners quickly realised that they needed faster solutions to dominate the competition.

Bitcoin has two types of rewards: block rewards and transaction fees.

(i) *Block rewards*: For each block solved, miners, get a reward in the form of Bitcoins. As the value of Bitcoin increases, mining becomes a profitable business for miners.
(ii) *Transaction fees*: The need to reward miners in a different way arises when the block creation phase is phased out. Currently, the network allows the transaction creator to stipulate a fee for authorising that particular transaction. This creates an incentive issue, as nodes will prefer to preserve the transactions to themselves rather than making them available to the whole network.

4.1.3. Disk space

Block size has been much of a debate in the Bitcoin community since its origin. Nakamoto designed an empty Bitcoin block header to be around 80 bytes. In late summer 2010, the network's source code was modified to set a maximum allowed size for new blocks added to the blockchain. This limit was set at 1 megabyte, which corresponds to around three transactions per second. In September 2015, a second modification to the code was made, which prevented the network from accepting blocks larger than 1 megabyte.

4.1.4. Consensus algorithm

Nodes in the blockchain need to agree on transactions in order to mine a new block. If this does not happen, the blockchain will end up with forks or divergences. A consensus mechanism is therefore needed in order to prevent forks from happening. Every time new data is updated, a new version is created (Wang 2018).

In order for a transaction to be inserted into a new block, a series of actions must be fulfilled (Figure 3) (Nakamoto 2008):

(1) The new transaction is sent to all nodes.
(2) Each miner node collects the transaction into a block.
(3) Each miner node tries to solve the PoW puzzle for its block.

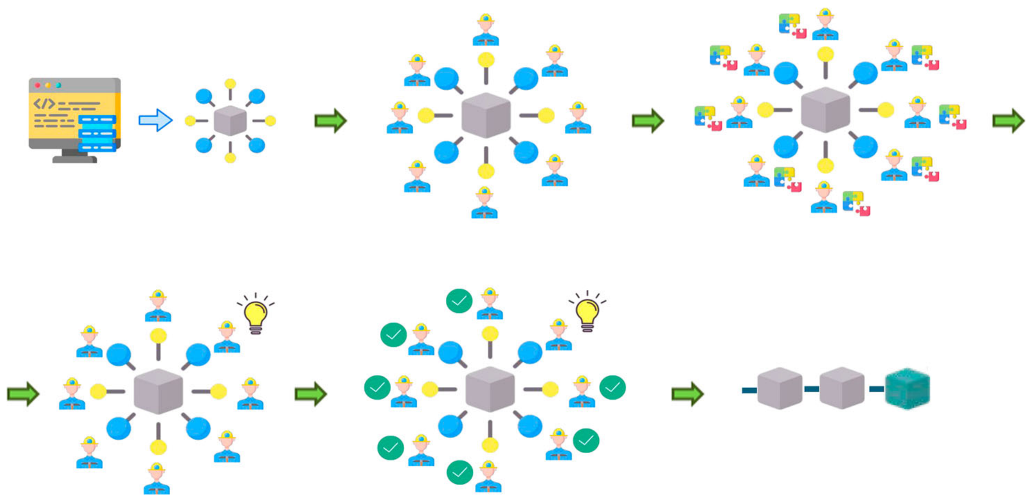

Figure 3. Steps in the creation of a new block.

(4) When a miner node solves the PoW, it is sent to all the nodes in the network.
(5) Nodes will accept the block if the transaction is valid.
(6) Nodes show acceptance by creating the next new block on the chain with a unique hash as well as the hash from the previous block. The longest chain in the network will always be considered by nodes to be the correct one, and these nodes will therefore keep extending it.

The first node to solve the puzzle has the right to stamp the block in the blockchain. In the event of finding the solution to the puzzle, that node sends the proposed block with its value to the other nodes in the network and notifies them that the solution has been found. Miners who are still working on the solution will then halt their attempt and will evaluate the proposed block. If the verifications are correct, the newly created block will be included in the current chain and the process will repeat again for the validation of a new transaction (Nguyen and Kim 2018).

4.2. Ethereum

Vitalik Buterin created Ethereum in 2013 (Buterin 2013), as an alternative protocol for creating decentralised applications. Ethereum has a particular emphasis on situations where rapid development time, security and efficient interaction between applications are important. One of the most relevant inquiries of the Ethereum network is smart contracts. Nick Szabo introduced the concept of smart contracts in 1994, creating a system that embedded the contractual clauses of a transaction in the user's personal computers (Szabo 1994).

In Ethereum, smart contracts are lines of code inserted in Ethereum's public ledger. They allow programmes to be run on the blockchain as decentralised applications. These contracts allow the creation of a set of arbitrary rules for ownership, transaction formats and functions. The code used in a smart contract is compiled and the Ethereum Virtual Machine (EVM) runs its bytecode documented into the blockchain (Pinna et al. 2019).

4.2.1. Network

The code used to write contracts in Ethereum is recorded in a low-level, stack-based bytecode language called the EVM code. The smart contract system is shown in Figure 4.

4.2.2. Incentive

In Ethereum, incentives are generated through mining and fees.

- *Mining*: similar to Bitcoin, blocks are created and added to the Ethereum network by miners. For every created block, miners receive rewards in the form of Ether, Ethereum's own currency.
- *Fees*: all of the programming computation that takes part in Ethereum is measured in units of gas and paid in Ethers. Transactions have specific quantities of gas associated with them, known as gas limits (Atzei et al. 2017).

4.2.3. Disk space

Whereas in Bitcoin, the maximum block size limit is specified in megabytes (currently 1MB), in Ethereum the block size depends on the complexity of the smart contracts being run. Ethereum has a gas limit per block rather than a block size. In relation to the data store, Ethereum blocks are around 2 KB in size.

4.2.4. Consensus algorithm

The transaction execution is one of the most complicated aspects of the Ethereum procedure. Similar to Bitcoin, Ethereum uses PoW to enforce the security of the network. It works both as a method of

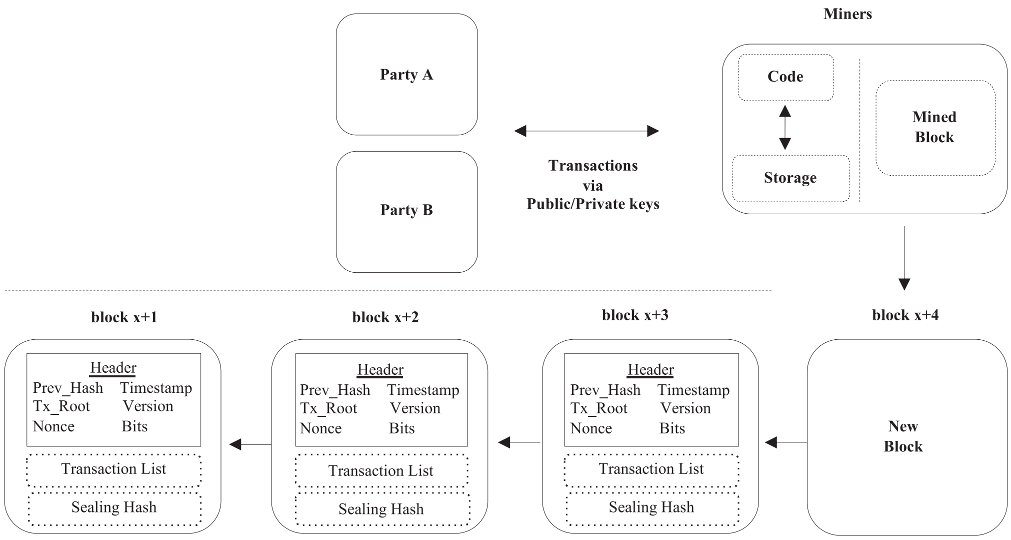

Figure 4. Smart contract system. The blockchain is denoted on the lower part. Parties involved in the transaction (i.e. Party A receives Y units from Party B, which obtains Z units) are represented in the upper bound. Transactions are only complete with the construction of a new block.

securing confidence in the system through rewards and as a mechanism of wealth distribution. The goals of PoW are, on one hand, accessibility to as many users as possible, making the network as open as possible and on the other hand, preventing super linear profits with high initial barriers. This is a mechanism that prevents well-funded opponents to obtain a big stake in mining power, skewing the distribution to their benefit and reducing the network's security.

4.3. Ripple

Ripple is a decentralised payment system, created in 2014 (Ripple Inc. 2015) and coded in open source. Its nodes have three main functions: make or receive payments, act as market makers and validate transactions in Ripple's consensus protocol. Users of the Ripple network have a pair of public and private keys that enable them to send payments to other users, either by using Ripple's own currency (known as XRP) or any other currency.

The main difference between Ripple and traditional banks or Bitcoin arises from the fact that transactions between users do not correspond to real-life amounts. The system modifies the balance but is unaware of how and when the money is deposited. Another main difference between Ripple and traditional banks is the speed of transactions. Due to the distributed agreement protocol that validates transactions, transactions in Ripple take only between 5 and 10 seconds to settle (Di Luzio, Mei, and Stefa 2017).

Even though Ripple is an open-source decentralised consensus protocol, Ripple Labs manages the deployment of the network. Ripple was created with a limited supply of 100 billion XRP, with 20% retained by the founders, 25% by Ripple Labs and the rest distributed for the promotion of the network.

4.3.1. Network

There are two main players in the Ripple network: gateways and market makers. Gateways are wallets established to bootstrap credit links to newly created wallets. They are similar to what today is known as banks and loan agencies. On the other hand, market makers are wallets that charge small fees for exchanging currencies received in their wallets. They facilitate transactions between different currency holders.

4.3.2. Incentive

Users within the Ripple network can either exchange XRPs or trade them with any other currency (XRPs act as a currency bridge). For every transaction within the system, a small XRP fee is collected. Fees in the XRP ledger protect the ledger against different types of abuse. In the XRP ledger, there are different types of fees (XRP 2019):

- *Inside the ledger*
  - Neutral fees: The transaction costs or fees are a very small amount of XRP that is destroyed every time a transaction is sent. This cost is associated with the network load, protecting the network from spam.
  - Optional Fees: These are fees that issuers charge for transferring currencies into other addresses inside the XRP Ledger.
- *Outside the ledger*: Users can invent different ways to charge fees associated with the XRP Ledger, such as banks charge their clients when sending money from one account to another.

4.3.3. Disk space

The disk space in Ripple depends on the ledger history the user aims at keeping locally. The Ripple server needs a maximum of 256 ledger versions in order to comply with the consensus protocol and report the whole state of the ledger. Online deletion is also available, which allows the server to delete the local copies of old ledger versions in order to keep disk usage from increasing over time.

4.3.4. Consensus algorithm

In order to maintain consensus in the network, the Ripple Protocol Consensus Algorithm (RPCA) is deployed almost every second by the nodes. When an agreement is reached the ledger is considered to be closed, becoming the last-closed ledger. This prevents forks from arising in the network as this last-closed ledger will be identical for all nodes (Schwartz, Youngs, and Britto 2014).

In order to reach consensus in the network, the RPCA runs in rounds as follows (Schwartz, Youngs, and Britto 2014):

(i) In this first step, every server takes all valid transactions prior to consensus and makes them public in what is called a candidate set.
(ii) In the second step, each server combines the sets of all servers in its Unique Node List (UNL), voting on the legitimacy of the transactions.
(iii) Through the consensus phase, transactions with a percentage of yes higher than the minimum go through to the next round. Transactions without the minimum votes are either rejected or incorporated into the set for the next ledger's consensus procedure. The validated server only sends proposals that have been agreed upon by more than 50% of the servers in its UNL. This process is repeated with vote requirements increasing by 10–60%, 70% with a final step of 80% (Armknecht et al. 2015).
(iv) A minimum consensus percentage of 80% of the servers in the UNL is required for the final round of consensus. When a transaction reaches this final stage, it is taken away from the candidate set and checked for double-spending versus the ledger transactions. If a transaction fulfils this requirement, it is applied to the ledger, becoming the new last-closed ledger.

When payments are made in a currency other than XRP, the system only records the payment but does not enforce it. These types of transactions are called 'I Owe You' (IOU). In Figure 5, Mary can only pay Diane if the latter trusts Mary and gives her enough credit. Therefore this payment can only occur if the payment value is within the upper bound allocated by Diane to Mary.

For payments where participants know each other or the amounts to be transferred are small, this could work, but transactions with large sums often require the involvement of market makers. These market makers act as intermediaries ensuring enough credit is available through the process for the payment to succeed.

4.4. Assessment criteria

This section is designed to present the different evaluation criteria that have been applied to the selected networks. There are two main categories: quantitative and qualitative.

4.4.1. Quantitative

We consider such parameters as quantitative in the sense of this paper whether they have a quantifiable property or can be critically evaluated. The criteria identified in this section are classified as quantitative when they can either be measured (quantifiable property) or assessed objectively (Table 1). This category's criteria are listed in detail below.

- *Currency* indicates the native cryptocurrency for each platform.
- *Creation* shows the network's year of development.
- *Consensus algorithm* outlines the process used to achieve agreement in each network. In the blockchain, a consensus algorithm is used to reach distributed consensus. Time and energy usage are directly affected block formation.
- *Smarts contracts allowed* denotes if the network supports the use of smart contracts.
- *Coin supply* indicates the maximum supply amount of a network's native cryptocurrency.
- *Block generation time* defines the measure of the time it takes to produce a new block.
- *Transactions per second (TPS)* indicates the number of transactions confirmed (or added to the blockchain) per second.
- *Block size* refers to the maximum size of one block in each platform.
- *Energy consumption* refers to the electrical power used by the consensus algorithm when mining a new block.
- *Language* denotes the main coding language used for each network.
- *Incentive* outlines the reward assigned to the participants in each network.
- *Privacy* examines the privacy mechanisms of each network. The higher the privacy, the more likely a network will be widely adopted.
- *Outlook* evaluates each network's sustainability in the near future.

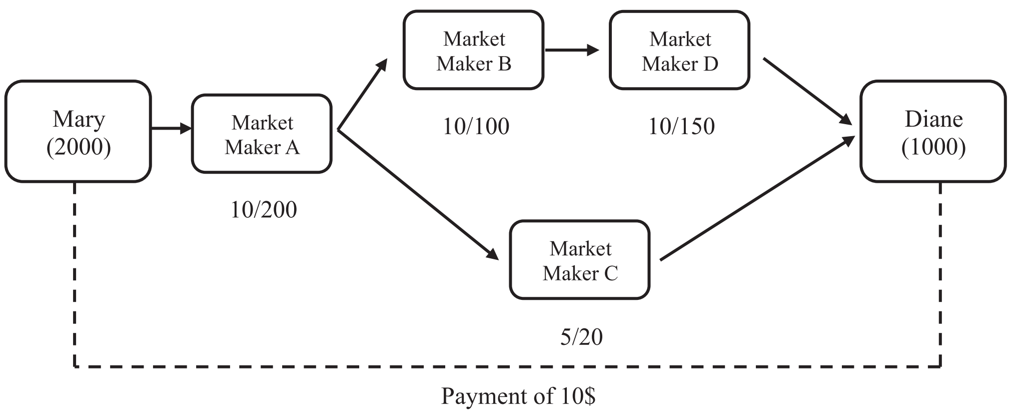

Figure 5. Ripple network's IOU flow.

Table 1. Quantitative analysis of the selected networks.

	Bitcoin	Ethereum	Ripple
Currency	Bitcoin (BTC)	Ether (ETH)	XRP
Creation	2009	2014	2013
Consensus algorithm	PoW	PoW	RPCA
Smart contract allowed	No	Yes	Yes
Coin supply	21,000,000 BTC	No cap	100 billion XRP
Block generation time	10 minutes	~14 seconds	5–10 seconds
Transactions per second processor	7	15–20	1500
Block size	1 MB block limit	Around 2 KB	No limit
Energy consumption	Very high	High	Very low
Daily volume ($)	41,185,185,761	19,585,998,814	2,313,819,448
Market cap. ($)	180,963,233,540	30,065,188,433	12,368,433,149
Language	C++	Solidity	C++
Incentive	Block rewards and transaction fees	Block rewards and transaction fees	Through transaction fees
Privacy	The identifiers in this database are pseudonyms. Transactions on public blockchain visible to everyone, hence transparent.	The identifiers in this database are pseudonyms. Transactions on public blockchain visible to everyone, hence transparent.	The identifiers in this database are pseudonyms. Transactions on public blockchain visible to everyone, hence transparent.
Outlook	High consumption of energy without a plan of improvement	High consumption of energy with a plan to move to PoS	Low energy consumptions guarantees future sustainability

4.4.2. Qualitative

The motivation of the qualitative criteria is regarded in a comparative analysis as an area to gain a stronger understanding of the underlying principles of the analysed networks, often through a prism of subjectivity (Table 2). In the absence of objective assessment, the criteria referring to this property are described below:

- *Level of trust* refers to the degree of trust or public confidence in terms of wide-scale adoption.
- *Upgrade availability* analyses the features and enhancements of each network in terms of adding new features when improvements or actualisations need to be integrated within older versions of the platform.
- *Governance* relates to the manner of governing each network and the degree of democratic and open ruling mechanisms.
- *General purpose* denotes the best-suited uses of each network.
- *Industry focus* outlines the desired applications for which each network is convenient.

