Universidad Complutense de Madrid

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Tesis doctoral

BLOCKCHAIN FOR THE GOVERNANCE OF COMMONS BASED PEER PRODUCTION COMMUNITIES

BLOCKCHAIN PARA LA GOBERNANZA DE COMUNIDADES DE PRODUCCIÓN COLABORATIVA DE BIENES COMUNES.

Memoria para optar al grado de doctore

presentada por

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Blockchain for the Governance of Commons Based Peer Production Communities

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UNIVERSIDAD COMPLUTENSE MADRID

DECLARACIÓN DE AUTORÍA Y ORIGINALIDAD DE LA TESIS PRESENTADA PARA OBTENER EL TÍTULO DE DOCTOR

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Resumen

La popularización de Internet permitió el surgimiento de un nuevo tipo de organizaciones productivas, como Wikipedia o Firefox, que crean valor más allá de los marcos tradicionales del mercado y el estado. En estas organizaciones, llamadas comunidades de producción colaborativa de bienes comunes, o comunidades Commons-Based Peer Production (CBPP) por sus siglas en inglés, las personas construyen bienes comunes tales como wikis o programas de código abierto de manera colaborativa, relativamente no jerárquica y, a menudo, sin recibir compensaciones económicas directas por sus contribuciones. A diferencia de las estructuras organizativas tradicionales, y de forma similar a otras organizaciones de la participación voluntaria, las comunidades CBPP experimentan fuertes desigualdades en el nivel de participación de sus miembros.

El primer objetivo de la tesis es contribuir al conocimiento sobre cómo las personas participan en estas comunidades. En particular, busca comprender las dinámicas de participación en las comunidades CBPP y profundizar en la comprensión y caracterización de la desigualdad de la participación en estas comunidades.

Además, estas comunidades son diferentes de las organizaciones jerárquicas tradicionales, ya que no existe una administración central o autoridades que organicen la producción. En cambio, los participantes se organizan y colaboran de manera descentralizada. Recientemente, las tecnologías blockchain han permitido nuevas formas de gobernanza descentralizada. Muchos afirman que estas tecnologías revolucionarán aún más la forma en que se organizan las comunidades CBPP.

Así, el segundo objetivo de este trabajo es comprender si estas afirmaciones son correctas y aportar algo de luz sobre lo que realmente podría significar el uso de tecnologías blockchain para la gobernanza de las comunidades online. Esto ayudará a responder preguntas como cuáles son las características de blockchain que lo hacen atractivo para la gobernanza de las comunidades CBPP, o qué prácticas de gobernanza específicas podría apoyar.

Al igual que con muchas nuevas tecnologías, existe un gran entusiasmo con las posibilidades de blockchain, y muchos creen que revolucionará los sistemas económicos y de gobernanza y que resolverá problemas tradicionalmente difíciles en estos y otros campos.

El tercer objetivo de la tesis es analizar qué ofrecen realmente las tecnologías blockchain en comparación con otras tecnologías distribuidas alternativas. De esta manera, las diseñadoras de sistemas totalmente descentralizados podrían decidir si blockchain es la tecnología que necesitan o si existen otras alternativas distribuidas.

El cuarto objetivo de este trabajo tiene como objetivo aplicar las lecciones

aprendidas al desarrollo de un prototipo basado en blockchain. Concretamente, desarrollará herramientas destinadas a mejorar el campo de las publicaciones en acceso abierto y la revisión por pares. La elección de este campo para desarrollar nuestras aplicaciones responde al potencial percibido de blockchain y otras tecnologías descentralizadas como IPFS para facilitar la distribución de contenido de acceso abierto y brindar transparencia y responsabilidad a las prácticas de revisión por pares.

En resumen, los objetivos de esta tesis son comprender y caracterizar mejor la participación en comunidades CBPP (Objetivo 1); identificar si blockchain puede apoyar la gobernanza de estas comunidades y de que manera (Objetivo 2); proponer un marco tecnológico para el diseño de sistemas descentralizados, que ayude a sus diseñadoras a decidir si se necesita blockchain (Objetivo 3); y finalmente, aplicar las lecciones aprendidas para construir una aplicación funcional descentralizada para la publicación académica y revisión por pares (Objetivo 4) que permitirá probar y validar los hallazgos de la tesis, así como ayudar a identificar sus posibles limitaciones. y desafíos.

El trabajo utiliza una diversidad de métodos y enfoques para estos propósitos:

Primero, para el estudio de la participación en comunidades CBPP, utiliza simulación social basada en agentes para modelar las dinámicas de participación de estas comunidades. A continuación realiza un estudio estadístico de la participación en más de 6.000 comunidades wiki. En estos estudios, encontramos que la participación en comunidades CBPP no sigue una distribución de ley de potencia, como sugieren numerosas publicaciones previas. En cambio, proporcionamos evidencia estadística de una mejor caracterización: la distribución de la ley de potencia truncada.

En segundo lugar, la tesis estudia los usos potenciales de las tecnologías blockchain mediante el desarrollo de un análisis detallado. Primero identifica cuáles son las posibilidades o "affordances" de blockchain (como el potencial que tiene para ofrecer transparencia o "tokenizar" roles y permisos). Luego, estudia a cuáles de los principios de gobernanza de Ostrom pueden respaldar estas "affordances" (como podría ser el uso de "tokens" para respaldar el establecimiento de límites comunitarios claros). Por lo tanto, Este estudio proporciona un marco valioso que detalla cómo las prestaciones específicas de blockchain pueden respaldar el desarrollo de principios de gobernanza concretos. Además, proporciona ejemplos de herramientas blockchain que pueden ayudar a abordar las limitaciones de estos principios cuando se aplican a bienes comunes a escala global.

En tercer lugar, la tesis desarrolla un marco para el diseño y desarrollo de sistemas distribuidos con el fin de ayudar a las diseñadoras en sus elecciones tecnológicas al definir formalmente cuándo se necesitan las tecnologías blockchain. Para eso, se basa en principios bien conocidos de las tecnologías distribuidas, como el teorema CAP o el principio Calm, que determinan las tensiones inevitables entre cualidades deseables de los sistemas distribuidos como la coherencia, la disponibilidad o la resistencia a particiones.

Finalmente, desarrolla diferentes iteraciones de una aplicación basada en blockchain para la publicación académica y la revisión por pares llamada Decentralized Science. Utilizamos la metodología Lean Design y el desarrollo agil de software para diseñar, validar y construir la aplicación. Así, el software evoluciona desde una prueba de concepto tecnológica a un "mínimo producto viable" completamente funcional.

Abstract

The popularization of the Internet enabled the emergence of a new type of productive organizations, such as Wikipedia or Firefox, that create value beyond the traditional frameworks of the market and the state. In these organizations, named Commons-Based Peer Production (CBPP) communities, people collaboratively build common resources such as wikis and open source software, in a relatively non-hierarchical manner, and often without receiving direct economic compensations for their contributions. Unlike traditional organizational structures, and more similar to other organizations that rely on voluntary participation, CBPP communities experience strong inequalities in the level of participation of their members.

The first objective of the thesis is to contribute to the understanding of how people participate in CBPP communities. In particular, it aims to understand the dynamics of participation in CBPP communities and deepen the understanding and characterization of the inequality of participation in these communities.

Moreover, these communities differ from traditional hierarchical organizations, as there is a lack of central management or authorities to organize production. Instead, contributors are able to self-organize and collaborate in a decentralized manner. Recently, blockchain technologies have enabled new forms of decentralized governance. Many claim that these technologies will revolutionize even further the way CBPP communities organize.

The second objective of this work is to understand whether these assertions are correct, and bring some light into what could actually mean the use of blockchain technologies for the governance of online communities. This will help to answer questions such as what are the characteristics of blockchain that make it attractive for the governance of CBPP communities, or which specific governance practices could it support.

As with many new technologies, there is strong enthusiasm with the possibilities of blockchain, and many believe it will revolutionize economic and governance systems and solve traditionally hard problems in these and other fields.

The third objective of the thesis is to analyze what are blockchains actually offering when compared with alternative distributed technologies. This way, designers of fully decentralized systems would be able to decide if blockchain is the technology they need or if there are other distributed alternatives.

The fourth objective of this work aims to apply the lessons learned to the development of a blockchain-based prototype. Concretely, it will develop tools aimed to improve the field of Open Access publishing and peer reviewing. The choice of this field to develop our applications respond to the perceived potential of blockchain and other decentralized technologies such as IPFS to facilitate the

distribution of Open Access content and to bring transparency and accountability to peer reviewing practices.

Summarizing, this thesis objectives are to better understand and characterize participation in CBPP communities (Objective 1); to identify if and how blockchain can support their governance (Objective 2); to propose a technological framework for the design of decentralized systems, that assist designers to in deciding if blockchain is needed (Objective 3); and finally, to apply the lessons learned to build a functional decentralized application for academic publication and peer reviewing (Objective 4) that will enable to test and validate the findings of the thesis as well as help identifying its potential limitations and challenges.

The work uses a diversity of methods and approaches for these purposes:

First, for the study of participation in CBPP communities, it uses Agent-Based Social Simulation to model participation dynamics of these communities, and later performs a statistical study of the participation in more than 6,000 wiki communities. In these studies, we find that the participation in CBPP communities do not follow a power law distribution, as numerous previous literature suggest. Instead, we provide statistical evidence of a better characterization: the truncated power law distribution.

Second, it studies the potential uses of blockchain technologies by developing a detailed analysis. It first identifies what are the blockchain affordances (such as the potential it has to offer transparency or tokenize roles and permissions). Then it studies to which specific Ostrom's governance principles these affordances can support (such as the use of tokens to support the establishment of clear community boundaries). Thus, This study provides a valuable framework that details how specific blockchain affordances can support the application of concrete governance design principles. Furthermore, it provides examples of blockchain tools that can help to tackle the limitations of these principles when applied to global scale commons.

Third, it develops a framework for the design and development of distributed systems in order to support designers in their technological choices by formally defining when blockchain technologies are needed. For that, it draws in well known principles of distributed technologies such as CAP Theorem or Calm principle, that determine the unavoidable tensions between desirable qualities of distributed systems such as consistency, availability, or partition resistance.

Finally, it develops different iterations of a blockchain based application for academic publication and peer reviewing called Decentralized Science. We used Lean Design methodology and Agile software development to design, validate and build the application. The software evolved from a technological proof of concept to a fully functional Minimum Viable Product (MVP).

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I would like to thank all the people that shared with me their knowledge, advice, time, care and love during the years I was developing this thesis.

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Thanks Dariusz and NeRDS (New Research on Digital Societies) research group for hosting me at Warsaw, where I learned about the many ways of studying online communities that still inspire me to these days.

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Thanks to my family, who cultivated my curiosity and passion, and never doubt I was going to finish this project.

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Part I

Content of the thesis

About this document

The research performed in this thesis has been published in a collection of publications, which are listed below and are included in the Part II of the thesis.

Journal articles

Á. Tenorio-Fornés, J. Arroyo, and S. Hassan, "Participation in wiki communities: Reconsidering their statistical characterization," *PeerJ Computer Science*, 2021

D. Rozas, A. Tenorio-Fornés, S. Díaz-Molina, and S. Hassan, "When ostrom meets blockchain: exploring the potentials of blockchain for commons governance," *SAGE Open*, vol. 11, no. 1, p. 21582440211002526, 2021

D. Rozas, A. Tenorio-Fornés, and S. Hassan, "Analysis of the potentials of blockchain for the governance of global digital commons," *Frontiers in Blockchain*, vol. 4, p. 15, 2021

P. De Filippi, O. Shimony, and A. Tenorio Fornés, "Reputation. glossary of distributed technologies.," *Internet Policy Review*, vol. 10, no. 2, pp. 1–9, 2021

Á. Tenorio-Fornés, S. Hassan, and J. Pavón, "Peer-to-peer system design trade-offs: A framework exploring the balance between blockchain and ipfs," *Applied Sciences*, vol. 11, no. 21, p. 10012, 2021

P. Ojanguren-Menendez, A. Tenorio-Fornés, and S. Hassan, "Building real-time collaborative applications with a federated architecture," *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 3, pp. 47–52, 12/2015 2015

Á. Tenorio-Fornés, E. P. Tirador, A. A. Sanchez-Ruiz, and S. Hassan, "Decentralizing science: Towards an interoperable open peer review ecosystem using blockchain," *Information Processing & Management*, vol. 58, no. 6, p. 102724, 2021

Conference articles

A. Tenorio-Fornés and S. Hassan, "Towards an Agent-supported Online Assembly: Prototyping a Collaborative Decision-Making Tool," in *COLLA 2014, The Fourth International Conference on Advanced Collaborative Networks, Systems and Applications*, 2014

A. Tenorio-Fornés, S. Hassan, and J. Pavón, "Open peer-to-peer systems over blockchain and ipfs: An agent oriented framework," in *Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems*,

pp. 19–24, ACM, 2018.

P. Ojanguren-Menendez, A. Tenorio-Fornés, and S. Hassan, "Awakening decentralised real-time collaboration: Re-engineering apache wave into a general-purpose federated and collaborative platform," in *Distributed Computing and Artificial Intelligence, 12th International Conference*, pp. 269–276, Springer, 2015

A. Tenorio-Fornés, V. Jacynycz, D. Llop, A. A. Sánchez-Ruiz, and S. Hassan, "Towards a Decentralized Process for Scientific Publication and Peer Review using Blockchain and IPFS," in *Proceedings of the 52st Hawaii International Conference on System Sciences*, 2019

A. Tenorio-Fornés, V. Jacynycz, D. Llop, A. A. Sánchez-Ruiz, and S. Hassan, "A decentralized publication system for open science using blockchain and ipfs," in *PEERE International Conference on Peer Review*, 2018

Extended Abstracts, posters and other minor peer reviewed contributions

P. Barbrook-Johnson and A. Tenorio-Fornés, "Modelling commons-based peer production: The "commoners framework"," in *Social Simulation Conference 2017 (SSC2017). Dublin, Ireland*, European Social Simulation Association (ESSA), 2017

A. Tenorio-Fornés and E. Pérez Tirador, "The challenges of finding peer reviewers: insights from our product design research," in *Second PEERE International Conference on Peer Review*, (accepted) 2020. Poster.

Chapter 1

Introduction

There is something fascinating about how Wikipedia, Firefox or Linux are produced. Part of the surprise comes from the fact that they are made by large communities of contributors that coordinate thanks to the Internet and without traditional hierarchies to produce goods that they do not charge for (i.e., common goods) [16, 17]. [1]. Thus, one of the first questions that comes to mind is how do they do it? Especially considering their ways of producing and organizing are very different to the traditional forms of organization, e.g., there is a lack of formal hierarchies and command and control chains [18, 16], and often contributions are voluntary and are not paid with salaries. These types of communities, called Commons-Based Peer Production (CBPP) communities, are the main subject of the thesis.

In particular, this work is motivated by the fact that many claim that the introduction of blockchain and other decentralized technologies will revolutionize even further the way these online communities organize. We aim to understand whether these assertions are correct, and bring some light into what could actually mean the use of blockchain technologies for the governance of online communities: *What are the characteristics of blockchain that make it attractive for the governance of CBPP communities? Which specific governance practices could it support? Is blockchain really needed for these purposes?*

Beyond answering these questions, this thesis aims to apply its findings to the development of software prototypes in a specific domain: academic publishing and peer reviewing. In fact, this is one of the fields that the Internet and blockchain could change the most. Despite the popularization of the Internet (that have deeply transformed other publishing industries such as music and video) and besides the efforts of the Open Access movements, many are surprised that the power of the academic publishing industry is increasing and that every year it is even more concentrated in a handful of big publishers. To this day, the prices have not dropped, and the oligopoly of publishers keeps concentrating the benefits and the control over the infrastructure of academic publishing. Thus, this work introduces blockchain-based prototypes and applications that aim to target these challenges.

[1]This passion about CBPP Communities, and the potential of Blockchain for their Governance come in part from the participation in P2PValue and P2P Models European Projects, where most of this work was developed.

1.1 Objectives of the thesis

This section provides a summary of the objectives of this thesis. The work studies a variety of topics, from the participation (Section 1.4) and governance (Section 1.4.2) of CBPP communities (Section 1.3), to how blockchain can support their governance (Section 1.4.2). It also explores the conditions under which blockchain is actually needed (1.6). Finally, it applies the lessons learned to the development of distributed software solutions in the domain of academic publishing and peer reviewing (Section 1.7). The concrete objectives are listed below.

1. *Participation*: Understand and characterize the distribution of participation in CBPP Communities.

2. *Governance*: Identify the potentials of blockchain technologies for the governance of CBPP communities.

3. *Decentralization*: Propose a technological framework for the design of full distributed systems, choosing the appropriate technologies.

4. *Case Study*: Development of a blockchain-based academic publishing and peer reviewing platform.

Thus, the aims of this work are to better understand CBPP communities (Objective 1); if and how blockchain can support their governance (Objective 2); if and when blockchain is actually needed to build these tools (Objective 3); and finally, to apply the lessons learned to build a functional prototype (Objective 4) in order to test and validate the findings of this thesis as well as finding potential limitations and challenges.

1.2 Document structure

This document is divided in two parts. Part I consists of three chapters: Introduction (Chapter 1), Discussion (Chapter 2), and Conclusions and Future Work (Chapter 3). These chapters are organized along the objectives of the thesis, and therefore are divided in sections that focus on participation in CBPP communities, blockchain and the governance of these communities, the framework and analysis of distributed technologies, and the development of the case study on distributed tools for academic publishing and peer reviewing. First, the remaining part of Chapter 1 provides the list of the publications that this thesis compiles. Afterwards, it provides an overview and context of each of the topics of the thesis, states the main related objective and explains the chosen methodological approach. Next, Chapter 2 will offer a presentation and discussion of the results of the thesis and Chapter 3 provides the concluding remarks and future work that conclude this thesis.

Finally, Part II includes the publications compiled in this thesis, in four Chapters (4 to 7) that organize the publications along the four objectives of the thesis. These publications are listed below.

1.2.1 Publications of the thesis

The list of the publications that this thesis compiles, follows these lines, organized in the categories that the four objectives of the thesis define.

Participation in Commons Based Peer Production Communities

Á. Tenorio-Fornés, J. Arroyo, and S. Hassan, "Participation in wiki communities: Reconsidering their statistical characterization," *PeerJ Computer Science*, 2021 (Publication 4.1)

P. Barbrook-Johnson and A. Tenorio-Fornés, "Modelling commons-based peer production: The "commoners framework"," in *Social Simulation Conference 2017 (SSC2017). Dublin, Ireland*, European Social Simulation Association (ESSA), 2017 (Publication 4.2)

Governance of Commons Based Peer Production Communities

D. Rozas, A. Tenorio-Fornés, S. Díaz-Molina, and S. Hassan, "When ostrom meets blockchain: exploring the potentials of blockchain for commons governance," *SAGE Open*, vol. 11, no. 1, p. 21582440211002526, 2021 (Publication 5.1)

D. Rozas, A. Tenorio-Fornés, and S. Hassan, "Analysis of the potentials of blockchain for the governance of global digital commons," *Frontiers in Blockchain*, vol. 4, p. 15, 2021 (Publication 5.2)

P. De Filippi, O. Shimony, and A. Tenorio Fornés, "Reputation. glossary of distributed technologies.," *Internet Policy Review*, vol. 10, no. 2, pp. 1–9, 2021 (Publication 5.3)

A. Tenorio-Fornés and S. Hassan, "Towards an Agent-supported Online Assembly: Prototyping a Collaborative Decision-Making Tool," in *COLLA 2014, The Fourth International Conference on Advanced Collaborative Networks, Systems and Applications*, 2014 (Publication 5.4)

Distributed Technologies

Á. Tenorio-Fornés, S. Hassan, and J. Pavón, "Peer-to-peer system design trade-offs: A framework exploring the balance between blockchain and ipfs," *Applied Sciences*, vol. 11, no. 21, p. 10012, 2021 (Publication 6.1)

A. Tenorio-Fornés, S. Hassan, and J. Pavón, "Open peer-to-peer systems over blockchain and ipfs: An agent oriented framework," in *Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems*, pp. 19–24, ACM, 2018. (Publication 6.2)

P. Ojanguren-Menendez, A. Tenorio-Fornés, and S. Hassan, "Building real-time collaborative applications with a federated architecture," *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 3, pp. 47–52, 12/2015 2015 (Publication 6.3)

P. Ojanguren-Menendez, A. Tenorio-Fornés, and S. Hassan, "Awakening decentralised real-time collaboration: Re-engineering apache wave into a general-purpose federated and collaborative platform," in *Distributed Computing and Artificial Intelligence, 12th International Conference*, pp. 269–276, Springer, 2015 (Publication 6.4)

Case Study: Decentralized Tools for academic publishing and peer reviewing

A. Tenorio-Fornés, V. Jacynycz, D. Llop, A. A. Sánchez-Ruiz, and S. Hassan, "Towards a Decentralized Process for Scientific Publication and Peer Review using Blockchain and IPFS," in *Proceedings of the 52st Hawaii International Conference on System Sciences*, 2019 (Publication 7.1)

Á. Tenorio-Fornés, E. P. Tirador, A. A. Sanchez-Ruiz, and S. Hassan, "Decentralizing science: Towards an interoperable open peer review ecosystem using blockchain," *Information Processing & Management*, vol. 58, no. 6, p. 102724, 2021 (Publication 7.2)

A. Tenorio-Fornés, V. Jacynycz, D. Llop, A. A. Sánchez-Ruiz, and S. Hassan, "A decentralized publication system for open science using blockchain and ipfs," in *PEERE International Conference on Peer Review*, 2018 (Publication 7.3)

A. Tenorio-Fornés and E. Pérez Tirador, "The challenges of finding peer reviewers: insights from our product design research," in *Second PEERE International Conference on Peer Review*, (accepted) 2020. Poster. ((Publication 7.4)

1.3 Commons-Based Peer Production

The popularization of the Internet enabled the emergence of a new type of productive organizations that create value beyond the traditional frameworks of the market and the state. This type of production was first identified by Powell in 1987 [19], and latter characterized and named as Commons-Based Peer Production (CBPP) by Benkler in 2002 [20, 16].

There are multiple examples of this phenomenon in a broad range of areas [21], including well-known projects such as Wikipedia, a project to collaboratively write a free encyclopedia; OpenStreetMap, a project to create free/libre maps; StackExchange, that host many Q&A communities which aim to provide accessible documentation and answers to technical questions; Thingiverse, which provides open 3D-printable digital designs; or Free/Libre and Open Source Software (FLOSS) projects such as the operating system GNU/Linux or the browser Firefox.

In these communities individuals collaborate in a relatively non-hierarchical manner, and contribute their time and energy for free, to produce goods and services that they do not charge for (i.e, commons resources). CBPP communities function without a traditional hierarchical organization [22] and their production practices have been said to be decentralized [23, 24, 25], as there are no central organizing authorities for the management and coordination of contributors, who are instead able to collaborate and self-organize.

It is this decentralized nature of CBPP that inspires our exploration on how blockchain technologies can support their governance practices. The following sections offer an introduction on the participation (Section 1.4) and governance (Section 1.4.2) of these communities.

1.4 Participation in CBPP Communities

Since the emergence of online communities, one of the major topics of interest is to understand the different levels in which members participate: that is, the distribution of participation, also named distribution of work, or effort. Far from classical organizational structures, and more similar to volunteer-driven social movements, communities show an inherent participation inequality across its participants. Specifically in peer production communities, such as those in wikis and free/open source software, this issue has derived multiple research questions: the concentration of participation in an elite [26, 27, 28, 29], the degree of participation inequality [30, 31, 32], the characterization of who participates more [33, 34], the process of changing user roles [35, 36], or the evolution of participation depending on multiple factors [37, 38].

> An important bulk of peer production research tends to say that the distribution of participation follows a power law[2] (Figure 1.1)

Several statistical studies focused on Wikipedia claim that the number of edits per user follow a power law distribution [28, 39], and other studies find similar behavior in free/open source communities [40, 41, 42, 43, 44] or other peer

[2]Formally, a power law is a simple relationship between two variables such that one is proportional to a fixed power of the other.

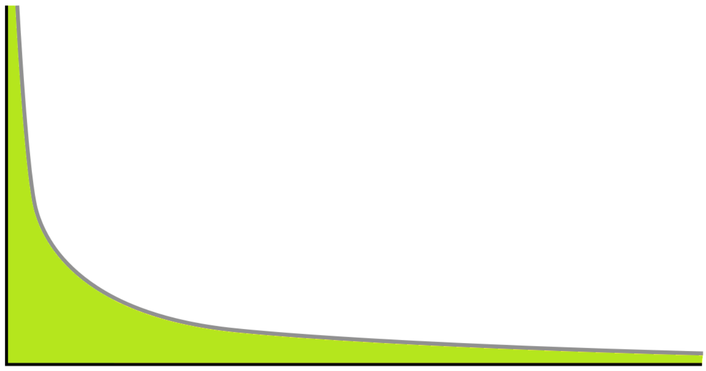

Figure 1.1: Power law distribution. For participation, the X axis represents the number of contributions made by a person and the Y axis the number of persons that made X contributions.

production communities [45, 46].[3]Intuitively, this means a very small number of contributors concentrates most of the participation (or work), highlighting participation inequality.

This thesis studies this distribution of participation in more detail using different methodological approaches, and finds that there are alternative functions to the famous power law that better fit real participation data (Section 2.1, Publications 4.1 and 4.2).

1.4.1 Main Objective

This thesis aims to contribute to the understanding of how people participate in CBPP communities. This knowledge is of great importance to researchers, but also to communities and those that aim to design and develop tools for them.

In particular, it aims to understand the dynamics of participation in CBPP communities and deepen the understanding and characterization of the inequality of participation in these communities. For that, it will develop a model of participation and study the detailed participation data of online communities. The following subsection summarizes these methods.

Following, we define this work's main objective regarding the study of participation in CBPP communities.

Objective 1 *Participation: Understand and characterize the distribution of participation in CBPP Communities*

The next subsection covers the methodological approach followed for this purpose.

1.4.2 Methodological Approach

One of the objectives of this thesis is to better understand and characterize participation in CBPP communities (Objective 1). This research adopts two

[3]Other studies just mention a highly skewed distribution or similar statements without further specification [47, 48, 49].

complimentary methods to study this phenomenon, namely Agent-Based Social Simulation (ABSS) and a quantitative data analysis using state of the art statistical tools to characterize heavy-tailed distributions [50]. Next, Subsection 1.4.2 describes ABSS methods and justifies its use for the study of CBPP communities participation. Then, Subsection 1.4.2 introduces the statistical data analysis performed over the 7000 communities of Fandom[4] that have more than 100 contributors.

Agent Based Social Simulation

Agent-Based Social Simulation (ABSS) is a research methodology that enables the study of complex and non-linear systems using computational models. These systems are often difficult to formalize with traditional methods [51].

The models of ABSS or Agent-Based Model (ABM)s use Software Agents [52] (autonomous, proactive, reactive and social software programs) to simulate the actions and interactions of the modeled system components and individuals in order to model the system and observe the complex and emergent behaviors at a system's level. It has been applied in multiple disciplines, such as anthropology [53], ecology [54] or sociology [55] as well as in topics studied in this thesis such as CBPP communities [56] or FLOSS communities [57].

There are previous efforts to model CBPP (most commonly FLOSS) communities. These have focused on the growth of communities and the competition between different communities for contributors [58], the reproduction of observed patterns in community behavior [59, 60], and the exploration of participation among larger user bases using bounded confidence models [61, 62]. These models are either built for specific communities or, while being general, were not focused in obtaining a structurally valid [63] representation of the contribution in these communities. Regarding specifically FLOSS communities, there are also efforts directed at exploring the micro-level dynamics of collaborative software code development, with emphasis on the development of code through time [64, 65], or on exploring teams' effectiveness [66].

The ABSS work presented in this thesis (Publication 4.2) seeks to model in detail the dynamics of CBPP communities. The model focuses specifically on the internal dynamics of communities (i.e. contributions, entry and exit, and interactions between individuals), to understand how these underpin outcomes at the community level (i.e. 'success' and 'failure' of communities, time-lines of communities, and distributions of contributions).The model specifically aims to replicate the participation dynamics observed in CBPP communities, which hinted at the need to perform a statistical analysis (Section 1.4.2).

Data analysis

Extensive literature suggested that the distribution of participation in CBPP communities should follow a power-law distribution.

However, we observed a more moderate behavior at our models (Publication 4.2), i.e. the most active contributors were not as extremely productive as a power law would predict. That is when we decided to look on the data of real communities, to see what the numbers were telling about such distribution of participation.

[4] `https://www.fandom.com`, Formerly Wikia

The study selected Fandom as its data source, as it was a diverse and large community of wikis. From the over 300,000 wikis of Fandom, we performed a study of the 7,000 communities with more than 100 contributors. To do so, we used the statistical tools presented at [50] to distinguish between different heavy tailed distributions and power laws. That work was key to unveil that phenomenons that were supposed to be characterized by power law distributions, were, in fact, statistically unlikely to follow that distribution. In fact, other heavy tailed distributions such as truncated power law, log-normal or stretched exponential functions better fit their data (Figure 1.2).

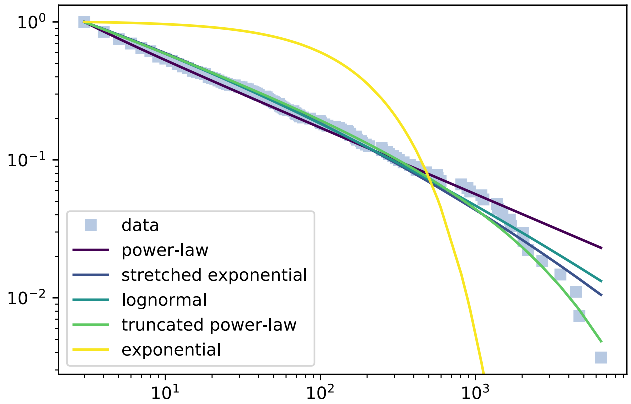

Figure 1.2: Fit of alternative heavy-tailed distribution to a Fandom community's participation data.

Our work applies these statistical tools to participation data of Fandom communities to discover if there are heavy-tailed distributions that better describe the participation in these communities. Concretely, it applies the *Goodness of fit* statistical test in order to assess if a distribution plausibly follows a power law, and then uses a *Likelihood-ratio* test to compare the likelihood of the empirical data fitting two competing distributions. We perform these tests to compare five competing heavy tailed distributions: exponential, stretched exponential, log-normal, power law, and truncated power law (Publication 4.1).

1.5 Blockchain and the Governance of CBPP Communities

Blockchain technology is often associated with currencies, markets, and finance. This is not surprising, as the technology was developed to enable the first decentralized currency [67]. This decentralization enabled for the first time to perform digital payments without intermediaries such as banks. Many saw in this innovation a potential for disruption of the monetary and financial status quo.

However, and thanks to the proposal of new blockchain systems that enable the development of smart contracts, the potential of blockchain disruption goes beyond innovation of economic systems. Governance is one of the applications of blockchain beyond currencies that have attracted more attention. In fact, the appearance of Decentralized Autonomous Organizations (DAOs) (Section 1.6), digital organizations that enable decentralized governance processes to control them, have enabled the development of tools that can facilitate and scale up governance processes at a global scale.

Thus, blockchain technologies have brought innovations to the development of governance tools, enabling for instance decentralized investment and control on the funds of DAOs. This has opened debates on the revolutionary potentials of blockchain technologies to substitute traditional organizations such as firms and even the State [68].

Despite the critics to over-enthusiastic perspectives on how disruptive blockchain technologies could be [69], it is true that they offer new opportunities for digital forms of organization, including the use of cryptocurrencies to exchange value, or the use of smart contracts to establish rules of digital organizations to regulate aspects such as who and how can decide about the expending of their funds.