5. Discussion

The following section presents the assessment and evaluation of the three most important networks with the defined evaluation criteria. Tables 1 and 2 show the quantitative and qualitative analysis of

Table 2. Qualitative analysis of the selected networks.

	Bitcoin	Ethereum	Ripple
Level of trust	High	High	Medium
Upgrade availability	Through forks	Through forks	Through forks
Governance	Bitcoin Developers	Ethereum Developers	ECAF
General purpose	Financial	B2B Businesses	Financial
Industry focus	Used best as a means of payment	Robust smart contract functionality and flexibility	Most suitable for cross-border payments due to scalability and speed

these networks. The quantitative group has been analysed using the information mainly from each platform's white paper (Nakamoto 2008; Buterin 2013; Ripple Inc. 2015). An explanation of the qualitative table has been added with supplementary comments.

PoW systems such as the ones used by Bitcoin and Ethereum have been worldwide adopted, having a high level of trust by the community. Features such as robustness and data immutability make it almost impossible for a user to change the information stored in the ledger. This contributes to a high level of trust in the system by its users. Upgrades on both platforms are achieved through hard forks. Due to the democratic nature of both open-source platforms, miners must agree about the new set of rules in order to indicate there has been a change in the network's protocol. These forks have lead, for example, to new cryptocurrencies such as Bitcoin Cash (BCH) or Litecoin (LTC) in the Bitcoin platform or Ethereum Classic (ETC) in the Ethereum blockchain. Ethereum adds an extra layer to the ledger through the allowance of smart contracts. In addition, the identifiers in this database are pseudonyms and the transactions on the public blockchain are visible to everyone, fostering the transparent nature of both networks. As a result of these characteristics, both platforms are extensively used accompanied by a strong trust level in their operations.

Nevertheless, these two platforms experience serious challenges in various aspects such as instability and volatility, scalability, cyber attack threats and privacy. Regarding privacy, for instance, blockchain's transparency, being one of the most important properties of this system, can also be a major concern. For example, two parties with transactions with one another may be reluctant to have this information tracked by a third party, largely due to the business and client privacy implications that this could have.

The high-energy consumptions of PoW algorithms make the sustainability of these networks to be doubtful in the near future. Although Ethereum is planning on changing to a more energy-efficient, less energy-consuming PoS algorithm, Bitcoin has shown no plans to tackle this aspect. Another characteristic worth considering is the limitation of Bitcoin related to data storage. In Ethereum there is a certain degree of flexibility, mainly due to the possibility of storing data through the use of smart contracts. Nonetheless, storing large amounts of data in both networks becomes expensive and impractical.

Ripple, on the other hand, tries to tackle some of the weaknesses of Bitcoin and Ethereum, mainly through the use of more energy-efficient consensus algorithms and improving the network's scalability. The generated transactions per second in these networks are much higher and their energy consumption close to zero. These networks also allow for the use of smart contracts, which help in the development of a wide variety of applications, although Ripple has been specifically designed for the financial world.

A remarkable feature in relation to these networks is their governance mechanism. On one hand, Bitcoin and Ethereum are the most democratic of the three. Users can submit development proposals that are then taken into account by the developers of these networks. On the other hand, Ripple, governed by Ripple Labs, is more reluctant to the intervention of users. As opposed to other networks, Ripple is not run by miners. Ripple Labs owns a big stake in the total amount of the released XRP.

The three networks are updated through mechanisms known as soft and hard forks. When a soft fork occurs, only one blockchain remains valid as users adopt the new update. On the other hand, in the event of a hard fork, both the old and new blockchains exist alongside. This means that the software must be updated to work by the new set of rules. Both soft and hard forks create a split, but a hard fork creates two different blockchains whilst a soft fork is meant to result in only one.

Most users would agree that one of the main efforts in recent years has been to increase security in the networks. This is due to a series of security breaches that are worth considering, especially regarding smart contracts. This can arise in many forms, for instance, criminal activities through smart contracts (also known as criminal smart contracts) have taken place through the leakage of private information or private key theft. In 2016, over 60 million US dollars worth of Ether were lost by a bug in the Distributed Autonomous Organization (DAO). Nevertheless, a hard fork that invalidated the stolen cryptocurrencies took place, although the stolen Ether could not be recovered (Frantz and Nowostawski 2016). The Ethereum protocol proved to remain secure, which fostered the level of trust in this network by the market.

In order for companies and enterprises to have a better understanding of each network, a summary of their main characteristics and the environments for which they are best suited is presented below:

Bitcoin: Bitcoin is the first and most widely used cryptocurrency in the world. It is arguably considered the most successful crypto ever created. This is precisely its biggest advantage. The United States, Japan, South Korea, Italy, the Netherlands, United Kingdom or Switzerland are some of the countries in which users can pay using Bitcoin, as it is widely accepted. One of the main advantages when using this currency as a means of payment relies on the fact that no ID card or passport is required to open an account. Accounts, or Bitcoin Addresses, are generated through a Bitcoin Wallet. Compared to traditional methods of money wiring, the transfer fees when using Bitcoin are less expensive (banks will generally charge 3–5% of the transfer amount). The main use of the Bitcoin network is related to the financial sector, where its competitive advantage remains.

Ethereum: Ethereum is well known for its robust smart contract functionality and flexibility. It is used extensively across numerous industries. This network has developed a big online support community that launches frequent product updates and developments, known as the Ethereum Enterprise Alliance (EEA). The EEA is a non-profit organisation with more than 250 members that connects Fortune 500 enterprises, start-ups, academia and technology specialists with Ethereum experts. Ethereum is a permissionless (or public) platform designed for mass consumption in comparison with restricted access networks. Also, its PoW protocol may result in latency issues, although this could change in the near future with the adoption of the faster PoS consensus algorithm. The main dApps (Decentralised applications) for which this network is being built include: games, gambling, finance, social, wallet and marketplaces.

Ripple: Ripple's obtains its competitive advantage by providing a payment mechanism to banks, currency exchanges, digital asset exchanges and corporations. This network is most suitable for cross-border payments, allowing entities to transact throughout national boundaries with low transaction fees, better scalability and fast processing speed. It works best for large size companies with high volumes rather than small and medium enterprises or single users. Companies like Banco Santander, American Express, MoneyGram International, SBI Holdings or Deloitte (Long 2016), are planning on integrating Ripple to make payments faster and more secure.

5.1. Limitation

Despite the ramifications and contributions to the area of blockchain research, this research has several limitations. Firstly, the quality of primary research and the technique utilised substantially influence the outcome of a comparative study. The nature of blockchain is a relatively new issue for research, and it is not well-studied; the majority of publications were published during the previous five years. The search of information was therefore limited to these articles and web pages. Secondly, while the research focuses on the top three permissionless networks, it may be expanded to look at more particular applications in other large and widely adopted networks. Thirdly, we are certain that our research can be broadened by doing case studies on additional blockchain permissionless networks, particularly those of recent creation which are attracting high industry interest such as Cardano White Paper (2015) or EOS.IO Technical White Paper v2 (2018).

6. Conclusion and future research

In this paper, we provide a comprehensive comparative analysis of the most prominent blockchain networks and their characteristics, with emphasis on the consensus algorithms, incentives and disk size. Starting from a brief introduction to blockchain and its applications, we have constructed an in-depth analysis of Bitcoin, Ethereum and Ripple networks from a technical perspective.

Based on the comprehensive analysis of the networks and their consensus protocols, we have set the grounds for further studies on the emerging applications of blockchain in different sectors. Our focus has been put on the analysis of each network's most relevant characteristics. This comparative analysis is expected to serve as a guideline for further understanding of the different blockchain networks and the exploration of promising research directions that can lead to inspiring outcomes in related areas.

There are a number of aspects that are important to be considered in future academic research. For instance, consistency achieved through the consensus solution or complexity, concurrency control or transaction confirmation speeds are parameters that can be integrated in order to have a more detailed comparison. Further research can point in the direction of exploring further blockchain networks such as Tron Foundation (2018), NEO (2017), R3's Corda or Hyperledger. Also, additional investigation on consensus algorithms such as proofs-of-space (Dziembowski et al. 2015), Equihash (Biryukov and Khovratovich 2017) or Algorand (Gilad et al. 2017) could be considered. Technical experiments can be carried out to evaluate the strengths and weaknesses of each network with respect to the implementation of the networks in the real world.

Note

1. Source: https://www.coinmarketcap.com as of 14/03/2021.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was partially supported by the Council of Gijón through the University Institute of Industrial Technology of Asturias (Ref. IUTA-20-GIJON-1-24). The views and opinions expressed herein do not necessarily reflect those of the IUTA.

Notes on contributors

Simon Fernandez-Vazquez is a lecturer in Business Management at the University of Oviedo (Spain) since 2020. His background studies are Business and MSc Finance degree.

Dr. ***Rafael Rosillo***, PhD. is a lecturer in Business Management at the University of Oviedo (Spain) since 2011. His background studies are an MBA and a Computer Engineering degree.

Luis Meijueiro is a professional specialised in Blockchain, working for a top scientific research entity.

Raul Alonso Alvarez is a professional specialised in Blockchain, working for a top scientific research entity.

Dr. ***David De La Fuente***, Full Professor, is a lecturer in Business Management at the University of Oviedo (Spain) since 1989. He has collaborated as the author or co-author in 170 international publications.

ORCID

Simon Fernandez-Vazquez http://orcid.org/0000-0003-0223-4065

References

Adefemi Alimi, K. O., K. Ouahada, A. M. Abu-Mahfouz, and S. Rimer. 2020. "A Survey on the Security of Low Power Wide Area Networks: Threats, Challenges, and Potential Solutions." *Sensors* 20: 5800. https://doi.org/10.3390/s20205800

Adner, R., and R. Kapoor. 2010. "Value Creation in Innovation Ecosystems: How the Structure of Technological Interdependence Affects Firm Performance in new Technology Generations." *Strategic Management Journal* 31: 306–333.

Armknecht, F., G. Karame, A. Mandal, F. Youssef, and E. Zenner. 2015. "Ripple: Overview and Outlook." In *Trust and Trustworthy Computing. Trust 2015. Lecture Notes in Computer Science*, edited by M. Conti, M. Schunter, and I. Askoxylakis, 163–180. Cham: Springer.

Atzei, N., M. Bartoletti, and T. Cimoli. 2017. "A Survey of Attacks on Ethereum Smart Contracts (SoK)." In *Principles of Security and Trust. POST 2017. Lecture Notes in Computer Science*, edited by M. Maffei, and M. Ryan, 164–186. Berlin: Springer.

Biryukov, A., and D. Khovratovich. 2017. "Equihash: Asymmetric Proof-of-Work Based on the Generalized Birthday Problem." *Ledger* 2: 1–30.

Buterin, V. 2013. "Ethereum: A Next-Generation Smart Contract and Decentralized Application Platform." Accessed April 3, 2021. https://github.com/ethereum/wiki/wiki/White-Paper

Cardano White Paper. 2015. Accessed August 15, 2021. https://whycardano.com/

Chaudhry, N., and M. M. Yousaf. 2018. "Consensus Algorithms in Blockchain: Comparative Analysis, Challenges and Opportunities." 12th International Conference on Open Source Systems and Technologies (ICOSST), Lahore, Pakistan.

Christidis, K., and M. Devetsikiotis. 2016. "Blockchains and Smart Contracts for the Internet of Things." *IEEE Access*. doi:10.1109/ACCESS.2016.2566339

Dai, F., Y. Shi, N. Meng, L. Wei, and Z. Ye. 2017. "From Bitcoin to Cybersecurity: A Comparative Study Of Blockchain Application And Security Issues." 4th International Conference on Systems and Informatics (ICSAI), Hangzhou, China.

Dennis, R., and J. P. Disso. 2019. "An Analysis into the Scalability of Bitcoin and Ethereum." Third International Congress On Information And Communication Technology, Book Series: Advances in Intelligent Systems and Computing, London, UK.

Di Luzio, A., A. Mei, and J. Stefa. 2017. "Consensus Robustness and Transaction De-Anonymization in the Ripple Currency Exchange System." 2017 IEEE 37TH International Conference On Distributed Computing Systems (ICDCS 2017), Atlanta, GA, USA.

Diffie, W., and M. Hellman. 1976. "New Directions in Cryptography." *IEEE Transactions On Information Theory* 22 (6): 644–654.

Dziembowski, S., S. Faust, V. Kolmogorov, and K. Pietrzak. 2015. "Proofs of Space, Advances in Cryptology – CRYPTO." 2015: 35th Annual Cryptology Conference, Santa Barbara, CA, Aug. 2015, 585–605.

EOS.IO Technical White Paper v2. 2018. Accessed August 15, 2021. https://github.com/EOSIO/Documentation/blob/master/TechnicalWhitePaper.md

Fernandez-Vazquez, S., R. Rosillo, D. De La Fuente, and P. Priore. 2019. "Blockchain in FinTech: A Mapping Study." *Sustainability* 11: 6366. https://doi.org/10.3390/su11226366

Frantz, C. K., and M. Nowostawski. 2016. "From Institutions to Code: Towards Automated Generation of Smart Contracts." IEEE, 1s. t International Workshops on Foundations and Applications of Self*Systems (FAS*W), 210–215, IEEE.

Garcia Ribera, E. 2018. "Design and Implementation of a Proof-of-Stake Consensus Algorithm for Blockchain." B.S. thesis, Universitat Politécnica de Catalunya.

Gendal Brown, R. 2018. "The Corda Platform: An Introduction." Accessed April 26, 2021. https://www.corda.net/content/corda-platform-whitepaper.pdf

Gilad, Y., R. Hemo, S. Micali, G. Vlachos, and N. Zeldovich. 2017. "Algorand: Scaling Byzantine Agreements for Cryptocurrencies." Proceedings of the 26th Symposium on Operating Systems Principles (SOSP '17).

Golder, S., Y. K. Loke, and L. Zorzela. 2014. "Comparison of Search Strategies in Systematic Reviews of Adverse Effects to Other Systematic Reviews." *Health Information and Libraries Journal* 31 (2): 92–105.

Greene, D., and J. L. David. 1984. "A Research Design for Generalizing from Multiple Case Studies." *Evaluation and Program Planning* 7: 73–85.

Hyperledger. 2017. "An Introduction to Hyperledger." Accessed April 16, 2021. https://www.hyperledger.org/wp-content/uploads/2018/07/HL_Whitepaper_IntroductiontoHyperledger.pdf

Iansiti, M., and R. Levien. 2004. *"The Keystone Advantage: What the New Dynamics of Business Ecosystems Mean for Strategy, Innovation, and Sustainability"*. Boston, MA: Harvard Business School Press.

Kuo, Tsung-Ting, Hugo Rojas, and Lucila Ohno-Machado. 2019. "Comparison of Blockchain Platforms: A Systematic Review and Healthcare Examples." *Journal of the American Medical Informatics Association: JAMIA* 26: 10. https://doi.org/10.1093/jamia/ocy185

Long, M. 2016. "Santander Becomes the First U.K. Bank to Use Ripple for Cross-Border Payments." Ripple blog entry. Accessed April 4, 2021. https://ripple.com/insights/santander-becomes-first-uk-bank-use-ripplecross-border-payments/

Nakamoto, S. 2008. "Bitcoin: A Peer-to-peer Electronic Cash System." Accessed April 2021. https://bitcoin.org/bitcoin.pdf

NEO. 2017. "NEO White Paper." Accessed April 24, 2021, https://docs.neo.org/docs/en-us/basic/whitepaper.html

Nguyen, G. T., and K. Kim. 2018. "A Survey About Consensus Algorithms Used in Blockchain." *Journal of Information Processing Systems*. https://doi.org/10.3745/JIPS.01.0024

Pinna, A., S. Ibba, G. Baralla, R. Tonelli, and M. Marchesi. 2019. "A Massive Analysis of Ethereum Smart Contracts Empirical Study and Code Metrics." *IEEE Access*. https://doi.org/10.1109/ACCESS.2019.2921936

Ripple Inc. 2015. "Implementing the Interledger Protocol in Ripple." Accessed April 25, 2021. https://www.ripple.com/insights/implementing-the-interledger-protocol/

Schwartz, D., N. Youngs, and A. Britto. 2014. "The Ripple Protocol Consensus Algorithm." Accessed April 4, 2021. https://ripple.com/files/ripple_consensus_whitepaper.pdf

Seawright, J., and J. Gerring. 2008. "Case Selection Techniques in Case Study Research." *Political Research Quarterly* 61: 294–308.