In fact, there is a growing interest on how blockchain can support the governance of CBPP communities. There are some recent attempts to connect blockchain with the Commons literature, either at a general conceptual level [70, 71, 72] or proposing specific theoretical systems [73, 74, 75]. Furthermore, there are existing blockchain projects which explicitly claim to rely on commons-oriented perspectives in different degrees. Some examples include Commons Stack[5] project, the Backfeed project [74], or the Aragon DAO platform [76] which claims to rely on Benkler's work.

Our study will draw on existing literature on governance of the Commons to study how blockchain can support the governance of CBPP communities. Concretely, we use Ostrom's Principles for the Governance of the Commons as a framework to frame our research (Section 2.2 and Publications 1.5.1 and 5.2). These principles are summarized in the following subsection.

1.5.1 Ostrom's Principles for the Governance of the Commons

The existence of 'the Commons' precede CBPP. Alike CBPP, they also constitute a production mode beyond the market and the state. Thus, and as we have already seen in Section 1.4.2, some have tried to apply the knowledge on the Governance of the Commons to the governance of CBPP communities, and

[5] https://commonsstack.org/

in particular, the set of principles Elinor Ostrom [77] identified for the successful management of the commons. These principles are the result of extensive research on communities managing common resources, such as fisheries or forests, around the globe. It collects the good practices of these communities, that were able to organize, beyond the logic of the market or the state, to sustainability share their resources. Her research proved the famous *tragedy of the commons* [78] to be wrong. Such tragedy "predicted" that common resources such as pastures were condemned to depletion because of an expected pervasive self-interest behavior; however, Ostrom empirically demonstrated how communities can be more efficient than both the Market and the State when self-governed respecting certain governance principles. These principles are summarized below:

1. **Clearly defined community boundaries** in order to define who has rights and privileges within the community. For example, to use certain resources or to perform certain actions on them.

2. **Congruence between rules and local conditions** the rules that govern behavior or commons use in a community should be flexible and based on local conditions that may change over time. These rules should be intimately associated with the commons, rather than relying on a "one-size-fits-all" regulation.

3. **Collective choice arrangements** in order to best accomplish congruence (principle number 2), people who are affected by these rules should be able to participate in their modification, and the costs of alteration should be kept low.

4. **Monitoring** some individuals within the community act as monitors of behavior in accordance with the rules derived from collective choice arrangements, and they should be accountable to the rest of the community.

5. **Graduated sanctions** community members actively monitor and sanction one another when behavior is found to conflict with community rules. Sanctions against members who violate the rules are aligned with the perceived severity of the infraction.

6. **Conflict resolution mechanisms** members of the community should have access to low-cost spaces to resolve conflicts.

7. **Local enforcement of local rules** local jurisdiction to create and enforce rules should be recognized by higher authorities.

8. **Multiple layers of nested enterprises** by forming multiple nested layers of organization, communities can address issues that affect resource management differently at both broader and local levels.

These principles were identified for local communities managing natural commons, however they can apply to digital commons [79, 80, 81] . For instance, regarding the principle of having clearly defined community boundaries, FLOSS projects have clear rules on who can directly perform changes in the code, although, in many cases, everybody can suggest, but not directly perform, changes[6] Similarly, Wikipedia has special contributors that review that all the articles and their edits follow the community rules and guidelines (Principle 4. Monitoring).

1.5.2 Main Objective

Despite the promises many see in blockchain for a more democratic ownership and governance for CBPP communities, there is a need to understand which are the characteristics of blockchain that could facilitate governance, and to which specific governance processes they could apply. This way we can provide a more precise and detailed understanding of what exactly is bringing blockchain to the field of CBPP governance.

In that sense, our study aims to deepen the understanding on how blockchain can support CBPP governance. Concretely, this thesis pursues the following objective, which is the object of this section.

Objective 2 *Governance: Identify the potentials of blockchain technologies for the governance of CBPP communities.*

The following section explains how we performed such analysis.

1.5.3 Methodological Approach

This thesis draws on Ostrom's principles [77] for the successful management of the commons (See Section 1.5.1) for the study of the potentials of blockchain technologies for CBPP communities governance.

It first formalizes what blockchain technologies offer through the identification and conceptualization of six affordances[82] that this technology may provide to communities. These affordances do not determine what communities would do with blockchain, but instead, help us frame and understand the possibilities it opens for CBPP actions (Publication 5.1).

Similar approaches have already been used for the study of the Internet [83], social media [84], and social movements [85], among others.

Then, for each of these identified affordances, it carries out a detailed analysis on their potential relationships with each of the Ostrom's principles, contextualizing blockchain affordances and actual uses of blockchain technologies within CBPP governance practices (Publication 5.1).

Additionally, we perform an analysis on how blockchain technologies could be of use for the governance of global commons. We had already studied how blockchain can support Ostrom's design principles. However, these principles were developed for local communities of smaller scale than those managing global commons. Thus, our study aims to find if blockchain can be useful to overcome some of these limitations of Ostrom's design principles when applied to the governance of larger global commons (Publication 5.2). We draw on the study of these limitations on the transfer of the principles for the management of global commons developed by Stern [86]. These limitations were in fact already identified by Ostrom herself [87], and include considerations such as

[6] Open Development practices such as the "pull request" enable the collaboration of individuals without any prior relation to the project. Usually, this happens in the form of code change suggestions that can be easily accepted and integrated by authorized project members.

the difficulties to scale-up democratic participation and collective choices, the challenges brought by cultural diversity, or the fact that global commons rely on the only planet we have, so there is a smaller chance for experimentation and learning from mistakes.

Our study however focuses on non-rival digital commons such as Wikipedia or FLOSS projects. These global commons are different to rival commons, such as global oil reserves, in the sense that they do not lose value each time somebody uses them. Thus, our work does not apply to social dilemmas concerning these rival global commons, such as those posed by global warming and pandemics. Instead, our study offers a perspective on a narrower portion of global commons: those digital global commons produced by CBPP communities.

The list of limitations of Ostrom's principles for the governance of global commons identified by Stern, that our study considers, is summarized below.

1. The commons studied by Ostrom are bounded at local to regional scale, in contrast to global commons.

2. The number of participants in Ostrom's case studies are in the tens to a few thousands, while in the global commons discussed by Stern, he assumes millions or even billions of actors involved.

3. The third of the differences concerns the degradation of the commons, typical of rival commons. Digital commons, such as FLOSS or digital encyclopedias, are non-rival and, furthermore, sometimes anti-rival [88]. Therefore, we do not include the limitations associated with this property in our analysis.

4. In the type of commons analyzed by Ostrom, the participants share common interests with respect to the management of the resource; while in the global commons discussed by Stern, their collective interests tend to diverge significantly.

5. The participants in the management of commons studied by Ostrom share a common cultural and institutional context; while in the global commons discussed by Stern they come from a wide variety of cultural, political, ideological and economic contexts.

6. Learning from experience is a possible strategy in the local commons studied by Ostrom, while it is unfeasible for the type of global commons analyzed by Stern. We discard this limitation placed by Stern, since the literature shows how large CBPP communities managing global digital commons develop mechanisms and structures to facilitate the learning and extension of communitarian practices (e.g., [89, 90, 91, 92].

Our study provides examples of how blockchain-based projects are overcoming some of these limitations for global commons' governance, as well as proposing potential ways of incorporating of such these solutions in existing practices of peer production communities. Our examples are taken from blockchain-native projects, as there is still a lack of use of blockchain tools by traditional CBPP communities.

Summarizing, the relationships that are found between blockchain affordances and Ostrom's principles will enable us to improve our understanding of the potentialities of blockchain technologies for CBPP governance, indicating which affordance could favor which governance principle (Objective 2). Additionally, we develop an analysis on how blockchain can support the scaling-up of Ostrom principles for the governance of global communities, and opens opportunities of experimentation for the development of blockchain applications for global communities.

1.6 Distributed Technologies

Nowadays, centralized cloud web services represent an increasingly large portion of the Internet [93]. This trend has been significantly accelerated since the emergence of the Web 2.0 model [94], in which web applications enabled user participation and user-generated contents. Thus, today's Internet activity is concentrated on highly successful web services which have dominance over their respective markets [95, 96]. During recent years, there are increasing concerns on the multiple issues this situation arises, with respect to e.g. privacy [97], governance [91, 95], legislation [93], surveillance [98] or security [99]. Consequently, there have been several proposals to tackle some of these issues through new legislation [100, 101] or through recommendations for platform developers [102]. In parallel, these issues have triggered the emergence of a wide range of technical solutions through different forms of decentralization.

1.6.1 Three Waves of Decentralized Technologies

We may divide the proposed decentralized solutions in three waves. The first wave has been through "federated" technology [103, 104, 105], i.e. multiple central nodes communicating with each other, where users are free to choose the node to interact with. E-mail is a classic example of an open protocol which is federated, together with more recent XMPP for chatting [106], OStatus for microblogging [107], ActivityPub for social networking [108], OAuth for authentication [109], or SwellRT for real-time collaboration [7]. This approach is based on interoperability across services and servers [103, 110, 111]. However, many of these technologies are still hindered by several drawbacks, such as the existence of points of failure [112] and control [113], or the lack of interoperability of the data beyond a few applications [111, 105].

The second wave of decentralized solutions has been achieved through fully distributed technology, i.e. P2P networks without classical servers but instead ordinary computers (different from classical cluster/grid parallel computing). There have been multiple attempts to offer P2P web services [114, 115], such as Freenet for censorship-resistant communication [116], although broad adoption was mostly limited to the field of file-sharing, e.g. eDonkey, BitTorrent [117].

The third wave appears when some unresolved technical challenges with P2P solutions [118, 119] became more evident. This opened the door to a new generation of solutions, most of them relying on cryptographic hashes organized in Merkle trees [120]. The advent of the first fully decentralized digital currency, Bitcoin [67], triggered a plethora of decentralized solutions based on its underlying technology, the Blockchain. In addition, another groundbreaking technology emerged around P2P storage: IPFS, or Inter-Planetary File System [121]. These two new decentralized technologies, often combined, enable a wide range of applications [122, 123, 124, 125, 126]. Furthermore, Conflict-free Replicated Data Types (CRDT) [127] technology enabled real-time collaboration for P2P systems.

Below we introduce some of the most relevant of these technologies, which are used in several chapters of the thesis.

IPFS [121] is a peer-to-peer hypermedia protocol that enables the distribution of files using a decentralized network. Files are divided in blocks that are indexed using cryptographic hashes [120]. These blocks are then distributed (and possibly replicated) among the network nodes. When a file needs to be retrieved, its blocks can be downloaded simultaneously from different peers. Note that new participants can add new nodes to the network and replicate the content they are interested in.

Blockchain is the underlying technology that supports Bitcoin [67], the first fully distributed digital currency. Monetary transactions are collected in blocks that are accepted or rejected by the peer network using a consensus mechanism in which at least half of the network needs to agree. Each new block is then linked to the previous one creating an immutable chain of blocks (blockchain) or public ledger that contains all the performed transactions. It is interesting to mention that each node of the network stores a full copy of the blockchain so that it can autonomously accept or reject future transactions. The order in which transactions are recorded in the public ledger is decided by the node (miner) that produces the next valid block. In order to produce new blocks, the nodes compete against each other to solve a computationally expensive problem. This computational effort is rewarded by the protocol with economic incentives (new bitcoins) to maintain the security of the ledger.

Ethereum [128] extends the blockchain technology to enable to execution of small programs or *smart contracts* creating the first blockchain-based distributed computing platform. These smart contracts are stored in the blockchain (so they are immutable) and are triggered using transactions that specifies which part of the program must be executed and with which paramenters. Similarly to the Bitcoin blockchain, in which all the nodes validate the bitcoin transactions, in Ethereum all the nodes execute the same smart contracts to reach a consensus regarding the changes they produce in the public ledger that defines the state of the network. Each smart contract, therefore, defines a set of rules based on its code and once they are deployed they can be executed autonomously. In summary, smart contracts are interesting because they allow the transparent execution of immutable programs in a trustless network. Some examples of Ethereum-based decentralized applications are prediction markets [129] or social networks [130].

Decentralized Autonomous Organization [131] A DAO is a blockchain-based system that mimic traditional organizations in the sense that they can own digital assets or have specific governance rules among others. These organizations facilitate the coordination and governance of people through a set self-executing rules deployed as Smart Contracts on a public blockchain. This may be understood as analogous to a legal organisation, with legal documents that define the rules of interaction among members. Similarly, the DAO members' interactions are mediated by the rules embedded in the DAO code. And such rules are automatically enforced by the underlying technology, the blockchain, instead of traditional laws and tribunals [132].

1.6.2 Fully Distributed Peer to Peer systems

> Fully distributed Peer to Peer systems are composed by a network of interconnected nodes that communicate and coordinate their actions without a central control entity.

Systems such as the Web and P2P File sharing programs are distributed systems composed by web servers, and computers sharing files, respectively [133, 134]. While centralized systems depend on a single component for their operation, distributed systems are resilient to the disconnection of some of their components, e.g., if a web server is disconnected, the Web will still be a functional system. However, some distributed systems still depend on single components for parts of the system to work. For instance, if a web server disconnects, their web pages will become unavailable. This work refers to *fully distributed systems* when referring to distributed systems that are independent of any single node.

1.6.3 Main Objective

This thesis aims to deepen the understanding of the potentials of new fully distributed systems and technologies such as IPFS and Blockchain. As with many new technologies, there is a hype on these technologies, and many predict these technologies will be key to solve hard problems, and find in them promises to change everything.

Our goal is understanding what are blockchains actually offering when compared with alternative distributed technologies. This way, designers of fully decentralized systems would be able to decide if blockchain is the technology they need or if there are alternatives. Thus, this thesis formally studies what these technologies provide, and aim to support designers when facing questions such as *do we really need a blockchain for this?*. Therefore, we define the objective of the thesis regarding the decentralization technologies, that this section introduces, as follows.

Objective 3 *Decentralization: Propose a Technological Framework for the design of decentralized systems, choosing the appropriate technologies.*

Following, we provide the theoretical framework and approach taken to tackle this issue.

1.6.4 Methodological Approach

One of the main challenges of distributed systems is maintaining a consistent state without needing to trust a specific node to resolve conflicts or coordinate the system. For instance, if in a decentralized currency system, an actor simultaneously tries to send the same digital coin to different people, who is the legitimate owner of the coin?. With centralized control, the answer is easy, or at least it only depends on the decision of a single trusted actor. However, in decentralized systems, no single node has authority over the others, and the whole system could have troubles deciding and coordinating the agreement on a consistent state where all agree on the current owner of the coin. Indeed, blockchain technology was a solution for a specific problem of this nature, the design of a decentralized currency system, that has very strong consistency requirements: users should know who owned money in the system, and that each transaction followed the rules. However, not all distributed open systems have such strong consistency requirements. Understanding the tensions between consistency, availability and partition resistance is key for the design of these systems (Table 1.1) [1]. This work aims to identify the different strategies decentralized systems can adopt in order to achieve consistency, and to decide whether blockchain technologies are actually needed.

Fortunately, existing literature has extensively studied the issue of consistency in decentralized systems. This section builds upon some of the most relevant literature on consistency of distributed systems, and provides a set of four guidelines to design distributed open systems based on them.Thus, to study when a blockchain is in fact needed and when it is not, we draw on three of the key findings and concepts that describe the limitations and trade-offs of distributed technologies. Namely:

Consistency, Availability, Partition resistance (CAP) Theorem Proves that no decentralized system can offer strong consistency, availability and partition resistance simultaneously (Table 1.1).

Consistency As Logical Monotonicity (CALM) Principle Establishes the conditions upon a decentralized system can remain consistent even when facing low availability or strong network partitions [135].

Eventual consistency Is defined as consistency among the nodes of a distributed system once all the messages have been delivered, and can be provided with technologies such as CRDTs [127].

***C*onsistency**	The requests of the distributed system behaves as if handled by a single node with updated information.
***A*vailability**	Every request should be responded.
***P*artition resistance**	the system is able to operate in presence of network partitions.

Table 1.1: Consistency, Availability and Partition resistance definitions of the CAP Theorem [1].

Thus, our work builds on these principles of distributed technologies to propose a technological framework for the design of fully distributed systems, providing tools for designers to decide whether blockchain technologies are needed, and proposing the use of an alternative stack of distributed technologies for those problems that does not require it (Publications 6.2 and 6.1). Section 2.3 provides a deeper look and discussion on these results.

1.7 Academic Publishing and Peer Reviewing

In the last decades, the Internet has revolutionized multiple fields. However, the production of science and its peer review process have not seen large changes with respect to the traditional paper-based publication and review practices [136]. The communication of knowledge still relies on academic articles, that journals collect and publish with certain periodicity for the consumption of scholars in academic institutions. The criticisms to nowadays scientific publication and peer review processes include concerns with respect to quality [137], fairness [138], cost [139, 140], performance [141], and evaluation metrics accuracy [142].

Still, the advent of the Internet brought some changes to the scientific process. Its reduction of distribution costs allowed for broader access to scientific knowledge, and thus further questioning the role of traditional publishers which previously assumed the distribution effort [143]. Thus, alternatives emerged, especially with respect to Science dissemination, i.e. Open Access [144]. The Open Access movement, leveraging the replicability of digital content, aims to provide free access to the published research articles. And even though it is far from universal, it is generally recognized that the Open Access movement has achieved to decrease the economic cost for readers to access knowledge [145].

However, despite its partial success, its potential to democratize access to knowledge has been questioned [146], since it has not successfully challenged traditional publishers' business models [147] which are often charging both readers and authors [148].

With respect to the traditional peer review system, despite the multiple criticisms received mentioned above, only few alternatives have gathered success [149, 150]. The literature provides multiple proposals around "open" peer review [151], which would enable transparent and public reviews, versus the traditional blind and private reviews [152]. In fact, relying on such open peer review models, we can find some proposals of reputation networks for reviewers [153], which may provide new quality control processes for the reviewers, authors and editors. It is worth noting that the start-up Publons[7], provides a platform to acknowledge reviews and open them up. The project reached quickly a large reviewer community, and it was recently absorbed by Clarivate Analytics publishing conglomerate.

In the last decades, other initiatives that challenge the traditional science publication process have emerged. *Preprints* are versions of scientific articles which have undertaken formal peer review, and have not been published formally in a journal or conference proceedings. Today, there are multiple widely successful platforms to host preprints and provide them visibility, like arXiv[8] or Preprints.org[9] [154].

Besides, social networks crafted for the scientific community have also found their niche. These enable scientists to upload their authored published articles, sharing them with fellow scientists whom they can connect. Example successful platforms include Academia[10] or Research Gate[11].

These platforms are all centralized, that is, relying on a single platform owner

[7]https://publons.com/
[8]https://arxiv.org/
[9]https://www.preprints.org/
[10]https://www.academia.edu/
[11]http://researchgate.com/

which controls the infrastructure. Such centralization has multiple consequences [155, 156, 133] for example, problems related to monopolistic business models which affect users and their data; the need to depend on and trust a third-party which may change its policies anytime (e.g. in case of a change of business model, or a buy-in); market dominance over derived services such as metrics (e.g. JCR Impact Factor) or databases (e.g. Scopus); paywalls and the derived need of subscription packages for research institutions; and overall, issues related with the lesser control of researcher community over their data and processes.

Decentralized alternatives potentially improve a wide variety of science publication and peer reviewing issues [157, 158]. Proposals use different blockchain affordances [159] to improve science publication. The transparency and immutability of blockchains is used to assert the time of existence and authorship of data and documents [160]. *Crypto-tokens*, i.e. transferable electronic representations of value (such as currency or permissions), are used to incentive collaboration [161], management of data access permissions [162], reproducibility of studies [163], or peer reviewing [164, 165] and other ways of endorsement of publications [166], as well as to propose new methods of funding research [167]. The openness and transparency of blockchains is used to enhance Open Access [168], Open Science practices [169], and transparency in publishing and funding processes [170]. Finally, smart contracts, i.e. software that is automatically executed in a decentralized blockchain network, are used to provide automatic processes for science publication [171, 161], or reproducibility of studies and experiments [172].

1.7.1 Main Objective

This thesis chooses academic publishing as the field to focus on during the development of our case study (Objective 4). Having witnessed first-hand the problems of academic publishing and the increasing power of a handful of publishers, this decision was taken considering the opportunities that distributed technologies offer to disrupt concentration of power.

Intuitively, distributed technologies such as IPFS and Blockchain can support an open access infrastructure to access and distribute academic articles, and can bring transparency[12] to the peer reviewing processes in order to improve their quality, speed and fairness. Additionally, blockchain technologies might enable the implementation of reputation mechanisms which improve the quality of the peer reviewing processes [5](Publication 5.3).

This thesis assumes the development of such tools as a way to test and study the potentials of blockchain technology, but also as an independent goal to build tools that support the efforts of the Open Access movement and Open Peer reviewing. Thus, we define the objective of this thesis that this section is introducing as follows.

Objective 4 *Case Study: Development of a Blockchain-Based academic publishing and peer reviewing platform.*

[12] A blockchain is a transparent open ledger where everybody can see the full history of transactions

1.7.2 Methodological Approach

The development of a blockchain-based prototype (Objective 4) as a case study will bring together the lessons learned in the thesis. On the one hand, it will incorporate the results of the studies on participation in CBPP communities (Objective 1) and on the potentials of blockchain technologies for CBPP communities (Objective 2). On the other hand, it will serve as a real software development project where to apply the guidelines and lessons of the developed framework of distributed technologies (Objective 3).

Our goal is therefore to use distributed technologies such as blockchain and IPFS to improve academic publishing and peer reviewing.

We foresee that IPFS, as a decentralized file system, offers great opportunities to build a decentralized network to distribute academic documents, such as papers and review reports, to make them accessible for all, and gain independence from the big publisher's infrastructure that now provides such content, even if it is Open Access.

Additionally, blockchain technologies offer us the opportunity to bring transparency and reputation to peer reviewing, an opportunity we believe can improve the quality, fairness and speed of peer reviewing.

In order to develop such system we need to follow different steps, from proving the interest of our ideas and solutions to the eyes of our target audience, or testing the appropriateness of the chosen technologies, to the development of a useful and functional product that realize our vision of a better peer reviewing. Thus, we detail these steps.

The first step for the development of the case study is the validation of the interest in the proposal. Lean Startup methodology [173] proposes to validate in these early phases of product development two things: 1) That the problem is relevant for your potential audience, and 2) that the proposed solution is attractive to your audience to satisfy their needs. For this, we will use methods such as surveys, problem and solution interviews [173] and iterative testing of the value proposition through mock-ups and software prototypes.

Then, developing a technological proof of concept serves to prove the adequacy of our technological choices (blockchain and IPFS) for the development of the desired decentralized peer review system. Technological proof of concepts are experiments that aim to assess if a technology is appropriate to implement a specific solution. They consist in the implementation of a system with similar functionalities to the desired solution, but simplifying and abstracting the parts that are not relevant for the experiment. In our case, we want to test if a combination of blockchain and IPFS technologies will enable us to have a simple peer reviewing system, supporting its basic interactions. Thus, the goal of the technological proof of concept is to test that these technologies would support such interactions, leaving out of scope the proposal of a usable interface or a product that was attractive to our potential users.

Finally, this thesis aims to develop a functional Minimum Viable Product (MVP) of a blockchain based peer reviewing platform. For that, we follow the methods and principles of Lean Startup methodology [173], which assist us in the design and validation of our product, involving in the processes our target audience (peer reviewers and journal editors), using tools such as the design and validation of Mock-ups (see Figure 1.3).

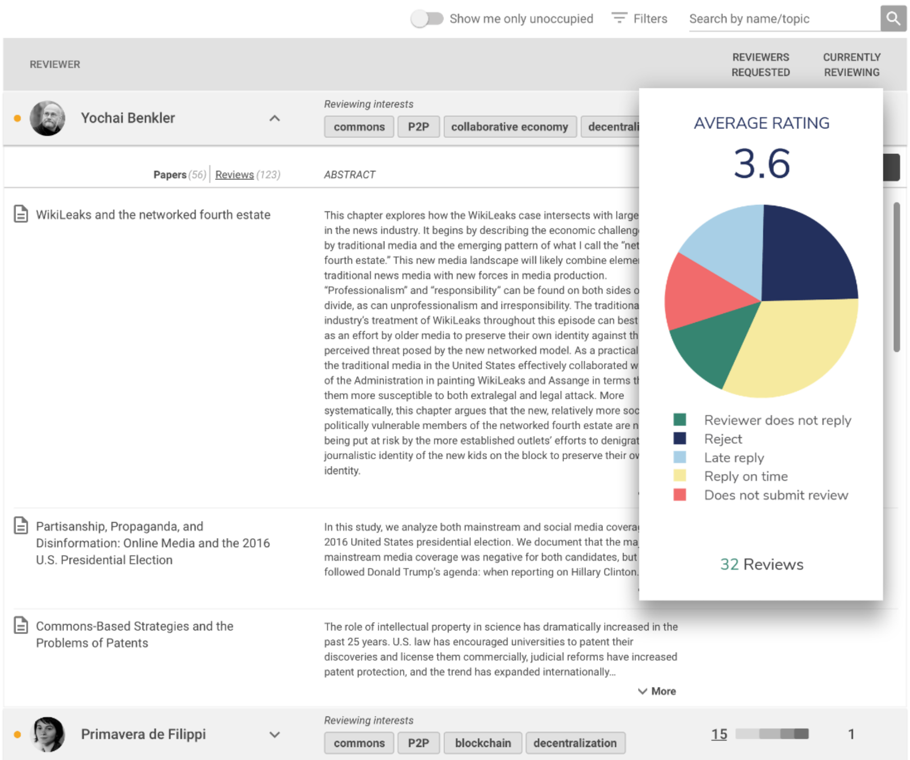

Figure 1.3: Detail of the first version of the prototype Mock-up.

Chapter 2

Discussion

This chapter discusses the main results of the thesis. It is divided in four sections, that correspond to the 4 objectives of the thesis (Section 1.1). Section 2.1 offers a discussion of the results of our studies of participation in CBPP communities. Then, Section 2.2 focuses on our findings on governance of these communities and how blockchain might support it. Next, Section 2.3 offers a perspective on this work's findings on its analysis of distributed technologies. Next, Section 2.4 discusses the results on the development of our case study, the development of a blockchain-based platform for academic publishing and peer reviewing.

2.1 Participation in CBPP Communities

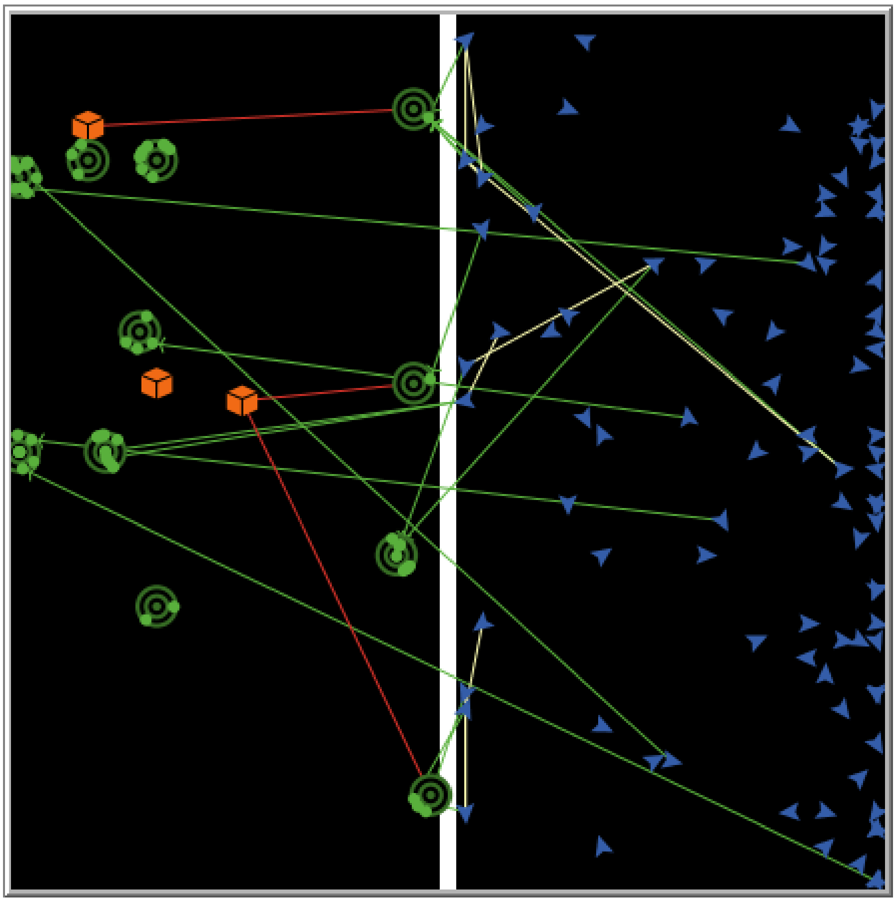

Figure 2.1: 'Commoners' ABM model.

In our studies, which consist of an Agent-Based Model (ABM) aimed to study the dynamics of participation in CBPP communities, and a comprehensive data analysis of 7,000 wiki communities of Fandom we find that the distribution of participation of these communities, deviates from the expected power law that many studies describe (Section 1.4). Thus, one of the main contributions of this work regarding participation in CBPP communities is the challenging of this famous power law characterization of the distribution of work in these communities. Moreover, we find a better candidate distribution to characterize the participation inequalities. Our statistical study compares the performance of different heavy tailed distributions in the fitting of real participation data. There, we not only find that the power law is statistically not a good candidate to represent the data, but also find that there is an alternative heavy-tailed distribution, the truncated power law, that actually fits the participation data better (and also performs significantly better than the other competing heavy tailed distributions).

Initially, this finding was suggested by our ABM on CBPP participation

(Figure 2.1, Publication 2.1). This model was designed and developed to simulate the behavior of individuals when contributing to CBPP communities. As in other ABM models, we defined how the individual elements of the model, such as the contributors, behave. Then, we observed the behavior of the model at its systemic level (e.g. how participation grew or declined, how was the inequality in participation, how productive the community was, etc.). If the model was correct, we should have been able to observe the predicted power law in the data, even if that property was not directly programmed in the system. This is one of the goals of ABM, to observe an expected emergent behavior at the general system's level from a model that only specifies how the individual parts of the system behave.

Although we were able to obtain something similar to a power law distribution in the participation of our model, we were not quite finding it in our results. Of course, that could mean that our model was not accurately capturing the behavior of CBPP communities and their contributors. However, we decided to have a look into the data of real communities to explore these insights of our model. Perhaps, what we were observing in the model was not as different to what we would observe in real communities' data.

Thus, after our explorations with the ABM of participation in CBPP communities, we performed a data analysis of actual participation data in communities. Concretely, we performed a study on a large data-set, the participation data of all the Fandom wiki communities with more than 100 contributors, and found that indeed, there is strong statistical evidence supporting that a truncated power law is the distribution that fits the data[1] (Publication 4.1).

However, and despite the diversity of Fandom communities (with topics as diverse as famous movies or pets), this finding does not let us generalize to other types of CBPP communities, and therefore, such generalization is left as future work.

Our study, however, allow us to suggest researchers of communities to perform rigorous statistical analysis of the participation data of their communities before claiming or assuming it follows a power law distribution.

The implications of these findings might seem of small interest to those who want to provide a rough understanding of the inequality of participation in CBPP communities. After all, any heavy-tailed distribution would give an approximate description of the strong inequalities observed between the few most active contributors and the many occasional contributors of online communities.

However, knowing that a truncated power-law is the most accurate representation could be of great interest for things such as 1) not to expect super-human behavior from members of your communities, 2) design tools and incentives that reflect the actual work (and not an idealization of it), or, indeed, 3) accurately measure participation data in communities and how it evolves over time.

Researchers of online communities are thus invited to use these statistical tools to study distribution of participation in their communities. This will provide them with more accurate tools to measure participation, and help them avoid mistakes they could make if they use non-accurate approximations and ideal models that do not fit the real participation behavior.

[1]Being the best or at least as good as any of the considered alternative heavy-tailed distributions in 97.35% of the 7,000 studied wikis.

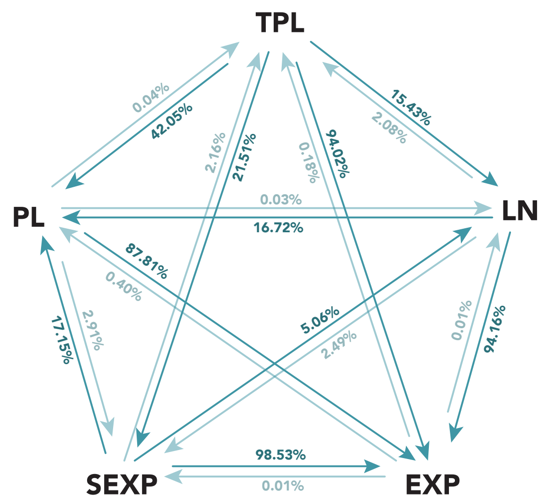

Figure 2.2: Results of the likelihood-ratio test between the five considered distributions for registered contributors. The distributions considered are: power law (PL), truncated power law (TPL), log-normal (LN), exponential (EXP) and stretched exponential (SEXP). Each arrow from A to B has the percentage of cases in which A was superior to B. The figure shows in a darker color the arrow with the higher percentage for each pair of distributions.

2.2 Governance of CBPP Communities

Participation is just one of the many important factors in CBPP governance. Our study considers the 8 famous principles for successful governance of the commons by Elinor Ostrom [77] (Section 1.5.1). The goal is to understand and systematize what many are saying; that blockchain offers valuable opportunities for the development of innovative governance tools for online communities.

Thus, our work first identified six affordances of blockchain technologies (Section 1.5.3), and then proposes relationships between these affordances and specific governance principles (Publication 5.1). For instance; it finds that tokenization can help communities to better define who is part of the community, and thus who has decision rights and power. (Figure 2.3 summarizes these relationships between Blockchain affordances and Ostrom's governance principles). In fact, these affordances and their relationships to governance principles have already been employed as analytical categories that assisted the co-design of these types of tools [73, 174]. Next, we offer the list of identified blockchain affordances.

Tokenization refers to the process of transforming the rights to perform an action on an asset into a transferable data element, a token, on the blockchain.

Self-enforcement and formalization of rules refer to the process of embedding organizational rules in the form of smart contracts.

Autonomous automatization refers to the process of defining complex sets of smart contracts as DAOs, which may enable multiple parties to interact with each other, even without human interaction. This is partially analogous to software communicating with other software today, but in a decentralized manner, and with higher degrees of software autonomy.

Decentralization of power over the infrastructure refers to the process of communalizing the ownership and control of the technological tools employed by the community through the decentralization of the infrastructure they rely on, such as the collaboration platforms (and their servers) employed for coordination.

Increasing transparency refers to the process of opening the organizational processes and the associated data by relying on the persistence and immutability properties of blockchain technologies.

Codification of trust refers to the process of codifying a certain degree of trust into systems which facilitate agreements between agents without requiring a third party, such as the federal agreements which might be established among different groups that form part of such communities.

To justify the use of Ostrom principles for our analysis we needed to show that these principles could apply to the studied communities. In fact, there are critics that point out that Ostrom's principles were identified for local communities, and that therefore they are not directly applicable to larger global commons [86].

Our study however focuses in non-rival commons such as Wikipedia, that does not lose value each time somebody uses them. Therefore, our work does

	Tokens	Self-enforce	Auton.Automat.	Dec. Power Infrastructure	Transp.	Trust
1. Boundaries	✓					
2. Local rules	✓			✓		
3. Participatory	✓			✓		
4. Monitoring		✓	✓	✓	✓	
5. Sanctions		✓	✓			
6. Conflict resol.			✓		✓	
7. Recognition		✓		✓		✓
8. Multiple layers			✓			✓

Figure 2.3: Summary of the relationships between the identified affordances of blockchain technologies for governance and Ostrom's principles.

not apply to social dilemmas concerning rival global commons, such as those posed by global warming and pandemics.

Another of our works (Publication 5.2) studies how blockchain cal help overcome the limitations of Ostrom's principles for the governance of global commons. It draws on the limitations of Ostrom's principles for the governance of global commons identified by Stern [86] and proposes that some of the blockchain affordances that we identified in our work [3] could help to face them.

Concretely, the contributions of the study are focused on global non-rival commons, such as those often managed by CBPP communities.

First, for each of the Ostrom's design governance principles (Section 1.5.1), we find which of the limitations of the principles for the governance of global commons that Stern identified apply (Section 1.5.3). Then, drawing on the identified blockchain affordances that our previous work identified, we propose which of these affordances could serve to overcome those limitations. Finally, we provide examples of actual blockchain projects and tools that illustrate our proposal.

As an example of this analysis, we summarize the findings regarding the fifth Ostrom's principle (Graduated Sanctions). One of the direct limitations of global commons to implement sanctions is the lack of clarity on who should be the authority that would apply the sanction. In fact, several jurisdictions would apply to different people when considering global scale commons, and some might recognize authorities that others do not.Our study suggest that the affordances of blockchain technologies that facilitate the *Self-enforcement and formalization of rules* (Affordance 2) and *Autonomous Automatization* (Affordance 3) could facilitate the implementation and scaling up of community's graduated sanctions. As an example of how blockchain technologies are actually facilitating this, we introduce how Kleros and Aragon [175] are implementing blockchain based courts to address community conflicts, with behaviors as complex and interesting as nested layers of courts that scale up to a "supreme court" or mechanisms to sanction jury members to the extreme of expel them from the system.

These types of considerations are developed for all Ostrom principles and concerns on their applicability to global scale commons.

Summarizing, our results show that, when considering the challenges of managing global commons (e.g. heterogeneity or scale), the potential of blockchain is particularly valuable to explore solutions that: distribute power, facilitate coordination, scale up governance, visibilise traditionally invisible work, monitor and track compliance with rules, define collective agreements, and enable cooperation across communities

2.3 Distributed Technologies Framework

One of the objectives of the thesis was the proposal of a technological framework for the design of decentralized systems choosing the appropriate technologies (Objective 3). After all, our study on how blockchain could help in the governance of CBPP communities identified that, indeed, affordances of blockchain technologies were attractive for concrete governance principles. However, blockchain is not yet a mature technology, and it presents important limitations such as cost, scalability, lack of usability, and a high complexity that constitute a great entry barrier for the average user. That is why the consideration of alternative decentralized technologies is of interest.

Our work (Publication 6.1) provides a set of guidelines for the design of fully distributed applications that help designers assess if blockchain technologies are needed, or if instead, other distributed technologies might suffice. These guidelines, listed below and summarized in Table 2.1, advise the designer about the appropriate technologies depending on their consistency requirements (e.g., they would need a strongly consistent system if they want to design a decentralized currency) and their availability requirements (e.g., for a collaborative writing application, waiting too long for other users changes to appear can create plenty of issues, while other applications such as online voting could be less sensitive to delays).

Guideline 1 *Monotonic[2] queries can be consistently resolved in open distributed systems without coordination technologies.*

Guideline 2 *Consistency requirements are a design decision. If inconsistent behavior is acceptable for the non-monotonic queries of the system, coordination technologies are not required for open distributed systems.*

Guideline 3 *Eventual consistency can be achieved without coordination in open distributed systems by ensuring that concurrent operations are commutative.*

Guideline 4 *The non-monotonic queries of an open distributed system with strong consistency requirements should be supported by a coordination technology such as Blockchain.*

	Weak consistency	**Eventual consistency**	**Strong consistency**
Weak availability	No need for coordination technologies (Guideline 2)		Logical Monotonicity or Blockchain (Guidelines 1, 4)
Strong availability		CRDTs (Guideline 3)	*Not possible, considering CAP Theorem*

Table 2.1: Summary of the guidelines for the design of distributed systems

[2] A system is considered as *logically monotonic* if the truth of a given statement cannot change by considering new information. In such systems, the responses to distributed queries are consistent.

Arguably, the guidelines use highly technical concepts such as 'Logical monotonicity'. However, these concepts are key to formally determine when using blockchain is the only available option, or if other coordination technologies such as CRDTs might be sufficient.

Additionally, we propose a framework to develop fully decentralized systems without using blockchain (Publication 6.2). This framework answers 1) how to provide and access data in such systems (using IPFS), 2) how to trust the data we receive (using cryptographic identities and agreed rules for how to update and modify data) and 3) how this data could be discovered and shared (proposing a system of distributed queries for data that satisfies certain conditions.)

In theory, such framework could enable the development of fully decentralized systems that provide similar functionality than blockchain (maintaining a consistent state in a distributed system). We presented as a case study applying this framework on how an hypothetical fully decentralized Questions and Answers (Q&A) system similar to Stack Exchange[3] could be built. In that case study, we show how the questions, answers and votes of the Q&A system do not have such strong consistency requirements (unlike, for instance, the maintenance of a digital currency), we conclude that blockchain is not a needed technology, and that the use of alternative distributed technologies that would result in an eventual consistency such as CRDTs might suffice.

Despite these theoretical findings and framework proposal, the development of our case study showed us how blockchain can in fact be helpful even when it is not strictly needed. Specially because there is not a functional implementation of the protocol we propose to use for data discovery in these alternative systems.

[3]https://stackexchange.com

2.4 Case study: decentralized tools for academic publication and peer review

This thesis includes several publications of the case study we developed to apply blockchain technologies to the academic publishing and peer reviewing world. Our contributions include publications that 1) validate the importance of the problems we targeted for our target community (Publications 7.3 and 7.1) 2) verify that the proposed solution was perceived as attractive to solve those problems (Publication 7.1), that 3) test the adequacy of blockchain and IPFS technologies for the development of the solution (Publication 7.1), and finally, that 4) present the co-design and development of a fully functional MVP of a decentralized peer reviewing platform which integrates with some of the most relevant applications of the current technological ecosystem of academic publishing and peer reviewing (Publications 7.4 and 7.2).

Our final product, named Decentralized Science [4], is an interoperable platform based on decentralized technologies that aims to enhance the transparency and accountability of the peer review and publication processes. n particular, we propose to decentralize 3 key components of the publication and peer reviewing processes and their infrastructure:

- The selection and recognition of the peer reviewers using a transparent reputation model
- The distribution of the academic papers through the IPFS peer to peer file system
- The transparency of the whole peer reviewing process, from submission to publication, using blockchain technologies.

One of the relevant contributions is the introduction of reputation and quality metrics for peer reviewers. Our proposal does not only aims to increase the transparency of peer reviewing by openly sharing the peer review reports (Open Peer reviewing [151]), but also offers additional metrics that aggregate and summarizes the behavior of peer reviewers, providing information such as what is their acceptance ratio (see figure 2.4), or how often they reply on time (or how often they don't).

2.4.1 Minimum Viable Product

This functional prototype was designed with participatory methodologies (Lean Design and User-Centered Design), in close collaboration with journal editors [176]. Thus, it is designed to respond to their needs. The principal value proposition [177] for these journal editors is 1) a tool to find reviewers that 2) provides relevant metrics about them such as their timeliness or acceptance ratio, and 3) offers direct access to the open peer reviews of these reviewers. Figure 2.5 shows a detail of the Graphic User Interface (GUI). The interface allows journal editors to find relevant reviewers in the system.

[4] https://decentralized.science

Figure 2.4: GUI Detail: Information about a reviewer's acceptance ratio.

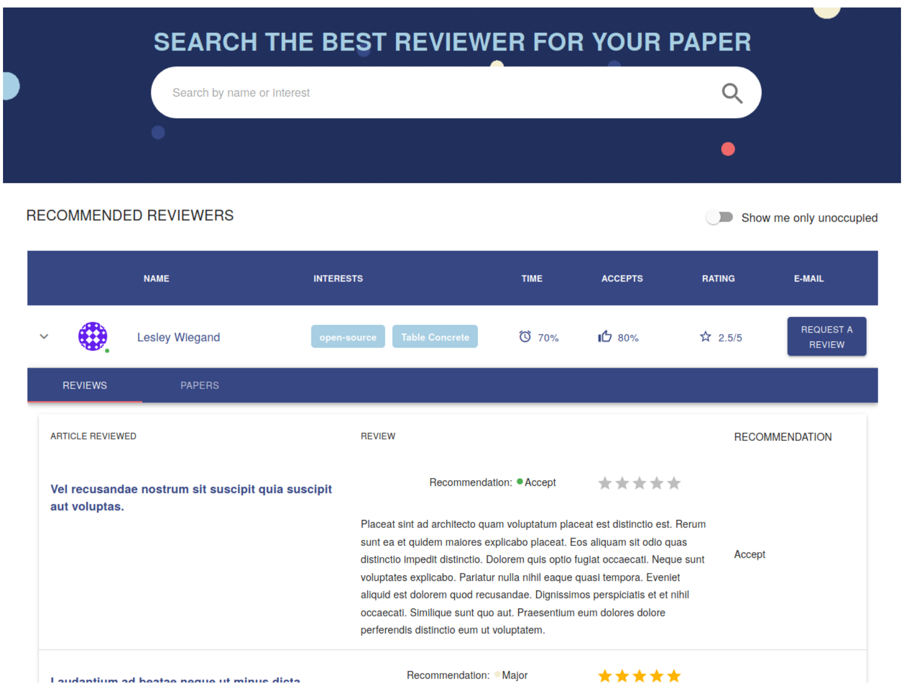

Figure 2.5: Decentralized Science Reviewer search GUI

2.4.2 Interoperability

Our MVP is integrated with the well-known publication management software Open Journal Systems (OJS)[5], enabling journal editors to see the journal's reviewers, and to request a review using their peer review management system. The GUI offers additional functionalities for the selection of peer reviewers currently unavailable at OJS GUI [15]. Concretely, it provides information about reviewers such as the acceptance ratio, the reputation, or the timelines, and facilitates access to their previous review reports.

However, this prototype does not just rely on centralized legacy software, but combines both centralized and decentralized technologies. In particular, (1) it uses Ethereum smart contracts to provide a decentralized management of the logic and state of the system, and (2) uses IPFS to store in a decentralized network larger files such as academic papers or the content of peer review reports. This way, using decentralized technologies we aim to promote the transparency of the peer reviewing process and provide an open access by design infrastructure for such information. Furthermore, maximizing interoperability and decentralization, we enable the participation of other third parties and prevent the enclosure of the information in data silos or walled gardens [133].

The implemented application interacts with these decentralized technologies to store, update and retrieve the needed information about the peer reviews managed by the system. Such implementation accesses both the existing centralized and private information of journals, and the publicly shared and decentralized information our system promotes (see Figure 2.6). Thus, the software provides a web search interface that access both centralized and decentralized data, abstracting the technological differences for a better user experience.Figure 2.6 also shows how a shared blockchain interface would enable the interoperability of several decentralized applications.

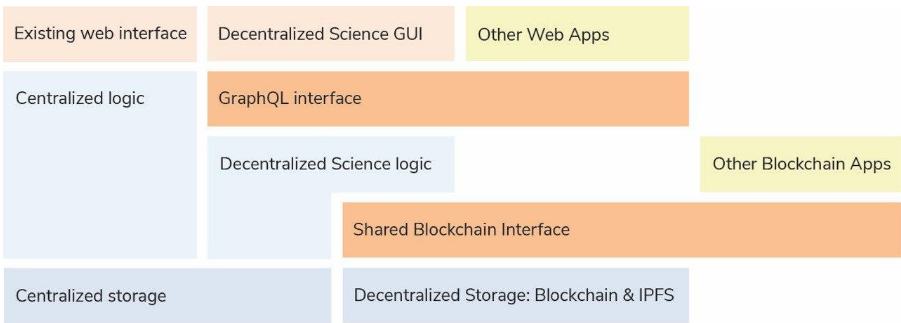

Figure 2.6: Decentralized Science hybrid Architecture.

In fact, there areseveral active blockchain projects and research that aim to share peer review information to improve recognition of reviewers' curriculum (e.g. Bloxberg's[6] [178] peer-review-app [179]), provide incentives for peer reviewers (e.g. Eureka [180]), or enable post publication peer review (e.g. Orvium [181]), among others [182]. Several of these projects are collaborating in the definition of a standard for the registration of Peer Review information [183] in Bloxberg's

[5]http://pkp.sfu.ca/ojs
[6]https://bloxberg.org

infrastructure. Bloxberg is an Ethereum-based blockchain which provides infrastructure for scientific research. This standard (named BLIP-3[7]) aims to generalize the initial implementation of Bloxgerg's peer-review-app to 1) enable a diversity of actors and applications to write and read the data, 2) facilitate sharing information and avoid information silos, and 3) promote interoperability with existing standards (such as ORCID[8], or Crossref[9]), decentralized applications (such as Decentralized Science, peer-review-app, PeerMiles, or Orvium), and important peer reviewer communities (such as Publons or F1000Research) (see Figure 2.7).

Figure 2.7: GUI Detail: Import peer reviews from interoperable platforms.

[7]BLoxberg Improvement Proposal 3
[8]https://orcid.org/
[9]https://crossref.org/

Chapter 3

Conclusion and future work

This thesis has studied CBPP communities and how fully decentralized technologies can support their governance. It includes a wide diversity of methods, that draw from different disciplines such as sociology, design and computer science. After all, the work has been carried within three European Projects (P2P Value, P2P Models and NGI LEDGER) with strong interdisciplinary approaches and teams including social researchers, economists, designers, anthropologists, developers, and experts in startups among others. It is perhaps this diversity what enabled the kaleidoscopic perspective of this thesis.

To offer some examples of the opportunities this diversity of methods provided, we can see that the development of an ABM in collaboration with a sociologist provided the key insight that inspired the development of a statistical study of a large data set in collaboration with a computer scientist and data analyst colleague. Similarly, the technological proof of concepts of decentralized peer reviewing applications that were initially developed in the Computer Science faculty evolved into fully functional MVPs thanks to the collaboration with designers, experts in product design and startups. Even more, the study of the adequacy of blockchain technologies would have been a mere theoretical analysis on decentralized technologies if was not completed with the perspectives of social scientists, that helped to provide a framework to contextualize blockchain technologies within the governance practices or CBPP communities.

Overall, this thesis shows an evolution from an early, almost techno-solutionist [184], perspective on how distributed technologies might revolutionize everything, towards a more comprehensive view of the many aspects that come into play when addressing such complex issues.

The following subsections provide some concluding remarks on the work that this thesis has presented (Sections 3.1- 3.4). Next, Section 3.5 provides an overview on the future work this thesis suggests.

3.1 Participation in CBPP Communities

The works on the inequality of participation in CBPP communities presented in this thesis provide a relevant insight, the characterization of participation in wiki communities of Fandom as a truncated power law, that allows a more accurate representation of this phenomenon. However, this work is far from enough the full complexity of this issue.

One of the relevant limitations of our work is the very specific and quantitative data it considers. It is key to understand that, both the communities and the researchers consider only some types of contributions. Often, those contributions are those that are directly reflected in what the community is building, such as code contributions in FLOSS projects or edits in Wikipedia [185], while other important types of contributions such as community building, or mentoring are frequently invisible [186, 187]. Therefore, one of the limitations of our quantitative study is that it only accounts for contributions registered in the wiki. Thus, it might be missing really valuable contributions that are out of what we can observe.

Additionally, our study only accounts for the number of contributions, without actually understanding or measuring how valuable those contributions might be for the community [188]. For instance, correcting a typo might not be a important as including a reference or writing a first draft of an wiki article. Thus, research on how communities measure and value contributions should be complimentary to quantitative studies like ours that miss such nuances.

It is also important to highlight the strong gender gap in participants of these communities[34, 189, 190, 191]. Our study of participation lacked a gender perspective [192], which could offer interesting insights, and answer questions such as whether there are quantitative differences between the levels and inequalities of participation among the participants of different genders.

Overall, our study on the inequality of participation in CBPP communities helped us to develop a better understanding of this phenomenon. This is of great value to inform the development of tools for these communities. After all, many of the blockchain based governance tools were designed thinking that thousands of members would participate in community decision-making thanks to blockchain technologies. For many, DAOs promised the ultimate democratic tools. In reality, few participants propose or vote [76] in these blockchain governance applications. Knowing that few members would actually participate enable the development of tools that account for that reality.

In fact, it is worth considering whether the combination of this strong inequalities in participation together with the strong barriers of adoption of blockchain technologies could be enough to dismiss all the dreams of blockchain as a tool for a "perfect democracy".

3.2 Blockchain and the Governance of CBPP Communities

Our work brings relevant contributions to the analysis of the potentials of blockchain technologies for governance. It provides 1) the identification of a set of affordances of blockchain technologies (Section 2.2, Publication 5.1), 2) the relationships between these affordances and Ostrom's principles (Section 1.5.1, Publication 5.1) for governance of the commons, and 3) a study on how these blockchain affordances could contribute to overcome the limitations of Ostrom principles when applying them to global communities (Publication 5.2).

These studies on blockchain affordances and how they could support the different governance principles (Objective 2) offers a framework that help us analyze the software we developed for our case study. Concretely, to understand what it is offering to improve the governance of academic peer reviewing, as the following paragraphs illustrate.

Arguably, our development mainly contributes to the monitoring (Principle 4) and graduated sanctions (Principle 5) of peer reviewing. Additionally, the decentralized nature of the technology and the interoperability efforts we incorporated in the development of the tool facilitates that different peer reviewing systems and application can codify their own rules and still be part of the ecosystem (Principle 2: Congruence between rules and local conditions) and develop their own system of rewards and sanctions (Principle and 7: Local enforcement of local rules), enabling a federation of initiatives that could operate at different levels (Principle 8: Multiple layers of nested enterprises).

It does that by offering transparency (*Increasing Transparency* affordance) of the peer reviewing processes (using blockchain and IPFS to make the content of review reports available), and by enabling a rating system to reward and sanction peer review reports (*Graduated Sanctions* affordance), as well as facilitating the trust in those reviewers with strong reputation (*Codification of Trust* affordance). Additionally, it incorporates the rules of peer reviewing into smart contracts (*Self-enforcement and formalization of rules* affordance): for instance establishing that peer reviewers are invited by journal editors, thus only authorized reviewers can review papers in this system. The system is deployed as a set of smart contracts in a blockchain, and thus, they cannot be controller or shut down, acquiring an autonomy that characterize these types of blockchain programs that enabled them to act as Decentralized Autonomous Organizations (DAOs) (*Autonomous Automatization* affordance). Furthermore, these blockchain programs are used by many parties, from different journals to the peer reviewers. The software and infrastructure is not controlled by either party, and thus, the use of our tool offers an opportunity to loosen the control and rights of the data, transforming information such as peer review reports and their ratings into common goods that are no longer in control of individual journals (*decentralization of power over infrastructure* affordance). Our software was designed to be interoperable, and in fact we contributed to the establishment of a standard for the publishing of peer reviewing information over blockchain.

These affordances and their relationship with governance principles can be useful for researchers and practitioners aiming to use or understand the use of blockchain to support the governance of CBPP communities. Concretely, it offers a framework that might open the possibilities of analysis and design of blockchain tools, as it provides a comprehensive list of characteristics and applications to consider.

Furthermore, we deepen our analysis of the potentials of blockchain technologies for the governance of global commons (Publication 5.2). In our study, we provide a detailed analysis of how blockchain technologies could help overcome the limitations that Stern [86] identified for the application of Ostrom principles to global commons. For each of the limitations, we identify which blockchain affordance could facilitate the implementation of the affected Ostrom's principles on a global scale, and provide specific examples of existing blockchain tools and practices that are already.

Thus, this work provides a detailed overview of specific ways by which blockchain could support global online communities such as CBPP communities. Overall, blockchain technologies could facilitate coordination, help to scale up commons governance and even be useful to enable cooperation among various communities in interoperable ways. In addition, our analysis reveals that, when considering the challenges of managing global commons, the role of blockchain is particularly valuable to explore solutions that tackle the scaling up of governance and the definition of global collective agreements within more heterogeneous conditions.

However, and despite the interest of blockchain technologies and the potentials for CBPP governance we have identified, many of the tools that blockchain could facilitate can be implemented with simpler and more accessible technologies. Thus, our study should not be seen as a prediction of blockchain applications solving many governance problems for communities. After all, decentralization is not a feature, as it does not provide of itself a solution to satisfy user needs. In fact, decentralization is often "not just a technical principle but a performative aspiration" [193]. Furthermore, often the use of decentralized infrastructure does not guarantee decentralized outcomes [193]. Ultimately, communities have been solving their governance needs before the invention of blockchain, and will continue to do so.

3.3 Distributed Technologies Framework

Our analysis of distributed technologies resulted in a collection of guidelines to support the design of distributed systems, and in a proposal of a framework for the development of fully decentralized applications without using blockchain when the availability and consistency requirements allow it (Section 2.3).

Our results, and specifically the guidelines, can be of great use for the design of distributed systems. Concretely, it aids to identify what blockchain is strictly needed for in these systems.

On the one hand, the development of the framework for the design of fully decentralized systems that we present in this thesis, helped to deepen our understanding of blockchain and other decentralized technologies. It provides sound analysis that challenge, in theory, the need of blockchain technologies to provide fully decentralized systems that are consistent.

On the other hand, the development of our case study ironically serves as a counter example of what we preached in the proposal of the framework. In fact, and according to our framework and guidelines, our MVP does not strictly need a string consistency on the information it handles (peer review reports, and ratings of such reports). For instance, a journal could still want to contact a reviewer for which it misses their last review, and it can even "risk" the fact that they might be missing a negative rating of this reviewer. Thus, if we followed the design principles of our own research, we could have opted for not using blockchain, as it was, in theory, not needed.

In reality, blockchain actually serves as a convenient coordination technology, and we adopted it, even when it was not strictly required. Other ideal fully decentralized systems such as those described in our papers (Sections 6.2 and 6.1) could have been used. However, these systems are still not developed and deployed, and even if they were, a blockchain already offer coordination, transparency, interoperability and many other desirable features (Publications 5.1 and 5.2).

3.4 Case Study: Decentralized Tools for Academic Publishing and Peer Reviewing

This thesis presents the development of blockchain-based tools for academic publishing and peer reviewing as a case study. The work has evolved from technological proof-of-concepts to a fully functional product (MVP).

One of the main lessons from this evolution is that real solutions depend on much more factors than the exciting possibilities of blockchain technologies. After all, decentralization is not a feature. Beyond small circles of technology enthusiasts, regular users do not care that their tools are distributed, although they might care about some benefits of decentralization, such as the transparency or autonomy that decentralization provides.

Moreover, even when we are able to identify some potentials of decentralized technologies to develop attractive and disruptive tools, there are many other aspects that come into play. During the development of our MVP, we gradually went away from the techno-solutionism of our initial optimistic views. The fact that we could develop decentralized peer reviewing and publishing software was in fact just a small part of the puzzle. We learned that there is a big gap between innovations and real adoption of technologies (the so-called innovation valley of death) [194], and that in addition to technology and a functional MVP, we needed to build a community of supporters of our cause for transparent peer reviews, and rewards for peer reviewers and even find sustainable business models that support it.

The development of the case study was also key to highlight the importance of the interoperability with existing systems when designing new tools. In practical terms, information systems are not built on the void, but on an existing context of platforms, technologies, third-parties and legacy systems. In fact, one of the criticisms made to blockchain and decentralized technologies is their lack of interoperability with both existing centralized systems, and other decentralized applications. The development of our case study contributed to this understanding, and beyond the ideal distributed tools, we ended up building a tool that integrated with centralized systems such as the FLOSS peer reviewing and publishing software OJS, the centralized and proprietary network of peer reviewers Publons, or the open peer reviewing system F1000.

Probably, one of the most controversial aspects of our proposal is the use of transparency, reputation and metrics for peer reviewers. Making openly accessible peer review reports is not new, and may have proclaimed the advantages of this approach to improve fairness, transparency and quality [151]. However, the inclusion of a reputation [5] system and other metrics might raise concerns about privacy and fairness. Furthermore, the introduction of a new public metric (reviewers' reputation) may also affect researcher careers, adding pressure to the already straining processes for academic survival [195]. Furthermore, despite our efforts to improve the usability of our tools, the low levels of *inclusiveness* and *usability* are important limitations of current blockchain technologies. We have developed a user experience for journal editors and the existing reviewers of their journals that do not require interacting with the blockchain, and therefore does not face these usability issues. However, reviewers that want to participate in our network should use a Bloxberg's blockchain account. Improving the usability of our tools is of great importance to make our proposal easy to adopt. However, this is an issue that many blockchain projects face, as the usability of the field has much to improve. Reducing these complexities of decentralized systems to users is one of the biggest design challenges. However, it is needed to reduce the barriers of adoption of blockchain solutions.

To conclude all these considerations, we can state that distributed technologies did in fact help us build attractive applications. However, they are a small tool in the tool-set of online communities. They may indeed help build innovative solutions. However, communities have been able to build their own applications with other tools, and the heavy lifting often lies in other important factors such as good design practices that build products that solve real needs [196] , or effective community building that create bonds and shared meaning.

3.5 Future Work

The work presented in this thesis opens new opportunities for research and development. This section shares some of these opportunities for each of the research topics of the thesis.

3.5.1 Participation in CBPP communities

The study of participation in online communities that this thesis introduces provides a relevant contribution in the mathematical characterization of the participation of the wiki communities in Fandom. However, these findings cannot be yet generalized for other CBPP communities. Applying the same statistical analysis to other types of communities would allow finding if in other communities, the participation of the most active contributors is significantly smaller than what a power law would predict, or if that was only a rare phenomenon we found in Fandom wikis. Actually, we can expect different participation behaviors depending on the type of organizations, as, for instance, large FLOSS projects have been found to be less active in recent years [197]. This could have a direct effect on the distribution of participation that is reflected in the studied data, and that could change the shape of the distribution of participation in these communities.

Moreover, our study offers a concrete and limited picture of participation in these communities, that would benefit from complementary perspectives of other types of studies. A quantitative characterization such as the one we propose gives only a small portion of the complex picture of participation in online communities. Thus, other methods and disciplines should be applied when studying participation, and indeed, some interdisciplinary research could help us better understand how to interpret the quantitative findings this thesis provides [198]. For instance, is it humanly impossible to contribute as much as the extreme values a power law would predict? does burn-out, role changes, or any other community dynamic play an important role in the numbers we are observing? can we predict factors such as the sustainability or the productivity of these communities from how strong is the inequality represented in the slope of the truncated power law, or how much its tail deviates from what a strict power law would predict?.

Additionally, our analysis studies a fixed photo of the state of a community (the number of contributions and contributors in the current date). Although this is a valuable perspective, communities do change in time. It is not the same a community in its early phases than the same community in a more mature phase. Understanding how the distribution of participation changes overtime in specific communities would be of strong interest [199]. Concretely, we could study successful communities and compare them with communities that did not succeed to try to find patterns that could explain what makes CBPP communities thrive. Thus, a more in depth analysis that studies how this participation changes overtime could give really valuable information.

Our study of participation in CBPP communities used two complementary methods, namely ABSS and data analysis. These two methods proved to be synergetic in our research, as the preliminary results of the model motivated the detailed quantitative analysis of the participation data of actual online communities. However, ABMs and data can be combined in many powerful ways, being one of the most interesting proposals the use of real data to feed these computer models [200].