Sun Yin, H. H., K. Langenheldt, M. Harlev, R. R. Mukkamala, and R. Vatrapu. 2019. "Regulating Cryptocurrencies: A Supervised Machine Learning Approach to De-Anonymizing the Bitcoin Blockchain." *Journal of Management Information Systems* 36 (1): 37–73.

Szabo, N. 1994. "Smart Contracts." Accessed April 12, 2021. http://www.fon.hum.uva.nl/rob/Courses/InformationInSpeech/CDROM/Literature/LOTwinterschool2006/szabo.best.vwh.net/smart.contracts.html

Tron Foundation. 2018. "TRON, Advanced Decentralized Blockchain Platform, Whitepaper Version 2.0." Accessed April 26, 2021. https://tron.network/static/doc/white_paper_v_2_0.pdf

Tschorsch, F., and B. Scheuermann. 2015. "Bitcoin and Beyond: a Technical Survey on Decentralized Digital Currencies." *IEEE*. http://doi.org/10.1109/COMST.2016.2535718

Wan, S., M. Li, G. Liu, and C. Wang. 2019. "Recent Advances in Consensus Protocols for Blockchain: A Survey." *Wireless Networks* 10. https://doi.org/10.1007/s11276-019-02195-0

Wang, S., et al. 2018. "Forkbase." *Proceedings of the VLDB Endowment* 11 (10): 1137–1150.

Wang, W., D. T. Hoang, P. Hu, Z. Xiong, D. Niyato, P. Wang, and D. I. Kim. 2019. "A Survey on Consensus Mechanisms and Mining Strategy Management in Blockchain Networks." *IEEE Access*. https://doi.org/10.1109/ACCESS.2019.2896108

XRP Ledger Overview. 2019. "Ripple Online Documentation." Accessed April 8, 2021. https://developers.ripple.com/xrp-ledger-overview.html

Yu, J. H., J. Kang, and S. Park. 2019. "Information Availability and Return Volatility in the Bitcoin Market: Analyzing Differences of User Opinion and Interest." *Information Processing & Management* 56 (3): 721–732.

5 Capítulo 5: Blockchain in sustainable supply chain management: an application of the analytical hierarchical process (AHP) methodology

Este capítulo corresponde con una publicación que tiene como objetivo resaltar los beneficios de blockchain en la gestión de la cadena de suministro. La intención de este artículo es aportar a la comunidad científica una nueva vía que puede ser de gran interés para el diseño, desarrollo y comparación de dos métodos de gestión en una cadena de suministro.

Con el objetivo de potenciar el uso de la tecnología blockchain en la gestión de la cadena de suministro, particularmente cuando se opera dentro de la misma industria, se utilizó una metodología AHP para su análisis. La metodología propuesta cubre un análisis que compara las cadenas de suministro tradicionales y las cadenas de suministro habilitadas para blockchain. Este estudio contribuye a enfatizar los efectos favorables de la tecnología blockchain en su aplicación para la industria, analizando el impacto relativo de varias posibles ventajas de tecnología blockchain en el desarrollo sostenible. Además, este trabajo también se centra en algunos de los principales desafíos con respecto a la implementación de la tecnología blockchain, como la privacidad de datos o la latencia.

Para desarrollar este modelo, se examinan un total de ocho elementos fundamentales intrínsecos a la tecnología blockchain, como son: descentralización, resiliencia, seguridad, contratos inteligentes, sostenibilidad, trazabilidad, transparencia y confianza. Posteriormente se calcula un índice de deseabilidad tanto para la cadena de suministro convencional como para la cadena de suministro habilitada para blockchain, comparando ambos resultados. Tras la comparativa de la puntuación de este índice entre las dos cadenas, se halla que la cadena de suministro habilitada para blockchain supera ampliamente a la cadena de suministro convencional en términos de aumento de la sostenibilidad.

Además de resaltar un problema, su origen y su interés para la comunidad científica, un de los mayores logros a la hora de realizar esta publicación, es la de la aplicación de la metodología AHP sobre blockchain. La originalidad de combinar dicho proceso con una tecnología reciente como blockchain destaca el valor de esta investigación.

Blockchain in sustainable supply chain management: an application of the analytical hierarchical process (AHP) methodology

Simon Fernandez-Vazquez, Rafael Rosillo, David de la Fuente and Javier Puente
Business Management Department, University of Oviedo, Oviedo, Spain

Received 30 November 2021
Revised 16 March 2022
9 May 2022
19 June 2022
Accepted 10 August 2022

Abstract

Purpose – The analytical hierarchical process (AHP)'s main purpose is to assess higher hierarchy levels based on the cooperation of its various levels. It results in a well-designed model-based method in which the weights for the selected attribute are calculated using dimensions, criteria, and indicators. This paper aims to highlight the benefits of blockchain in supply chain management with the help of a literature review along with opinions of experts from various sectors.

Design/methodology/approach – With the goal of enhancing the use of blockchain technology in supply chain management, particularly when comparing within the same industry, the AHP methodology has been used. In order to develop the AHP model, a total of eight elements are examined in this study, which are decentralization, resiliency, security, smart contracts, sustainability, traceability, transparency and trust. A calculation of a Desirability Index for conventional supply chain and blockchain-enabled supply chains has been also developed.

Findings – Findings where that in a blockchain-enabled supply chain, the global weights of individual benefit variables are considerably larger than in conventional supply chains. When the score of the Desirability Index for conventional supply chain and blockchain-enabled supply chain is compared, the blockchain-enabled supply chain significantly surpasses the conventional supply chain in terms of increasing sustainable development in today's supply networks.

Originality/value – This study takes into account the AHP methodology applying it on blockchain. This has not been done before in the academic world, at least as far as the authors may be aware of. The originality of combining such process with a recent technology such as blockchain highlights the value of this research.

Keywords Blockchain, Supply chain management, Analytical hierarchical process

Paper type Research paper

1. Introduction

With the growth and popularization of information systems and network technology, the supply chain has become a complex system that is rapidly evolving. It has moved away from the traditional linear single chain model towards a nonlinear network chain model, in which the supply chain's operation efficiency is measured not only in terms of the profit of the core enterprise but also in terms of the profit of all relevant enterprises throughout the supply chain (Fu and Zhu, 2019; Vafadarnikjoo *et al.*, 2021).

Executives and managers are interested in blockchain because it looks to be the missing component that will enable widespread use of data-gathering technology (e.g. Radio Frequency Identification, Energy Performance Certificates, etc.) (Farnoush *et al.*, 2021). Several big corporations are now working on blockchain technology testing or pilot

Funding: This work is supported by the Spanish State Research Agency of the Spanish Ministry of Science and Innovation (MCIN/AEI) via the project "SPeeding Up the transition towards Resilient circular economy networks: forecasting, inventory and production control, reverse logistics and supply – PID2020-117021 GB-I00 and ERASMUS+ Program via the project Academic System Resource Planning: A Fully-Automated Smart Campus (ASRP) – UE-19-ASRP-598757".

Business Process Management Journal
© Emerald Publishing Limited
1463-7154
DOI 10.1108/BPMJ-11-2021-0750

programs. Wal-Mart or Marks and Spencer (M&S), for instance, are experimenting with blockchain technology to incorporate it in its food items (Malik *et al.*, 2018; Cole *et al.*, 2019).

Blockchain technology has been hailed as having the ability to address the challenge of establishing end-to-end transparency. It is a networking technology that utilizes a peer-to-peer (P2P) system to verify and exchange data, becoming increasingly popular for simplifying corporate operations (Akter *et al.*, 2020; Milani *et al.*, 2021; Hudson and Urquhart, 2021). It denotes a decentralized environment in which all transactions are recorded on a public or private ledger that is available to all users (Fosso Wamba and Queiroz, 2020). A private blockchain, for example, can offer provide its users with security, timeliness, and transparency, bringing numerous applications in operations and supply chain management (OSCM) (Batwa and Norrman, 2020; Sivula *et al.*, 2020).

The incorporation of blockchain technology into the traditional supply chain is more likely to tackle existing supply-chain difficulties and dangers. Blockchain-enabled supply chain management needs a lot of upkeep and technological know-how. Early adopters of blockchain have encountered a number of obstacles that need technical skills to convey the technology's virtues with greatest clarity. Businesses must determine if their investment in blockchain is justified in terms of delivering long-term or sustainability-related advantages and whether blockchain's characteristic outweighs the benefits received from the old supply chain. As a result, the primary goal of this research is to add to the supply chain literature by comparing and assessing the conventional supply chain system and the blockchain-enabled supply chain system in terms of their capacity to provide sustainability-related advantages. This research also shows how much more advantageous a blockchain-enabled supply chain is than a conventional supply network. This research will then be used to justify investing in blockchain technology in a company in order to construct progressive supply chains in the near future. The study's findings will also aid future empirical research in this field.

The remainder of the paper is laid out as follows. Section 2 presents a review of important literature on blockchain technology and OSCM integration. Section 3 describes the proposed research methodology. The suggested model's applicability is discussed in Section 4. Section 5 covers the discussion, Section 6 analyses research implications, Section 7 explores managerial implications, Section 8 covers limitations and future research and Section 9 presents the concluding remarks.

2. Literature review

2.1 Blockchain

The increased use of information and communication technology has given businesses the chance to develop new models and procedures to cope with the contemporary business environment's complexity, particularly in the areas of logistics and supply chain management (Queiroz *et al.*, 2019; Xue *et al.*, 2020). One of the innovations that has shown itself with the ability to redesign the OSCM is blockchain, with the increase in the usage of this technology beyond the financial sector (Kshetri, 2018).

In 2008, Nakamoto published the initial version of blockchain through Bitcoin, which was utilized in the financial industry. Its main characteristics are its immutability, distributed nature, and synchronized data recording technique in which each new piece of information creates a new block within a chain of blocks (Nakamoto, 2008). As a result, it is described as a database with records disseminated and shared across all network users who consent to participate (Salah *et al.*, 2018; Fernandez-Vazquez *et al.*, 2019).

The technology creates a growing list of encrypted records as a result of this method of operation, ensuring that the data is safe from manipulation and hiding. Technology is compared to a digital transaction book that can be designed to record almost anything of value and relevance to mankind (Fanning and Centers, 2016; Poblet and Konashevych, 2018; Feng *et al.*, 2020a, b). The technical framework enables for the deployment of a variety of application services and is built on a shared database with chaining technology, validation using consensus techniques, and the use of system security including hashing and digital signatures (Andoni *et al.*, 2018).

The capacity to generate and trade unique digital records is at the heart of blockchain technology, thus the entire process may be carried out without the need for centralized, dependable party management (Sai *et al.*, 2021). Exclusive records, encryption, and the usage of P2P networks assure the openness and correctness of the information exchanged, as well as the preservation of its historical record (Yeow *et al.*, 2017; Casino *et al.*, 2019).

2.2 Supply chain management integration with blockchain

One of the technologies that has the potential to disrupt OSCM in big ways is blockchain (Wang *et al.*, 2018). In manufacturing, production networks are typically developed as a reaction to worldwide rivalry, integrating innovative computer technology and procedures (Chang *et al.*, 2019). In the foreseeable future, robots and components in manufacturing are unlikely to require human control to interact. These enhancements make it easy to build and join multi-person interactive and collaborative development networks (Lezoche *et al.*, 2020; Hsiao and Sung, 2021). Also, virtual reality (VR) and augmented reality (AR), both of which enable real-time meetings and immersive data sharing in dynamic settings, are promising collaboration techniques between blockchain and supply chain management, which could improve product quality and consistency (De Souza Cardoso *et al.*, 2019).

Many developments have disrupted operations management, the discipline of managing assets connected to product manufacture and delivery, in the setting of the 4th industrial revolution (Xu *et al.*, 2018). The financial, cultural, and social dynamics that impact global company operations are all influenced by the internet of Things (IoT), cloud computing and big data analysis (Wang *et al.*, 2018; Kotha *et al.*, 2021). To store and handle data, almost all industries and organizations rely on central information management systems, and the great majority of these platforms are vulnerable to numerous types of attacks (Rossit *et al.*, 2018).

All stakeholders in the supply chain may see, trace, and verify information about a product's origin, processes, and the parties participating in associated transactions and logistics using blockchain (Pearson *et al.*, 2019). Information security and time stamping can help with the application of sustainability criteria for selecting manufacturers, contractors, resources, and commodities, as well as the construction of more sustainable logistical systems and internal processes (Kouhizadeh and Sarkis, 2018; Bai *et al.*, 2022; Agi and Jha, 2022). This would eventually assist customers in making decisions that do not jeopardize environmental protection, as well as human rights and working conditions, in nations all along the supply chain (European Commission, 2019).

Despite concerns about energy usage and e-waste, blockchain technology can help to safeguard the environment. It can, for example, give opportunities to improve the long-term sustainability of existing consumption and production processes by making them more visible (Zhang *et al.*, 2019). There are currently standards and certification programs in place to ensure sustainable and ethical supply chains, but in many places, the current methods are still too expensive and unreliable (EPRS, 2017). Supply chain management in industries including forestry, energy, food, and mining can benefit from the integration of blockchain technology (Gao *et al.*, 2018; EEA, 2020).

2.3 Application of blockchain in supply chain management

The blockchain's practical uses extend beyond digital currencies, thanks to its auditability, which is especially important for maintaining confidence among all parties involved (Natoli and Gramoli, 2016; Bodkhe *et al.*, 2020). Also, blockchain can be used in combination with RFID (Radio Frequency Identification) in the food sector. The production, storage, and distribution data about a product is registered into the RFID and wirelessly transmitted to the blockchain (Jangirala *et al.*, 2019; Aslam *et al.*, 2021). Through a shared link, the blockchain assures that the data does not alter and may be examined by customers or public authorities (Ko *et al.*, 2018).

In the pharmaceutical supply chain, temperature, light, and humidity are continuously monitored by sensors during the transport process to guarantee that the medicines are transported in the best possible circumstances (Uddin *et al.*, 2021). The sensor data is transmitted to a blockchain that is verified with smart contracts once the medication gets at its destination. The cargo is delivered once the transit circumstances stay within the pre-determined parameters (Ko *et al.*, 2018; Kshetri, 2018).

Maersk, a shipping and supply chain management company, is partnering with IBM for the integration of blockchain technology into its systems. Immigration, customs, and port agencies are all involved in the distribution and shipping of goods between continents. Perishable goods are tracked via blockchain as they are moved across continents. Supply chain partners, as well as border, customs, and port officials, are all involved in these initiatives (Pu and Lam, 2020; Munim *et al.*, 2021). Walmart is also beginning to implement blockchain across its supply chain, from cultivation, manufacturing, processing, and distribution, to warehousing and retail (Zhao *et al.*, 2016; Bai *et al.*, 2022). Food safety is improved through blockchain because tainted food can be traced to determine its source and journey, allowing items to be removed from sales and distribution and preventing future spread (Wang *et al.*, 2020b; Hong *et al.*, 2021).

Blockchain analyses environmental factors by installing sensors surrounding assets in transportation, comparing the findings to smart contract limitations to ensure that health and safety requirements are met (Kshetri, 2018; Dhagarra *et al.*, 2019). Modum, a company with the goal to digitalize supply chains of sensitive goods with the help of modern technology, and Swiss Post, are both using blockchain technology to enforce policies (by verifying and paying for assets' emissions when they exceeded environmental limits) and monitor its supply chain (Rohr, 2019).

In the automotive industry, Toyota Motor Corporation and Toyota Financial Services have developed the Toyota Blockchain Lab. Launched as a cross-virtual organization, they are using blockchain in the delivery and financing of goods and services across borders. Blockchain technology keeps track of the provenance and condition of car components as they move between nations and manufacturers, as well as assisting in the prevention and management of supply chain interruptions (Toyota, 2020).

Data-driven supply chains are among the most significant innovations that blockchain will offer. These information chains have several benefits, including the availability of data, which allows for multiple opportunities for information exchange and long-term decision-making (Fernandez-Carames *et al.*, 2019; Sundarakani *et al.*, 2021). For instance, in the agriculture sector, blockchain in combination with IoT will provide social advantages to some impoverished areas (Braganza *et al.*, 2016; Jabbour *et al.*, 2019; Torky and Hassanien, 2020). The traceability of products will provide information to the ultimate customer regarding pesticides and other potentially harmful items used in the manufacturing process. The tracking of agricultural goods will increase, as will transparency and authenticity, thanks to the unique characteristics of blockchain (Maru *et al.*, 2018; Kamble *et al.*, 2019; Yadav and Singh, 2019; Yiyan *et al.*, 2020).

As a result, blockchain has the potential to alter the nature of data flow in supply chains. For instance, since transactions cannot be altered by any of the participants, they can be confirmed at any moment by all chain members. This increases confidence between users, which is especially beneficial in chains that operate with items that require traceability, such as those in the food, medical, energy, and aerospace industries, to name a few.

Regarding blockchain's main challenges, most of the current issues are applicable to current supply chain management issues. Despite the fact that technology has digitized and automated different aspects of supply chain management, there are still certain obstacles to overcome in making it more efficient, dependable, and safe. For instance, regarding data privacy, only a few stakeholders should have access to sensitive and proprietary information regarding a supply chain, such as financial records, raw material costs, margins or surpluses (Dhagarra *et al.*, 2019; Zhao *et al.*, 2019). There are several hurdles to using blockchain in the supply chain to increase traceability, visibility, and transparency that are stymieing its development. These issues include, but are not limited to, high investment costs, scalability, storage capacity, compatibility, bidirectionality, data privacy, scaling latency, time verification, and disruption caused by rival systems (Azzi *et al.*, 2019; Nayal *et al.*, 2021; Bellucci *et al.*, 2022).

2.4 Sustainable benefits of blockchain technology

Blockchains can have an impact on sustainable supply chain networks because they are distributed, immutable, transparent, and trustworthy databases that are shared by a community. A key application emphasis for the blockchain is tracking possible social and environmental variables that might cause environmental, health, and safety risks (Adams *et al.*, 2017; Nuseir, 2020). Data gathering, storage, and administration are all possible with blockchain technology, which may handle large product and supply chain information. In this technical framework, openness, transparency, impartiality, dependability, and safety for all supply chain agents and consumers are possible (Abeyratne and Monfared, 2016).

The use of blockchain technology can also help to ensure the long-term viability of supply chains that are environmentally friendly. It is capable of doing so from a variety of perspectives. For starters, precisely tracking inferior items and detecting subsequent transactions of the goods can assist prevent rework and recall, lowering resource consumption and greenhouse gas emissions. Conventional energy systems are centralized, but a peer-to-peer network blockchain based for energy systems can eliminate the need to transport electricity across vast distances, therefore saving a significant amount of energy (Korpela *et al.*, 2017; Sunmola, 2021). It would also eliminate necessity energy storage, so conserving resources. To improve supply chain transparency and traceability, blockchain has been combined with digital technologies like as radio-frequency identification (RFID) and the IoT (Tian, 2017; Feng *et al.*, 2020a).

Transparency, data auditability, security, value transfer, and operational efficiencies are all fundamental characteristics of blockchain technology that may be used to drive the systemic reforms required to create sustainable infrastructure. Real-time ownership transfers are possible due to the characteristics of decentralized trust and unchangeable records (Khan *et al.*, 2022; Garg *et al.*, 2021; Hardjono and Smith, 2021; Guerreiro, 2020; Chowdhury *et al.*, 2020). As a result, the distinctive sustainability advantages of blockchain technology are outlined here based on relevant publications on this matter. This research has been carried out using articles from the Web of Science Core Collection, using blockchain, sustainable and benefits as major keywords. The justification in using this database relies on the fact that only high-quality, peer-reviewed publications are included in this collection. The search did not include grey literature (i.e. unpublished papers, Master's or PhD theses, materials not published as a scientific work, or Google Scholar). This may have an impact on the findings' validity to some extent. Using a respected database, on the other hand, assures that the study's results are of high quality. Furthermore, the authors have followed the recommendations of the well-known "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) proposed by Moher (Moher *et al.*, 2009), which consisted on an iterative process of selection of relevant publications to conduct the research.

2.4.1 Decentralization (DC). Decentralization refers to the fact that the database is spread among all peers rather than being reliant on a single organization or administrator. A decentralized database is essentially what blockchain is. The blockchain ledger is duplicated in every full node. The information recorded by all nodes will be detected if the database is changed (Shakow, 2018; Liu *et al.*, 2021). Due to the decentralization of blockchain, coordination on the present state of the ledger must be accomplished, and transactions must be appended to the next block (Makhdoom *et al.*, 2019), through consensus mechanisms such as Proof-of-Work (PoW), Proof-of-Authority (PoA), Proof-of- Stake (PoS), or alternates of Byzantine Fault Tolerance algorithms. This functionality simplifies commercial and social interactions by removing the need for middlemen in the network (Andrychowicz and Dziembowski, 2015; Liaskos and Wang, 2018; Nguyen and Kim, 2018; Leal *et al.*, 2021).

2.4.2 Resiliency (RES). Resiliency refers to resistance to many sorts of assaults and previously unheard-of mistakes (Chowdhury *et al.*, 2019). Blockchain must be built on a robust network architecture with strong security, privacy, and trust support to realize its full potential (Mylrea and Gourisetti, 2017; Ferdous *et al.*, 2019). Nodes (miners) should preferably be geographically distributed and geopolitically dispersed to improve the network's resiliency (Hardjono and Smith, 2021). The higher the resiliency of the network, the more unaffected it will be by the growing number of malicious nodes (Shala *et al.*, 2020).

2.4.3 Security (SEC). Data security, in the form of immutability improves auditability since data is available in an unalterable and secure state; this is particularly important in the event of a legal dispute. Through encryption, e-based operations, instead of paper-based transactions, improve the security of data (Macrinici *et al.*, 2018). The cryptographic method used by blockchain technology ensures data confidentiality and anonymity in the supply chain system (Sompolinsky and Zohar, 2015; Kosba *et al.*, 2016). Due to the fact that data information is available at each ledger in the system, this process guarantees that information cannot be stolen, and saved data cannot be deleted (Li *et al.*, 2017). Security contributes to better risk management and lowers trade settlement concerns. As a result, parties engaged in the transaction process no longer have to be concerned about payment failures or trade settlement delays (Wang *et al.*, 2018; Taylor *et al.*, 2019).

2.4.4 Smart contracts (SC). Blockchain has been developed in a wider sense in recent years. Smart contracts, for example, have been made possible as a result of this (Badruddoja *et al.*, 2021). Szabo was the first to present these intelligent contracts, defining them as a computerized transaction procedure that carries out a contract's terms (Szabo, 1994). Smart contracts are governed by contractual rules that are embedded in each user's hardware and software (collateral, clauses, property rights, etc.). These provisions are recognized as property, removing the need for them to be regulated by a third party or central agency (Frantz and Nowostawski, 2016; Alharby and Van Moorsel, 2017; Morabito, 2017). The great degree of customization and flexibility is one of the primary advantages of smart contracts (Egelund-Müller *et al.*, 2017; Rizk *et al.*, 2018). In the supply chain, technology allows for self-verification and contract execution, which has a favourable impact on business operations. This functionality also reduces the risk of supply chain technical interruption and fraud (Agrawal *et al.*, 2021; Nanayakkara *et al.*, 2021).

2.4.5 Sustainability (SUS). Nowadays, industries are extremely competitive and demanding, with a constant need to enhance the long-term supply chain performance in order to provide value to their consumers. In this sense, businesses must be creative from a sustainable point of view (Nassar *et al.*, 2019; Kamble *et al.*, 2021). Since both share related aspects of altering business and the global economy, blockchain technology and the circular economy model potentially have strong correlation (Wang *et al.*, 2020a; Jamwal *et al.*, 2021; Zhang *et al.*, 2022; Khan *et al.*, 2022). By allowing nations and stakeholders to collect data and information on infrastructure projects, blockchain could improve visibility of alignment with sustainability goals (Esmaeilian *et al.*, 2020). Blockchain-enabled platforms are a way to standardize data, assess asset performance, and improve compliance (such as with sustainability or environmental, social and corporate governance (ESG) standards), which can be further enhanced when they are linked to deep analytics like AI applications or integrated with remote sensors (IoT), for instance in the pharmaceutical sector (Seddigh *et al.*, 2022; Shokouhyar *et al.*, 2022). In addition, blockchain sustainable attributes could be relevant for supply chain applications such as: agrochemicals, biodiversity, labour, climate, deforestation, land management, value distribution, and water productivity (OECD, 2019; United Nations, 2020).

2.4.6 Traceability (TRC). In many sectors, the demand for transparent, traceable, observable, and efficient supply chains will stimulate digital transformation (Tiwari *et al.*, 2017). The blockchain may be used to store traceability information such as artefacts and traceability links generated by dispersed participants. Because of the intrinsic features of blockchain, all authorized stakeholders have access to a comprehensive, dependable, and trustworthy traceable knowledge base that they may examine at any moment (Rempel *et al.*, 2013; Demi *et al.*, 2021). Data on the blockchain is error-proof and has great visibility across the supply chain, guaranteeing that any system is auditable and efficient (Atzori, 2017). Evidence suggests that implementing blockchain in automotive supply chain, for instance, will increase its competency through an increase in traceability (Kotha *et al.*, 2021).

2.4.7 Transparency (TRN). A blockchain file may be read and audited by anybody due to the virtue of openness. This establishes provenance, which may be used to determine asset lifespan (Madavi, 2019). Participants are aware of the origins of the asset and how ownership has changed through time. For all stakeholders, real-time processing allows for a considerable increase in openness. All partners have simultaneous, independent access, which enhances agility. The specific area of failure in transparency is eliminated with the decentralized system (Peck, 2017; Fleischmann and Ivens, 2019). The features of blockchain, such as consensus and immutability, allow for the creation of systems that are more transparent and resistant to fraud and corruption (Cunha *et al.*, 2021; IADB, 2021).

2.4.8 Trust (TRU). Trust may be seen of as a facilitator of social relationships, since it symbolizes one party's readiness to have confidence in and rely upon another in settings marked by social complexity and ambiguity (Gefen and Pavlou, 2011). Through the integration of blockchain, conventional business practices are being reconsidered, primarily to decrease the need for human intervention in transactions (Hawlitschek *et al.*, 2018; Queiroz *et al.*, 2019, Shokouhyar and Seddigh, 2020). Human mediation is not necessary in the blockchain ecosystem, and transactions may be completed faster and at a lower cost. There is increased mutual trust since all network members have a copy of every transaction record (Xu *et al.*, 2019; Alrakhami and Al-Mashari, 2021). The network's blocks include immutable, encrypted and tamper-proof transactions that are validated by a distributed network's decentralized consensus protocol (Aitzhan and Svetinovic, 2016; Seebacher and Schüritz, 2017).

3. Methodology

3.1 Analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) methodology was developed by Saaty (1980). It compares criteria, or alternatives with regard to a criterion, in a step-by-step manner. It has been used to solve issues in mathematical psychology and multicriteria decision-making problems (Kou and Ergu, 2016). Due to its simple design, ease of use, and versatility in including a large number of criteria and sub criteria, AHP has been a tool in the hands of decision makers and academics since its conception, and it is one of the most commonly used multicriteria decision-making (MCDM) techniques (Wang *et al.*, 2009; Franek and Kresta, 2014; Mastrocinque *et al.*, 2020).

Comparisons between different criteria are done using an absolute scale that shows how much more one element dominates another in terms of a particular attribute. The AHP model is founded on three principles: decomposition, comparative judgment, and priority synthesis (Leake and Malczewski, 2000). Hierarchy is the most common approach to illustrate the decision framework in AHP. Its main purpose is to assess higher hierarchy levels based on the cooperation of its various levels. It results in a well-designed model-based method in which the weights for the selected attribute are calculated using dimensions, criteria, and indicators (Taslicali and Ercan, 2006). The employment of a Consistency Ratio (CR) assures the accuracy and stability of pairwise comparisons, which aids in the calculation of the parameter's durability index (Vaidya and Kumar, 2006).

Meetings were used to gather data for the study, which included a standardized questionnaire with a 9-point scale developed by Saaty (2008) (Table 1). In this numerical scale, the value 1 shows that both choices are equal, while the value 9 indicates the maximum degree of preference for the first option.

Matrix A summarizes the responses from the questionnaire. It is represented by $Matrix\ A = (a_{ij})$, where the elements $a_{ij} = \frac{w_i}{w_j}$ are the weights of alternative i with respect to j, being w the priority vector derived from the questionnaire's responses. As a result, the matrix is written as:

$$A = (a_{ij}) = \begin{bmatrix} 1 & \frac{w_1}{w_2} & . & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & . & \frac{w_2}{w_n} \\ . & . & . & . \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & . & 1 \end{bmatrix}$$

Table 1.
The fundamental absolute number scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

Source(s): Saaty (2008)

Matrix A has a dimension of $n * n$, which corresponds to the total number of productive options being compared. Matrix A has the following properties:

(1) it is inverse, in the sense $a_{ij} = \frac{1}{a_{ij}}$ for all $i,j = 1,2, \ldots, n$;

(2) $a_{ii} = 1$ for all,$i = 1,2, \ldots, n$; and

(3) if all of decisions are exactly consistent, then $a_{ij} = a_{ik}a_{kj}$. In the case that this last property is satisfied, then there are no mistakes of judgment in the constituents of matrix A, being $a_{ik}a_{kj} = \frac{w_i w_k}{w_k w_j} = \frac{w_i}{w_j} = a_{ij}$ for all $i,j,k = 1,2, \ldots, n$.

The pairwise comparison matrices are verified for consistency to guarantee the validity of the results obtained. A consistency check ensures that experts' decisions were rational and not arbitrary. When there are discrepancies in the judgements, the eigenvector technique is used to estimate weightings in the AHP methodology. By computing w as the primary correct eigenvector of matrix A, the discrepancy may be corrected: $A_w = \lambda_{max} W$, being λ_{max} the maximum eigenvector of matrix A. The ultimate weightings are calculated using the eigenvector technique, which takes the mean of all feasible methods to evaluate the options in the choice issue. The measurement of inconsistency given by this method is calculated as $\lambda_{max} - n$ is a helpful metric for determining the level of inconsistency (Li *et al.*, 2009; Nnaji and Banigo, 2018). If we take this measurement and normalize it for the size of A, we can construct the Consistency Index (CI) as:

$$CI = \frac{\lambda_{max} - n}{(n-1)}$$

The Consistency Index is compared to a Random Consistency Index (RI) to get the Consistency Ratio (CR):

$$CR = \frac{CI}{RI}$$

The Random Consistency Index is obtained from the Random Index Table (Saaty, 2000; Rao, 2007) (Table 2). The number of attributes in the study are eight, corresponding to decentralization, resiliency, security, smart contracts, sustainability, traceability, transparency and trust. The RI for the purpose of calculations is therefore 1.4.

If the CI and CR values are less than 0.10, the consistency criterion is fulfilled. When the CR surpasses 0.10, the judgements are frequently re-examined. The higher this number, the less consistent the comparisons are (Martínez and Escudey, 1998; Rosdi *et al.*, 2017).

3.2 Procedure

To establish priorities in an organized manner, the choice was broken down into the following phases following the methodology proposed by Saaty (2008):

First step: Definition of the problematic and selection of criteria. Decomposing a decision problem into its basic pieces is the initial stage. In its most basic form, this structure consists of a top-level objective or focus and a bottom-level set of options.

Attributes	3	4	5	6	7	8	9	10
Random Index	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

Source(s): Rao (2007)

Table 2. Random index values

Second step: Prioritization of criteria based on pairwise comparison. The relative significance of the criteria is determined by assigning a relative weight to each criterion on Saaty's scale (Saaty, 2008) of relative importance, which ranges from 1 to 9 (Table 1). Pairwise comparison matrices are created in order to compare criteria in relation to the aim. After that, the alternatives are evaluated to the requirements, and comparison matrices are created.