Summarizing, some relevant future work for this research line is:

- To use a different base population in further studies, in order to appropriately generalize for peer production communities and not just wikis.
- To perform a temporal analysis with a rolling time window, in order to understand how these distributions evolve over time.
- To explore how the parameters of the truncated power law relate to factors such as maturity stage, community dynamics and sustainability of the communities.
- To develop data-driven ABMs to better understand and model participation in CBPP communities.

3.6 Blockchain and the Governance of CBPP Communities

Our analysis of how blockchain technologies can support the governance of CBPP communities offers a detailed perspective, matching what blockchain offers (affordance) to specific governance principles.

However, our study is of a theoretical and speculative nature, as there are still very few CBPP communities using blockchain tools to support their governance. It is yet to be seen if the potentials of blockchain we identified are materialized in concrete tools for real CBPP communities. We might also witness that only blockchain-native CBPP communities will adopt these tools, therefore we should pay attention to how blockchain communities evolve and the way they use blockchain for their governance practices. Furthermore, the ways these communities use blockchain might actually contradict or complement our analysis, proving the relevance of some affordances and principles, and dismissing the importance of others. Thus, A better understanding of the capabilities of blockchain technologies to support global forms of commons governance will require further empirical research.Furthermore, the interest and usefulness of our results is yet to be assessed. There are studies that have already applied our analysis of affordances and governance principles to guide or inform their research. However, it should be applied to more studies to test how useful it proves to be. In that way, the strengths and limitations of our work will be discovered.

Additionally, our contribution might be of interest to the researchers of blockchain and online communities. However, it might seem of small direct use for the practitioners such as developers designers and members of these communities. The development of practical tools based on our findings, such as guides for the design of blockchain applications for communities or a collection of existing governance tools and good practices, would be of great interest.

However, our study analyzes what are the potential advantages of blockchain technologies, and not their potential risks or disadvantages. Taking these limitations and risks into consideration is also key to mitigate the potential damages of that adopting blockchain technologies can cause. Therefore, future research that specifically studies the negative consequences of blockchain affordances is an important future work. Some of these potential risks are the extreme quantification of data and data fetishism that tokenization could enhance [201]; the difficulties to implement the right to be forgotten [202] in transparent immutable public blockchains; or the risk of extremely strict rules imposed and automatically enforced by smart contracts [132].

Summarizing, there are some important future work our research of blockchain for the governance of CBPP communities opens:

- Empirical testing of our findings.
- Application of our contribution to more studies to find its strengths and weaknesses.
- Development of practical tools for communities, developers and designers based on our findings.

3.6.1 Distributed Technologies

This thesis provides an analysis of fully distributed technologies, such as blockchain, IPFS, or CRDTs to understand how they compare, and when to use them. Particularly, it provides a set of design guidelines that support the design of decentralized systems in answering which is the appropriate distributed technologies for them, depending on their consistency and availability requirements.

This analysis is valuable to theoretically frame and understand what blockchain is providing in the field of decentralized technologies. It also aims to be of practical utility for designers and developers of distributed tools. However, it studies these technologies from a very concrete perspective. Therefore, while our framework might assure that blockchain is not needed for a specific system, designers might find blockchain is their best technological choice. This is ironically what happens with our case study, which does not have strong consistency requirements, but chooses to use blockchain for other conveniences (transparency, interoperability with other blockchain tools in the domain, easy ways to develop reputation systems, etc.).

One of the main future extensions of our guidelines for designers of distributed systems would be the inclusion of other dimensions in our analysis beyond the formal study of availability and consistency requirements. That would provide a more complete perspective to assist designers to choose the best technologies for their systems.

Furthermore, our studies suggest that a combination of IPFS, cryptographic signatures and a peer to peer network to share and find content might provide an alternative to blockchain in some cases where strong consistency is not needed. However, this is a theoretical system that was not implemented or deployed. A clear future work step would be to implement and deploy such distributed infrastructure and develop distributed tools that use them. Only then we would see the technical viability of the proposal, as well as identify how to overcome the potential limitations.

Moreover, our analysis only focused on fully distributed or peer to peer systems, while other decentralized technologies (such as federated systems) might be of more interest. In fact, some early publications included in this thesis (Publications 6.4,6.3 and 5.4) actually explored the use of real time federated technologies for the development of collaborative applications. The next subsection explores future work to explore with those technologies.

Other decentralized technologies

This work has focused on a very specific type of decentralized technologies, namely the fully distributed or peer-to-peer technologies that do not depend on single nodes to operate.

However, there are many other decentralized technologies that, not being fully distributed, could offer great advantages for the governance of online communities. In fact, some early publications of this research project contributed to the field of federated technologies (Publications 6.3 and 6.4). First, by providing the first open general purpose real-time collaboration API (Publications 6.3 and 6.4). For that, we re-engineer Apache Wave [203] (former Google Wave) technology providing a JavaScript and a Java API. Such real-time collaboration technology enabled the development of the P2PValue's tool Teem[1], where many of the technical knowledge of this thesis, and experience about capturing the needs of online communities using Lean Design principles were acquired.

The first publication of this PhD research project was indeed a real-time collaborative decision-making tool prototype using this types of technologies (Publication 5.4).

3.6.2 Case Study: Decentralized Tools for academic publishing and peer reviewing

This work presents the development of a decentralized academic publication and peer review platform, from its initial stages as a technological proof of concept to its realization as a MVP.

Despite the successful evolution of this development (or perhaps, because of it), there are many open lines to explore that deserve consideration.

Our developments have proved to be of interest in the lab, as technological proof of concepts, and even proved their interest to our potential customers as a MVP. However, they still need to pass many tests to cross the innovation Valley of Death [194]. In our case, to transfer the results of our research into a product that is attractive and available for the general public we consider of special importance the following future work:

- Bootstrap a community of early adopters, and develop a strategy for community growth.
- Research and characterize our audience, finding the profiles for our early adopters and identifying what is the main value they perceive in our product.
- Improving the usability, specially facilitating the use of blockchain for users without prior blockchain experience.
- Find sustainable business models for our products, that allow us to maintain the software as open source and respect the values of the Open Access community.
- Obtain additional funding that is compatible with the Open and Cooperative nature of the project[2].

The adoption of alternative and more sophisticated reputation systems is one of the opportunities of further development of this work. Our proposal uses a simple system where peer review reports can be rated with 0 to 5 stars. However, there are many other reputation systems that could be valuable, some of them introduced by blockchain technologies [5] (Publication 5.3). For instance, the reputation could be weighted on the importance of who is valuing each contribution (e.g., the positive review of an active and reputable member is of more relevance than a novice's positive rating). Such weighted reputations are already implemented in blockchain projects such as the social network

[1] `https://github.com/P2Pvalue/teem`

[2] Establishing a European Cooperative for the development of these tools is in the medium-term plans of the project

Steemit [3] [204], or the DAO framework Colony[4] [205, 206]. In fact, reputation can provide access to voting power such as in the governance frameworks proposed by Aragon or DAOStack [76] and even represent rights over the assets of a distributed organization. Exploring such uses of reputation would be of great interest or the project.

Perhaps, one of the most important research questions that our proposal open are about the impact, consequences and implications of using reputation systems and metrics for peer reviewing, while also increasing the transparency of peer reviewing using blockchain technologies. Indeed, the academic career is already full of pressures to survive, and adding additional metrics could challenge even further the stability of these works [195]. Further research would be necessary to explore who would use such features and would benefit from them; who would be hesitant to use them, and of course, who would be negatively impacted by them. Additionally, we should study the consequences on a system's level of our proposal. After all, one of the main issues of reputation systems is that they might amplify existing social inequalities [5] (Publication 5.3). Thus, this needed research on the implications of our proposal should incorporate traditionally marginalize people in the center of the discussion and re-design of our tools [196, 192].

Additionally, some important technical challenges still remain open. Among them, the detection and prevention of system's abuses such as the use of Sybil identities [207], the detection of fake science, and the prevention of ways of gaming the system of reputation, e.g. through a chain of personal favors.

This thesis has studied the application of blockchain technologies for the governance of CBPP communities. It provides a comprehensive perspective on the potentials these decentralized technologies have, and presents a functional software prototype that incorporates these learnings. However, the real potential of blockchain is yet to be realized. In the near future, CBPP communities could decide to keep generally ignoring blockchain technologies, or they might surprise us with innovative ways of using Blockchain technologies we could not foresee. Probably, we will witness both scenarios, and we can only hope our study helps to inspire or to bootstrap some of these initiatives.

[3] `https://steemit.com/`
[4] `https://colony.io`

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Acronyms

ABM Agent-Based Model. iii, 9, 24, 25, 38, 45, 46

ABSS Agent-Based Social Simulation. x, 9, 45

CALM Consistency As Logical Monotonicity. 18

CAP Consistency, Availability, Partition resistance. 18

CBPP Commons-Based Peer Production. vii–x, 3, 4, 7–9, 11, 13–15, 21, 23–25, 27, 28, 30, 38–41, 45–47

CRDT Conflict-free Replicated Data Types. 16, 18, 30, 31

DAO Decentralized Autonomous Organization. 11, 16, 17, 40

FLOSS Free/Libre and Open Source Software. 7, 9, 12, 14, 39, 43

MVP Minimum Viable Product. x, 21, 32, 34, 38, 42, 43, 49

Part II

Publications

Chapter 4

Participation in Commons Based Peer Production Communities

4.1 Participation in wiki communities: Reconsidering their statistical characterization

Reference

Á. Tenorio-Fornés, J. Arroyo, and S. Hassan, "Participation in wiki communities: Reconsidering their statistical characterization," *PeerJ Computer Science*, 2021

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Abstract

Peer production online communities are groups of people that collaboratively engage in the building of common resources such as wikis and open source projects. In such communities, participation is highly unequal: few people concentrate the majority of the workload, while the rest provide irregular and sporadic contributions. The distribution of participation is typically characterized as a power law distribution. However, recent statistical studies on empirical data have challenged the power law dominance in other domains. This work critically examines the assumption that the distribution of participation in wikis follows such distribution. We use statistical tools to analyse over 6,000 wikis from Wikia/Fandom, the largest wiki repository. We study the empirical distribution of each wiki comparing it with different well-known skewed distributions. The results show that the power law performs poorly, surpassed by three others with a more moderated heavy-tail behavior. In particular, the truncated power law is superior to all competing distributions, or superior to some and as good as the rest, in 99.3% of the cases. These findings have implications that can inform a better modeling of participation in peer production, and help to produce more accurate predictions of the tail behavior, which represents the activity and frequency of the core contributors. Thus, we propose to consider the truncated power law as the distribution to characterize participation distribution in wiki communities. Furthermore, the truncated power law parameters provide a meaningful interpretation to characterize the community in terms of the frequency of participation of occasional contributors and how unequal are the group of core contributors. Finally, we found a relationship between the parameters and the productivity of the community and its size. These results open research venues for the characterization of communities in wikis and in online peer production.

Participation in wiki communities: reconsidering their statistical characterization

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ABSTRACT

Peer production online communities are groups of people that collaboratively engage in the building of common resources such as wikis and open source projects. In such communities, participation is highly unequal: few people concentrate the majority of the workload, while the rest provide irregular and sporadic contributions. The distribution of participation is typically characterized as a power law distribution. However, recent statistical studies on empirical data have challenged the power law dominance in other domains. This work critically examines the assumption that the distribution of participation in wikis follows such distribution. We use statistical tools to analyse over 6,000 wikis from Wikia/Fandom, the largest wiki repository. We study the empirical distribution of each wiki comparing it with different well-known skewed distributions. The results show that the power law performs poorly, surpassed by three others with a more moderated heavy-tail behavior. In particular, the truncated power law is superior to all competing distributions, or superior to some and as good as the rest, in 99.3% of the cases. These findings have implications that can inform a better modeling of participation in peer production, and help to produce more accurate predictions of the tail behavior, which represents the activity and frequency of the core contributors. Thus, we propose to consider the truncated power law as the distribution to characterize participation distribution in wiki communities. Furthermore, the truncated power law parameters provide a meaningful interpretation to characterize the community in terms of the frequency of participation of occasional contributors and how unequal are the group of core contributors. Finally, we found a relationship between the parameters and the productivity of the community and its size. These results open research venues for the characterization of communities in wikis and in online peer production.

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Keywords Commons-based peer production, Open collaboration, Participation inequality, Power-law, Truncated power-law, Online communities, Wiki communities

INTRODUCTION

Since the emergence of online communities, one of the major topics of interest is to understand the different levels in which members participate: that is, the distribution of participation, also named distribution of work, or effort. Far from classical organizational

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structures, and more similar to volunteer-driven social movements, communities show an inherent participation inequality across its participants. Specifically in peer production communities, such as those in wikis and free/open source software, this issue has derived multiple research questions: the concentration of participation in an elite (*Shaw & Hill, 2014*; *Matei & Britt, 2017*; *Kittur et al., 2007*; *Priedhorsky et al., 2007*), the degree of participation inequality (*Fuster Morell, 2010*; *Ortega, Gonzalez-Barahona & Robles, 2008*; *Neis & Zielstra, 2014*), the characterization of who participates more (*Hill & Shaw, 2013*; *Reagle, 2013*), the process of changing user roles (*Arazy et al., 2015*; *Preece & Shneiderman, 2009*), or the evolution of participation depending on multiple factors (*Vasilescu et al., 2014*; *Serrano, Arroyo & Hassan, 2018*).

An important bulk of peer production research tends to say that the distribution of participation follows a power law. Intuitively, this means a very small number of contributors concentrates most of the participation (or work), highlighting participation inequality. Formally, a power law is a simple relationship between two variables such that one is proportional to a fixed power of the other.

In the issue at hand, *i.e.,* participation, the two quantified dimensions are the number of contributions, and the share of people in the community that has made such number of contributions. The relationship among them is negative, that is, the higher the number of contributions, the smaller the share of contributors that has made such number of contributions. According to this idea, a small amount of contributions would be common, while larger amounts would be more rare. This fits with the assumption of participation inequality in which most members of the community tend to participate very little (occasional contributors), while a few of them account for an enormous amount of contributions (core contributors). In fact, the statement is not ungrounded, since several statistical studies focused on Wikipedia claim that the number of edits per user follow a power law distribution (*Kittur et al., 2007*; *Stuckman & Purtilo, 2011*), and other studies find similar behavior in free/open source communities (*Healy & Schussman, 2003*; *Sowe, Stamelos & Angelis, 2008*; *Schweik & English, 2012*; *Cosentino, Izquierdo & Cabot, 2017*) or other peer production communities (*Wu, Wilkinson & Huberman, 2009*; *Wilkinson, 2008*)[1].

Figure 1 shows an example of the power law[2]. If we consider it represents a distribution for participation, the distribution models how frequent is to find a person that contributes X times. It can be seen that the frequency quickly declines as X grows, because most users only contribute a few times. However, it shows how we can find a small amount of contributors with a very high number of contributions.

The power law implies an underlying regularity in the behavior of the phenomenon under study. In particular, the power relationship should hold independently of which particular scale we are looking at. This may not be the case in real data, where the tails may exhibit a more conservative behavior, and other distributions may suit better (*Mitzenmacher, 2004*).

While the power law has been considered a suitable distribution in many fields including online communities (*Johnson, Faraj & Kudaravalli, 2014*) and organizations (*Andriani & McKelvey, 2009*), recent studies in statistics challenge its apparent pervasiveness (*Clauset, Shalizi & Newman, 2009*; *Broido & Clauset, 2019*). According to these studies, power

[1] Other studies just mention a highly skewed distribution or similar statements without further specification (*Howison, Inoue & Crowston, 2006*; *Crowston et al., 2006*; *Barbrook-Johnson & Tenorio-Forns, 2017*).

[2] Original picture by Hay Kranen PD. available at Wikimedia Commons. Our version is a slight variation from the original one.

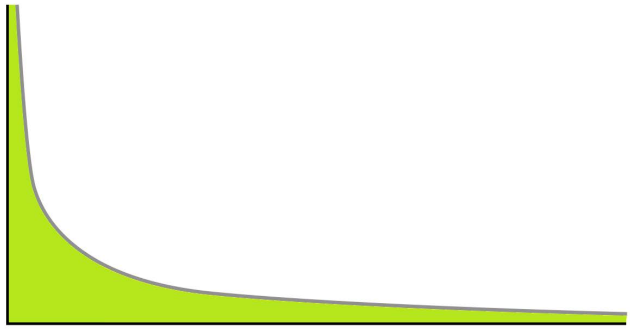

Figure 1 Power law distribution. For participation, the X axis represents the number of contributions made by a person and the Y axis the number of persons that made X contributions.
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law distributions are complicated to detect because fluctuations occur in the tail of the distribution, and because of the difficulty of identifying the range over which power law behavior holds.

For some cases this difference between a power law distribution and other heavy tailed distributions may not be relevant, since the former may be enough to roughly represent the participation. However, using the power law as statistical characterization of wiki participation can lead to unrealistic predictions regarding the likelihood and the productivity of extremely active core contributors. A power law is a relationship in which a relative change in one quantity gives rise to a proportional relative change in the other quantity, independent of the initial size of those quantities. In the peer production field, the regularity of the power law would imply that the relationship that holds for the occasional contributors would be the same to that for the core members, which may be a strong assumption for a community when it comes to predicting the activity level and the frequency of core contributors. In other words, the tail of the distribution, which represents the activity of core contributors, may not have an extreme behavior as the power law suggests, *i.e.,* the number of extremely active contributors and their productivity may not be as high. If that is the case, more conservative distributions, such as the the truncated power law, would provide a better fit. In fact, such distribution was found suitable in a comparative analysis of the ten largest Wikipedias (*Ortega, 2009*).

According to these premises, it seems reasonable to question the characterization of the participation in peer production as a power law, and consider other heavy-tailed distributions. Thus, we will apply the statistical tools proposed by *Broido & Clauset (2019)* to study peer production distributions, and more precisely participation distributions from wiki communities. The statistical tools proposed in that work provide a test to determine whether a distribution provides a better fit than another with respect to the empirical data provided. Thus, we will use them to analyze whether one candidate distribution consistently provides a better fit than the others. The candidates will be five well-known distributions, namely, the power law, three heavy-tailed distributions with a tail more conservative than the power law (truncated power law, stretched exponential and log-normal) and a non-heavy tailed distribution (exponential), following the example by *Broido & Clauset (2019)*.

In our work, we focus on Fandom/Wikia, the largest wiki repository which provides a large and diverse sample of peer production communities. Fandom/Wikia accounts for over 300,000 wikis. However, because of constraints of the statistical methods used, which require a certain minimum of observations, we will use for our analysis the ~6,000 wikis which have at least 100 registered contributors.

The rest of the article proceeds as follows. "Methodology and Data Collection" details the process followed to perform the statistical analysis and for the data collection. "Results of the statistical tests" shares the results of the statistical study of user contributions, and discusses its results through the explanation of series of graphs. The next section offers an analysis of the winning distribution, *i.e.,* the truncated power law, and proposes an interpretation of its parameters and how they characterize the different wikis under study. The paper closes with some concluding remarks and future work.

METHODOLOGY AND DATA COLLECTION

Methodology

Following *Clauset, Shalizi & Newman (2009)* and *Broido & Clauset (2019)*, our study is divided in two analyses. First, in order to assess if the power law distribution is a plausible model for the given empirical data, we use the authors' goodness of fit test. Then, we perform an exhaustive analysis in order to identify which distribution better describes each wiki within the data set. These two methods are explained in this section.

Goodness of fit

Clauset, Shalizi & Newman (2009) proposed a statistical test in order to assess if a distribution plausibly follows a power law. First, the power law distribution is used to model the data, finding its slope, or α parameter, and the minimum value from which the power law behavior is observed, or x_{min} parameter.

Afterwards, in order to compare the empirical data to different distributions, we create a set of comparable synthetic data sets that follow the distribution (*i.e.,* have the same parameters). This allows us to compare the real data with the synthetic data, and see how they deviate from each other. This method is considered more accurate than comparing the deviation with an ideal distribution which real data may never fit. Thus, we artificially create 100 synthetic data sets per wiki, for each of the five distributions.

Thus, the distance of the real data to its power law model is compared with the distance of the synthetic data sets to their power law models. Note that the synthetic data sets are also fit to power law models to compete in similar conditions These distances are calculated using the Kolmogorov–Smirnov (KS) statistic. The goodness-of-fit test returns a p-value between 0 and 1 representing the number of synthetic data set fits that outperformed the real data fit. *E.g.*, a p-value of 0.4 represents that the real data fits the power law better than 40% of the synthetically generated data. This p-value is then used to decide whether to rule out the hypothesis of the data following a power law. In our study, we rule out the power law model hypothesis if the p-value is smaller than 0.1, as *Clauset, Shalizi & Newman (2009)* and *Broido & Clauset (2019)* do, *i.e.,* if the probability of obtaining a worse fit by chance is smaller than 10%. The number of synthetic data sets used to calculate the p-value determines the accuracy of the result. Following *Clauset, Shalizi & Newman (2009)*, for the result to be accurate to within ε, we should generate about $\varepsilon^{-2}/4$ samples. Our study generates 100 synthetic data sets per test, therefore, the results are within an ε of 0.05.

When the number of observations is relatively small, this goodness of fit test cannot rule out a power law model in those cases in which the data follows other distributions such as the log-normal or exponential. For instance, for data following an exponential distribution with $\lambda = 0.125$, at least 100 observations are needed for the average p-value to drop bellow our threshold of 0.1, while for data following a log-normal distribution with $\mu = 0.3$, the average p-value drops below 0.1 from around 300 observations (*Clauset, Shalizi & Newman, 2009*). Thus, high p-values in these distributions with small number of observations should not be interpreted as the data following a power law. Moreover, as studied in the following section, even if a distribution plausibly follows a power law, other distributions may fit the data better.

This work considers wikis with more than 100 observations (*i.e.,* wikis with over 100 registered contributors) for the p-value study for two reasons. First, as already mentioned, the goodness-of-fit test would not be able to rule out the power law. Second, as the wikis with less than 100 contributors represent more than 98% of wikis (See "Methodology and Data Collection"), the percentage of wikis passing the test due to the small number of observations may further obfuscate the result about the adequacy of the power law.

Summarizing, our study considers distributions with more than 100 observations (*i.e.,* wikis with over 100 registered contributors), performs the goodness-of-fit tests proposed by *Clauset, Shalizi & Newman (2009)* considering those with a p-value greater or equal to $0.1(\pm 0.0158)$[3] to plausibly follow a power law. See "Results of the statistical tests" for more details.

This study was performed using the *poweRlaw* R package (*Gillespie, 2014*). Besides, the R script source code, required for applying these statistical tests to our data, is available as free/open source software to facilitate replication[4].

[3]The confidence interval is due to the test resolution that depends on the number of synthetic data sets considered.

[4]Goodness of fit tests script: https://github.com/atfornes/WikiaDistComparison/blob/master/p-value.r.

Likelihood-ratio test

The previously described goodness of fit test provides a tool to decide whether to rule out a power law distribution as a good model for the data. However, even if a power law model is not rejected, there may be better alternative distributions. The likelihood-ratio test allows us to compare the likelihood of the empirical data fitting two competing distributions. That is, it establishes which distribution is more likely to fit the data, and whether the difference is significant.

Following the approach described by *Clauset, Shalizi & Newman (2009)*, our study compares the likelihood of 5 different skewed distributions. Our hypothesis is that the power law is too "ambitious" for the observations of the tail. We also expect the distribution to be heavy tailed, *i.e.,* with a decrease of the tail slower than in an *exponential* *distribution*. In addition to these two distributions that frame the expected tail of our data, our study adds three skewed distributions that would lie in between, presenting a slower decrease in the tail than the exponential but a stronger decrease than the power law: the *truncated power law* (also named power law with exponential cut-off), the *log-normal* and the *stretched exponential*. Both the truncated power law and the log-normal distributions have two terms, while the power law, exponential and stretched exponential have only one. The number of terms of the distributions is relevant, since it is a factor for fitness.

The study exhaustively compares, for each wiki, the fit of the data to those five skewed distributions (power law, truncated power law, log-normal, exponential and stretched exponential), and identifies when the likelihood differences are statistically significant. It uses the Vuong method (*Vuong, 1989*), which considers the variance of the data, and returns a *p*-value that states if the likelihood differences may be due to the data fluctuations, or are significant in order to favor one distribution over the other[5]. As *Clauset, Shalizi & Newman (2009)*, we consider significant the differences with a *p*-value smaller than 0.1, *i.e.,* those that have less than 10% probabilities of being a result of the data fluctuations. Additionally, in order to avoid over-fitting to the tail of the distribution, we force the method to fit every contributor with at least 10 contributions. If we do not impose this condition, the method could exclude many contributors in order to find a better fit for the most active contributors, for instance a fit for the people with more than 500 contributions.

[5]The method is adapted by Clauset et al.'s for nested distributions such as power law and truncated power law, where a family of distributions is a subset of the other. Such modified method, which we use as well, allows to state whether the larger family is indeed needed or both distributions are good models.

This study was performed using the *Powerlaw* Python package (*Alstott, Bullmore & Plenz, 2014*). Similar to the previous subsection, the Python script source code, required for the performed analysis, is available as free/open source software to facilitate replication[6].

[6]Likelihood-ratio test script: https://github.com/atfornes/WikiaDistComparison/blob/master/powerLawVsPowerExp.py.

Data collection

This work investigates the distribution of participation in wikis from Wikia/Fandom studying the number of edits per user. Wikia/Fandom is a suitable research object to draw conclusions about participation in wikis in general. As argued by *Shaw & Hill (2014)*, Wikia is an ideal setting in which to study peer production. Wikia only hosts publicly accessible, openly-licensed, volunteer-produced, peer production projects. To date, it is the largest and most diverse repository of open knowledge peer production, with a rich ecosystem of a broad diversity of topics, languages, community and wiki sizes. Furthermore, Wikia never restricts viewership, nor participation (except that from spammers or vandals). Wikia hosts some of the largest and most successful wikis in multiple topics and languages, such as Marvel or Star Wars fandom wikis, LyricWiki on song lyrics, Proteins scientific wiki, or AmericanFootballDatabase.

To collect our data we used the publicly available Wikia census described by *Jiménez-Díaz, Serrano & Arroyo (2018)* and retrieved on the 20th of February 2018[7]. However, as explained in the methodological section, we limit our analysis to wikis with at least 100 registered contributors which have done at least one edit, and excluding bot users.

[7]Wikia census: https://www.kaggle.com/abeserra/wikia-census.

Thus, starting from this census data, and complementing it with additional information as explained below, we have created a new data set to study the distribution of participation, *i.e.,* which is the distribution of edits made by registered contributors, excluding bots. By only including registered contributors we exclude anonymous contributors, which can be identified by their IP address. However, it is problematic to unambiguously match the IP address to a single anonymous contributor and vice versa. Furthermore, it is also difficult to consider an anonymous contributor as a member of the wiki community.

This data set is complete, since it includes all the Wikia/Fandom wikis with at least 100 contributors which made at least one contribution, resulting in 6,676 wikis, as explained in detail below.

The mentioned Wikia census provides information of ∼300,000 wikis. However, the census does not provide information on the number of edits of each participant in each wiki. Thus, such information needs to be retrieved to complement the data set.

Therefore, in order to retrieve the required data, we need to query the API of each of the wikis hosted in Wikia. Spefically, we need to query the Special:ListUsers API endpoint that every MediaWiki wiki has[8]. Such Special:ListUsers page lists the information of every registered user in a given wiki, *e.g.*, username, number of edits, groups she belongs to, or date of last edit made. A perl script was developed in order to use that endpoint and obtain the number of edits performed by each registered user. In particular, the script queries the endpoint making a request for all users. Afterwards, it filters out the bot users, removing the users belonging to the *bot* and *bot-global* groups. As with the previous scripts, this perl script source code is available as free/open source software to facilitate replication[9].

The data collection was performed on November 6, 2018 and it is publicly available (https://www.kaggle.com/atenorio/wikia-participation-data-20181106). It contains information about 295,658 wikis, since 8,433 wikis endpoints were technically unavailable[10].

This data, *i.e.*, the census wikis with the edits information, was curated to avoid duplicates and to filter out wikis without human participation (*i.e.*, bot only) and without statistical data provided by Wikia/Fandom. After removing them, the collection contains information about 282,039 wikis.

The reliability of the data collected is considered high. The edit numbers are as reliable as Wikia/Fandom publicly accessible statistics are (*i.e.*, those from the Special:ListUsers endpoint). Furthermore, we have also done a consistent effort in bot identification in order to filter them out, as they may alter the participation distribution.

For statistical reasons already explained in the methodological section, this work considers only wikis with at least 100 registered (non-bot) contributors. Thus, the number of considered wikis was further reduced to 6,676. Hence, this is not a sample, but the observed full population of Wikia/Fandom wikis with at least 100 registered users with contributions.

RESULTS OF THE STATISTICAL TESTS

According to the goodness of fit test described in the methodological section, the power law is a plausible distribution (*i.e.*, it cannot be ruled out) for the 83% of the 6,676 wikis from Wikia/Fandom with at least 100 registered non-bot contributors. However, as explained in the same section, that does not mean that the power law is the best choice, since other distributions may fit the empirical data better.

[8] Note all Wikia/Fandom wikis use the same wiki software, MediaWiki, the maintained by Wikimedia Foundation and used by its projects, including Wikipedia.

[9] Script to retrieve user contributions: https://github.com/Grasia/wiki-scripts/tree/master/users_with_edits/.

[10] Wikis may be unavailable for a number of reasons, *e.g.*, being removed from the platform, or having changed their name. Unavailable wikis represent 3,5% of the total wikis, constituting a small percentage of expected noise that should not compromise the results of the study.

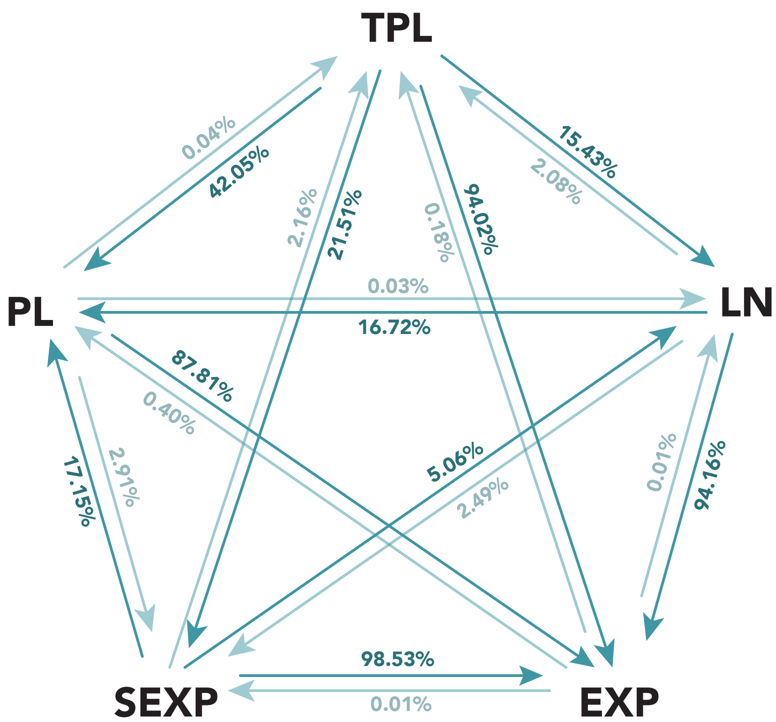

Figure 2 Results of the likelihood-ratio test between the five considered distributions for registered contributors. The distributions considered are: power law (PL), truncated power law (TPL), log-normal (LN), exponential (EXP) and stretched exponential (SEXP). Each arrow from A to B has the percentage of cases in which A was superior than B. The figure shows in a darker color the arrow with the higher percentage for each pair of distributions.