Third step: Calculation of eigenvalue, eigenvector and Matrix A. Due to its simplicity, the Geometric Mean (GM) (or importance weight) of each attribute is calculated in ease of determining the highest eigenvalue.

Fourth step: The result of the CI and the CR are used to verify consistency in pairwise comparisons.

Fifth step: Priorities are weighted at the level below using the priorities derived from the comparisons. The weighted values are then summed for each element on the level below to get the overall DI.

4. Proposed model for comparative evaluation of conventional supply chain and blockchain-enabled supply chain

The AHP-based approach's workflow, as assessed in this study, may be described in the following phases. Goal definitions were created in the first stage, composed by a literature review and the formation of a decision-making committee. The literature research was utilized to develop the model's criteria, which were then validated by a decision-making panel. The same decision-making committee that helped finalize the criterion, alternatives, and hierarchical structure utilized in this study also generated pairwise comparison matrices for criteria and alternatives. The AHP structure is introduced in the second phase as described in Section 3. The AHP technique was also used to determine alternative weights. In the last step, once the results were reliable, they were duly reported. Figure 1 shows the flowchart of the decision process.

4.1 Identification of criteria

The criteria for evaluating supply chain sustainability were generated from the literature and were backed up by a panel of specialists. This committee was invited to fill in the matrices according to their expertise and knowledge in order to obtain more impartial findings. The decision-making committee was comprised of a total of seven people: three specialists with more than 10 years of expertise each in the operation management, energy and blockchain technology sectors; and four university professors with more than 20 years expertise each on supply chain management. They are considered to be suitable volunteers for this study because of their extensive expertise the operations management and the blockchain sector. In order to avoid bias, the matrices required to be filled in were clear and simple, only to be answered with numerical data. The respondents were assured that their company's name would not be used in the survey to minimize biases (Seddigh *et al.*, 2022). Convenience and purposive samples were avoided. Also, the same model of data collection was used for the whole sample (Shelley and Horner, 2021). Table 3 shows the characteristics of the respondents.

4.2 Weights of criteria

The identified criteria and alternatives were used to create the structure shown in Figure 2. Following the formation of the decision hierarchy, the essential weights to be utilized in the assessment process were calculated using the AHP technique. The goal for the decision-making group was to create paired comparison matrices by using the scale in Table 1.

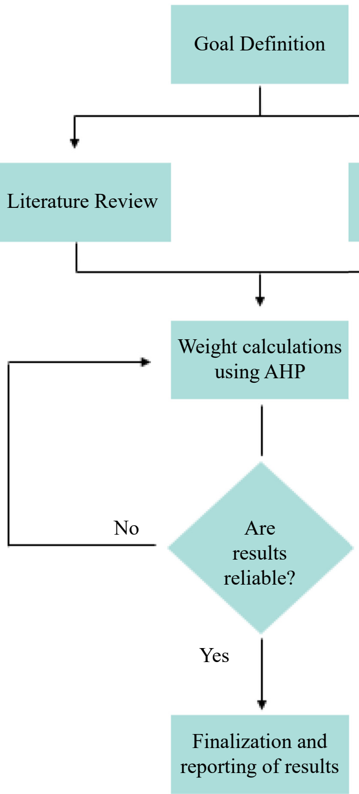

Figure 1. Flowchart of the decision process

Table 3. Decision-making committee profile

Expert number	Years of experience	Educational background	Sector of expertise
1	10	Engineering	The company is a New York-based blockchain technology company. It is an open-source platform for assets and apps that can upgrade themselves. Updates to the core protocol, such as the amendment process itself, are governed by stakeholders
2	15	Business, Management	The company is one of the leading electricity businesses in Europe. The firm has a compromise to contribute to creating a new energy model based on clean energies, respect for the environment and sustainable development
3	15	Business, Management	The company is specialized in the distribution of beverages and food. It is compromised with improving traceability processes along its supply chain (Coca-Cola, Pernod Ricard, Diageo)
4 to 7	20+	Engineering and Business	Supply Chain Management lecturer(s) part of the Operations and Technology Management group within the University

Table 4 shows the results of the calculations conducted on pairwise comparison matrices. The pairwise comparison matrix's CR was determined to be 0.087, therefore lower than 0.1. As a result, the relevant weights were deemed to be consistent and were utilized in the subsequent study.

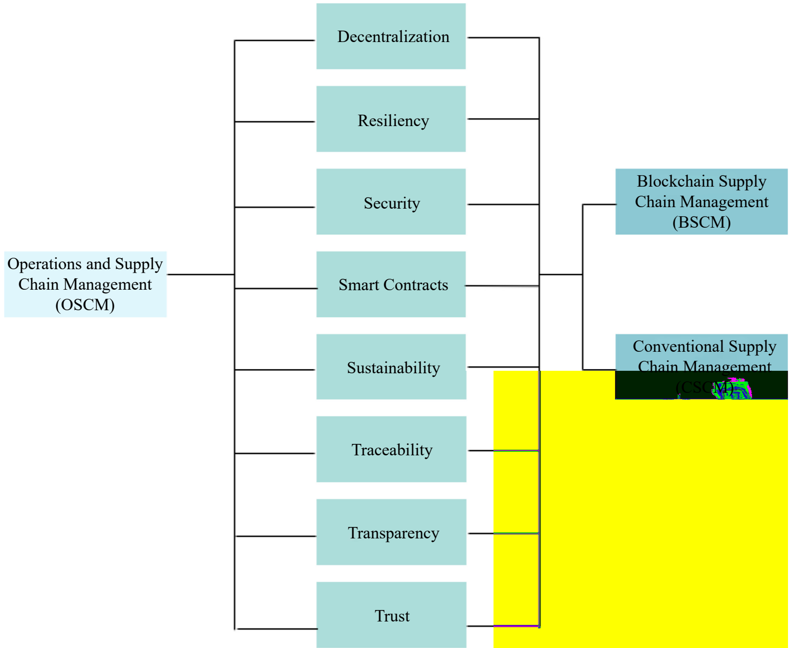

Figure 2.
Supply chain selection in a hierarchical framework following AHP

Table 4.
Matrix of pairwise comparisons of prospective benefits in relation to the objective

	DC	RES	SEC	SM	SUS	TRC	TRN	Tru	Importance weight
DC	1	0.35	0.18	0.33	0.45	0.50	0.23	0.16	0.03
RES	2.88	1	0.45	0.67	0.79	0.56	0.32	0.19	0.06
SEC	5.57	2.21	1	0.34	0.40	1.77	0.34	0.37	0.09
SM	3.05	1.50	2.96	1	0.28	0.86	0.33	0.23	0.08
SUS	2.21	1.27	2.50	3.61	1	0.54	0.40	0.19	0.10
TRC	2.00	1.78	0.57	1.16	1.87	1	0.29	0.20	0.08
TRN	4.31	3.10	2.91	3.00	2.48	3.46	1	0.20	0.19
TRU	6.29	5.29	2.71	4.43	5.14	5.00	5.00	1	0.37

4.3 Evaluation of alternatives and determine the desirability index

At this point, assessment matrices were created to compare blockchain-based supply chain management (BSCM) and conventional supply chain management (CSCM) against each of the eight criteria using the scale provided in Table 1. Tables 5–12 provide the assessment matrices of both BSCM and CSCM in relation to decentralization, resiliency, security, smart contracts, sustainability, traceability, transparency and trust.

After constructing the evaluation matrices, the individual weight for every criterion against each alternative was calculated using the procedures outlined in Section 3. The next

Table 5.
Assessment of blockchain and conventional supply chains regarding decentralization

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	6.50
Conventional supply chain management (CSCM)	0.15	1

stage was to determine the overall weight of criteria for each supply chain type. The global weights of criteria for each supply chain were calculated by multiplying the local weight of each criterion with its significance weight (Table 13).

For instance, local weights regarding decentralization for blockchain-enabled and conventional supply chains were determined to be 0.86 and 0.13, respectively, while the

Table 6. Assessment of blockchain and conventional supply chains regarding resiliency

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	7.00
Conventional supply chain management (CSCM)	0.14	1

Table 7. Assessment of blockchain and conventional supply chains regarding security

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	8.00
Conventional supply chain management (CSCM)	0.13	1

Table 8. Assessment of blockchain and conventional supply chains regarding smart contracts

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	7.50
Conventional supply chain management (CSCM)	0.13	1

Table 9. Assessment of blockchain and conventional supply chains regarding sustainability

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	5.00
Conventional supply chain management (CSCM)	0.20	1

Table 10. Assessment of blockchain and conventional supply chains regarding traceability

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	9.00
Conventional supply chain management (CSCM)	0.11	1

importance weight was assessed to be 0.03. As a result, the global weights of blockchain-enabled and conventional supply chains will be 0.03*0.87 = 0.03 and 0.03*0.13 = 0.004 respectively. Table 13 shows the results for local and global BSCM and CSCM alternative weights and indices.

The DI for conventional supply chains and blockchain-enabled supply chains was then calculated by adding the global weights of each criterion for each supply chain type, with a value of 0.87 for blockchain-enabled supply chains and 0.12 for conventional supply chains.

5. Discussion

With the goal of enhancing the use of blockchain technology in supply chain management, particularly when comparing within the same industry, the AHP methodology has been used. In order to develop the AHP model, a total of eight elements are examined in this study, which are: decentralization, resiliency, security, smart contracts, sustainability, traceability, transparency and trust.

It was noticed that in a blockchain-enabled supply chain, the global weights of individual benefit variables are considerably larger than in conventional supply chains. When the score of the DI for conventional supply chain and blockchain-enabled supply chain is compared, the blockchain-enabled supply chain significantly surpasses the conventional supply chain in terms of increasing sustainable development in today's supply networks.

Table 11. Assessment of blockchain and conventional supply chains regarding transparency

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	8.00
Conventional supply chain management (CSCM)	0.13	1

Table 12. Assessment of blockchain and conventional supply chains regarding trust

	Blockchain supply chain management (BSCM)	Conventional supply chain management (CSCM)
Blockchain supply chain management (BSCM)	1	7.50
Conventional supply chain management (CSCM)	0.13	1

Table 13. Local and global BSCM and CSCM alternative weights and DI index

	Importance weight	BSCM local weight	CSCM local weight	BSCM global weight	CSCM global weight
DC	0.03	0.86	0.13	0.02	0.00
RES	0.06	0.87	0.12	0.05	0.00
SEC	0.08	0.88	0.11	0.07	0.00
SM	0.08	0.88	0.11	0.07	0.00
SUS	0.09	0.83	0.16	0.08	0.01
TRC	0.08	0.9	0.1	0.07	0.00
TRN	0.18	0.88	0.11	0.16	0.02
TRU	0.37	0.88	0.11	0.33	0.04
DI				*0.87*	*0.12*

This study also supports the findings of previous research, which show that blockchain has a beneficial impact on several aspects of supply chain performance as well as in its sustainability (Kumar and Iyenger, 2017; Park and Li, 2021; Mukherjee *et al.*, 2021). This research goes on to illustrate how several potential advantages of blockchain technology prioritize supply chain sustainability. The study's findings show that trust has the greatest impact on sustainable practices, followed by transparency, sustainability, security, traceability, smart contracts, resiliency and decentralization. This study also contains specialists' opinions on the application of blockchain technology in supply chain management, which is likely to entice researchers to learn more about this area.

6. Research implications

The proposed methodology covers an analysis that compares traditional and blockchain-enabled supply chains. As a result, this study will assist researchers in taking further steps towards the investigation on blockchain adoption in current supply chains. Scholars may be interested in performing sophisticated and precise studies to provide technical standards and real-world applications in supply chains based on the foundation provided by this research. Also, it contributes by emphasizing the favourable effects of blockchain-enabled supply chains on sustainability and discusses the relative impact of several possible advantages of blockchain technology on sustainable development, which might be developed in further investigations through improved analytic models. Finally, this work also draws attention to some of the main challenges regarding the implementation of blockchain technology, such as data privacy or scaling latency, which could demand further research in order to provide practical solutions.

7. Managerial implications

Through this research, the outcomes of extensive computations applied to each level of the ladder system give a multi-faceted viewpoint. Strong ability to synthesize the components of the hierarchy and simple logic algorithms helps managers examine each aspect and see the big picture where all issues are taken into account. Companies may choose to start implementing blockchain based supply chain management processes that come with appealing value such an increase in trust, resiliency or security among other things, or might choose companies which have blockchain implemented supply chains when looking for a partner. Furthermore, the study illustrates how, in the future, focusing on the involvement of blockchain application in supply chains may improve the technology's relevance and adoption by companies willing to benefit from blockchain's attributes.

8. Limitations and future research

This research uses the interview and questionnaire surveys approach to get access to expert groups, with data obtained being slightly skewed and subjective. It is possible to delve deeper into the theoretical model for additional examination. As a result, it is suggested that alternative acceptable approaches be used instead of the AHP methodology in order to enhance this article for future researchers. Other approaches in multi-criteria decision-making analysis (MCDM), such as Rating, Ranking, Fuzzy AHP, or Weight of Evidence (WoE) technique, might be investigated further.

Every sort of business and every firm will have its own set of requirements and necessities. Therefore, it is important to keep in mind that the design of an assessment model provider based on the industry's features and the company's unique qualities should be used.

9. Concluding remarks

Supply chain is one of the most probable industries to be changed by blockchain. Blockchain enables valid and effective evaluation of outcomes and performance of critical supply chain processes, among other things. In this paper, we began by providing an overview of blockchain, as well as identifying and explaining the key characteristics of this technology. Then we looked at the practical applications of blockchain in supply chains. Further, an AHP was created to address the numerous restrictions that exist in the OSCM sector. This method works well when dealing with complicated and competing restrictions.

Efforts to leverage these developing technologies to create innovative supply chain applications have fragmented research into several areas. Technological research and prototype architectural design are giving way to a more diversified focus on industrial applications, managerial consequences, and social effect. This study, we feel, will make a significant contribution to a better understanding of the evaluation of the usefulness of blockchain technology in supply chain management. The research provides by emphasizing the favourable effects of a blockchain-enabled supply chain on long-term sustainability. It goes on to discuss the relative influence of several prospective blockchain technology advantages on sustainable development. The conclusions of the study are mostly applicable to major industrial companies throughout their supply chain operations. The logistics, medical, insurance, and public sectors are just some of the promising areas for blockchain applications and study. We anticipate that this paper will offer an overview of existing blockchain-related supply chain research, as well as identify relevant research gaps and future research initiatives.

References

Abeyratne, S. and Monfared, R. (2016), "Blockchain ready manufacturing supply chain using distributed ledger", *International Journal of Research in Engineering and Technology*, Vol. 5 No. 9.

Adams, R., Kewell, B. and Parry, G. (2017), "Blockchain for good? Digital ledger technology and sustainable development goals", doi: 10.1007/978-3-319-67122-2_7.

Agi, M. and Jha, A. (2022), "Blockchain technology in the supply chain: an integrated theoretical perspective of organizational adoption", *International Journal of Production Economics, Elsevier*, Vol. 247(C).

Agrawal, T., Kumar, V., Pal, R., Wang, L. and Chen, Y. (2021), "Blockchain-based framework for supply chain traceability: a case example of textile and clothing industry", *Computers and Industrial Engineering*, Vol. 154, 107130, doi: 10.1016/j.cie.2021.107130.

Aitzhan, N. and Svetinovic, D. (2016), "Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams", *IEEE Transactions on Dependable and Secure Computing*, p. 1, doi: 10.1109/TDSC.2016.2616861.

Akter, S., Michael, K., Uddin, M., McCarthy, G. and Rahman, M. (2020), "Transforming business using digital innovations: the application of AI, blockchain, cloud and data analytics", *Annals of Operations Research*. doi: 10.1007/s10479-020-03620-w.

Alharby, M. and Van Moorsel, A. (2017), "Blockchain based smart contracts: a systematic mapping study", *Conference: 3rd International Conference on Artificial Intelligence and Soft Computing*, pp. 125-140, doi: 10.5121/csit.2017.71011.

Alrakhami, M. and Al-Mashari, M. (2021), "A blockchain-based trust model for the Internet of things supply chain management", *Sensors*, Vol. 21, p. 15, doi: 10.3390/s21051759.

Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., Mccallum, P. and Peacock, A. (2018), "Blockchain technology in the energy sector: a systematic review of challenges and opportunities", *Renewable and Sustainable Energy Reviews*, Vol. 100, pp. 143-174, doi: 10.1016/j.rser.2018.10.014.