Full-size DOI: 10.7717/peerjcs.792/fig-2

Thus, we perform the likelihood-ratio test to compare the pairs of the five candidate distributions as explained above. The distributions are: power law, truncated power law, exponential, stretched exponential and log-normal. For each wiki, we perform likelihood-ratio tests comparing all the competing distributions against each other. That is, we perform 10 likelihood-ratio tests for each wiki, since there are 10 possible couples.

Figure 2 summarizes the results of these comparisons. The figure's pentagon apexes shows each of the five considered distributions. An arrow from distribution A to distribution B represents the percentage of wikis in which distribution A was preferred over distribution B in the likelihood-ratio test, while the opposite arrow represents the percentage of wikis where distribution B was superior to distribution A. Note in some cases, the likelihood-ratio test may be inconclusive to determine which of the two distributions is better for a given wiki, and in those cases neither A nor B is superior. It is important to remark that the test

Table 1 Aggregated results of the likelihood-ratio tests for each wiki counting the cases where a candidate distribution wins all tests and loses at least one test.

Distribution	Wins all tests	Loses at least one test
Power law	0 (0%)	2816 (42,18%)
Truncated power law	596 (8.93%)	177 (2,65%)
Log-normal	41 (0.61%)	1159 (17.36%)
Stretched exponential	2 (0.03%)	1492 (22,35%)
Exponential	0 (0%)	6578 (98.53%)

being inconclusive means that both distributions fare similarly, which could mean that both are adequate or even that both are inadequate. For the sake of clarity, the figure omits the complementary percentage where the likelihood-ratio test was inconclusive, although it can be easily calculated[11].

[11] In all cases, percentage of $A > B +$ percentage of $A < B+$ percentage of inconclusive = 100%.

The analysis of the figure results shows that the power law is not a strong contender, as it is rarely a more likely distribution than any of its competitors, with the exception of the exponential distribution, which is also overwhelmingly defeated by the rest of the candidates.

The defeat of the exponential distribution by all candidates means that a large tail of core contributors is clearly present in the wiki participation distributions, and thus that an exponential distribution, which is not able to represent heavy tails, is not a good candidate.

However, the power law being defeated by the rest of the heavy-tailed distributions means that the tail is not as heavy or large as a power law would predict. Hence, more moderated heavy-tailed distributions are required. This conclusion is similar to the one drawn in recent works that disprove the supposed prevalence of the power law in other domains (*Clauset, Shalizi & Newman, 2009*; *Broido & Clauset, 2019*).

Thus, a correct characterization of the distributions, in nearly all cases, lies in between the exponential and the power law distributions. Among the rest of the candidates, the truncated power law stands out, since as seen in Fig. 2, it is rarely beaten by its competitors: 2.16% against the stretched exponential, 2.08% against the log-normal, 0.18% against the exponential, and 0.04% against the power law distribution. Hence, the likelihood-ratio test clearly supports the truncated power law as the most appropriate distribution to characterize participation.

The appropriateness of the truncated power law is better appreciated when we aggregate the results of the likelihood-ratio tests for each wiki as shown in Table 1. We count the cases where a candidate distribution won all the likelihood-ratio tests for each wiki, which means that that distribution is the right choice for that wiki. In addition, we also counted the times where a candidate distribution lost at least one test, which means that for that wiki the candidate distribution was not the best choice.

It is important to remark that only in 10 wikis (0.15%) no candidate distribution won any likelihood-ratio test which means that they all were equally good (or, more precisely, bad) candidates. We have inspected these cases and they all exhibit uncommon participation distributions.

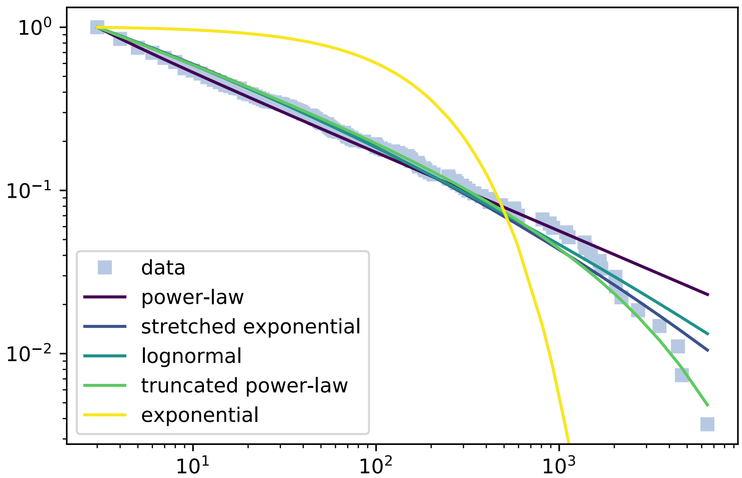

Figure 3 Complementary cumulative distribution function of participation of a wiki and the fitted distributions. The X axis represents the logarithm of number of edits and the Y axis the inverse cumulative relative frequency the percentage of contributors that made at least X edits in the wiki.
Full-size DOI: 10.7717/peerjcs.792/fig-3

According to Table 1, the truncated power law is significantly better than all the candidates in 596 wikis out of the 6,676, *i.e.,* approx. 9% of the wikis considered. While the rest of the distributions fare much worse: only the log-normal and stretched exponential distributions are the best candidates in 41 and 2 wikis, respectively. The power law and the exponential are not the best candidates for any wiki, which reinforces the idea of the suitability of a heavy-tailed distribution but not as heavy as that from the power law.

According to the aggregated results in Table 1, the truncated power law is not the best or among the best candidates for only 177 wikis out of 6, 676 wikis (2.65%); more precisely in 67 wikis (1%) looses one test, in 101 wikis (1.51%) loses two tests and in 9 wikis (0.1%) loses three tests. The rest of the distributions fare much worse, *e.g.*, log-normal can be ruled out as the best candidate in the 17.36% of the wikis and the stretched exponential in the 22.73%. This result reinforces the idea of the truncated power law being the *distribution of choice* when trying to characterize the participation distribution in wikis, because it seems difficult to find a better one for most of the cases.

We show an example of participation distribution where the truncated power law won all the tests in Fig. 3. The figure shows a log–log plot of the complementary distribution function where the X axis represents the logarithm of the number of edits in the wiki and the Y axis the inverse cumulative relative frequency, *i.e.,* the percentage of contributors that made at least X edits in the wiki. The figure displays the observations (grey squares) and the fitted distributions, *i.e.,* the truncated power law and all the candidate distributions. The observations in the left side of the graph represent the contributors with fewer edits, while those most towards the right are the core contributors that made most edits, *i.e.*, the tail of the participation distribution.

In this figure, first we can observe the different tails of the considered distribution. While the exponential has the most conservative tail, the power law is the one that has a heavier tail, while the rest of the distributions have a tail in between them. Regarding the data fitting, the exponential with his bounded tail is not able to model the community behavior at all. The rest of them fit the initial slope, but only the truncated power law is able to successfully grasp the tail behavior, because the others predict a heavier tail.

Note the participation distribution in Fig. 3 is one of the 9% examples in which the truncated power law wins all test. Still, as mentioned, in most of the cases (97, 35%), the Truncated power law is not defeated by any other distribution. Such cases typically correspond with participation distributions with tails that can be conveniently fitted by the truncated power law, but also by the log-normal and/or the stretched exponential. So, according to this statistical evidence, the truncated power law is in fact the most adequate distribution for wiki participation.

The statistical analysis carried out shows that the truncated power law is the best distribution to characterize the participation in wikis among those considered, as it is barely rejected and is the only proper fit in 9% of the cases. In the next section, we will interpret the parameters of this distribution in the context of participation and will relate them with the characteristical features of the wiki communities.

ANALYSIS OF THE TRUNCATED POWER LAW FOR CHARACTERIZING PARTICIPATION DISTRIBUTIONS

In this section, we will explore the diversity of participation distributions that are modelled by the truncated power law, but before that, we need to understand better the effect and interpretation of the parameters that define the the truncated power law.

Interpretation of the truncated power law parameters

The truncated power law is defined as a power law multiplied by an exponential: $x^{-\alpha}e^{-\lambda x}$. In the log–log plot, the parameter α is related to the slope of the power law function, while the parameter λ is related to the starting point and/or the steepness of the decay in the tail.

As a result, lower alphas can be associated with a higher frequency of participation of occasional contributors. While the number of contributions increase, their frequency decreases less conspicuously than in the case of higher alphas. In other words, in communities with lower alphas the frequency of contributors with more contributions decreases less significantly.

On the other hand, higher lambdas can be associated with more pronounced deviations from the power law in the tail, which means that more active contributors are less frequent as what the power law would predict. Thus, higher lambdas relate to less inequality among active contributors than predicted by the power law.

In Fig. 4, we show the truncated power law of nine wikis with different α and λ parameters that illustrate how diverse may be the participation distributions in wikis. From left to right we show three plots each of them with three participation distributions with roughly

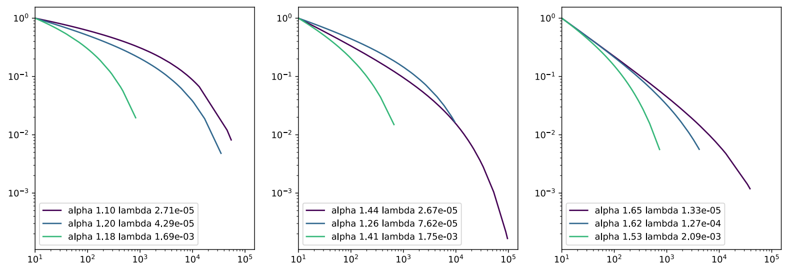

Figure 4 Complementary cumulative distribution functions in logarithmic scales of truncated power laws. Each sub-figure plots three wikis with similar α parameter, adopting smaller values in the left plot, average values in the middle and higher values in the right. The X axis represents the logarithm of number of edits and the Y axis the inverse cumulative relative frequency the percentage of contributors that made at least X edits in the wiki.

Full-size DOI: 10.7717/peerjcs.792/fig-4

similar α values (the alpha values grow from the left to the right plot). In each plot, we show participation distributions with similar α but with different λ values. This figure illustrates the idea that the initial slope of the distributions depends on α values, as it is steeper from the left to the right plots. Besides, in each figure we can appreciate that higher values in the λ parameter are associated with a more pronounced and earlier decay sooner, or, conversely, smaller values allow the power law relationship to prevail longer.

Relationships of the parameters with features from the wiki communities

In this section we explore whether the α and λ parameters are related to some features from wiki communities, namely, the number of edits and the number of participants. We will use scatter plots in which each dot represents a wiki in a 2-dimensional plot. The plot axes represent the values of the α and λ parameters, and the dot is colored according to a color gradient related with the specific wiki feature. More precisely, in Fig. 5 the color represents the number of edits, and in Fig. 6, it represents the number of contributors of the wiki. For the sake of clarity, the plot will only display the wikis where the truncated power law distribution won all the likelihood-ratio tests.

The scatter plots show a cloud of dots with no clear relationship among the parameters. The relationship could be inverse, since the cloud rarely includes wikis with large α and λ values or wikis with small α and λ values. However, the variability is very high to see a clear pattern.

When studying the relationship of the parameters with the size of the community in Fig. 5, we can observe how the λ parameter seems to be inversely related to the number of edits of the wiki, as the largest wikis are distributed in the lower part of the figure and vice versa. In other words, larger wikis (those with millions of edits) have smaller lambdas, which means that the decay in the tail of their participation distributions is not as significant. It reveals that, given an alpha value, there are more core contributors than in

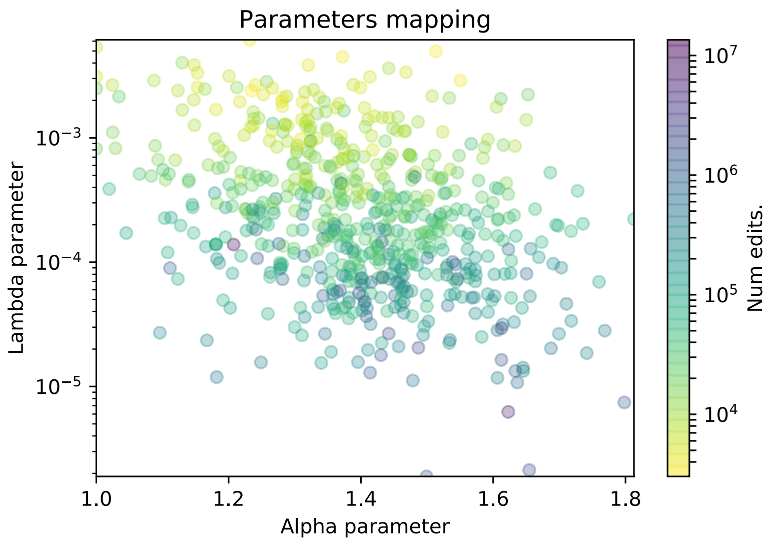

Figure 5 Scatter plot of the TPL-distributed wikis where the color represents the number of edits.
Full-size DOI: 10.7717/peerjcs.792/fig-5

wikis whose participation distributions have higher lambda values, and that results in more productive communities in terms of edits. On the contrary, wikis with higher lambdas have a less populated elite of core contributors which results in smaller wikis in terms of edits.

At Fig. 6, we can observe that the number of contributors of the wiki is related to the combination of both parameters, as we can see that the color gradient shifts from the upper-left towards the bottom-right corner. Participation distributions characterized by high alpha values and low lambda values belong mostly to larger wiki communities (blue dots). Those parameter values determine an extremely sharp decrease in the (relative) frequency of editors as the number of edits increases, and also a more pronounced decay on the frequency of the most active contributors. In other words, extremely unequal participation distributions can be found mostly in large wiki communities. Conversely, we can find that less unequal distributions of participation –those with low alpha and high lambda values–characterize mostly the distribution of participation of wikis with smaller communities (yellow dots).

We cannot conclude if higher inequality is cause or consequence of larger communities and vice versa. Such confirmation would require further research. However, it seems that there is a clear link between community size and participation distribution.

Furthermore, it is important to bear in mind that we are observing the participation distribution during the whole life of the wiki, that is, the aggregated effect of different communities that interacted in the wiki across time, since new contributors come and other leave, or contribute in different degrees, throughout their evolution. In fact, larger

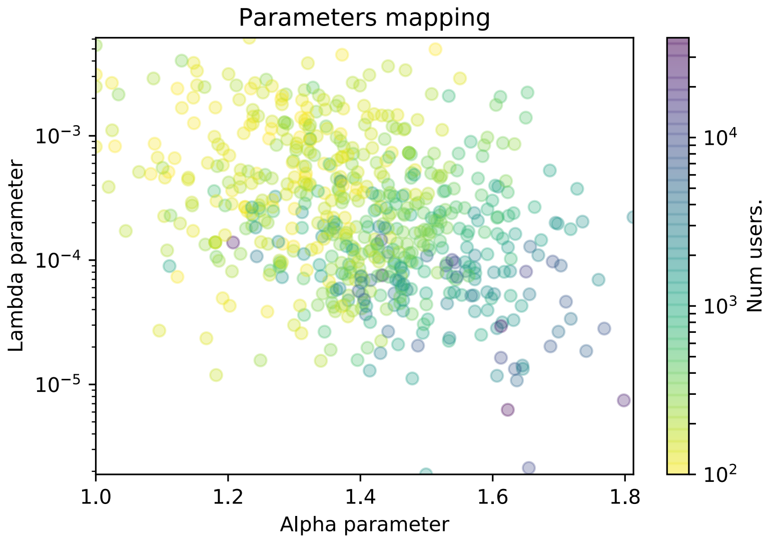

Figure 6 **Scatter plot of the TPL-distributed wikis where the color represents the number of contributors.**

Full-size DOI: 10.7717/peerjcs.792/fig-6

communities are usually older communities. In this sense, it would be interesting to observe how the yearly participation distribution in these wikis evolved, because the highlighted inequality could potentially be the result of the aggregation throughout the years of more egalitarian distributions of participation.

CONCLUDING REMARKS

In this work, we have critically studied the distribution of participation in wikis. We aimed to analyze Wikia/Fandom, which hosts ∼300,000 wikis. From those, we selected the 6,676 wikis with at least 100 registered contributors to perform our statistical analysis. This is considered an extensive and diverse population, appropriate for an analysis following the approach defined by *Clauset, Shalizi & Newman (2009)*. According to our results, the power law is not an appropriate distribution for wiki participation, as it predicts that core contributors are more frequent and more active than the observed in these communities. This contradicts the bulk of the peer production literature, which refers to the power law as the reference distribution when discussing about contributor participation.

In our statistical analysis we have considered potential alternatives, and from these distributions, the truncated power law gives clearly the best fit with the empirical data. Consequently, it should be considered as the distribution of participation of choice when characterizing wiki communities. Of course, it may not be adequate for some specific communities, and yet it has been able to characterize effectively the vast majority of them, while the other candidates performed significantly worse. These findings have implications that can inform a better modeling of participation in peer production, and help to produce more accurate predictions of the tail behavior, that is, predictions about the frequency and the activity level of the core contributors.

In our analysis, we have also found that the parameters of the truncated power law distribution (that govern the slope and the decay of the power law relationship in a wiki project) are related with the number of members in the community and the number of edits in the project. However, the reasons behind these findings deserve deeper consideration and are a matter of future research.

The prevalence of the truncated power law as the distribution of choice for characterizing the participation distribution in wikis has several implications. For instance, it means that the truncated power law fits better, especially concerning the frequency and the activity level of the core contributors. The change of slope of the truncated power law may also serve to empirically determine a clear division between core and non-core contributors instead of using arbitrary divisions as in other studies (*Kittur et al., 2007*). Further research may provide insights on how and why the inner dynamics change, and how we can study better the different emergent roles within peer production communities.

In a truncated power law, the frequency and activity level of core contributors, *i.e.,* the highly active members, is smaller than that predicted by a power law with the same slope. That means that, when looking at the distribution tail, we can observe a sharper decrease in the frequency of extremely active contributors as the edit activity increases.

The reasons behind this fact need to be determined. They could be related with community dynamics such as some kind of elitism that prevents more people to be involved as much as those more active in the community, or that many active contributors experiment a burnout at some point and cease or decrease their activity level (*Jiang et al., 2018*), or even with the fact that it is not possible to find people as productive as a power law distribution predicts for certain participation levels.

Still, the difference in the participation level between core and non-core contributors is remarkable and it seems to reinforce the idea that core contributors are somehow special, in the sense that there is a qualitative change in their work and motivations (*Burke & Kraut, 2008*) and thus higher barriers to join them, and/or the elitization of the core leads to oligarchies (*Shaw & Hill, 2014*).

The approach followed by this work has several limitations. It is a descriptive quantitative work, and thus it lacks explanatory aspects that further qualitative research could contribute with. Besides, we are cautious with the generalizability of our findings beyond Wikia/Fandom, *i.e.,* to every wiki communities or to peer production communities in general. That is, could we argue that the distribution of participation in peer production is a truncated power law? We cannot prove that empirically, and yet we have a good base for cautious claims in that regard; similar to other generalizations performed in the field, *e.g.*, by *Shaw & Hill (2014)*. That is, considering the significant size and diversity of the sample used, there is good evidence for potential generalizability. In order to support this generalization, these results would need to be validated in other projects, the such as the Wikimedia Foundation projects, as well as in other peer production communities such as

Free/Open Source Software projects. Thus, we encourage other researchers to replicate our approach with other peer production communities.

Furthermore, the statistical analysis methods employed require a certain number of observations to have conclusive results, which constrains their applicability for studying the participation distribution of wikis with small communities. Despite of having near 300,000 wikis in Wikia, most of them have under 100 registered contributors and were discarded, using "only" 6,676 wikis in the analysis. For wikis with smaller communities statistical methods may find difficult to provide conclusive results as the differences are subtle and mostly related with the tail behavior.

We have analyzed the participation in the communities aggregated through time (years), that is, accumulating the participation of all the members from the beginning. However, the members of a wiki community change through time, as change the participation dynamics. The participation distribution could be different when analyzed in a smaller time window, such as a year.

We have already defined several potential lines for future work, but we would like to mention those that we consider more interesting. First, it would be relevant to use a different base population, in order to appropriately generalize for peer production communities and not just wikis. For instance, we could analyze in a similar manner communities from Github, Wikimedia Foundation projects, or Stack Exchange. Second, it would be useful to perform a temporal analysis with a rolling time window, in order to understand how these distributions evolve over time. This is especially relevant if we consider the evolution of the truncated power law parameters and how they relate with participation dynamics and inequality. In fact, we can highlight the importance to deepen the study the characterization of wikis based on their truncated power law parameters. That is, it would be interesting to cluster similar wikis and explain the causes or consequences of the different typologies. Moreover, we could explore how they relate with factors such as maturity stage, community dynamics and sustainability.

Our work asserts the truncated power law is probably the most appropriate distribution to represent the distribution of participation in wikis from Wikia. Our results can be better understood if they are observed in the context of a previous study that questioned the prevalence of power law in several fields (*Clauset, Shalizi & Newman, 2009*) and the ground-breaking finding that the power law was indeed rare in real-life networks (*Broido & Clauset, 2019*). Our finding will thus open new lines of research, revisiting old assumptions in the field, exploring further the causes behind the observed structural change in core contributor participation and the relationships with the sizes of the community and the project and other factors behind the behavior.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Ámbar Tenorio-Fornés conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Javier Arroyo conceived and designed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Samer Hassan conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data and code are available in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj-cs.792#supplemental-information.

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4.2 Modelling Commons-based Peer Production: The ‘Commoners Framework’

Reference

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Modelling Commons-based Peer Production: The 'Commoners Framework'

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1 Introduction

This extended abstract introduces a novel conceptual framework - the 'Commoners Framework' - to be used when conceptualising and modelling the behaviour of commons-based peer production (CBPP) communities. The framework is currently being finalised, implemented in NetLogo, and tested on a case study; this process will be completed by the time of SSC2017. The current version of the NetLogo model, still in development, can be accessed at https://github.com/P2Pvalue/CommonersFramework.

The Commoners Framework can be used to represent the behaviour and operation of a wide-range of CBPP communities, and similar organisations (such as those that make use of volunteers). It represents the processes behind individuals' decisions to contribute to, enter or exit, or make 'friends' in, communities. Through this representation of individuals' behaviour, the framework aims to account for patterns of behaviour observed at the community level. For example, the distribution of participation rates among individuals, which often follows a power law distribution, also known as the '1-9-90 rule' (Crowston et al 2006; Howison et al 2006; Arazy et al 2015); where 1% of the community – the core members – perform most of the work, 9% of the community – the contributors – occasionally contribute and 90% of the community – the users or consumers - use the commons without directly contributing to produce it. The framework was developed based on recent empirical findings (Morell et al 2016; Arvidsson et al 2016) on behaviour in a wide variety of communities and was refined using the structural rigour imposed when building an agent-based model (ABM).

At SSC2017 we intend to present (i) the framework, (ii) its implementation in NetLogo, and (iii) its use, exemplified using a case study from the EU FP7 P2PValue project. P2PValue developed 'TEEM', a software platform designed to support collaborative working and the operation and development of CBPP communities. We are building an ABM utilising the framework to simulate the potential effects of TEEM on CBPP communities. We believe this use of a conceptual framework in an ABM, to explore the potential effects of a software tool such as TEEM, fits well with the theme of 'Social Simulation for a Digital Society' at SSC2017. Finally, other potential uses of the framework will be discussed, such as in other simulation and modelling efforts, in participatory and qualitative research, and in quantitative social research.

2 Commons-based peer production

This form of productive organisation was orginally identified in the 1980s by Powell (1987). Since named 'Commons-based peer production' (CBPP) (Benkler 2002; 2006), it differs from traditional forms and structures of production, such as firms and markets. Instead, individuals collaborate in a relatively non-hierarchical manner, and contribute their time and energy for free, to produce goods and services that they do not charge for (i.e, commons resources). Often cited examples include Wikipedia, and Free/Libre and Open Source Software (FLOSS) projects such as GNU/Linux or Modzilla Firefox.

CBPP, typically reliant on the internet to aid coordination of efforts, is expanding from its initial popularity in FLOSS communities, to be used in areas such as citizen science, product design and open data (Salcedo et al 2014). Maker spaces such as Fab Lab London (fablabs.io/fablablondon), and WeMake (wemake.cc/), and farming groups such as Rural Hub (ruralhub.it/en/) are all examples of CBPP and exemplify the breadth of domains, and types, of communities.

Previous research has focussed on three elements of CBPP (or FLOSS, and specifically Wikipedia, as these have dominated the field) (Salcedo et al 2014): motivation for contributions (i.e. the individual), governance (i.e. the group), and competitive dynamics (i.e. relation to external groups such as firms) (von

Krogh and von Hippel 2006; Rozas and Gilbert 2015). Within these streams attention has been on describing in detail individual cases of CBPP, or comparisons of similar communities (Salcedo et al 2014); for example, Wikipedia (e.g. Kittur et al 2007; O'Neil 2009; Reagle 2010; Viégas et al 2007). The literature has tended to be based on ethnographic and qualitative accounts of CBPP, giving a deep understanding of how communities govern themselves, and why people are motivated to contribute to them (e.g., Kelty 2008; Coleman 2012). Recent efforts have been made (e.g. Salcedo et al 2014) to broaden understanding, and map out the wider 'universe' of CBPP. Examples of non-qualitative approaches being used, include traditional social science statistics (Schweik and English 2013) and network analysis (Huang et al 2011; Howison et al 2006).

There is value in building generalisable understandings and theoretical frameworks of CBPP and similar communities. These understandings will help community organisers and policy makers better support communities, structure and design their operation, and improve their sustainability. The formalisation of the knowledge produced by qualitative social research using formal models enables its application to different communities, studying their characteristics and behaviour in an experimental and comparative manner. Examples of models developed in this area include: explorations of what makes communities successful (Radtke et al 2009); attempts to reproduce observed patterns in communities (Wagstrom et al 2005; Gao et al 2005), and; participation and conflict in communities – specifically Wikipedia 'type' communities (Ciampaglia 2011; Iniquez et al 2014). None of these studies provide a holistic framework for understanding participation (i.e. contributions, exit and entry, and making 'friends') in a wide range of communities. They either focus on a specific type of community, on competition between communities, or on one narrow aspect of participation. The Commoners Framework aims to fill this gap in the literature.

3 The Commoners Framework

The framework is currently being finalised and implemented in NetLogo, however, Figure 1 outlines the overall logic of the framework. When finished, the framework will be presented using diagrams like this, alongside text descriptions, and tables connecting activities (e.g. making friends) with factors.

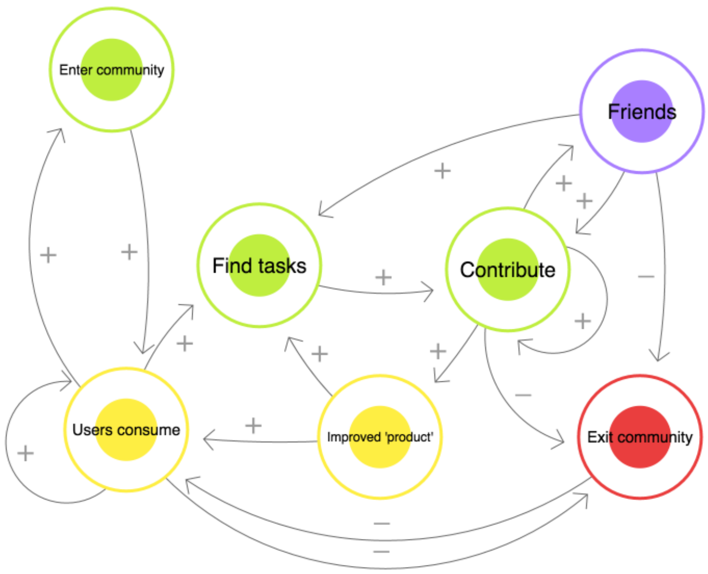

Figure 1: Commoners Framework Logic (Drawn in Loopy - ncase.me/loopy/)

The focus of the framework are Commoners. Commoners is the name given to individuals in a community – both those that contribute, and those that consume the product(s) of a community. The core productive activity of any Commoner is to find tasks in the community, and contribute to them. Their ability to, and likelihood of, contributing will depend on their interests (a Commoner and task parameter), skill types (a

Commoner and task parameter), and past activity. Commoners may stay in a community, only consuming but not contributing, if no tasks meet their interest or skills. Commoners may make 'friends' with others contributing to the same tasks. Having friends increases the chance of finding tasks and contributing. Friends may be lost over time with a certain probability. Commoners' probability of leaving a community decreases as they make more contributions and have more friends. Contributions improve the quality, or number, of products in the community. More consumption of products increases the probability of existing consumers of these products continuing to consume them, and new Commoners entering the community.

The implementation of the framework in NetLogo, including the *.nlogo* file, and a description of the model can be found at https://github.com/P2Pvalue/CommonersFramework. This will be updated as development continues, but readers can find the current version using the history function in Github.

4 Using the Framework

The example we will present at SSC2017 of using the framework will be on simulating the use of TEEM in CBPP communities. However, we will also present next steps, guidelines, and resources for researchers thinking of using the framework in other contexts – something we wish to encourage. We envisage these uses may include: (i) modelling other CBPP communities, and other communities where voluntary contributions are important; (ii) participatory and qualitative research, where the framework can be used to inform the development of topic guides and analytical approaches; and finally, (iii) quantitative social research, where the framework can be used to identify topics and formats for survey questions.

5 Next steps

Over the next five and half months, the framework's implementation in NetLogo will be finalised and then tested against real world data on a selection of different communities. Longitudinal data on the number of contributions, peoples' entry and exit, and social networks in communities has already been collected on a range of online communities from Github. Data is also being collected for other types of communities, notably data from collaboration tools such as Trello used by offline communities (i.e. those that meet and work together in person, rather than online only). Data may also be collected from Wikidata.org. These different datasets will be used to paramterise and validate the framework as implemented in an ABM. Once the framework has successfully reproduced a range of communities' past histories, the ABM will then be run for each community with the TEEM platform being introduced during the communities' history. This introduction of the platform will be operationalised via the adjustment of some of the rules and parameters of the framework's implementation in NetLogo, changing how Commoners interact with one another and make contributions. The resulting changes in communities' histories (measured by outputs such as number of contributions, entry and exit, and social networks) will be used to make tentative suggestions about the impact the platform may have on communities.

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Chapter 5

Governance of Commons Based Peer Production Communities

5.1 When Ostrom Meets Blockchain: Exploring the Potentials of Blockchain for Commons Governance

Reference

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Abstract

Blockchain technologies have generated enthusiasm, yet their potential to enable new forms of governance remains largely unexplored. Two confronting standpoints dominate the emergent debate around blockchain-based governance: discourses characterised by the presence of techno-determinist and market-driven values, which tend to ignore the complexity of social organisation; and critical accounts of such discourses which, whilst contributing to identifying limitations, consider the role of traditional centralised institutions as inherently necessary to enable democratic forms of governance. In this article, we draw on Ostrom's principles for self-governance of communities to explore the transformative potential of blockchain beyond such standpoints. We approach blockchain through the identification and conceptualisation of six affordances that this technology may provide to communities: tokenisation, formalisation and decentralization of rules, autonomous automatisation, decentralization of power over the infrastructure,

increasing transparency and codification of trust. For each affordance, we carry out a detailed analysis situating each in the context of Ostrom's principles, considering both the potentials of algorithmic governance and the importance of incorporating communities' social practices into blockchain-based tools to foster forms of self-governance. The relationships found between these affordances and Ostrom's principles allow us to provide a perspective focussed on blockchain-based commons governance.