Andrychowicz, M. and Dziembowski, S. (2015), "PoW-based distributed cryptography with No trusted setup", *Annual Cryptology Conference*, pp. 379-399, doi: 10.1007/978-3-662-48000-7_19.

Aslam, J., Saleem, A., Khan, N. and Kim, Y. (2021), "Factors influencing blockchain adoption in supply chain management practices: a study based on the oil industry", *Journal of Innovation and Knowledge*, Vol. 6, doi: 10.1016/j.jik.2021.01.002.

Atzori, M. (2017), "Blockchain technology and decentralized governance: is the state still necessary?", *Journal of Governance and Regulation*, Vol. 6, doi: 10.22495/jgr_v6_i1_p5.

Azzi, R., Kilany, R. and Sokhn, M. (2019), "The power of a blockchain-based supply chain", *Computers and Industrial Engineering*, Vol. 135, doi: 10.1016/j.cie.2019.06.042.

Badruddoja, S., Dantu, R., He, Y., Upadhayay, K. and Thompson, M. (2021), "Making smart contracts smarter", *2021 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, pp. 1-3, doi: 10.1109/ICBC51069.2021.9461148.

Bai, C., Quayson, M., Sarkis, J. and Chunguang, B. (2022), "Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry", *Journal of Cleaner Production*, Vol. 358, doi: 10.1016/j.jclepro.2022.131896.

Batwa, A. and Norrman, A. (2020), "Blockchain technology and trust in supply chain management: a literature review and research agenda", *Operations and Supply Chain Management An International Journal*, Vol. 14, pp. 203-220, doi: 10.31387/oscm0450297.

Bellucci, M., Cesa Bianchi, D. and Manetti, G. (2022), "Blockchain in accounting practice and research: systematic literature review", *Meditari Accountancy Research*, Vol. 30, pp. 121-146, doi: 10.1108/MEDAR-10-2021-1477.

Bodkhe, U., Mehta, D., Tanwar, S., Bhattacharya, P., Singh, P. and Hong, W.C. (2020), "A survey on decentralized consensus mechanisms for cyber physical systems", *IEEE Access*. doi: 10.1109/ACCESS.2020.2981415.

Braganza, A., Brooks, L., Nepelski, D., Ali, M. and Moro, R. (2016), "Resource management in big data initiatives: processes and dynamic capabilities", *Journal of Business Research*, Vol. 70, doi: 10.1016/j.jbusres.2016.08.006.

Casino, F., Dasaklis, T.K. and Patsakis, C. (2019), "A systematic literature review of blockchain-based applications: current status, classification and open issues", *Telematics and Informatics*, Vol. 36, pp. 55-81.

Chang, Y., Iakovou, E. and Shi, W. (2019), "Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities", *International Journal of Production Research*, Vol. 58, pp. 1-18, doi: 10.1080/00207543.2019.1651946.

Chowdhury, M., Ferdous, S., Biswas, K., Chowdhury, N., Kayes, A.S.M., Alazab, M. and Watters, P. (2019), "A comparative analysis of distributed ledger technology platforms", *IEEE Access*, Vol. 7, pp. 167930-167943, doi: 10.1109/ACCESS.2019.2953729.

Chowdhury, M., Ferdous, S., Biswas, K., Chowdhury, N. and Muthukkumarasamy, V. (2020), "A survey on blockchain-based platforms for IoT use-cases", *The Knowledge Engineering Review*, Vol. 35, doi: 10.1017/S0269888920000284.

Cole, R., Stevenson, M. and Aitken, J. (2019), "Blockchain technology: implications for operations and supply chain management", *Supply Chain Management: An International Journal*, Vol. 24, doi: 10.1108/SCM-09-2018-0309.

Cunha, P.R., Soja, P. and Themistocleous, M. (2021), "Blockchain for development: a guiding framework", *Information Technology for Development*, Vol. 27, pp. 417-438, doi: 10.1080/02681102.2021.1935453.

De Souza Cardoso, L.F., Queiroz, F.C. and Zorzal, E. (2019), "A survey of industrial augmented reality", *Computers and Industrial Engineering*, Vol. 139, 106159, doi: 10.1016/j.cie.2019.106159.

Demi, S., Sánchez-Gordón, M. and Colomo-Palacios, R. (2021), "What have we learnt from the challenges of (semi-) automated requirements traceability? A discussion on blockchain applicability", *IET Software*. doi: 10.1049/sfw2.12035.

Dhagarra, D., Goswami, M., Sarma, P. and Choudhury, A. (2019), "Big Data and blockchain supported conceptual model for enhanced healthcare coverage: the Indian context", *Business Process Management Journal*. doi: 10.1108/BPMJ-06-2018-0164.

EEA (2020), *Blockchain and the Environment*, European Environment Agency, available at: https://www.eea.europa.eu/publications/blockchain-and-the-environment/blockchain-and-the-environment.

Egelund-Müller, B., Elsman, M., Henglein, F. and Ross, O. (2017), "Automated execution of financial contracts on blockchains", *Business and Information Systems Engineering*, Vol. 59, doi: 10.1007/s12599-017-0507-z.

EPRS (2017), *How Blockchain Technology Could Change Our Lives*, European Parliamentary Research Service, Brussels, available at: www.europarl.europa.eu/RegData/etudes/IDAN/2017/581948/EPRS_IDA(2017)581948_EN.pdf.

Esmaeilian, B., Sarkis, J., Lewis, K. and Behdad, S. (2020), "Blockchain for the future of sustainable supply chain management in Industry 4.0", *Resources Conservation and Recycling*, Vol. 163, 105064, doi: 10.1016/j.resconrec.2020.105064.

European Commission (2019), "European countries join Blockchain Partnership", available at: https://digital-strategy.ec.europa.eu/en/news/european-countries-join-blockchain-partnership.

Fanning, K. and Centers, D. (2016), "Blockchain and its coming impact on financial services", *Journal of Corporate Accounting and Finance*, Vol. 27, pp. 53-57, doi: 10.1002/jcaf.22179.

Farnoush, A., Gupta, A., Dolarsara, H., Paradice, D. and Rao, S. (2021), "Going beyond intent to adopt Blockchain: an analytics approach to understand board member and financial health characteristics", *Annals of Operations Research*. doi: 10.1007/s10479-021-04113-0.

Feng, H., Wang, X., Duan, Y., Zhang, J. and Xiaoshuan, Z. (2020a), "Applying blockchain technology to improve agri-food traceability: a review of development methods, benefits and challenges", *Journal of Cleaner Production*, Vol. 260, 121031, doi: 10.1016/j.jclepro.2020.121031.

Feng, T., Pei, H., Ma, R., Tian, Y. and Feng, X. (2020b), "Blockchain data privacy access control based on searchable attribute encryption", *Computers, Materials and Continua*, Vol. 66, pp. 871-890, doi: 10.32604/cmc.2020.012146.

Ferdous, S., Biswas, K., Chowdhury, M., Chowdhury, N. and Muthukkumarasamy, V. (2019), "Integrated platforms for blockchain enablement", *Role of Blockchain Technology in IoT Applications*. doi: 10.1016/bs.adcom.2019.01.001.

Fernandez-Carames, T., Blanco-Novoa, Ó., Froiz-Míguez, I. and Fraga-Lamas, P. (2019), "Towards an autonomous industry 4.0 warehouse: a UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management", *Sensors*, Vol. 19, p. 2394, doi: 10.3390/s19102394.

Fernandez-Vazquez, S., Rosillo, R., De La Fuente, D. and Priore, P. (2019), "Blockchain in FinTech: a mapping study", *Sustainability*, Vol. 11, p. 6366, doi: 10.3390/su11226366.

Fleischmann, M. and Ivens, B. (2019), "Exploring the role of trust in blockchain adoption: an inductive approach", *Proceedings of the 52nd Hawaii international conference on system sciences*, Vol. 6, pp. 6845-6854, doi: 10.24251/hicss.2019.820.

Fosso Wamba, S. and Queiroz, M. (2020), "Blockchain in the operations and supply chain management: benefits, challenges and future research opportunities", *International Journal of Information Management*, Vol. 52, 102064, doi: 10.1016/j.ijinfomgt.2019.102064.

Franek, J. and Kresta, A. (2014), "Judgment scales and consistency measure in AHP", *Procedia Economics and Finance*, Vol. 12, pp. 164-173, doi: 10.1016/S2212-5671(14)00332-3.

Frantz, C. and Nowostawski, M. (2016), "From institutions to code: towards automated generation of smart contracts", *2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W)*, pp. 210-215, doi: 10.1109/FAS-W.2016.53.

Fu, Y. and Zhu, J. (2019), *Big Production Enterprise Supply Chain Endogenous Risk Management Based on Blockchain*, IEEE Access, p. 1, doi: 10.1109/ACCESS.2019.2895327.

Gao, Z., Xu, L., Chen, L., Zhao, X., Lu, Y. and Shi, W.K.H. (2018), "CoC: a unified distributed ledger based supply chain management system", *Journal of Computer Science and Technology*, Vol. 33, pp. 237-248, doi: 10.1007/s11390-018-1816-5.

Garg, P., Gupta, B., Chauhan, A., Sivarajah, U., Gupta, S. and Modgil, S. (2021), "Measuring the perceived benefits of implementing blockchain technology in the banking sector", *Technological Forecasting and Social Change*. doi: 10.1016/j.techfore.2020.120407.

Gefen, D. and Pavlou, P. (2011), "The boundaries of trust and risk: the quadratic moderating role of institutional structures", *Information Systems Research*, pp. 1-20, Articles in Advance, doi: 10.2307/23274654.

Guerreiro, S. (2020), "Conceptualizing on dynamically stable business processes operation: a literature review on existing concepts", *Business Process Management Journal*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/BPMJ-02-2020-0072.

Hardjono, T. and Smith, N. (2021), *Towards an Attestation Architecture for Blockchain Networks*, World Wide Web, doi: 10.1007/s11280-021-00869-4.

Hawlitschek, F., Notheisen, B. and Teubner, T. (2018), "The limits of trust-free systems: a literature review on blockchain technology and trust in the sharing economy", *Electronic Commerce Research and Applications*, Vol. 29, doi: 10.1016/j.elerap.2018.03.005.

Hong, W., Mao, J., Wu, L. and Pu, X. (2021), "Public cognition of the application of blockchain in food safety management - data from China's Zhihu platform", *Journal of Cleaner Production*, Vol. 303, 127044, doi: 10.1016/j.jclepro.2021.127044.

Hsiao, S.-J. and Sung, W.-T. (2021), "Employing blockchain technology to strengthen security of wireless sensor networks", *IEEE Access*, p. 1, doi: 10.1109/ACCESS.2021.3079708.

Hudson, R. and Urquhart, A. (2021), "Technical trading and cryptocurrencies", *Annals of Operations Research*, Vol. 297, doi: 10.1007/s10479-019-03357-1.

IADB (2021), *Blockchain Uses for Microfinance Institutions in the Water and Sanitation Sector: Pilot Study*, Inter-American Development Bank, Washington, DC. doi: 10.18235/0003273.

Jabbour, C., Sarkis, J., Jabbour, A.B., Renwick, D., Singh, S., Grebinevych, O., Kruglianskas, I. and Filho, M. (2019), "Who is in charge? A review and a research agenda on the 'human side' of the circular economy", *Journal of Cleaner Production*, Vol. 222, doi: 10.1016/j.jclepro.2019.03.038.

Jamwal, A., Agrawal, R., Sharma, M. and Giallanza, A. (2021), "Industry 4.0 technologies for manufacturing sustainability: a systematic review and future research directions", *Applied Sciences*, Vol. 11, p. 5725, doi: 10.3390/app11125725.

Jangirala, S., Das, A.K. and Vasilakos, A. (2019), "Designing secure lightweight blockchain-enabled RFID-based authentication protocol for supply chains in 5G mobile edge computing environment", *IEEE Transactions on Industrial Informatics*. doi: 10.1109/TII.2019.2942389.

Kamble, S., Gunasekaran, A. and Gawankar, S. (2019), "Achieving sustainable performance in a data-driven agriculture supply chain: a review for research and applications", *International Journal of Production Economics*, Vol. 219, pp. 179-194, doi: 10.1016/j.ijpe.2019.05.022.

Kamble, S., Gunasekaran, A., Subramanian, N., Ghadge, A., Belhadi, A. and Mani, V. (2021), "Blockchain technology's impact on supply chain integration and sustainable supply chain performance: evidence from the automotive industry", *Annals of Operations Research*, pp. 1-26, doi: 10.1007/s10479-021-04129-6.

Khan, H., Malik, M., Konečná, Z., Chofreh, A., Goni, F. and Klemeš, J. (2022), "Blockchain technology for agricultural supply chains during the COVID-19 pandemic: benefits and cleaner solutions", *Journal of Cleaner Production*, Vol. 347, 131268, doi: 10.1016/j.jclepro.2022.131268.

Ko, T., Lee, J. and Ryu, D. (2018), "Blockchain technology and manufacturing industry: real-time transparency and cost savings", *Sustainability*, Vol. 10, p. 4274, doi: 10.3390/su10114274.

Korpela, K., Hallikas, J. and Dahlberg, T. (2017), "Digital supply chain transformation toward blockchain integration", doi: 10.24251/HICSS.2017.506.

Kosba, A., Miller, A., Shi, E., Wen, Z. and Papamanthou, C. (2016), "Hawk: the blockchain model of cryptography and privacy-preserving smart contracts", *2016 IEEE Symposium on Security and Privacy (SP)*, pp. 839-858, doi: 10.1109/SP.2016.55.

Kotha, R., Gunasekaran, A., Kalpana, P., Sreedharan, V. and Kumar, A. (2021), "Developing a blockchain framework for the automotive supply chain: a systematic review", *Computers and Industrial Engineering*, Vol. 157, 107334, doi: 10.1016/j.cie.2021.107334.

Kou, G. and Ergu, D. (2016), "AHP/ANP theory and its application in technological and economic development: the 90th anniversary of Thomas L. Saaty", *Technological and Economic Development of Economy*, Vol. 22, pp. 649-650, doi: 10.3846/20294913.2016.1202353.

Kouhizadeh, M. and Sarkis, J. (2018), "Blockchain practices, potentials, and perspectives in greening supply chains", *Sustainability*, Vol. 10, 3652, doi: 10.3390/su10103652.

Kshetri, N. (2018), "Blockchain's roles in meeting key supply chain management objectives", *International Journal of Information Management*, Vol. 39, pp. 80-89, doi: 10.1016/j.ijinfomgt.2017.12.005.

Kumar, M. and Iyenger, N.S. (2017), "A framework for blockchain technology in rice supply chain management plantation", *Conference: Future Generation Communication and Networking*, pp. 125-130, doi: 10.14257/astl.2017.146.22.

Leal, F., Chis, A. and Gonzalez-Velez, H. (2021), "Multi-service model for blockchain networks", *Information Processing and Management*, Vol. 58, 102525, doi: 10.1016/j.ipm.2021.102525.

Leake, C. and Malczewski, J. (2000), "GIS and multicriteria decision analysis", *The Journal of the Operational Research Society*, Vol. 51, p. 247, doi: 10.2307/254268.

Martínez, E. and Escudey, M. (1998), *Evaluación Y Decisión Multicriterio: Reflexiones Y Experiencias. Colección Tecnología*, UNESCO, Editorial de la Universidad de Santiago de Chile, Santiago de Chile.

Lezoche, M., Hernandez, J.E., Alemany, M., Panetto, H. and Kacprzyk, J. (2020), "Agri-food 4.0: a survey of the supply chains and technologies for the future agriculture", *Computers in Industry*, Vol. 117, doi: 10.1016/j.compind.2020.103187.

Li, W., Gao, L. and Li, X. (2009), "Application of intelligent strategies for cooperative manufacturing planning", *Journal of Universal Computer Science*, Vol. 15 No. 9, pp. 1907-1923.

Li, X., Jiang, P., Chen, T., Luo, X. and Wen, Q. (2017), "A survey on the security of blockchain systems", *Future Generation Computer Systems*, Vol. 107, doi: 10.1016/j.future.2017.08.020.

Liaskos, S. and Wang, B. (2018), "Towards a model for comprehending and reasoning about PoW-based blockchain network sustainability", *SAC '18: Proceedings of the 33rd Annual ACM Symposium on Applied Computing*, pp. 383-387, doi: 10.1145/3167132.3167175.