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When Ostrom Meets Blockchain: Exploring the Potentials of Blockchain for Commons Governance

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Abstract
Blockchain technologies have generated enthusiasm, yet their potential to enable new forms of governance remains largely unexplored. Two confronting standpoints dominate the emergent debate around *blockchain-based* governance: discourses characterized by the presence of techno-determinist and market-driven values, which tend to ignore the complexity of social organization; and critical accounts of such discourses which, while contributing to identifying limitations, consider the role of traditional centralized institutions as inherently necessary to enable democratic forms of governance. In this article, we draw on Ostrom's principles for self-governance of communities to explore the transformative potential of blockchain beyond such standpoints. We approach blockchain through the identification and conceptualization of six affordances that this technology may provide to communities: tokenization, self-enforcement and formalization of rules, autonomous automatization, decentralization of power over the infrastructure, increasing transparency, and codification of trust. For each affordance, we carry out a detailed analysis situating each in the context of Ostrom's principles, considering both the potentials of algorithmic governance and the importance of incorporating communities' social practices into *blockchain-based* tools to foster forms of self-governance. The relationships found between these affordances and Ostrom's principles allow us to provide a perspective focused on blockchain-based commons governance.

Keywords
algorithmic governance, blockchain, commons governance, commons-based peer production, decentralization

Introduction

The growth of the blockchain development ecosystem has encompassed the rise of a new generation of applications and capabilities which surpass those of cryptocurrencies. We can find applications beyond Finance in multiple sectors (Hassan et al., 2020), including supply chains, energy, internet of Things or, notably, governance. In this article, we draw on the work of the Nobel laureate economist Ostrom (1990) to focus on the relationship between blockchain properties and the generation of potentialities that could facilitate governance processes. Ostrom's research showed that under certain conditions resources can be managed in a sustainable way by local communities of peers. Her work, therefore, enables us to reflect on the use of blockchain technologies to foster experimentation with new forms of *blockchain-based* governance in ways that go beyond markets and public administration. With this purpose, we develop from classic studies on the organizational aspects of how commons are governed and evaluate the potential use of blockchain technologies in this context. The purpose is twofold: on one hand, this work aims to throw some light on the current—and often polarized—theoretical discussions concerning both the transformative potentials of blockchain, and the consideration of emerging decentralized technologies to facilitate a new generation of commons-oriented communities. On the other hand, this analysis expects to facilitate the development of blockchain-enabled software tools which rely on commons-oriented principles, with practical examples to draw inspiration from.

In the case of blockchain-related technologies, we are still witnessing the early stages, and thus their future potential is just starting to be explored. The first cryptocurrency based purely on a peer-to-peer system, Bitcoin, was presented in

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November 2008 in a paper published pseudonymously (Nakamoto, 2008). For the first time, no third parties were necessary to solve problems such as double-spending, while providing a novel consensus method. The solution was achieved through the introduction of a data structure known as a blockchain. In simple terms, a blockchain can be understood as a distributed and append-only ledger. Data, such as the history of transactions generated using cryptocurrencies, can be stored in a blockchain without the need to trust a third party, such as a bank server. Thus, blockchain enables the implementation of novel properties at an infrastructural level in a fully decentralized manner.

The first wave of blockchain technologies (2009–2013) starts with the advent of Bitcoin and the subsequent emergence of a broad range of cryptocurrencies ("altcoins"). The second wave (2014–today) is the extension of these blockchains with capabilities beyond currencies, that is, automatic agreements or complex tokens. These blockchains (most notably, Ethereum[1]) have introduced the ability to upload small snippets of code, so-called *smart contracts* (Szabo, 1997), directly onto the blockchain. Clauses are encoded in a manner by which they are automatically enforced and executed without the need for a central authority.

Thus, a complex set of smart contracts may be set up in such a way as to make it possible for multiple parties to interact with each other. This has enabled the emergence of a new kind of organization: the Decentralized Autonomous Organization (DAO). A DAO is a blockchain-based system that enables people to coordinate and self-govern themselves mediated by a set of self-executing rules deployed on a public blockchain, and whose governance is decentralized (i.e., independent from central control; Hassan & De Filippi, 2021). This may be understood as analogous to a legal organization, with legal documents that define the rules of interaction among members. Similarly, the DAO members' interactions are mediated by the rules embedded in the DAO code. And such rules are automatically enforced by the underlying technology: the blockchain.

Commonly associated with cryptocurrencies, the untapered potential of blockchain lies in its capacity to enable the implementation of novel properties at an infrastructural level in a fully decentralized manner. The properties most cited include immutability, transparency, persistency, resilience, and openness (Underwood, 2016; Wright & De Filippi, 2015). There have been other decentralized technical infrastructures with varying degrees of success which also reflect some of these properties, for example, the Web has been traditionally shown as an example of openness, although with varying persistence (Koehler, 1999), or BitTorrent peer-to-peer sharing networks are considered open, resilient, and partially transparent (Cohen, 2003). However, none of the existing decentralized technologies have enabled the presence of all these properties at once in a robust manner, while maintaining a high degree of decentralization. It is precisely this possibility of developing technological artifacts that rely on a fully decentralized infrastructure that has been generating enthusiasm, or "hype" according to some authors (Reber & Feuerstein, 2014), with regards to the potential applications of blockchain. It is worth noting that despite the promises, "full decentralisation" is a goal that is not fully realized by actual blockchain implementations (e.g., Beikverdi & Song, 2015).

In this article, we focus on some of these potential applications of blockchain. More precisely, we reflect on the relationship between blockchain properties and the generation of potentialities which could facilitate governance processes. Particularly, we focus on the governance of Commons-Based Peer Production (CBPP) communities. There are multiple examples of this phenomenon in a broad range of areas (Salcedo & Fuster-Morell, 2014), including well-known projects such as Wikipedia, a project to collaboratively write a free encyclopedia; OpenStreetMap, a project to create free/libre maps of the World collaboratively; Stack Exchange, which are Q&A communities which aim to provide accessible documentation; Thingiverse, which provides open 3D-printable digital designs; or Free/Libre Open Source Software (FLOSS) projects such as the operating system GNU/Linux or the browser Firefox.

The term CBPP, originally coined by Benkler (2002), refers to a model of socioeconomic production in which groups of individuals cooperate with each other to produce shared resources without a traditional hierarchical organization (Benkler, 2006). The mode of production of CBPP has been characterized as decentralized (Arvidsson et al., 2017; Forte et al., 2009; Rozas & Huckle, 2021), meaning there is a lack of a central organizing authority that coordinates the contribution of individual agents, which are instead able to collaborate without such centralized control. These two characteristics of CBPP—decentralization and the frequent use and production of shared resources—led us to explore the role of blockchain technologies in the context of supporting the coordination efforts of CBPP communities. This debate is frequently discussed from polarized approaches from both blockchain idealists and skeptics (as seen in section "Potentials of Blockchain for Commons Governance"). Meanwhile, it is emerging a growing ecosystem of blockchain projects aiming to contribute to the "social good" through peer-to-peer communities, although typically lacking awareness of how to appropriately support CBPP (Hassan et al., 2020). Thus, we aim to contribute to the ongoing debate with an analysis of which affordances blockchain technologies generate that may facilitate the governance[2] of, specifically, CBPP communities. We hope that this analysis will facilitate the implementation of new blockchain projects specifically designed to support these commons-oriented communities.

This article is structured as follows: The section "Potentials of Blockchain for Commons Governance" reviews the main standpoints on *blockchain-based* governance[3] and the section "Ostrom's Principles: Beyond Markets and Public Administration" provides an overview of Ostrom's principles employed to carry out our analysis. The section "Affordances Generated by Blockchain for Commons Governance" places our argument in the context of a set of identified affordances drawing on Ostrom's principles: tokenization, self-enforcement and formalization of rules, autonomous automatization, decentralization of power over the infrastructure, increasing transparency, and codification of trust. We conclude, in section "Discussion and Concluding Remarks," providing a discussion of the contribution provided by the identification of these affordances as a result of bringing together literature on CBPP and blockchain-based governance.

Potentials of Blockchain for Commons Governance

The use of blockchain technologies to facilitate governance processes is beginning to attract the attention of social scientists (Risius & Spohrer, 2017). The emergent literature revolves around speculation on whether blockchain technologies could foster the experimentation and rise of new forms of *blockchain-based* governance.

Two confronting standpoints dominate the emergent debate on blockchain and governance. On one hand, there are perspectives characterized by a high degree of techno-determinism. These perspectives envisage the emergence of new forms of *blockchain-based* governance on the basis of the potential of these technologies for decentralization and trustlessness. These discourses inherently embed the idea of "market" and tend to ignore the complexity of social organization. For example, they commonly assume that hierarchies between the participants in decision-making processes vanish: thanks to the disintermediation enabled by blockchain technologies (e.g., Hayes, 2016; Heuermann, 2015; Swan, 2015). Overall, they tend to provide reductionist accounts with regards to the distribution of power, failing to acknowledge issues such as the generation of oligarchies (De Filippi & Loveluck, 2016; Freeman, 1972; Shaw & Hill, 2014). These techno-determinist perspectives are not new, nor a particular issue for blockchain technologies: they resemble, for example, the techno-determinist discourses during the popularization of access to the internet in the 1990s (Wellman et al., 2006). Still, they seem to be reinvigorated from the multiple scenarios that blockchain technology brings, as an exemplification of Hayek-like libertarian views (Bodon et al., 2019).

On the other hand, a critical stand against these techno-determinist perspectives has successfully identified and criticized the limitations of such approaches (e.g., Atzori, 2015; Atzori & Ulieru, 2017). Nevertheless, this critique is built upon the reinforcement of the role of central authorities, resembling traditional responses against unregulated markets. In other words, these views consider traditional central authorities as inherently necessary to enable democratic governance and, as a result, ignore the potential for communities, such as the aforementioned CBPP communities, to successfully self-organize. By drawing on this assumption, the potentialities of blockchain are envisioned in non-transformative ways: to support the control required by traditional centralized forms of governance, for example, providing more transparency to their central institutions (Nguyen, 2016) or more efficient mechanisms to avoid tax fraud (Ainsworth & Shact, 2016).

In this article, we reflect on the extent to which it would be feasible to incorporate into the development of *blockchain-based* tools principles from commons governance. We contribute a perspective which neither relies on the logics of private markets, as implicitly assumed by these former perspectives, nor on the coercion of traditional centralized institutions, as in the case of the latter accounts. To this end, we bring together the literature on governance of CBPP for the emerging debate on these new forms of *blockchain-based* governance.

Recently, a few authors have attempted to link the commons with blockchain capabilities, either at a general conceptual level (Bollier, 2015; Davidson et al., 2018; O'Dwyer, 2015) or proposing specific theoretical systems (Cila et al., 2020; Ducrée et al., 2020; Pazaitis et al., 2017). Some relevant attempts include Calcaterra (2018), who hastily mentions how Ostrom's governance principles could be applied to DAOs, and Shackelford and Myers (2017), who review the applicability of these principles focusing on governance *of* blockchains (instead of *by* blockchains). Other authors, without mentioning blockchain, consider how Ostrom's principles could be formalized and mathematized (Pitt et al., 2012, 2017), or applied to algorithmic governance (Clippinger & Bollier, 2014).

In contrast, in this article, we will perform a detailed and systematic analysis of the affordances of blockchain for CBPP community governance which brings previous literature on organizational aspects of CBPP together with the emerging literature on *blockchain-based* governance. In other words, we explore functional and relational aspects that, while not determining, shape and frame the possibilities for agentic action of CBPP communities with respect to the blockchain (Hutchby, 2001). This approach is in line with previous studies of technical affordances in the study of the internet (Wellman, 2004), social media (boyd, 2010), and social movements (Juris, 2016), to name but a few examples. Thus, the aim of this article is to study which affordances blockchain technologies generate that may facilitate the governance of CBPP communities.

With this aim, we develop from classic studies on the organizational aspects of commons governance, and evaluate the potential use of blockchain technologies in this context. More specifically, we contribute to this discussion by drawing on the work of the Nobel laureate economist Ostrom (1990), whose research showed that under certain conditions commons can be managed in a sustainable way by local communities of peers. Her work, therefore, enables us to reflect on the use of blockchain technologies to foster experimentation with new forms of *blockchain-based* governance in ways that go beyond markets and public administration. As mentioned above and expanded in section "Discussion and Concluding Remarks," we aim to contribute with a fresh perspective on the often polarized debate on the transformative power of blockchain, while facilitating the building of new software tools that seek to rely on commons-oriented approaches.

Ostrom's Principles: Beyond Markets and Public Administration

Ostrom's studies focused on how communities manage to successfully govern communal resources by revisiting Hardin's (1968) influential article on "The tragedy of the commons." In this article, Hardin states how resources shared by individuals acting as homo-economicus, that is, out of self-interest to maximize their own benefit, results in the depletion of the commons. The individuals' interests enter into conflict with the group's, and because they act independently according to their short-term interests, the result of the collective action depletes the commons. As a consequence, the traditional view was that to avoid this logic, it was necessary to manage these commons through either private ownership or public administration. Parallels can be found between these standpoints and those previously summarized with regards to the emergent discussion on new forms of *blockchain-based* governance: they envision forms of governance which either rely on markets or on traditional forms of public administration.

Refuting Hardin's argument, Ostrom's work shows how, under certain conditions, commons can indeed be managed in a sustainable way by local communities of peers. Her approach takes into account that individual agents do not operate in isolation, nor are they driven solely by self-interest, that is, beyond homo-economicus approaches. Instead, she argues that communities communicate to build common protocols and rules that ensure their sustainability. This hypothesis was strongly supported by a meta-analysis of a wide range of case studies of communities managing as diverse resources as fisheries or irrigation infrastructure (Ostrom, 1990), and has been confirmed in later research (Cox et al., 2010; Ostrom, 2009). Furthermore, her work was subsequently employed to understand how communities develop and maintain digital commons (e.g., Fuster-Morell, 2010; Hess, 2008; Hess & Ostrom, 2007), such as Wikipedia (Forte et al., 2009; Viégas et al., 2007) and Free/Libre Open Source Software (Rozas, 2017), and even to understand how online communities share copyrighted materials through P2P networks avoiding free-riding (Harris, 2018). As part of this work, she identified a set of principles (Ostrom, 1990) for the successful management of these commons:

1. Clearly defined community boundaries: to define who has rights and privileges within the community, for example, to use certain resources or to perform certain actions on them.
2. Congruence between rules and local conditions: the rules that govern behavior or commons use in a community should be flexible and based on local conditions that may change over time. These rules should be intimately associated with the commons, rather than relying on a "one-size-fits-all" regulation.
3. Collective choice arrangements: to best accomplish congruence (Principle number 2), people who are affected by these rules should be able to participate in their modification, and the costs of alteration should be kept low.
4. Monitoring: some individuals within the community act as monitors of behavior in accordance with the rules derived from collective choice arrangements, and they should be accountable to the rest of the community.
5. Graduated sanctions: community members actively monitor and sanction one another when behavior is found to conflict with community rules. Sanctions against members who violate the rules are aligned with the perceived severity of the infraction.
6. Conflict resolution mechanisms: members of the community should have access to low-cost spaces to resolve conflicts.
7. Local enforcement of local rules: local jurisdiction to create and enforce rules should be recognized by higher authorities.
8. Multiple layers of nested enterprises: by forming multiple nested layers of organization, communities can address issues that affect resource management differently at both broader and local levels.

Over the course of the next section, we draw on these principles to identify affordances generated by blockchain technologies which could foster, limit, or shape the governance of communities which collectively manage and produce commons.

Affordances Generated by Blockchain for Commons Governance

We incorporate the new generation of blockchain technologies and identify a set of affordances[4] (Hutchby, 2001), understood as the potential uses and applications these technologies enable. Each affordance is situated in the context of commons governance drawing on the aforementioned principles of Ostrom's work.[5] Table 1 provides a summary of the relationships between these affordances and Ostrom's principles.

To extract the affordances we have listed, we have aimed to cover the main properties of blockchain found in the literature, while focusing on those relevant for governance *by* blockchains (Ølnes et al., 2017), that is, the organization processes of communities which rely at least partially on blockchain infrastructure (e.g., an organization using a blockchain voting application to approve and fund a project), as opposed to governance *of* blockchains, that is, the organization processes of developers to

Table 1. Summary of the Relationships Between the Identified Affordances of Blockchain Technologies for Governance and Ostrom's (1990) Principles.

Affordance\principle	Tokenization	Self-enforcement and formalization	Autonomous automatization	Decentralization of power over infrastructure	Increasing transparency	Codification of trust
1. Clearly defined community boundaries	✓					
2. Congruence between rules and local conditions	✓	✓		✓		
3. Collective choice arrangements	✓			✓		
4. Monitoring		✓	✓	✓	✓	
5. Graduated sanctions		✓	✓			
6. Conflict resolution mechanisms			✓		✓	
7. Local enforcement of local rules		✓		✓		✓
8. Multiple layers of nested enterprises			✓			✓

build and evolve blockchains and their rules (e.g., the rules that check if that a transaction is valid in a cryptocurrency such as Bitcoin). The blockchain properties most cited include immutability, transparency, persistency, resilience, and openness (Underwood, 2016; Wright & De Filippi, 2015). However, properties concerning DAOs are also relevant to blockchain governance, even if not a property of blockchain itself. Taking these issues into account, we have decided to group the blockchain properties relevant to governance *by* blockchains into six affordances: (a) tokenization, or how blockchain facilitates the creation and management of tokens (Cong et al., 2020; Lo & Medda, 2020); (b) self-enforcement and formalization, referring to the self-enforcing capabilities of smart contracts, which facilitate formalizing rules as code (De Filippi & Hassan, 2016); (c) autonomous automatization, or how DAOs present new capabilities and challenges (DuPont, 2017); (d) decentralization of power over infrastructure, or how decentralized technologies enable new power dynamics between social and technical power (Forte et al., 2009); (e) increasing transparency, relying on the persistency and immutability properties which enable all users to access the blockchain data (De Filippi, 2018); (f) codification of trust, one of the most cited properties of blockchain, which supposedly enables "trustless" systems (Werbach, 2018).

To illustrate the identified affordances, we use a recurring example. We select a specific type of CBPP: a community network. In these communities, participants provide and manage technical infrastructure as a common resource to provide internet access. Examples of these communities include Guifi.net,[6] Ninux,[7] or Sarantoporo.[8] Usually, these communities involve complex governance including online and offline interactions at several levels of organization, from local nodes to umbrella communities.

Tokenization

An essential feature of blockchain technologies is their capacity for tokenization. Tokenization refers to the process of transforming the rights to perform an action on an asset into a transferable data element (named *token*) on the blockchain. For example, in the medical field, tokenization has been employed to provide authorization regarding access to reports (Azaria et al., 2016; Liu, 2016).

In the Bitcoin blockchain, the term *token* is used as an abstraction of the actual "coin," that is, the cryptocurrency being transferred among users. The rise of *blockchain-based* cryptocurrencies is a product of such a feature because blockchain's facility for the creation, transfer, and management of tokens in a distributed manner is unparalleled. This process of tokenization facilitates the distribution of value and incentives. Third parties, such as banks or gateways, are not necessary to transfer value between individuals or across networks. Furthermore, such tokens may be used as more than holders of monetary value: they may represent equity, decision-making power, property ownership, or labor certificates[9] (Huckle & White, 2016). This capacity for tokenization of blockchain technologies provides a series of affordances for technological artifacts constructed to facilitate governance. In the context of CBPP communities, tokenization relates to several of Ostrom's principles.

Ostrom's first principle states the importance of the definition of community boundaries for governance. These boundaries are reflected in the rules embedded in the software employed to coordinate communal activity in CBPP. This software typically defines permissions or rights to access or modify resources or community rules. In such a context, we can envision the use of tokens to construct tools, in which participation rights can be more easily and granularly defined, propagated, and/or revoked. For example, in the case of a community network, access to the infrastructure could be granted with tokens, for example, those people who have contributed enough infrastructure, or paid the agreed price, could access the internet through the community network. This specific use of blockchain has been proposed by Guifi.net, one of the largest, most prominent community networks (Kabbinale et al., 2019).

Negotiations regarding the definition of boundaries and their reflection in the technical artifacts connect additionally to the second and third principles of Ostrom. CBPP communities require constant processes of development of collective choice arrangements regarding their governance (e.g., Forte et al., 2009; Rozas, 2017; Schweik & English, 2013). They define rules based on local conditions, and seek to find ways in which those affected by these rules can participate in their modification, as understood in the second and third of the principles. For instance, to compensate contributions, Guifi.net differentiates between volunteers and professional actors, and further categorized professional actors depending on their level of commitment (from full to opportunistic).

Overall, the capacity for tokenization of blockchain technologies could be employed to readdress latent power relations in these communities. Negotiations in these communities, while maintaining a social character, would be mediated by *blockchain-based* artifacts which in turn would be communally constructed. This implies an exercise by the community to specify the tasks to be carried out providing an opportunity for certain often-forgotten tasks—such as care labor (Pérez-Orozco, 2014)—to be made visible. That is, care tasks, such as emotional labor, conflict management, maintenance, or events organization, may be made visible and acknowledged by the community—along with those undertaking such tasks. Tokenization, therefore, provides an opportunity to rethink existing power dynamics within CBPP communities.

In this respect, some concepts from feminist economic theory—such as that of invisible labor (Pérez-Orozco, 2014)—can shed light on the usefulness of blockchain-based tools for governance. Instead of narrowing the use of tokens to grant rights to access, we consider their potential to address the imbalance of invisible labor, such as making certain forms of power more visible, an issue which tends to become more critical when CBPP communities need to scale up their self-organizational processes.

While techno-determinist discourses assume that "anything that can be decentralized will be" (Johnston, 2014), and at least partially tokenized as a result, this is a controversial view, as tokenization also presents risks. An example of these risks includes extreme quantification and data fetishism (Sharon & Zandbergen, 2017). Thus, we must seek a balance in the limits regarding what kind of actions should or should not be tokenized, what kind of mechanisms are established to change the status quo, and how communities assess the desirable degree of tokenization in their governance. In other words, there is a need to further understand the affordance of tokenization and explore how self-organized communities may or may not incorporate it into the technological artifacts employed for collaboration and to what extent.

Self-Enforcement and Formalization of Rules

Blockchain entails an affordance for self-enforcement and formalization of rules which are intertwined with Ostrom's principles. Examples of these rules are those which regulate monitoring and graduated sanctions, as reflected in Ostrom's fourth and fifth principles. Blockchain technologies could partially embed some of these governance rules in technological artifacts. Scenarios in which communities define certain rules regarding the allocation of common resources —through actions such as pooling, capping, or mutualizing—and in which these rules are automatically enforced can be envisioned. Following previous examples, one can imagine a capping rule agreed by a community network which automatically enforces a previously negotiated internet bandwidth limit, or which automatically penalizes a misuse of the common network. Another example could consist of a set of self-enforced rules for a redistribution mechanism that grants internet access to those in the communities with fewer resources. It can be envisioned how at least a significant part of the monitoring could be embedded into the code, instead of requiring participants to manually perform some of these monitoring operations.

In addition, blockchain technologies require the rules to be unambiguously understood by machines. This implies a need to formalize the governance rules which are usually expressed in the inherently ambiguous natural language. Thus, this explicitation could lead to the need to discuss these rule changes to formalize and encode them. It therefore provides an affordance for formalizing rules which presents several limitations, which will be subsequently discussed, as well as a set of potentialities.

Research on how self-organization occurs in CBPP communities has shown that—counterintuitively to the initial accounts criticized by authors such as Viégas et al. (2007) or Mateos-García and Steinmueller (2008)—the changes experienced in the self-organizational processes of CBPP communities tend to show an increase in the degree of formalization around decision-making over time when they grow, which is explained as a means to achieve decentralization and to scale up communities (e.g., Forte et al., 2009; Rozas & Huckle, 2021; Schweik & English, 2013). This has been identified even in cases with a generally anti-bureaucratic attitude, such as communities with a strong hacker culture which aim to avoid formal and bureaucratized systems (Rozas, 2017). Thus, the process of explicitation of rules which is encompassed in the development of smart contracts related to the use of distributed technologies also provides opportunities to make these rules more available and visible for discussion, as noted in the second principle of Ostrom. Furthermore, formalization in combination with self-enforcement relates to the seventh principle of Ostrom: local nodes of CBPP communities could more easily ensure that the local jurisdiction[10] and enforcement of local rules is acknowledged by higher authorities or by other nodes.

For example, an organizational structure of a large community network in which a set of local nodes are federated, and each node possesses local autonomy to develop its own rules regarding the management of the local infrastructure. A node might be based in Madrid and another in Berlin. Rules can be established in which the autonomy to take decisions regarding the node in Madrid belongs, by code, to the participants of that node, and vice-versa. Furthermore, if higher authorities exist in this context, such as a European federation of nodes, to continue with our example, we can imagine rules which are self-enforced by code to ensure that the local aspects are only decided by participants of the local nodes. Overall, blockchain technologies provide affordances to foster the formalization and enforcement of this type of agreement.

Several issues, however, require further exploration with regards to the affordances of self-enforcement and formalization in the context of governance of CBPP communities. First, rules embedded in smart contracts rely on an *ex-ante* nature, rather than *ex-post* (De Filippi & Hassan, 2016). Instead of third parties or community members monitoring and enforcing them, the rules would be automatically enforced according to agreements previously negotiated by the community. While this theoretically increases the difficulty to breach them, it also presents problems with regards to the difficulty to define exceptions (De Filippi & Hassan, 2016). Ongoing recent blockchain projects, such as DAOStack[11] or Aragon,[12] provide the potential to more easily upgrade the rules embedded in smart contracts over time, in congruence with the second principle of Ostrom (congruence between rules and local conditions). Thus, this increasing capacity for upgradability which is being developed in the new generation of blockchain technologies could help incorporate these exceptions over time. However, even if a rule is updated after reaching an agreement in the community, the original code will have been applied and the new rules will only be applicable the next time. For instance, continuing with the example of community networks, a person could lose internet access due to a strict community rule that is later relaxed. From these limitations, we foresee at least two questions which require further empirical research: What are the consequences for CBPP communities of moving from *ex-post* forms of regulation toward *ex-ante*? Which aspects should remain in/off the blockchain, or further completely in/out of code?

Second, the process of formalization of these rules requires, at least with the most current technology, a high degree of technical knowledge in the translation of these rules into source code. Thus, while formalization might help make these rules more visible and available for discussion in the community, the power to specify these rules may now be shifted to those coding them. In this context, it is necessary to consider the biases—such as gender, race, and class (Platero, 2014)—of those possessing this technical knowledge. Another issue to be considered is the tendency toward accommodation or less reflexivity over time as a consequence of automation (De Filippi & Hassan, 2016).

Third, in a similar way as with the risk of extreme tokenization presented in the previous section, there is a risk of extreme formalization in the rules that regulate the behavior of participants in these communities. The effects are unknown. Ostrom's work highlighted, for example, the relevance of informal social norms (Ostrom, 2000) for the successful self-management of resources. The effects of an excessive formalization of norms into explicit rules self-enforced "by code" might become a source of distortions within the dynamics of the communities.

Autonomous Automatization

DAOs present multiple, unparalleled characteristics. The level of autonomy of these pieces of code surpasses all forms of autonomous software agents (Franklin & Graesser, 1997). Because DAOs do not rely on central servers, DAOs cannot be shut down, unless explicitly programmed in their code. Thus, they are fully autonomous including with respect to their creator, and they function as long as a user (human or software) continues to interact with them. This may prevent censorship and the halt of malicious code, for example, a virus. In addition, DAOs may interact as autonomous users in the network, holding tokens and assets, or purchasing services from other DAOs. In fact, they can even *hire* users to perform tasks for them, and *sell* their own services or resources to third parties. Hence, individuals can transact with a DAO to benefit from the service it provides, or to be paid for a contribution. Thus, DAOs may be self-sufficient, to the extent that they can charge users for their own services (or assets) to pay for the services they need (De Filippi & Hassan, 2016).

There is already an emerging ecosystem of DAO examples (El Faqir et al., 2020), of which may mention a few examples: the venture capital fund with the (confusing) name, "TheDAO,"[13] which was one of the earliest examples; the prediction market, Augur;[14] the digital assets platform focused on gold assets, Digix;[15] or the decentralized exchange with a stable coin, MakerDAO.[16] As it is true for the vast majority of projects in the blockchain field, they are directly related to finance, although there are already some nonfinancial examples such as the virtual world Decentraland,[17] or the job market Ethlance.[18] These DAOs are designed to work in a decentralized manner without central intermediaries, yet their governance model is strictly market-driven. For instance, in TheDAO, voting power was correlated to the number of tokens possessed, that is, it works as a plutocracy, controlled by the wealthy minority (as opposed to a democracy).

However, DAOs provide new possibilities with regards to CBPP. In fact, scenarios in which DAOs aid several of Ostrom's principles can be conceived. As mentioned in the previous section, smart contracts may help in the monitoring and application of sanctions for those violating the community rules (fourth and fifth principles). When DAOs are considered, this feature is strengthened because communities may rely on an automated entity for such monitoring and sanctioning. The agency of this entity, which may take the initiative and react upon circumstances, may have multiple implications. On one hand, its impersonalization may be positive to see that sanctions come from a community decision, preventing the common effect of reacting against the enforcer ("killing the messenger"). On the other hand, the same impersonalization may trigger frustrations and impotence (Frost & Postman, 1993) similar to the reactions against machines.

DAOs may also contribute to higher degrees of automatization of the processes in communities, facilitating scaling up and thus the creation of layers of nested entities, as the eighth principle states. Because we are aware that scaling up communities involves an increase of formalization and bureaucratization (e.g., Forte et al., 2009; Rozas, 2017; Schweik & English, 2013), a higher degree of automatization of processes could reduce the burden of bureaucracy, accelerate processes, and facilitate scaling up. For instance, in a community network with multiple nodes, it is common to have multiple spaces for coordination, monitoring, verification, or transfers of value and resources.

Despite clear rules, the need remains for humans to carry out multiple actions. Many communities rely on software to automate parts of this process, although this implies either governance of such software/infrastructure, or dependence on third parties and their rules for their inner processes. In such a context, a DAO can be set up to facilitate interaction and coordination across nodes. Once the rules are agreed and clear, they can be embedded in the DAO code, which can automate a large proportion of the processes, monitoring the nodes' actions, facilitating coordination, even transferring value and resources in relation to the nodes' contributions. In fact, this may be scaled up easily, with DAOs coordinating other "smaller" DAOs. Also, if other communities have their own DAOs, it may be easier to establish cooperation across communities.

To continue with previous examples, we could expect collaboration among different community networks, granting internet access to all members of any other community. These communities could share information about unconforming users to prevent network abuses and could even negotiate exchanges to account for the differences in use of the networks, scaling the compensation mechanisms that already exist within these communities.

Finally, DAOs provide a space in which governance is digitalized and formalized, and where most organizational processes should be tackled in some way, including conflicts. That is, governance formalization demands an exploration of the potential conflicts which may occur, and their possible resolution. This is directly related to Ostrom's sixth principle. Combined with the aforementioned automatization and scaling up, we may observe a space in which conflicts are made explicit, between members of a DAO, across DAOs, and between DAOs and humans. This encourages communities to establish clear mechanisms for conflict resolution, which may be at least partially tackled by automated processes. In fact, projects such as Aragon[19] are already working on creating digital jurisdictions for conflict resolution within, and across, DAOs. Moreover, community networks such as Guifi.net already use conflict resolution systems similar to these proposals, standardizing how conflicts should be resolved aiming to reduce the time and increase the scalability of conflict resolutions (Baig et al., 2015).

There are, however, some shortcomings of this affordance. Indeed, such a "DAO world" has multiple potentials, and yet, it is worth remembering that DAOs are constrained to the digital world. That is, digitalization is expanding quickly and affecting the physical world in multiple ways, and yet the physical world continues to operate with its own rules. Although techno-determinist views often disregard this fact, humans have bodies, which are constrained by their physical reality, and cannot be ignored or "disappear" in cyberspace (Le Breton, 2015). Thus, DAOs may allow digital voting, but a DAO cannot know if a person is being coerced to vote in a certain way. DAOs may allow the transfer of digital assets, and yet laptops can be stolen.