Liu, L., Zhou, S., Huang, H. and Zheng, Z. (2021), "From technology to society: an overview of blockchain-based DAO", *IEEE Open Journal of the Computer Society*, p. 1, doi: 10.1109/OJCS.2021.3072661.

Macrinici, D., Cartofeanu, C. and Gao, S. (2018), "Smart contract applications within blockchain technology: a systematic mapping study", *Telematics and Informatics*, Vol. 35, doi: 10.1016/j.tele.2018.10.004.

Madavi, D. (2019), "A comprehensive study on blockchain technology", *International Research Journal of Engineering and Technology (IRJET)*, Vol. 06 No. 01, pp. 1765-1770.

Makhdoom, I., Abolhasan, M., Abbas, H. and Ni, W. (2019), "Blockchain's adoption in IoT: the challenges, and a way forward", *Journal of Network and Computer Applications*, Vol. 125, pp. 251-279, doi: 10.1016/j.jnca.2018.10.019.

Malik, S., Kanhere, S. and Jurdak, R. (2018), "ProductChain: scalable blockchain framework to support provenance in supply chains", *International Symposium on Network Computing and Applications (NCA)*. doi: 10.1109/NCA.2018.8548322.

Maru, A., de Beer, J., Ballantyne, P., Pesce, V., Kalyesubula, S., Fourie, N., Addison, C., Collett, A. and Chaves, J. (2018), "Digital and data-driven agriculture: harnessing the power of data for smallholders", *Global Open Data for Agriculture and Nutrition*.

Mastrocinque, E., Ramirez, F.J., Honrubia-Escribano, A. and Pham, D. (2020), "An AHP-based multi-criteria model for sustainable supply chain development in the renewable energy sector", *Expert Systems with Applications*, Vol. 150, 113321, doi: 10.1016/j.eswa.2020.113321.

Milani, F., García-Bañuelos, L., Filipova, S. and Markovska, M. (2021), "Modelling blockchain-based business processes: a comparative analysis of BPMN vs CMMN", *Business Process Management Journal*. doi: 10.1108/BPMJ-06-2020-0263.

Moher, D., Liberati, A., Tetzlaff, J. and Douglas, A. (2009), "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement", *BMJ*, Vol. 8, pp. 336-341, doi: 10.1371/journal.pmed.1000097.

Morabito, V. (2017), *Business Innovation through Blockchain*, Springer, doi: 10.1007/978-3-319-48478-5.

Mukherjee, A.A., Singh, R., Mishra, R. and Bag, S. (2021), "Application of blockchain technology for sustainability development in agricultural supply chain: justification framework", *Operations Management Research*. doi: 10.1007/s12063-021-00180-5.

Munim, Z., Duru, O. and Hirata, E. (2021), "Rise, fall, and recovery of blockchains in the maritime technology space", *Journal of Marine Science and Engineering*, Vol. 9, p. 266, doi: 10.3390/jmse9030266.

Mylrea, M. and Gourisetti, S. (2017), "Blockchain for smart grid resilience: exchanging distributed energy at speed, scale and security", *Conference: 2017 Resilience Week (RWS)*, pp. 18-23, doi: 10.1109/RWEEK.2017.8088642.

Nakamoto, S. (2008), "Bitcoin: a peer-to-peer electronic cash system".

Nanayakkara, S., Perera, S., Senaratne, S., Weerasuriya, T. and Bandara, D. (2021), "Blockchain and smart contracts: a solution for payment issues in construction supply chains", *Informatics*, Vol. 8, p. 36, doi: 10.3390/informatics8020036.

Nassar, S., Kandil, T., Er, M. and Ghadge, A. (2019), "Automotive recall risk: impact of buyer-supplier relationship on supply chain social sustainability", *International Journal of Productivity and Performance Management*. doi: 10.1108/IJPPM-01-2019-0026.

Natoli, C. and Gramoli, V. (2016), "The blockchain anomaly", *The 15th IEEE International Symposium on Network Computing and Applications (NCA 2016)*. doi: 10.1109/NCA.2016.7778635.

Nayal, K., Raut, R., Narkhede, B., Priyadarshinee, P., Panchal, G. and Gedam, V. (2021), "Antecedents for blockchain technology-enabled sustainable agriculture supply chain", *Annals of Operations Research*, doi: 10.1007/s10479-021-04423-3.

Nguyen, T. and Kim, K. (2018), "A survey about consensus algorithms used in Blockchain", *Journal of Information Processing Systems*, Vol. 14, pp. 101-128, doi: 10.3745/JIPS.01.0024.

Nnaji, C. and Banigo, A. (2018), "Multi-criteria evaluation of sources for self-help domestic water supply", *Applied Water Science*, Vol. 8, doi: 10.1007/s13201-018-0657-2.

Nuseir, M. (2020), "Potential impacts of blockchain technology on business practices of bricks and mortar (B&M) grocery stores", *Business Process Management Journal*. doi: 10.1108/BPMJ-06-2020-0267.

OECD (2019), "Blockchain technologies as a digital enabler for sustainable infrastructure", OECD Environment Policy Papers, No. 16, OECD Publishing, Paris. doi: 10.1787/0ec26947-en.

Park, A. and Li, H. (2021), "The effect of blockchain technology on supply chain sustainability performances", *Sustainability*, Vol. 13, p. 1726, doi: 10.3390/su13041726.

Pearson, S., May, D., Leontidis, G., Swainson, M., Brewer, S., Bidaut, L., Frey, J., Parr, G., Maull, R. and Zisman, A. (2019), "Are distributed ledger technologies the panacea for food traceability?", *Global Food Security*, Vol. 20, pp. 145-149, doi: 10.1016/j.gfs.2019.02.002.

Peck, M. (2017), "Reinforcing the links of the blockchain. White paper", *IEEE Future Directions Blockchain Initiative White Paper*.

Poblet, M. and Konashevych, O. (2018), "Is blockchain hashing an effective method for electronic governance? Frontiers in artificial intelligence and applications", *Legal Knowledge and Information Systems*, 1st ed., Chapter: 23, IOS Press, Vol. 313, pp. 195-199, doi: 10.3233/978-1-61499-935-5-195.

Pu, S. and Lam, J.S.L. (2020), "Blockchain adoptions in the maritime industry: a conceptual framework", *Maritime Policy and Management*. doi: 10.1080/03088839.2020.1825855.

Queiroz, M., Telles, R. and Bonilla, S. (2019), "Blockchain and supply chain management integration: a systematic review of the literature", *Supply Chain Management: An International Journal*, Vol. 25, doi: 10.1108/SCM-03-2018-0143.

Rao, V.R. (2007), *Decision Making in the Manufacturing Environment. Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods*, Springer Series in Advanced Manufacturing Book Series (SSAM). doi: 10.1007/978-1-84628-819-7.

Rempel, P., Mäder, P., Kuschke, T. and Philippow, I. (2013), "Requirements traceability across organizational boundaries - a survey and taxonomy", *Proceedings of the 19th international conference on Requirements Engineering: Foundation for Software Quality*, pp. 125-140, doi: 10.1007/978-3-642-37422-7_10.

Rizk, A., Bisbal, J., Bergsträßer, S. and Steinmetz, R. (2018), "Brokerless inter-domain virtual network embedding: a blockchain-based approach", *IT - Information Technology*, p. 60, doi: 10.1515/itit-2018-0033.

Rohr, J. (2019), "SAP helps Swiss Post and modum build blockchain solution for temperature-controlled logistics", available at: https://news.sap.com/2019/03/swiss-post-modum-blockchain-solution-temperature-logistics/.

Rosdi, M., Othman, A., Zubir, M., Abd Latif, Z. and Yusoff, Z. (2017), "Sinkhole susceptibility hazard zones using gis and analytical hierarchical process (AHP): a case study of Luala Lumpur and Ampang Jaya", *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-4/W5, pp. 145-151, doi: 10.5194/isprs-archives-XLII-4-W5-145-2017.

Rossit, D., Tohmé, F. and Frutos, M. (2018), "Industry 4.0: smart scheduling", *International Journal of Production Research*, Vol. 57, pp. 1-12, doi: 10.1080/00207543.2018.1504248.

Saaty, T. (1980), *The Analytic Hierarchy Process*, McGraw-Hill, New York.

Saaty, T. (2000), *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*, RWS Publications, ISBN: 978-0962031762.

Saaty, T. (2008), "Decision making with the analytic hierarchy process", *International Journal of Services Sciences*, Vol. 1, pp. 83-98, doi: 10.1504/IJSSCI.2008.017590.

Sai, A., Buckley, J., Fitzgerald, B. and Gear, A. (2021), "Taxonomy of centralization in public blockchain systems: a systematic literature review", *Information Processing and Management*, Vol. 58, 102584, doi: 10.1016/j.ipm.2021.102584.

Salah, K., Habib ur Rehman, M., Nizamuddin, N. and Al-Fuqaha, A. (2018), *Blockchain for AI: Review and Open Research Challenges*, IEEE Access.

Seebacher, S. and Schüritz, R. (2017), "Blockchain technology as an enabler of service systems: a structured literature review", *International Conference on Exploring Services Science*, pp. 12-23, doi: 10.1007/978-3-319-56925-3_2.

Seddigh, M.R., Shokouhyar, S. and Loghmani, F. (2022), "Approaching towards sustainable supply chain under the spotlight of business intelligence", *Annals of Operations Research*, Vol. 9, p. 9, doi: 10.1007/s10479-021-04509-y#citeas.

Shakow, D.J. (2018). "The tao of the DAO: taxing an entity that lives on a blockchain", University of Penn, Tax Notes, Inst for Law and Econ Research Paper No. 18-23, Vol. 160, p. 929, available at: https://ssrn.com/abstract=3247155.

Shala, B., Trick, U., Lehmann, A., Ghita, B.V. and Shiaeles, S. (2020), "Blockchain and trust for secure, end-user-based and decentralized IoT service provision", *IEEE Access*, Vol. 8, p. 1, doi: 10.1109/ACCESS.2020.3005541.

Shelley, A. and Horner, K. (2021), "Questionnaire surveys - sources of error and implications for design, reporting and appraisal", *British Dental Journal*, Vol. 230, pp. 251-258, doi: 10.1038/s41415-021-2654-3.

Shokouhyar, S., Seddigh, M.R. and Panahifar, F. (2022), "Impact of big data analytics capabilities on supply chain sustainability: a case study of Iran", doi: 10.1108/WJSTSD-06-2019-0031/full/html.

Shokouhyar, S. and Seddigh, M.R. (2020), "Uncovering the dark and bright sides of implementing collaborative forecasting throughout sustainable supply chains: an exploratory approach", *Technological Forecasting and Social Change*, Vol. 158, doi: 10.1016/j.techfore.2020.120059.

Sivula, A., Shamsuzzoha, A. and Helo, P. (2020), "Requirements for blockchain technology in supply chain management: an exploratory case study", *Operations and Supply Chain Management: An International Journal*, pp. 39-50, doi: 10.31387/oscm0440284.

Sompolinsky, Y. and Zohar, A. (2015), "Secure high-rate transaction processing in Bitcoin", *International Conference on Financial Cryptography and Data Security*, New York, Springer, pp. 507-527, doi: 10.1007/978-3-662-47854-7_32.

Sundarakani, B., Ajaykumar, A. and Gunasekaran, A. (2021), "Big data driven supply chain design and applications for blockchain: an action research using case study approach", *Omega*, Vol. 102, 102452, doi: 10.1016/j.omega.2021.102452.

Sunmola, F. (2021), "Context-aware blockchain-based sustainable supply chain visibility management", *Procedia Computer Science*, Vol. 180, pp. 887-892, doi: 10.1016/j.procs.2021.01.339.

Szabo, N. (1994), "Smart contracts".

Taylor, P., Dargahi, T., Dehghantanha, A., Parizi, R. and Choo, K.-K. (2019), "A systematic literature review of blockchain cyber security", *Digital Communications and Networks*, Vol. 6, doi: 10.1016/j.dcan.2019.01.005.

Taslicali, A. and Ercan, S. (2006), "The analytic hierarchy and the analytic network processes in multicriteria decision making: a comparative study", *Journal of Aeronautics and Space Technologies*, Vol. 2, pp. 55-65.

Tian, F. (2017), "A supply chain traceability system for food safety based on HACCP, blockchain & Internet of things", pp. 1-6, doi: 10.1109/ICSSSM.2017.7996119.

Tiwari, S., Wee, H. and Daryanto, Y. (2017), "Big data analytics in supply chain management between 2010 and 2016: insights to industries", *Computers and Industrial Engineering*, Vol. 115, doi: 10.1016/j.cie.2017.11.017.

Torky, M. and Hassanien, A.E. (2020), "Integrating blockchain and the Internet of things in precision agriculture: analysis, opportunities, and challenges", *Computers and Electronics in Agriculture*. doi: 10.1016/j.compag.2020.105476.

Toyota (2020), "Toyota blockchain lab, accelerating blockchain technology initiatives and external collaboration", available at: https://global.toyota/en/newsroom/corporate/31827481.html.

Uddin, M., Salah, K., Jayaraman, R., Pesic, S. and Ellahham, S. (2021), "Blockchain for drug traceability: architectures and open challenges", *Health Informatics Journal*, Vol. 27, doi: 10.1177/14604582211011228.

United Nations (2020), "Blockchain applications in the United Nations system: towards a state of readiness", *Report of the Joint Inspection Unit*, Geneva, JIU/REP/2020/7.

Vafadarnikjoo, A., Badri Ahmadi, H., Liou, J., Botelho, T. and Chalvatzis, K. (2021), "Analyzing blockchain adoption barriers in manufacturing supply chains by the neutrosophic analytic hierarchy process", *Annals of Operations Research*. doi: 10.1007/s10479-021-04048-6.

Vaidya, O. and Kumar, S. (2006), “Analytic hierarchy process: an overview of applications”, *European Journal of Operational Research*, Vol. 169, pp. 1-29, doi: 10.1016/j.ejor.2004.04.028.

Wang, J., Jing, Y.Y., Zhang, C.F. and Zhao, J.H. (2009), “Review on multi-criteria decision analysis aid in sustainable energy decision-making”, *Renewable and Sustainable Energy Reviews*, Vol. 13, pp. 2263-2278, doi: 10.1016/j.rser.2009.06.021.

Wang, Y., Han, J.H. and Beynon-Davies, P. (2018), “Understanding blockchain technology for future supply chains: a systematic literature review and research agenda”, *Supply Chain Management: An International Journal*, Vol. 24, doi: 10.1108/SCM-03-2018-0148.

Wang, B., Luo, W., Zhang, A., Tian, Z. and Li, Z. (2020a), “Blockchain-enabled circular supply chain management: a system architecture for fast fashion”, *Computers in Industry*, Vol. 123, 103324, doi: 10.1016/j.compind.2020.103324.

Wang, Y., Chen, K., Hao, M. and Yang, B. (2020b), “Food safety traceability method based on blockchain technology”, *Journal of Physics: Conference Series*, Vol. 1634, 012025, doi: 10.1088/1742-6596/1634/1/012025.

Xu, L., Xu, E. and Li, L. (2018), “Industry 4.0: state of the art and future trends. International”, *Journal of Production Research*, Vol. 56, pp. 1-22, doi: 10.1080/00207543.2018.1444806.

Xu, X., Weber, I. and Staples, M. (2019), *Architecture for Blockchain Applications*, Springer, doi: 10.1007/978-3-030-03035-3.

Xue, X., Dou, J. and Shang, Y. (2020), “Blockchain-driven supply chain decentralized operations – information sharing perspective”, *Business Process Management Journal*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/BPMJ-12-2019-0518.

Yadav, V. and Singh, A.R. (2019), “Use of blockchain to solve select issues of Indian farmers”, *AIP Conference Proceedings*, Vol. 2148, 030050, doi: 10.1063/1.5123972.

Yeow, K., Gani, A., Ahmad, R., Rodrigues, J. and Ko, K. (2017), “Decentralized consensus for edge-centric internet of things: a review, taxonomy, and research issues”, *IEEE Access*, p. 1, doi: 10.1109/ACCESS.2017.2779263.

Yiyan, C., Ye, L. and Cunjin, L. (2020), “Electronic agriculture, blockchain and digital agricultural democratization: origin, theory and application”, *Journal of Cleaner Production*, Vol. 268, 122071, doi: 10.1016/j.jclepro.2020.122071.