In the same vein, DAOs may hire services or resolve conflicts, and yet there is a legal framework that humans are subject to that may contradict the DAOs' decisions. In fact, DAOs open up multiple unresolved challenges with respect to law (De Filippi & Wright, 2018). For instance, on liability, they are as follows: Who is liable for a DAO misaction, such as the loss of money? The creator of the DAO, who may not control it? The members of the DAO, who could influence its evolution? The project managing the blockchain where the DAO operates? Or is it worth considering the DAO itself as a subject of liability?

Summing up, the use of DAOs for commons governance remains speculative, and it may imply challenges and risks. However, multiple opportunities may arise from using these new "agents" as automatic helpers for communities, which would enable the automatization of bureaucratic processes, facilitate scaling up, and making conflict resolution mechanisms more explicit.

Decentralization of Power Over Infrastructure

This affordance refers to the process of communalizing the ownership and control[20] of the technological artifacts employed by the community through the decentralization of the infrastructure they rely on.

This affordance can be illustrated when exploring the relationships between technical and social power (Forte et al., 2009) which occur in CBPP communities together with the forms of pressure which surround them. The control over the infrastructure that sustains, for example, the main platforms of collaboration, commonly emerges as a point of tension and conflict. When CBPP communities start to grow substantially, they normally try to decentralize control over this infrastructure, which is commonly achieved by incrementing the degree of formalization, for example, defining more explicit and rigid organizational processes, roles and even formal institutions, such as identified for Wikipedia (Forte et al., 2009) or FLOSS communities (Rozas, 2017). These organizational changes entail constant negotiation which, when framed through Ostrom's principles, can be understood as part of the generation of collective choice arrangements (third principle) and do not commonly occur in a scenario of equality in terms of power.

The use of decentralized technologies offers, in this respect, a promising field of experimentation and exploration of potential changes in the relationships between technical and social power. An illustration can be found in the "right to fork" which, while it may be perceived as an aspect unique to FLOSS communities, has indeed been identified in other CBPP communities (Jemielniak, 2016; Tkacz, 2014). The inherent properties of decentralized technologies facilitate the forking of the whole infrastructure and, as seen, even the communitarian rules encoded in smart contracts. In other words, those in control of the infrastructure might not only fear the forking of the contents (e.g., source code or wiki pages), but of the whole infrastructure and a large set of the codified community rules. These examples allow us to imagine scenarios of the possible opportunities gained by decentralizing power over infrastructure in CBPP. Decentralized technologies may shape these dynamics by offering a higher degree of pressure for negotiation on those holding more power in the community and fostering permissionless innovation (Thierer, 2016).

Continuing with our community network example, part of the centralized infrastructure—such as that related to monitoring and compensating imbalances in the uses of the shared infrastructure—could be decentralized (Rozas, 2020). Community networks, such as Guifi.net, have developed compensation systems as part of their governance which relate to several of Ostrom's principles (Baig et al., 2015). Decentralization of the infrastructure reduces the technical cost to fork the infrastructure, reducing the power within the community of those previously in control of it.

When we analyze this affordance through Ostrom's principles, we identify a set of aspects which relate to them. First, those holding more power within the community may experience higher pressure with regards to the constant processes of negotiation of collective choice arrangements—the third principle. Second, in connection with the fourth principle of Ostrom, those monitoring the commons could also experience new forms of pressure regarding their expected accountability in the eyes of the community. Third, within this scenario, the decentralization of power over infrastructure could facilitate permissionless innovation and thus a higher degree of autonomy[21] to the local spaces which emerge over time. Thus, the differences in the forms of pressure may provide new conditions for the negotiations that relate to having their local contexts and jurisdictions acknowledged by higher authorities—in congruence with the second and seventh principle of Ostrom, respectively.

Nevertheless, the affordance for decentralization of power over infrastructure is not free of risks. A risk that can be expected is a shift of power to those coding the rules, as previously discussed for the cases of tokenization, self-enforcement, and formalization of rules. In addition, the aforementioned higher degree of pressure for negotiation or permissionless innovation could result in increasing risks of the constant fragmentation of the community. The issue is not new. Large CBPP communities, for example, constantly aim to navigate these tensions to "loosen control without losing control" while trying to scale up (Rozas & Huckle, 2021). The key resides in furthering our understanding on how to integrate this affordance for decentralization of power over the infrastructure into the day-to-day practices of these communities.

Increasing Transparency

Increasing transparency refers to the process of opening the organizational processes and the associated data by relying on the persistency and immutability properties of blockchain technologies. Blockchain enthusiasts envision a blockchain governance as one that "takes advantage of the public record-keeping features of blockchain technology: the blockchain as a universal, permanent, continuous, consensus-driven, publicly auditable, redundant, record-keeping repository" (Swan, 2015, p. 44).

Blockchain technologies provide a potential for CBPP communities to socially construct software in which certain actions and operations are more easily trackable, auditable, and communally fiscalized by their participants. CBPP communities have, indeed, a long tradition of aiming to make their processes as open and participative as possible. Examples of these data are the materials generated as a result of encounters when decisions are made, or the indicators of the degree of participation in the community. This strong culture of openness and participation in CBPP communities connects with the fourth and sixth principles of Ostrom (monitoring and conflict resolution). The opening of the data generated in the collaboration processes in the communities is a useful means by which CBPP communities successfully carry out and scale up their processes of monitoring. They increase the legitimacy of these processes and provide means of accountability for those who participate in them in the eyes of the community. These data are also commonly employed as part of conflict resolution mechanisms as well as in the constant processes of negotiation. One can think, for example, of the enormous amount of contents which can be found in the discussion pages of Wikipedia or in the issues lists of FLOSS communities. These large amounts of data are not solely related to the contents but also to the organizational processes themselves.

The experimentation with software drawing on blockchain technologies provides new possibilities for CBPP communities to track and communally fiscalize new aspects of their processes. Continuing with the example of community networks, this transparency can help identify who uses more resources, the community can then either try to grant these resources or to penalize excessive usage; those who contributed more can also be rewarded or recognized accordingly. For instance, in the case of the aforementioned compensation system of Guifi.net (Baig et al., 2015), it would facilitate the monitoring beyond central points of control (Rozas, 2020).

As with the previously discussed affordances, however, commons-based approaches toward the use of *blockchain-based* tools for governance should be aware of the limitations. Khan (2017), for instance, places this into the more general discussion of privacy and the right to be forgotten in the digital age (Mayer-Schonberger, 2009). The permanent nature of blockchain opens up scenarios in which "everything is recorded" and "will forever tether us to all our past actions, making it impossible, in practice, to escape them" (Rosen, 2010). Extreme transparency in the context of self-governance of CBPP communities raises similar questions: What kind of participation information should be permanently stored? Or, how might a scenario with a higher degree of transparency shape the development of participants' identities in the communities?

Codification of Trust

Trustlessness is one of the most cited characteristics by blockchain enthusiasts to argue for the disruptive potential of this technology. When framed in terms of processes, it can be understood as that of codifying trust into "trustless systems" developed under a blockchain. In simple terms, trustless systems are those which enable participants to enter into an agreement, without requiring a third party to provide a certain degree of trust between them.

Commons-based approaches require a re-interpretation of "trustlessness" as a partial property, however, which may act as a potential source of affordances in the context of commons governance. An example of these limitations relates to the transfer of trust encompassed in the design and development of these trustless systems. For example, when considering the use of smart contracts to facilitate governance, trust is transferred to the code that defines them, and subsequently to those who write the code. In fact, some have characterized blockchains as a new architecture of trust (Werbach, 2018).

The codification of trust can bring interoperability into CBPP communities. In technical terms, interoperability refers to the property of a system to operate with other systems through a series of software interfaces. Blockchain provides affordances to increase the degree of collaboration through the generation of interoperable interfaces and, furthermore, providing a full communal infrastructure. In practice, blockchain has been cited as enabler of interoperable ecosystems, for instance, in Internet of Things (Reyna et al., 2018), although global standards are still rare beyond templates (such as those from Open Zeppelin), Ethereum-like Request for Comments (RFCs, that is, ERCs), and some fractioned attempts at inter-blockchain interoperability (e.g., Interledger, Polkadot).

This affordance for the codification of trust relying on a communal infrastructure allows us to imagine potentialities at several levels: first—and in connection with the seventh and eighth principles of Ostrom—to facilitate internal interoperability among the different groups or nodes that form part of CBPP communities, or the multiple layers of nested enterprises in Ostrom's terms.

Returning again to our previous example of a community network—with local nodes in Berlin and Madrid—one can envision artifacts designed to facilitate the governance of CBPP communities in the form of different platforms which are customized according to local conditions. These platforms could be autonomously governed by the participants who belong to each of the nodes, but interoperate between them and/or with a federal platform at a broader level. The process of codification of trust would not simply refer to the individuals and their interactions. Instead, it could include the agreements arranged between the nodes that form part of the community, fostering the capacity of these communities to scale up some of their self-organizational processes.

Second, a blockchain as a common database infrastructure generates affordances for interoperability beyond the boundaries of a particular CBPP community. For example, a set of smart contracts which encode agreements between community networks, or by reflecting the decisions made by different community networks with regards to their different notions of value (Rozas et al., 2021) and ways to make them interoperable (De Filippi & Hassan, 2015). Nevertheless, as with the previously discussed affordances, the processes related to the codification of trust in ways that facilitate interoperability between and within CBPP communities will remain as social processes of negotiation. As such, they are not exempt from similar risks as those discussed for the previous affordances.

Discussion and Concluding Remarks

We explored blockchain as an artifact to facilitate the governance of communities, with an emphasis on CBPP communities. CBPP communities are characterized by Ostrom's (1990) principles for commons governance, and our analysis showed the different affordances that blockchain technology provides to those communities in view of these. We contribute a systematic identification of such affordances and discuss their implications.

Our study does not only highlight blockchain affordances with respect to CBPP communities, but analyzes how each individual affordance may support Ostrom's principles and discusses how community governance may be affected. Moreover, we contribute to the emergent literature on *blockchain-based* governance by providing a novel perspective which does not rely on techno-determinist views and logics of private markets (e.g., Hayes, 2016; Heuermann, 2015; Swan, 2015), nor on the assumption of the need for coercion by traditional centralized institutions (Atzori, 2015). Our perspective allows us to open up new questions for exploration. Examples of these research questions are those discussed with regards to the limits of the processes of the tokenization or formalization of rules: Which aspects should remain in/off the blockchain, or further completely in/out of code? Thus, by providing a perspective focused on commons governance, we do not simply identify the potentialities, but also possible drawbacks and limitations which are not addressed by techno-determinist views, nor identified and properly analyzed by approaches that disregard the power of the self-organization of communities.

Furthermore, the identified affordances, which emerged by bringing together literature on the governance of commons within that of *blockchain-based* governance, can be employed as analytical categories (e.g., Rozas, 2020; Rozas, Díaz-Molina, 2019) to co-design *blockchain-based* tools to facilitate cooperation and foster CBPP practices. Table 1 provided a summary of these relationships between them and Ostrom's principles.

As discussed, CBPP communities face challenges trying to decentralize their organizational processes to scale-up. The relationships that we identify informed our analysis on the impact that decentralized *blockchain-based* technologies can have on governance processes in these communities. Examples of issues previously identified in the literature (e.g., Forte et al., 2009; Rozas & Huckle, 2021; Schweik & English, 2013) that relate to the identified affordances are the need to increase the degree of formalization of their processes to provide higher degrees of legitimacy, transparency, and trust. More generally, we find that *blockchain-based* technologies offer potentialities to facilitate coordination, help scale up commons governance and can even be useful to share agreements and different forms of value among various communities in interoperable ways.

Moreover, this study aims to contribute not only to the theoretical debate but also to provide ground for new blockchain projects to rely on, to build appropriate tools for CBPP communities. As mentioned above, there is already an emerging ecosystem of blockchain projects aiming to contribute to the "social good" through peer-to-peer communities, although typically lacking awareness of how to appropriately support CBPP (Hassan et al., 2020). There are though a few projects which do claim to rely on commons-oriented perspectives in different degrees, and thus we believe there is potential for our contribution to be of use. Relevant examples are the Commons Stack project,[22] the Backfeed project,[23] or the Aragon DAO platform which claims to rely on Benkler's work.[24]

In fact, there are already applications of this study which go beyond its theoretical contributions. The project P2PModels[25] has used this theoretical framework to inform the design and development of blockchain-based applications for established commons-oriented communities (e.g., Rozas, 2020; Rozas & Díaz-Molina, 2019). Besides, another paper provides design guidelines for tools relying on this work (Cila et al., 2020).

In sum, this article identifies blockchain affordances and connects them to Ostrom's principles for commons governance. We contribute to the emergent debate on *blockchain-based* governance through a commons-based approach while also providing a basis for the essential empirical research needed to improve our understanding of the role of blockchain technologies for the governance of communities.

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Notes

1. See https://www.ethereum.org (accessed September 27, 2019).
2. By "governance" we draw on Fuster-Morell's (2014) analysis and characterization of commons governance as a complex system, which incorporates social norms and the role played by the infrastructure.
3. This article focuses on governance through or with blockchains, rather than on governance of the communities which develop and maintain blockchain projects.
4. Concretely, we consider the affordances of *public permissionless* blockchains, that is, blockchains which new participants can freely join and use.
5. Table 1 summarizes the relation among the affordances and Ostrom's principles.
6. See http://guifi.net (accessed September 27, 2019).
7. See http://ninux.org (accessed September 27, 2019).
8. See http://www.sarantaporo.gr (accessed September 27, 2019).
9. Similar to those described by Marx (1875).
10. In this context, we refer to jurisdiction as the area over which the members of a communitarian node have control (Sullivan, 2009).
11. See https://daostack.io (accessed September 27, 2019).
12. See https://aragon.one (accessed September 27, 2019).
13. See https://medium.com/swlh/the-story-of-the-dao-its-history-and-consequences-71e6a8a551ee for the history of TheDAO that suffered a large "hack," which influenced the blockchain ecosystem and its evolution (accessed September 27, 2019).

14. See https://augur.net (accessed January 10, 2019).
15. See https://digix.io (accessed September 27, 2019).
16. See https://makerdao.com (accessed January 10, 2019).
17. See https://decentraland.org (accessed January 7, 2020).
18. See https://ethlance.com (accessed January 7, 2020).
19. See https://github.com/aragon/whitepaper (accessed October 3, 2019).
20. As discussed in Footnote 3, in this article, we focus our analysis on governance through blockchains. For this reason, we will not tackle the relationships between technical and social power in the underlying protocols (Atzori, 2015). Examples of these are the identification of strategies regarding the mining protocol to control the system by Eyal and Sirer (2014), and the inequalities generated by the accumulation of hashing-power.
21. The coordination of different local groups would tentatively require a higher degree of interoperability. Interoperability will be discussed in further detail as part of the affordance of codification of trust.
22. Commons Stack aims to build "commons-based microeconomies to sustain public goods through incentive alignment, continuous funding and community governance" with "web3 components" (aka blockchain components; https://commons-stack.org).
23. Backfeed is a novel system of value which relies on the blockchain and aims to aid the creation of commons-oriented ecosystems (Pazaitis et al., 2017).
24. Aragon is a platform to facilitate the creation of new DAO communities. See https://wiki.aragon.org/about/history/ for some background on their inspiration from Benkler's theories.
25. See https://www.p2pmodels.eu (accessed February 23, 2021).

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5.2 Analysis of the Potentials of Blockchain for the Governance of Global Digital Commons

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Abstract

In recent years, the increasing need for global coordination has attracted interest in the governance of global-scale commons. In the current context, we observe how online applications are ubiquitous, and how emerging technologies enable new capabilities while reshaping sectors. Thus, it is pertinent to ask: could blockchain technologies facilitate the extension and scaling up of cooperative practices and commons management in this global context? In order to address this question, we propose a focus on the most paradigmatic and widely successful examples of global cooperation: global digital commons. Examples of these are the digital resources maintained by large peer production communities, such as free/libre open source software and Wikipedia. Thus, this article identifies and analyzes the potentialities of blockchain to support the sustainability and management of global digital commons. Our approach draws on Elinor Ostrom's classic principles for commons governance, although revisiting and adapting these to the more challenging scope of global digital commons. Thus, in this work we identify the affordances which blockchain provides (e.g., tokenization, formalization of rules, transparency or codification of trust) to support the effective management of this type of global commons. As part of our analysis, we provide numerous examples of existing blockchain projects using affordances in line with each principle, as well as potential integrations of such affordances in existing practices of peer production communities. Our analysis shows that, when considering the challenges of managing global commons (e.g., heterogeneity or scale), the potential of blockchain is particularly valuable to explore solutions that: distribute power, facilitate coordination, scale up governance, visibilize traditionally invisible work, monitor and track compliance with rules, define collective agreements, and enable cooperation across communities. These affordances and the subsequent analysis contribute to the emergent debate on blockchain-based forms of governance, first by providing analytical categories for further research, but also by providing a guide for experimentation with the development of blockchain tools to facilitate global cooperation.

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Analysis of the Potentials of Blockchain for the Governance of Global Digital Commons

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In recent years, the increasing need for global coordination has attracted interest in the governance of global-scale commons. In the current context, we observe how online applications are ubiquitous, and how emerging technologies enable new capabilities while reshaping sectors. Thus, it is pertinent to ask: could blockchain technologies facilitate the extension and scaling up of cooperative practices and commons management in this global context? In order to address this question, we propose a focus on the most paradigmatic and widely successful examples of global cooperation: global digital commons. Examples of these are the digital resources maintained by large peer production communities, such as free/libre open source software and Wikipedia. Thus, this article identifies and analyzes the potentialities of blockchain to support the sustainability and management of global digital commons. Our approach draws on Elinor Ostrom's classic principles for commons governance, although revisiting and adapting these to the more challenging scope of global digital commons. Thus, in this work we identify the affordances which blockchain provides (e.g., tokenization, formalization of rules, transparency or codification of trust) to support the effective management of this type of global commons. As part of our analysis, we provide numerous examples of existing blockchain projects using affordances in line with each principle, as well as potential integrations of such affordances in existing practices of peer production communities. Our analysis shows that, when considering the challenges of managing global commons (e.g., heterogeneity or scale), the potential of blockchain is particularly valuable to explore solutions that: distribute power, facilitate coordination, scale up governance, visibilize traditionally invisible work, monitor and track compliance with rules, define collective agreements, and enable cooperation across communities. These affordances and the subsequent analysis contribute to the emergent debate on blockchain-based forms of governance, first by providing analytical categories for further research, but also by providing a guide for experimentation with the development of blockchain tools to facilitate global cooperation.

Keywords: algorithmic governance, blockchain, distributed systems, global commons, digital commons, Ostrom, peer production

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INTRODUCTION

This article explores the potentialities of blockchain linking it to the literature on the management of global digital commons. We draw firstly on Ostrom's classic governance principles (1990), which remind us how human communities have successfully self-organized to manage their common resources ("commons[1]"). Such principles provide guidance for the conditions a community should respect in order to be sustainable, effective, and successful in the long-term in its commons management. Ostrom's principles were, however, derived from studies of small-scale local communities. In this article, we explore the role of emergent blockchain technologies as an opportunity to improve and scale-up communities' governance within a global scale. Concretely, we draw on the challenges of Ostrom's principles when adapted to global commons, identified by Stern (2011), in order to explore how blockchain technologies could help to overcome some of the limitations of Ostrom's principles. Our analysis focuses on global and digital commons, such as the digital commons generated and maintained by Wikipedia or large Free/Libre Open Source Software Software (FLOSS) communities, building on Commons-Based Peer Production (CBPP) literature.

Commons Governance at a Global Scale

Ostrom (1990) studied commons-based communitarian practices and identified eight design principles[2] that contributed to the sustainable management of commons. These principles include diverse considerations such as the need to define boundaries in the community, having participatory and inclusive decision-making, or appropriate conflict resolution mechanisms. These principles remain a source of inspiration for the new global challenges. However, under the global scale of the resources and the communities which manage them, these principles require further re-consideration. Stern (2011) analyzed the degree to which Ostrom's design principles were transferable to the management of global commons. The conclusion was that, although they have considerable external validity, Ostrom's classic principles required adaptation when applied to global commons (Stern, 2011, 229). This conclusion is in line with the evaluation of the applicability of these principles to global commons undertaken by Ostrom herself (Ostrom et al., 1999, 281–282). Ostrom identified a set of challenges for global commons regarding governance, that include difficulties to scale up participation and define collective choices, challenges due to the cultural diversity, complications because of increasing rates of interdependency and change, and the fact that global commons depend on a single planet, from which there is no place to move.

Considering the challenges posed by global commons, in this article, we explore the potentialities of *blockchain-based governance* in a global context. Concretely, we look at the role of blockchain in the context of CBPP communities managing global commons in the form of digital resources. The term CBPP, originally coined by Benkler (2002), refers to an expanding model of socio-economic production in which groups of individuals cooperate with each other to produce shared resources without a traditional hierarchical organization (Benkler, 2006). There are multiple, well-known examples of this phenomenon, such as Wikipedia, a project to collaboratively write a free encyclopedia; OpenStreetMap, a project to create free/libre maps of the World collaboratively; StackExchange, which are Q&A communities which aim to provide accessible documentation; Thingiverse, which provides open 3D-printable digital designs; or FLOSS projects such as the operating system GNU/Linux, the web server Apache, the content management system Drupal and the browser Firefox. Given the popularity of Wikipedia and FLOSS, we will use these as recurring examples of large CBPP communities throughout the paper.

Blockchain: Beyond Cryptocurrencies and Finance

Since its appearance with the proposal of Bitcoin, the first distributed digital currency, blockchain technology has attracted attention for its ability to support a global scale currency and its potential to coordinate large communities without centralized control or a centralized infrastructure. Blockchain is a distributed and append-only database which, drawing on cryptography, enables coordination over the Internet without requiring central parties. Its origins are to be found in an article published anonymously under a pseudonym (Nakamoto, 2008). Drawing on a new data structure, the blockchain, problems such as double-spending - how can you ensure that digital currency is not spent twice? - could be solved in a decentralized manner. The result was that third parties, such as bank central servers in this case, could be avoided.

Considering these origins, blockchain technologies are, unsurprisingly, commonly associated with cryptocurrencies, new markets around emergent currencies, and overall with the disruption of finance. Nevertheless, the potential of blockchain goes beyond cryptocurrencies: it lies in its capacity to enable the implementation of novel properties at an infrastructural level in a fully decentralized manner. These properties have significant potentials, for example, for the development of tools that mediate and scale up governance processes.

To frame our analysis and in order to incorporate the identified challenges for global commons in our analysis, Section "Local Versus Global Commons" discusses the differences between the types of commons studied by Ostrom and global digital commons. Then, Section "Applications of Blockchain for Commons Governance" introduces the debate on *blockchain-based* forms of governance to situate the potential affordances of blockchain technology in this context. Next, Section "Affordances of Blockchain for the Governance of Global Digital Commons" analyzes the role played by blockchain technologies, drawing on the aforementioned affordances, for the governance of global digital commons. The result is the identification of a set of potentialities of blockchain technologies to tackle challenges (Ostrom et al., 1999, 281–282) regarding the scaling up of governance in managing global commons since, as

[1]The commons are resources held in common, with shared ownership, and typically managed by a community under certain norms. It is distinct from both State or Market resource management. Classic examples include common lands or international waters, but also classical music (in public domain), a self-managed social center, the Internet, or Wikipedia.

[2]Section "Affordances of Blockchain for the Governance of Global Digital Commons" includes a definition of each of these principles.

the number of participants and heterogeneity of global CBPP communities increase, it becomes more difficult for them to organize and to reach agreements on rules and their enforcement. Section "Discussion and Conclusion" will discuss this result and provide some concluding remarks concerning the potential of blockchain to contribute to large CBPP communities in several ways.

LOCAL VERSUS GLOBAL COMMONS

For our analysis, we draw on Stern's (2011) identification of limitations of Ostrom's principles, which has been widely employed in the commons literature (e.g., Nayak and Berkes, 2012; Cox, 2014; Allen and Potts, 2016; Potts, 2019). In his analysis of the limitations of Ostrom's principles, Stern identifies a set of distinctive characteristics of the commons studied by Ostrom from which her principles were derived (Stern, 2011, 215). Developing from these characteristics, he identifies (Stern, 2011, 216–218) a series of differences between local and global commons that are relevant regarding governance. Stern's work, however, is focused on rival and global commons, such as global fossil supplies. Thus, in order to analyze the potentialities of blockchain for the governance of CBPP communities managing global digital commons, we need firstly to revisit these characteristics for the narrower scope of global digital commons.

According to Stern (2011, 215), the main characteristics of the commons studied by Ostrom, from which she derived her principles, are:

1. The commons studied by Ostrom are bounded at local to regional scale, in contrast to global commons. Thus, for the cases we are going to analyze, Stern's differences and limitations are aligned with those from our analysis.
2. The number of participants in Ostrom's case studies are in the tens to a few thousands, while in the global commons discussed by Stern, he assumes millions or even billions of actors involved. For our analysis, we consider large cases of CBPP communities, such as Wikipedia and large FLOSS projects such as Apache, Firefox and Drupal, that have from few millions to hundreds of thousands of participants (Fuster-Morell et al., 2016). Thus, we consider large CBPP communities, and incorporate Stern's limitations partially.
3. The third of the differences concerns the degradation of the commons, typical of rival commons. Digital commons, such as FLOSS or digital encyclopedias, are non-rival and, furthermore, sometimes anti-rival (Weber, 2004). Therefore, we do not include the limitations associated with this property in our analysis.
4. In the type of commons analyzed by Ostrom, the participants share common interests with respect to the management of the resource; while in the global commons discussed by Stern, their collective interests tend to diverge significantly. Tensions, regarding different interests, appropriation and co-optation by internal and external actors, are also a common problem in large CBPP communities (e.g., De Filippi and Vieira, 2014; Birkinbine, 2015; Sandoval, 2019). Therefore, we incorporate Stern's identified limitations regarding this characteristic in our analysis.
5. The participants in the management of commons studied by Ostrom share a common cultural and institutional context; while in the global commons discussed by Stern they come from "all cultures, all countries, all political-economic systems, all political ideologies, and so forth" (Stern, 2011, 217). While large CBPP communities managing global digital commons develop a common cultural context (Fuster-Morell, 2014), the challenges regarding cultural diversity, also identified by Ostrom et al. (1999, 281–282) for global commons, are similarly present in large CBPP communities. Therefore, we incorporate this characteristic and its derived limitations in our analysis.
6. Learning from experience is a possible strategy in the local commons studied by Ostrom, while it is unfeasible for the type of global commons analyzed by Stern. We discard this limitation placed by Stern, since the literature shows how large CBPP communities managing global digital commons develop mechanisms and structures to facilitate the learning and extension of communitarian practices (e.g., Viégas et al., 2007; Forte et al., 2009; Fuster-Morell, 2010, 2014; Rozas, 2017).

Table 1, derived from a similar summary as in Stern (2011, 216), summarizes the characteristics identified by Stern, but

TABLE 1 | Differences between local commons (Ostrom, 1990), rival global commons (Stern, 2011) and the type of global digital commons which we will discuss in our analysis.

	Local commons (Ostrom, 1990)	Rival global commons (Stern, 2011)	Global digital commons
1. Scale	Local	Global	Global
2. Number of participants	Tens to thousands	Millions to billions	Hundreds of thousands to a few millions
3. Actors' awareness of degradation	Resource use is a conscious purpose	Resource degradation is an unintended byproduct of intentional acts	Not applicable for digital commons
4. Distribution of interests and power	Benefits and costs mainly internal in a small group of participants	Significant externalities between participants and others	Externalities between internal participants and external actors, as in rival global commons
5. Cultural and institutional homogeneity	Homogeneous	Heterogeneous	Heterogeneous, but with a stronger shared communal culture than for rival global commons
6. Feasibility of learning	Good	Limited	Similar to that described for local commons, although typically online mediated

extends and adapts them to the narrower scope of global digital commons from which we will develop our analysis.

Having provided the ground to incorporate the limitations identified by Stern (2011) for Ostrom's principles to our context of analysis, we next discuss the general affordances of blockchain for commons governance.

APPLICATIONS OF BLOCKCHAIN FOR COMMONS GOVERNANCE

The use of blockchain technologies to mediate governance has been increasingly attracting the attention of social scientists (Risius and Spohrer, 2017; Cagigas et al., 2021). The result is a growing body of literature which revolves around discussions on whether blockchain technologies could foster the experimentation and rise of new forms of *blockchain-based governance*[3].

Within the debate about the potentialities of blockchain-based governance we find, on the one hand, a myriad of perspectives characterized by a high degree of techno-solutionism (Morozov, 2013). According to them, given the right code, in this case in the form of smart contracts[4] and DAOs[5] (Decentralized Autonomous Organization), blockchains allegedly can solve Humanity's problems by finding the right algorithms. In fact, this is considered inevitable – following techno-determinism – since "anything that can be decentralized will be" (Johnston, 2014). These perspectives, however, tend to simplify or simply ignore the complexity which lies behind social organization. For example, they usually assume that hierarchies between the participants might vanish thanks to the disintermediation enabled by the use of decentralized technologies (e.g., Heuermann, 2015; Swan, 2015; Hayes, 2016). In other words, they tend to provide over-reductionist accounts with regards to the distribution of power, failing to acknowledge issues such as the generation of oligarchies and the consequences of inherently embedding private market logics (e.g., Freeman, 2013; Shaw and Hill, 2014; De Filippi and Loveluck, 2016; De Filippi and Lavayssière, 2020). In this respect, we agree with Schneider (2019) in understanding decentralization not simply as a technical concept, but as a performative act whose socio-political consequences need further exploration, since the use of decentralized technologies does not inherently imply the decentralization of other outcomes, such as power. These types of issues, however, are not new. Parallels can be traced, for example, to the discourses which emerged during the popularization of access to the Internet in the 1990s, embedding ideas to "create a world that all may enter without privilege or prejudice accorded by race, economic power, military force, or station of birth" (Barlow, 1996). On this occasion, similar discourses are being generated, instead, around blockchain technologies.

On the other hand, a critical stand against these techno-solutionist perspectives, particularly the pioneering work of Atzori (2015), has identified and criticized the limitations of such approaches. This critical stand, however, tends to consider traditional centralized authorities as inherently necessary to enable democratic governance. As a result, as we have previously argued (Rozas et al., 2021b), this critical stand has ignored the potential of some collectives to self-organize. Again, the issue is not new. Similar responses can be traced when reflecting on unregulated markets from positions that, as a result, aim to strengthen the role of traditional centralized authorities.

This lack of commons-oriented perspectives into the emergent debate of *blockchain-based governance* led us to consider incorporating the principles of commons governance present in self-organized collectives into the development of blockchain-based tools (Rozas et al., 2021b). Our aim was to contribute to building perspectives which neither rely on the logics of private markets, as implicitly assumed by these former perspectives, nor on the coercion of traditional centralized institutions, as in the case of the latter accounts. The result was the identification of six affordances[6] (Hutchby, 2001), which constitute functional and relational aspects that frame the potentialities of self-organized collectives for agentic action, with regards to blockchain-based tools for commons governance (Rozas et al., 2021b, 8–20):

I. **Tokenization:** refers to the process of transforming the rights to perform an action on an asset into a transferable data element, a token, on the blockchain.
II. **Self-enforcement and formalization of rules**: refer to the process of embedding organizational rules in the form of smart contracts. As a result, firstly, there is an affordance for the self-enforcement of communitarian rules, such as those which regulate the monitoring and graduated sanctions in these communities. Secondly, this encoding of rules implies explicitation, since blockchain technologies require these rules to be defined in ways that are unambiguously understood by machines.
III. **Autonomous automatization:** refers to the process of defining complex sets of smart contracts as DAOs, which may enable multiple parties to interact with each other, even without human interaction. This is partially analogous to software communicating with other software

[3]This paper focuses on the governance of global commons *through* or *with* blockchains, rather than the governance *of* blockchains, i.e., governance of the communities which develop and maintain blockchain projects. This is a relevant distinction since both debates are sometimes blurred. Conceptualizing a public blockchain like Bitcoin as a global commons, and therefore its governance as a commons-based process, is a promising approach to further our understanding of the social aspects behind the development of these decentralized technologies, but it is out of the scope of this paper.