Zhang, Y., Chen, L., Battino, M., Farag, M., Xiao, J., Simal-Gandara, J., Gao, H. and Jiang, W. (2022), “Blockchain: an emerging novel technology to upgrade the current fresh fruit supply chain”, *Trends in Food Science and Technology*, Vol. 124, doi: 10.1016/j.tifs.2022.03.030.

Zhang, A., Zhong, R., Farooque, M., Kang, K. and Venkatesh, G. (2019), “Blockchain-based life cycle assessment: an implementation framework and system Architecture”, *Resources Conservation and Recycling*, Vol. 152, doi: 10.1016/j.resconrec.2019.104512.

Zhao, J., Fan, S. and Yan, J. (2016), “Overview of business innovations and research opportunities in blockchain and introduction to the special issue”, *Financial Innovation*, Vol. 2, doi: 10.1186/s40854-016-0049-2.

Zhao, G., Liu, S., Lopez, C., Lu, H., Elgueta, S., Mileva-Boshkoska, B. and Chen, H. (2019), “Blockchain technology in agri-food value chain management: a synthesis of applications, challenges and future research directions”, *Computers in Industry*, Vol. 109, doi: 10.1016/j.compind.2019.04.002.

Corresponding author
Simon Fernandez-Vazquez can be contacted at: fernandezsimon@uniovi.es

6 Conclusiones

6.1. Conclusiones

En los últimos años, hemos presenciado el advenimiento de una ola innovadora de tecnología transformadora distribuida a través de múltiples industrias, conocida como Industria 4.0 Este término se introdujo por primera vez en 2011, en referencia a cómo los avances tecnológicos cambiarían profundamente la organización de las cadenas globales de suministro. Aunque la Industria 4.0 ha sido generalmente aceptada por el ámbito académico y profesional, también se han desarrollado otros conceptos en este período de tiempo que se refieren al uso de tecnologías digitales en la producción. En este contexto, esta nueva industria representa un cambio desde una producción planificada y centralizada a una producción dinámica y descentralizada, diseñada para mejorar la calidad de los bienes, los procesos a medida y la flexibilidad de los sistemas.

Este espectro propio de la revolución de la Industria 4.0 engloba una amplia variedad de innovaciones, como la computación en la nube, el IoT, la inteligencia artificial (IA) o la tecnología blockchain. Cabe destacar que la rapidez en los cambios mundo que nos rodea es de tal calibre, que ya se comienza a hablar de industria 5.0, una industria que acentúa la cooperación entre máquinas y humanos con el objetivo de mejorar la productividad y la eficiencia. En el sistema actual, los datos incorrectos o fraudulentos pueden dar lugar a una toma de decisiones errónea y convertirse en un gran desafío para los procesos de desarrollo dinámicos y conectados. Para la toma de decisiones colaborativas, una plataforma controlada centralmente no puede impedir la privacidad de los datos de otros usuarios, ya que es esencial conocer las capacidades y condiciones de cada uno. Las empresas manufactureras también tienen que resolver la baja robustez de los sistemas centralizados desde un solo nodo clave, lo que genera redes y servicios de datos poco fiables. La gestión de fabricación actual depende típicamente de una red centralizada, con trazabilidad de datos limitada y procesos propensos a fallas. Precisamente debido al sistema global y condiciones cambiantes (crisis energéticas o pandemias, por ejemplo) el beneficio de estas tecnologías reside en su capacidad de aprender a través de la IA, sus procesos altamente seguros y su capacidad de predicción.

Mediante el uso de un novedoso marco tecnológico como en el caso de blockchain, se pueden resolver muchos de los principales retos de la industria en cuanto a seguridad o monitoreo de productos durante toda la cadena de suministro. Blockchain proporciona un marco abierto y compartido entre sus usuarios. Las características innatas de esta tecnología hacen que la confianza de todas las partes involucradas aumente, a través de una mayor claridad en la trazabilidad de las transacciones. El objetivo en el medio plazo es permitir que máquinas, como las computadoras, desarrollen e interpreten conceptos como los de la mente humana.

Esta investigación trata de enfatizar los efectos favorables de una cadena de suministro habilitada para blockchain en la sostenibilidad en el largo plazo, ponderando además, la influencia relativa de varias posibles ventajas de la tecnología blockchain en el desarrollo sostenible. Las conclusiones del estudio son aplicables a las principales empresas industriales a lo largo de sus operaciones de cadena de suministro. Los sectores de logística, médico, de seguros y público son solamente algunas de las áreas prometedoras para las aplicaciones y el estudio de blockchain.

Se considera haber alcanzado los objetivos de esta tesis mediante compendio de publicaciones, dividido en capítulos de la misma. En este sentido, en el segundo capítulo de esta tesis doctoral, se introduce la temática blockchain y se realiza una primera aproximación a sus aplicaciones en la cadena de suministro, identificando aspectos clave como la sostenibilidad, la descentralización, la inmutabilidad de datos y el uso de contratos inteligentes. Se introducen además los principales algoritmos de consenso, que serán desarrollados posteriormente en el capítulo cuarto.

El tercer capítulo aborda un estudio de la literatura enfocado al sector fintech, caracterizado como uno de los sectores más propensos a la adopción de esta novedosa tecnología. Los resultados muestran un profundo enfoque en desafíos como seguridad, escalabilidad, legal y regulatorio, privacidad, latencia, riesgos cibernéticos o desarrollo tecnológico. Las brechas que han surgido de este estudio resaltan que, aunque en los últimos años hay un número creciente de artículos publicados sobre blockchain, el marco de conocimiento en la disciplina aún está disperso y una gran mayoría de temas y direcciones de investigación aún están sustancialmente sin explorar. No obstante, los principales resultados del estudio muestran que el interés por esta tecnología está aumentando y su marco está en expansión.

En la segunda parte de la investigación, el cuarto capítulo es el resultado de un análisis comparativo de las principales redes blockchain. El objetivo de esta publicación es poner de manifiesto, mediante un análisis técnico, las principales diferencias existentes en las redes blockchain para así poder guiar a las empresas a elegir un algoritmo de consenso que se adecúe a sus características.

Finalmente, el último artículo utilizado para esta tesis doctoral expone las principales ventajas del uso de blockchain en las cadenas de suministro y su mayor contribución a la sostenibilidad en el largo plazo. En esta publicación, se comienza realizando una descripción general de blockchain, así como identificando y analizando las características clave de esta tecnología. Posteriormente se pasa a analizar las aplicaciones prácticas de blockchain en las cadenas de suministro y su comparación con las cadenas de suministro tradicionales.

Tanto la comunidad científica como la industria están cada vez más interesadas tanto en blockchain como en su aplicación. No obstante, esta tecnología se enfrenta obstáculos que deben superarse antes de poder expandirse aún más. Las mejoras en sus funciones, como la privacidad o la ineficiencia, se beneficiarían de una investigación más rigurosa y una mayor inversión promovida desde la óptica empresarial. Si bien todavía estamos muy lejos de usar blockchain para resolver muchos de los problemas de la actualidad, sus características brindan motivos para el optimismo.

6.2. Conclusions

In recent years, the world has witnessed the advent of an innovative wave of transformative technology distributed across multiple industries, known as Industry 4.0. This term was first introduced in 2011, referring to how technological advances would profoundly change the organization of companies. global supply chains. Although Industry 4.0 has been generally accepted by the academic and professional worlds, other concepts have also been developed in this time period that refer to the use of digital technologies in production. In this context, this new industry represents a shift from planned and centralized production to dynamic and decentralized production, designed to improve the quality of goods, tailor-made processes and the flexibility of systems.

This spectrum of the Industry 4.0 revolution encompasses a wide variety of innovations, such as cloud computing, IoT, artificial intelligence (AI) or blockchain technology. It should be noted that the speed of change in the world around us is of such a caliber that we are already beginning to talk about industry 5.0, an industry that emphasizes cooperation between machines and humans with the aim of improving productivity and efficiency. In today's system, incorrect or fraudulent data can lead to poor decision-making and become a major challenge for dynamic and connected development processes. For collaborative decision-making, a centrally controlled platform cannot prevent the privacy of other users' data, since it is essential to know the capabilities and conditions of each agent. Manufacturing companies also have to resolve the low robustness of centralized systems from a single key node, leading to unreliable networks and data services. Today's manufacturing management typically relies on a centralized network, with limited data traceability and failure-prone processes. Precisely due to the global system and changing conditions (energy crises or pandemics, for example) the benefit of these technologies lies in their ability to learn through AI, their highly secure processes and their ability to predict.

Through the use of a new technological framework such as blockchain, many of the main challenges of the industry in terms of security or monitoring of products throughout the supply chain can be solved. Blockchain provides an open and shared framework among its users. The innate characteristics of this technology increase the trust of all parties involved, through greater clarity in the traceability of transactions. The goal in the medium term is to allow machines, such as computers, to develop and interpret concepts like those of the human mind.

This research emphasizes the favorable effects of a blockchain-enabled supply chain on long-term sustainability, while also weighing the relative influence of various possible advantages of blockchain technology on sustainable development. The study's findings are applicable to major industrial companies throughout their supply chain operations. The logistics, medical, insurance, and public sectors are just a few of the promising areas for blockchain applications and study.

The objectives of this thesis have been reached through a compendium of publications, divided into chapters. In this sense, in the second chapter of this doctoral thesis, the blockchain concept is introduced and a first approach to its applications in the supply chain management is made, identifying key aspects such as sustainability, decentralization, data immutability and the use of smart contracts. The main consensus algorithms are also introduced, which will be developed later in the fourth chapter.

The third chapter deals with a study of the literature focused on the fintech sector, characterized as one of the sectors most likely to adopt this new technology. The results show a deep focus on challenges such as security, scalability, legal and regulatory, privacy, latency, cyber risks or technological development. The gaps that have emerged from this study highlight that, although there is an increasing number of articles published on blockchain in recent years, the knowledge framework in the discipline is still scattered and a large majority of research topics and directions are still substantially unresolved. However, the main results of the study show that interest in this technology is increasing and its framework is expanding.

In the second part of the investigation, the fourth chapter is the result of a comparative analysis of the main blockchain networks. The objective of this publication is to highlight, through a technical analysis, the main differences in blockchain networks in order to guide companies to choose a consensus algorithm that suits their characteristics.

Finally, the last article used for this doctoral thesis exposes the main advantages of using blockchain in supply chains and its greatest contribution to long-term sustainability. This article begins with an overview of blockchain, as well as identifying and discussing the key features of this technology. Subsequently, it goes on to analyze the practical applications of blockchain in supply chains and its comparison with traditional supply chains.

Both the scientific community and industry are increasingly interested in both blockchain and its application. However, this technology faces obstacles that must be overcome before it can be expanded further. Improvements to its features, such as privacy or inefficiency, would benefit from more rigorous research and more business-driven investment. While we are still a long way from using blockchain to solve many of the world's problems, its features provide reason for optimism.

7 Extensiones y futuras líneas de trabajo

Desde un prisma de la continuación en la investigación realizada para la presente tesis doctoral, se estaría interesado en una línea clara de investigación: la aplicación de la tecnología blockchain a casos reales para empresas fintech. El estudio llevado a cabo en para el capítulo 3 demostró un potencial de crecimiento y de expansión de esta tecnología revolucionaria, que podría realizarse desde un punto de vista técnico para implementar soluciones a casos reales de mejora. Resulta de gran interés combinar las ventajas de esta tecnología con los retos de las empresas en su día a día.

Otra de las principales líneas de investigación de la presente tesis ha sido la relativa a las cadenas de suministro. En este sentido, una futura línea de trabajo sería apostar por una mejora real, mediante el desarrollo de aplicaciones descentralizadas, que ayude a mejorar las cadenas de suministro de las empresas. Además, permitiría la aplicación de blockchain en industrias menos desarrolladas, mejorando por ejemplo aspectos como la trazabilidad de materias primas o productos con la gestión del fraude en las cadenas. Estas características reales de blockchain ayudarían a sentar las bases para una mejor gestión de la cadena de suministro en las empresas.

Finalmente, uno de los aspectos fundamentales para la mejora y la evolución de blockchain es la colaboración con empresas pertenecientes a centros tecnológicos. Así, siguiendo la línea de trabajo llevada a cabo en la presente tesis doctoral, en la que se ha tenido oportunidad de colaborar con un centro de investigación especializado en blockchain, una futura línea de trabajo es seguir apostando por esta colaboración. La sabiduría académica combinada con los desarrollos más vanguardistas de esta tecnología sería de gran utilidad tanto para la comunidad científica como para los profesionales de la industria.

Bibliografía

Büchi, G., Cugno, M. & Castagnoli, R. (2020). Smart factory performance and Industry 4.0. Technological Forecast & Social Change. doi:10.1016/j.techfore.2019.119790.

Chang, S.E., Chen, Y. & Lu, M.-F. (2019). Supply chain reengineering using Blockchain technology: A case of smart contract-based tracking process. Technological Forecasting and Social Change. 144. 1-11. doi:10.1016/j.techfore.2019.03.015.

Cunha, P.R., Soja, P. and Themistocleous, M. (2021), Blockchain for development: a guiding framework, Information Technology for Development, Vol. 27, pp. 417-438, doi: 10.1080/ 02681102.2021.1935453.

Ferreira, C., Rabelo, R., Sá S. & Cavalcanti, C. (2020). Blockchain for Machine to Machine Interaction in Industry 4.0. In book: Blockchain Technology for Industry 4.0, Secure, Decentralized, Distributed and Trusted Industry Environment (pp.99-116), Springer. Doi:10.1007/978-981-15-1137-0_5.

Lim, C. H., Lim, S., How, B. S., Ng, W. P. Q., Ngan, S. L., Leong, W. D., & Lam, H. L. (2021). A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach. Renewable and Sustainable Energy Reviews, 135, 110223. doi:10.1016/j.rser.2020.110223

Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System. 2008. Disponible en: https://bitcoin.org/bitcoin.pdf. Accedido en septiembre 2022.

Nayal, K., Raut, R., Narkhede, B., Priyadarshinee, P., Panchal, G. and Gedam, V. (2021), Antecedents for blockchain technology-enabled sustainable agriculture supply chain", Annals of Operations Research, doi: 10.1007/s10479-021-04423-3.

Qu, Y., Pokhrel, S. R., Garg, S., Gao, L., & Xiang, Y. (2020). A Blockchained Federated Learning Framework for Cognitive Computing in Industry 4.0 Networks. IEEE Transactions on Industrial Informatics, 1–1. doi:10.1109/tii.2020.3007817

Schwab K. (2017) The fourth industrial revolution. Crown Publishing Group, New York.

Anexo I. Informe sobre la calidad de las publicaciones

A continuación, se detalla información sobra la calidad y el factor de impacto de las publicaciones presentadas en esta tesis.

Capítulo de libro 1

Título: *The application of distributed ledger technology in Industry 4.0.* Lecture Notes in Management and Industrial Engineering (LNMIE). Springer. Pending publication.
Autores: Simón Fernández-Vázquez, Rafael Rosillo, Paolo Priore, Javier Puente.
Estado: Aceptado. Pendiente de publicación.
Fecha de aceptación: 15/09/2021

Artículo 1

Título: *Blockchain in FinTech: A Mapping Study.* Sustainability 11: 6366. https://doi.org/10.3390/su11226366.
Autores: Simón Fernández-Vázquez, Rafael Rosillo, David de la Fuente, Paolo Priore.
Estado: Publicado.
Fecha de aceptación: 06/11/2019
Factor de Impacto: JCR (2021): 3.889, Categoría: Environmental Sciences (Q2) 133/279.

Artículo 2

Título: *A comparative study of blockchain's largest permissionless networks.* Technology Analysis & Strategic Management, doi: 10.1080/09537325.2021.1976748.
Autores: Simón Fernández-Vázquez, Rafael Rosillo, Luis Meijueiro, Raúl Alonso, David de la Fuente.
Estado: Publicado.
Fecha de aceptación: 20/08/2021
Factor de Impacto: JCR (2021): 3.745, Categoría: Management (Q3) 139/226.

Artículo 3

Título: *Blockchain in sustainable supply chain management: an application of the analytical hierarchical process (AHP) methodology*, Business Process Management Journal, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/BPMJ-11-2021-0750.
Autores: Simón Fernández-Vázquez, Rafael Rosillo, David de la Fuente, Javier Puente.
Estado: Publicado.
Fecha de aceptación: 10/08/2022
Factor de Impacto: JCR (2021): 3.715, Categoría: Business (Q3) 103/154.