[4]A Smart Contract (De Filippi et al., 2020) is a software program deployed in a blockchain environment and executed in a distributed manner once the underlying conditions are met.

[5]A Decentralized Autonomous Organization (Hassan and De Filippi, 2021) is a blockchain-based system that enables people to coordinate and self-govern themselves mediated by a set of self-executing rules deployed on a public blockchain, and whose governance is decentralized (i.e., independent from central control).

[6]The reasoning to frame our analysis through "affordances" relates to the need to navigate the Scylla and Charybdis of technological determinism and technological constructivism present in the field of science and technology studies (Juris, 2012). See Wellman et al. (2003), Boyd (2010), and Juris (2012) for examples in the use of affordances in the context of analysis in the Internet, social media and social movements, respectively.

today, but in a decentralized manner, and with higher degrees of software autonomy.

IV. **Decentralization of power over the infrastructure:** refers to the process of communalizing the ownership and control of the technological tools employed by the community through the decentralization of the infrastructure they rely on, such as the collaboration platforms (and their servers) employed for coordination.

V. **Increasing transparency:** refers to the process of opening the organizational processes and the associated data by relying on the persistence and immutability properties of blockchain technologies.

VI. **Codification of trust:** refers to the process of codifying a certain degree of trust into systems which facilitate agreements between agents without requiring a third party, such as the federal agreements which might be established among different groups that form part of such communities.

These affordances drew on Ostrom's classic principles (1990), that were derived from her studies on communities managing local commons. In the next section, we discuss them in the context of large CBPP communities managing global digital commons, such as Wikipedia and large FLOSS communities, incorporating the challenges identified by Stern (2011) for each of Ostrom's design principles.

AFFORDANCES OF BLOCKCHAIN FOR THE GOVERNANCE OF GLOBAL DIGITAL COMMONS

This section will analyze the role played by blockchain technologies, drawing on the aforementioned affordances, for the governance of global digital commons. Thus, it is divided into eight subsections, one for each of Ostrom's governance principles. For each principle, we analyze how the blockchain affordances may contribute to the management of global digital commons, considering the challenges for global commons by Stern (2011). In addition, and again for each principle, we provide examples, first on how the affordance may be used in large CBPP communities (using Wikipedia and FLOSS as recurring examples), and second on how such affordance already operates in other contexts. The reason to use examples of these affordances "in action" out of the CBPP context is the lack of mature implementations of blockchain. **Table 2** summarizes how the principles, the blockchain affordances and Stern's challenges relate to each other.

Thus, next we bring together the aforementioned affordances of blockchain for each of Ostrom's principles, contextualized within global digital commons.

Clearly Defined Community Boundaries

This principle refers to the need to have clear boundaries regarding who has rights and privileges over the community's commons, which becomes more challenging for global communities because of its size[7]. In the case of large CBPP communities, such as Wikipedia and large FLOSS cases, boundaries are usually defined to coordinate contribution activities. Such boundaries are reflected, for instance, in

TABLE 2 | Summary of the relationships between the affordances of blockchain technologies for the governance of global digital commons.

Ostrom (1990) design principle	Stern's (2011) challenges in the application, adapted to global digital commons	Related affordances of blockchain (Rozas et al., 2021b)
1. Define boundaries for resources and participants	- Size of participants group and required granularity	- Tokenization (I)
2. Devise rules congruent with conditions	- Identifying the relevant conditions - Developing enforceable rules for a global context	- Self-enforcement and formalization of rules (II)
3. Allow most users to participate in developing rules	- Size of participants' groups and required granularity	- Tokenization (I) - Decentralization of power over the infrastructure (IV)
4. Hold monitors accountable to users	- Conflicts of interest between parties - Establishing monitors' independence - Need for global monitoring - Uncertainty about what to monitor - Greater difficulty establishing accountability across jurisdictions	- Self-enforcement and formalization of rules (II) - Autonomous automatization (III) - Increasing transparency (V)
5. Apply graduated sanctions	- Authority to sanction limited because of loosely connected parties	- Self-enforcement and formalization of rules (II) - Autonomous automatization (III)
6. Develop low-cost conflict resolution mechanisms	- Loosely connected parties - Heterogeneity in the participants	- Autonomous automatization (III) - Increasing transparency (V)
7. Ensure that authorities permit participants to devise their rules	- Need to affirmatively facilitate local governance - Need to facilitate the learning and extension of peer-to-peer practices	- Self-enforcement and formalization of rules (II) - Decentralization of power over the infrastructure (IV) - Codification of trust (VI)
8. Establish nested layers of organization	- Same as above cell	- Codification of trust (VI)

The table is inspired by a similar summary by Stern (2011, 220), but adapted to this narrower scope. For example, we have added a challenge concerning the definition of boundaries, which Stern (2011, 220) considers inapplicable, and we remove the additional principles (e.g., invest in science) as well as the challenges regarding principles (1990) which do not fit within this scope (e.g., because digital commons are non-rival/anti-rival).

[7]Stern (2011, 221) argues that "defining boundaries for resources and appropriators is not a meaningful exercise for global commons, even though it is possible to treat political jurisdictions as boundaries for the enforcement agreements made by sovereign authorities." However, for the case of global digital commons discussed in this article, we incorporate Ostrom's first principle in our analysis since these boundaries have been found relevant in large cases of CBPP (e.g., Forte et al., 2009; Jemielniak, 2016; Dulong de Rosnay and Stalder, 2020; Rozas and Huckle, 2021).

the platforms employed to coordinate collaboration. The software usually defines permissions and rights to modify the commons managed (e.g., who can edit a protected article in Wikipedia) as well as the rules for participants to gain or lose permissions and transit between roles (e.g., who can accept changes in a FLOSS project). For example, in the case of Wikipedia, this demarcation was found when exploring the relationship between technical and social power (Forte et al., 2009; Jemielniak, 2014). Similarly, for large FLOSS communities, boundaries operate to participate in the production and management of FLOSS subprojects (Rozas and Huckle, 2021).

In this context, the capacity of blockchain for tokenization (I) provides new capabilities to experiment with the use of different types of tokens in collaboration platforms. In particular, the distribution of tokens allows for participation rights to be more easily and granularly defined, propagated and revoked. Blockchain tokens can represent both the participation in an organization and the voting rights and power of each actor. For example, tokens can be employed to define the rights of and support decision-making around collectively managed assets, such as a co-working space or the resources employed by a cooperative of taxi drivers (Voshmgir, 2019, 376; Eva Coop, 2021). The use of tokens to represent rights and power in blockchain systems is central in some blockchain frameworks such as Aragon, DAOStack or Colony (Karjalainen, 2020). Within them, programs can authorize or deny certain actions to users depending on the tokens they own or expend. Thus, these tokens may be used by communities managing global digital commons, such as Wikipedia, to represent the different users' roles and permissions, as well as the rules to obtain access to them.

Congruence Between Rules and Local Conditions

This principle defines that the rules that govern behavior or resource use in a community should be: flexible and based on local conditions that may change over time, and intimately associated with the characteristics of the resources, rather than relying on a "one-size-fits-all" regulation. As noted by Stern (2011), the challenge for global commons resides in identifying the relevant conditions in such a heterogeneous environment.

In a blockchain context, the required explicitation of rules (II) which is encompassed in the development of smart contracts has an impact on visibilizing otherwise invisible tasks, such as reproductive labor (Jarrett, 2014; Fuchs, 2018). Thus, it provides opportunities to make these rules more available and visible for discussion, and therefore increase the degree of reflection which may lead to a higher degree of adaptability. In fact, new projects focus on increasing the customization and adaptability of blockchain applications. For instance, SourceCred[8] enables online communities to decide which contributions to recognize, and how are they valued. It provides a framework to automatically acknowledge contributions including online participation, e.g., from software repositories (Github), community chats (Discord), and forums (Discourse). Furthermore, it has developed explicit mechanisms for users to request acknowledgment for activities that are not yet automatically recognized. Thus, such software promotes an active discussion of the notion of value in the community, beyond that directly related to the digital commons themselves (Rozas et al., 2021a). Furthermore, it enables voices from different types of contributors to be heard and valued.

Also, it is worth noting that the first implementations of blockchain systems did not provide ample smart contract flexibility given the blockchain immutability, which could have affected the implementation of this principle. However, current implementations provide tools to overcome former limits and upgrade smart contracts as needed. Examples are the upgradeability[9] of Aragon's DAO platform and Open Zeppelin's tools for smart contract updating[10].

Collective Choice Arrangements

This principle defines that in order to best achieve the congruence called for in the previous principle, the members who are affected by these rules should be able to participate in their modification, and the costs of such modifications should be kept low. In line with Stern's (2011) review for global commons, allowing most users to participate in developing the rules is a huge challenge leading to the need to unpack this principle: which groups of participants should be involved in creating and modifying which rules? How might blockchain influence the relationship between social (e.g., users) and technical power (e.g., platform developers and owners)?

This principle connects to two of the affordances. Firstly, as in the case of the previous principle, the aforementioned capacity for tokenization (I) of blockchain technologies could be employed to readdress latent power relations in these communities. The result could help to increase the participation of members who have traditionally had less power, and to give greater visibility to the differences of power within a community. Secondly, it relates to the affordance provided by blockchain to decentralize the power over the infrastructure (IV).

The control over the infrastructure (e.g., servers) which sustains, for example, the main collaboration platforms (e.g., Wikipedia's), commonly emerges as a point of organizational tension, that entails constant negotiation to generate collective-choice agreements (e.g., who can access and control Wikipedia's servers). When CBPP communities start to grow substantially, they normally try to decentralize control over this infrastructure, which is commonly achieved by incrementing the degree of formalization. For example, defining more explicit and rigid organizational processes, roles and even formal institutions, such as the Wikimedia Foundation (Forte et al., 2009; Jemielniak, 2014) and FLOSS associations (Rozas and Huckle, 2021) returning to our previous examples.

[8]See https://sourcecred.io, for an example of a reputation protocol for open collaboration.

[9]See https://hack.aragon.org/docs/upgradeability-intro

[10]See https://docs.openzeppelin.com/learn/upgrading-smart-contracts

In large FLOSS communities the "threat of forking[11]," for example, conditions the members or institutions holding more power, to be perceived as accountable and legitimate in the eyes of the community, and they commonly respond by limiting and distributing their power over time. Similar dynamics have been found in other large CBPP communities beyond FLOSS, such as Wikipedia (Tkacz, 2014; Jemielniak, 2016).

While, in technical terms, forking code has become a simple operation, forking the infrastructure remains a complex matter which is significantly costly in terms of effort. Indeed, when forks in FLOSS communities occur, those who decide to fork the code usually need to create a new infrastructure from scratch. The use of blockchain technologies offers, in this respect, a promising field of experimentation and exploration of potential changes in these dynamics. The inherent properties of blockchain technologies facilitate the forking of the whole infrastructure and even the communitarian rules which have been encoded in them. Thus, the decentralization of the infrastructure reduces the technical cost to fork the community, reducing the power within the community of those previously in control of the infrastructure. In other words, the "threat of forking" conditions the processes of negotiation since participants holding more power are expected to maintain a general direction of the project which acknowledges and includes the main desires of the community.

These examples allow us to imagine scenarios of the possible opportunities gained by decentralizing power over the infrastructure in CBPP. Blockchain technologies may shape these dynamics by offering a higher degree of pressure for negotiation on those holding more power in the community, and eventually it may foster permissionless innovation (Thierer, 2016). In fact, many current blockchain projects are indeed forks of original blockchains implementing different rules. Unlike in other FLOSS software, these forks do not only duplicate the code of the programs, but can also duplicate the existing community, data, and value (e.g., if you own a bitcoin before a fork happens, you will also own a 'forked-bitcoin' in the forked blockchain, retaining both the original bitcoin and the new one). The Hive fork of the original Steem blockchain is a recent relevant example of these community forks (Jeong, 2020). Steem is the blockchain supporting the Steemit social network, one of the most used blockchain applications (Jeong, 2020). In February 2020, the Tron Foundation acquired the company developing Steemit, and a large proportion of the blockchain tokens. This raised concerns about the centralization of power in the network, as the new owners could exclusively control the network using their tokens. The Hive is a community fork of the original Steem that aims to avoid such a concentration of power, and has successfully attracted most of the original platform users. Thus, blockchain technology seems to facilitate community efforts to fork a software and its community, increasing the decision-making power of online communities while decreasing the power of the infrastructure's owners.

[11] Forking, in FLOSS communities, occurs when participants take a copy of source code from one project and start a new, independent and distinct version of it. This may or may not cause the fragmentation of the community in two different projects. Thus, the "threat of forking" reflects the fear of such fragmentation to occur.

Monitoring

This principle concerns some participants in the community acting as monitors of behavior in accordance with the rules derived from collective choice arrangements. These participants should be accountable to the rest of the community. Stern (2011) argues that this principle remains essential for global commons, although it becomes more difficult to implement.

Several of the affordances of blockchain for commons governance remain potentially useful in the context of global digital commons. On the one hand, the affordances for self-enforcement (II) of smart contracts and, more widely, that of autonomous automatization (III) – without human mediation – provide further means to track and communally fiscalize new aspects of the organizational processes. Secondly, the blockchain affordance of increasing transparency (V) may enable higher accountability, and might lead to more peer-to-peer forms of monitoring. Peer-to-peer monitoring is usual in CBPP communities, as part of their strong culture of openness. This culture of openness also involves the opening of the data generated in the collaboration processes. This constitutes a useful means for CBPP communities to successfully carry out and scale up their processes of monitoring.

Thus, blockchain might facilitate the monitoring of community rules. On the one hand, smart contracts represent rules of the online communities, which may include automatic mechanisms for specific monitoring. On the other hand, all interactions are recorded in the blockchain and can be observed in real time by any party. This has already enabled users to detect and mitigate the effects of users behaving against the perceived community rules. For instance, in 2017 a hacker stole $32 million worth of cryptocurrencies in Ethereum, exploiting a software vulnerability. As a first response, a group of users called "The White Hat Group" stole all the other accounts affected by the same vulnerability ($208 million), in order to avoid it being stolen by other hackers taking advantage of it. Afterward, they returned that money to their owners, once the vulnerability was fixed (Zetzsche et al., 2018).

The use of blockchain to support transparent and open peer-reviewing (Ford, 2013) is another example of the applications of blockchain for community monitoring. This is seen in the blockchain-based system implemented by Tenorio-Fornés et al. (2019), intended to increase the quality and accountability of peer-reviewing practices in academia. The system relies upon three pillars supported by decentralized technologies (Tenorio-Fornés et al., 2019, 4637–4368). Firstly, an "open access by-design" approach to store publications. Secondly, more transparent decision-making regarding peer-reviewing practices. The system proposes the storage of metadata of the publication process, such as who the reviewers are and the changes between the different revisions, into a decentralized ledger. In this way, such interactions are time-stamped, tamper-proof and subject to communitarian monitoring. Thirdly, the system proposes an open reputation network of reviewers supported by blockchain, which would reward positive behavior and reduce and expose unfair or biased reviews.

Therefore, large online communities can also use blockchain to automate certain rules and enable the monitoring of communitarian behavior transparently. In fact, existing large communities such as Wikipedia already make extensive use of transparent records to monitor user interactions, and automate a large part of the monitoring using bots, programmed with specific responsive automatic actions. Thus, blockchain may be useful to enhance this transparency, improve CBPP community monitoring, and its automation.

Graduated Sanctions

This principle states that participants not only actively monitor but also sanction one another when behavior is found to conflict with community rules. These sanctions against participants who violate the rules should be aligned with the perceived severity of the infraction. As with the case of monitoring, Stern (2011) argues that this principle is also essential for global commons, although it is more difficult to implement because the participants are more loosely connected. For example, the parties in conflict are likely to live in different countries with largely different cultural settings. How to define and execute sanctions in such contexts becomes a significant challenge.

The affordances of self-enforcement (II) and autonomous automatization (III) for blockchain-based governance for large CBPP communities managing digital commons offer, in this respect, several avenues of exploration. Smart contracts can be employed by these communities to automatically self-enforce the rules that regulate the graduated sanctions agreed in the community. Furthermore, this capacity for self-enforcement could be even more intense when considering DAOs. DAOs can take the initiative when certain events happen, and react autonomously upon circumstances or user actions. In other words, they increase the degree of impersonalization with regards to the application of the sanctions agreed by the community. The effects are unknown and could vary: from preventing the usual effect of reacting against the enforcer or "killing the messenger," to the triggering of frustration and impotence as has been the case with previous reactions against machines (Postman, 1993).

In this respect, we can find existing examples in which blockchain software implements community sanctions. For instance, Kleros is a blockchain project providing blockchain-supported courts. In these courts, a jury formed by community members would mediate community conflict resolutions, delivering blockchain-supported verdicts. Furthermore, projects implementing these blockchain courts such as Aragon Court, have specific rules to sanction misbehaving members of the jury, since the community can start a vote to remove their power in the jury. Thus, large online communities can both encode sanctions in their smart contracts (e.g., losing a privilege if the community agrees so) and use blockchain courts to sanction behaviors against the community rules.

Conflict Resolution Mechanisms

This principle specifies that members of the community should have easy access to spaces in which to resolve conflicts. As in the case of the principle regarding the graduated sanctions, the difficulties identified by Stern (2011) for global commons are derived from the challenges posed by these communities being more loosely connected than those studied by Ostrom.

In this respect, the affordances of increasing transparency (V) and autonomous automatization (III) might be valuable for the design of blockchain-based tools which facilitate the scaling up of conflict resolution mechanisms in these large communities. On the one hand, transparency is commonly employed by large CBPP communities as part of their conflict resolution mechanisms. One can think, for example, of the enormous amount of content which can be found in the discussion pages of Wikipedia; or in the issue lists of FLOSS communities. These large amounts of data are not usually solely related to the digital commons maintained, but also to the organizational processes which surround them. Such transparency facilitates access, participation and visibility of conflict resolution processes.

On the other hand, the employment of the aforementioned DAOs could lead to spaces in which conflicts are made explicit, between members of a DAO, across DAOs, and between DAOs and humans. This encourages communities to establish more explicit mechanisms for conflict resolution, which may be at least partially tackled by automated processes. In fact, Aragon is already working on creating digital jurisdictions for conflict resolution within, and across, DAOs.

As previously introduced in the graduated sanctions section, some blockchain projects are developing blockchain-supported courts and other arbitration mechanisms (Metzger, 2019). In the case of Aragon Court, there is a hierarchy of courts for conflict resolution. Primary courts are "low cost" (since they imply a small cost in cryptocurrency), although the system enables appeals to higher and more expensive courts if a party is not satisfied with the verdict. However, despite these developments, these courts are far from replacing standard courts of laws, nor do they tackle major conflicts. In fact, we often see the resolution of conflicts in blockchain projects themselves being discussed and resolved in more traditional online platforms, such as social networks, forums and blogs. At times, these conflicts have also been escalated to traditional state courts. For instance, in the ecosystem of Aragon, a conflict over funding allocation and contractual obligations between the Aragon Association and the company Autark ended up in the Swiss court[12].

The blockchain-supported courts and similar conflict resolution mechanisms could lower the cost to solve conflicts within global communities, and provide transparency to the conflict resolution processes. Moreover, the sole discussion and definition of a legitimate conflict resolution mechanism in an online community can reduce the effects of the so called "Tyranny of Structurelessness" (Freeman, 2013), in which power dynamics are strengthened when no formal structure is provided. Thus, blockchain can offer additional conflict resolution mechanisms to the tools already in use by global communities managing digital commons.

Local Enforcement of Local Rules

This principle states that the local jurisdiction to create and enforce rules should be recognized by higher authorities. In the

[12] See https://defirate.com/aragon-autark/

case of the commons studied by Ostrom, these higher authorities are commonly referred to as those of traditional institutions, such as states, regional or local governments. An example could be government officials who acknowledge the creation of local rules in the context of self-organized fishing communities. Parallelisms have been established in the case of digital commons, but referring to higher authorities as the most formal and centralized institutions which commonly emerge in these communities, such as the Wikimedia Foundation (Forte et al., 2009), or FLOSS associations (Rozas and Huckle, 2021), to continue with the previous cases. In the emergence of Wikipedia's autonomous WikiProjects, jurisdiction to devise their own local rules is acknowledged by the more central authorities of Wikipedia. Also, the local jurisdiction of sub-projects is acknowledged within the general project in FLOSS communities (Rozas and Huckle, 2021). This is in line with Stern's (2011) challenges within this global scope, regarding the need to affirmatively facilitate local governance and peer-to-peer learning.

This principle, hence, connects with several affordances of blockchain. First of all, with the capacity of blockchain to self-enforce rules (II) and its relationship to formalize and codify agreements to facilitate the scaling up of trust (VI). Continuing with our examples of Wikipedia and large FLOSS communities, such smart contracts could embed the agreements within the aforementioned WikiProject or FLOSS sub-projects, in ways which encode that the local aspects are only decided by participants belonging to such projects. In other words, if we think of these communities as networks, blockchain-based tools for commons governance might help local nodes of CBPP communities to more easily ensure, by code, that their local jurisdiction[13] and enforcement of local rules are acknowledged by higher authorities as well as by other nodes.

Additionally, this principle relates to the decentralization of power over infrastructure (IV). In Section "Collective Choice Arrangements," several examples of this affordance were discussed regarding the increasing capacity for forkability and its relationship to social aspects. Similarly, in this scenario it can facilitate a higher degree of autonomy to the local spaces which emerge over time. In other words, the differences in forms of pressure may provide new conditions for the negotiations that relate to having their local contexts and jurisdictions acknowledged by higher authorities.

The use of blockchain in virtual reality projects such as Decentraland (Chaudhari et al., 2019) offers an intuitive example of how blockchain can be applied to facilitate local enforcement of local rules. In Decentraland, users can purchase virtual land. They can also modify virtual land, incorporate 3D elements into it and change the colors and textures of this virtual world. The owners are the only users allowed to modify the land, and to sell it to other users. These users can also participate in the decisions that affect the whole functioning of Decentraland, such as the rules regulating land auctions. Thus, blockchain can facilitate the autonomy of users and groups beyond this virtual reality example. For example, groups of users in large FLOSS projects can receive crypto-currencies to develop a sub-project. Furthermore, blockchain can facilitate the autonomous handling of the funds by these groups. Examples of the autonomous management of funding are numerous in the blockchain space, for example in Gitcoin (Qayum and Razzaq, 2020), Aragon (Aragon Flocks[14]) and Ethereum (Moloch DAO[15]).

[13] In this context, we refer to jurisdiction as the area over which the members of the node have control (Sullivan, 2009).

Multiple Layers of Nested Enterprises

The last of Ostrom's principles states that, by forming multiple nested layers of organization, communities can address issues that affect resource management differently at broader and very local levels in order to scale up their governance. This is in line with Stern's (2011) challenges within the global scope concerning the need to find effective combinations of institutional types which facilitate local governance and allow it to scale up. In the commons literature, such institutional types commonly rely on the notion of *polycentrism*, which refers to the co-existence of several centers of governance which blend the distribution of authority and power with effective coordination between these centers (Ostrom et al., 1961). The concept *polycentric governance* was originally coined for the study of the organization of government in metropolitan areas, and subsequently employed for the study of management of natural resources. However, this concept has been more recently employed to explain self-governance in communities managing the peer production of digital commons (Mindel et al., 2018), such as Wikipedia (Hartswood et al., 2014; Safner, 2016) and large FLOSS communities (Rozas, 2017, 313–316).

In this respect, the affordance of blockchain for the codification of trust (VI), implemented through interoperability, offers avenues for future exploration. In technical terms, interoperability refers to the property of a system to operate with other systems through a series of interfaces. Such interfaces codify the rules of interaction of different units, and thus codify part of the trust, facilitating interaction. Blockchain provides affordances to increase the degree of collaboration not only through the generation of interfaces, but also by providing a full communal infrastructure: a shared decentralized database. This process of codification of trust may simply refer to the individuals and their interactions, as in the case of the transactions of cryptocurrencies. However, it may also involve the agreements arranged between the different groups that form part of the community, fostering the capacity of these communities to scale up governance in polycentric ways. Thus, and returning again to our previous examples of Wikipedia and large FLOSS projects, one can envision tools designed to facilitate polycentric governance in CBPP communities in the form of different locally shaped platforms encoding agreements according to the local conditions of each group, such as WikiGroups and FLOSS sub-projects within the general project. These platforms could be autonomously governed by the participants who belong to each of the groups, but interoperate between them and with the general platform at a broader level through federal agreements.

[14] See https://aragon.org/blog/flock-funding-for-aragon-teams

[15] See https://www.molochdao.com/

Cryptokitties (Min et al., 2019), a blockchain based collectable game where you can breed and trade *virtual cats*, offers an example of blockchain interoperability capabilities. First, as it uses a blockchain interoperable standard for non-fungible tokens such as collectables. Thus, these collectables can be traded and used in multiple applications that support this standard, that is they can be exchanged for others. Furthermore, given its popularity, several games have been developed in which you can play using your own *cryptokitties*. These games are grouped in the so-called KittyVerse (Min et al., 2019). Thus, global online communities managing digital commons may implement such interoperability among their communities using blockchain applications. This would enable the creation of federations of online communities, and enhance the exchanges and interactions among them.

DISCUSSION AND CONCLUSION

In this article, we have explored the potentialities of blockchain to facilitate and scale up the governance of large and global CBPP communities managing digital commons. As we have shown, there are numerous examples of blockchain communities that make use of practices that may be beneficial if adopted by these CBPP communities. These practices reinforce Nobel laureate Elinor Ostrom's principles (1990) for sustainable community governance, taking into account the adaptation of such principles for global commons (Ostrom et al., 1999; Stern, 2011). To sum up, we can observe that blockchain has the potential to contribute to large CBPP communities in multiple ways, helping to: distribute power, facilitate coordination, scale up governance, visibilize traditionally invisible work, monitor and track compliance with rules, define collective agreements, and enable cooperation across communities.

This article and the theoretical framework it relies on (Rozas et al., 2021b) contribute to linking commons literature with blockchain technologies. Previous literature includes: Cila et al. (2020), who draw on the aforementioned blockchain affordances to develop a framework with three mechanisms and six design dilemmas for blockchain-based platforms to support local forms of CBPP; Calcaterra (2018), who discusses how Ostrom's principles could be applied to DAOs; and Shackelford and Myers (2017), who review the applicability of Ostrom's principles focusing on the governance *of* blockchains (instead of *with* blockchains). Other authors, without including blockchain within their analyses, have explored how Ostrom's principles could be mathematized (Pitt et al., 2012, 2017) and applied to algorithmic governance (Clippinger and Bollier, 2014).

This work contributes to the emergent literature on blockchain-based forms of governance in several ways. First, it analyzes the challenges encompassed by the different nature of global digital commons, when compared to those from which Ostrom's principles were derived, while linking them with the role of blockchain. This analysis has allowed us to reflect on the role that blockchain-based technologies already play in existing blockchain projects, and their potential role in current large CBPP communities. Overall, blockchain technologies could facilitate coordination, help to scale up commons governance and even be useful to enable cooperation among various communities in interoperable ways. In addition, our analysis reveals that, when considering the challenges of managing global commons (Ostrom et al., 1999, 281–282), the role of blockchain is particularly valuable to explore solutions that tackle the scaling up of governance and the definition of global collective agreements within more heterogeneous conditions (Stern, 2011).

A better understanding of the capabilities of blockchain technologies to support global forms of commons governance will require, however, further empirical research. In fact, we strongly recommend those willing to develop blockchain tools to support CBPP to do so guided by research. Moreover, the development of such tools should be carried out hand-in-hand with the CBPP community participants, in order to avoid the multiple problems of top-down software building and algorithmic biases (O'Neil, 2016; Eubanks, 2018). This should enable the development of blockchain-based technology which incorporates particular social practices into the design. In other words, the development should be aware of the cultural context of each CBPP community, as well as aiming to place the people who have been traditionally marginalized by design in the center (Costanza-Chock, 2020). The aforementioned relationships between the blockchain affordances and the challenges for global commons summarized in **Table 2**, could be employed as analytical categories from which to start the co-designing of this type of tools (e.g., Cila et al., 2020; Rozas, 2020).

Blockchain technologies are still young, and it is still early to envision the applications and practices that will take hold within communities. Further experimentation will enable their study and monitoring to extract best practices and successful patterns that may be incorporated more easily and with lower risks into existing CBPP communities. In fact, the analysis of the current practices of existing blockchain communities (El Faqir et al., 2020) is an open research line which may provide fruitful results to draw from.

This article has focused on the potentialities of blockchain for the governance of global digital commons. The challenges concerning other types of global commons, such as oceans and the atmosphere, would require a different analysis which incorporates specific characteristics and challenges. Future work may also explore more systematically the limitations, drawbacks and risks posed by the use of blockchain in this overall global context. The use of the blockchain affordances as categories for analysis could be useful in order to identify such risks. For example, with regards to tokenization, it would be relevant to explore the risks posed by extreme quantification and data fetishism (Sharon and Zandbergen, 2017); with regards to increasing transparency, those risks related to the need to comply with the "right to be forgotten" (Stevenson, 2010); or with regards to formalization and self-enforcement of rules, the risks related to the tools leading to extreme strictness and intrusiveness (De Filippi and Hassan, 2016).

Commons-Based Peer Production communities render radically different values and practices when compared with those that operate within the hegemonic logic of markets. As we have aimed to show, blockchain may facilitate the experimentation of ways in which to scale-up such forms of cooperation. We hope this combination may open up new avenues for the extension of commoning practices, and the much-needed cooperation in our world at these unsettled times.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DR coordinated the elaboration of the manuscript and participated in all the phases, including conceptualization, literature review, structuration, analysis, and overall writing of the article. AT-F participated in the conceptualization, structuration, analysis, and writing of the manuscript. In addition, he provided most of the blockchain examples used in Section "Affordances of Blockchain for the Governance of Global Digital Commons." SH supervises the project this manuscript is part of, P2P Models, of which he is the Principal Investigator. In addition, he discussed the manuscript's general approach, reviewed the manuscript, contributed to parts of it across all sections and to the discussions and examples. All authors contributed to the article and approved the submitted version.

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5.3 Reputation. Glossary of Distributed Technologies.

Reference

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Abstract

Definition Reputation in a blockchain-based system is a digital representation of an entity’s standing or status in a specific domain.

INTERNET POLICY REVIEW
Journal on internet regulation

GLOSSARY ENTRY
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Reputation
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Reputation

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Keywords: Reputation, Blockchain, Identity

Abstract: Reputation in a blockchain-based system is a digital representation of an entity's standing or status in a specific domain.

This article belongs to the **Glossary of decentralised technosocial systems**, a special section of *Internet Policy Review*.

Definition

Reputation in a blockchain-based system is a digital representation of an entity's standing or status in a specific domain.

Origin and evolution of the term

A. Origin

Technologies such as the internet, or blockchain, enable large scale interactions among total strangers. Reputation systems (Resnick et al., 2000) appeared as a solution to facilitate these interactions when some level of trust was required, such as in online shopping in peer to peer marketplaces like eBay, or online production communities (Benkler, 2006). Yet, these systems generally relied on a centralised operator, in charge of managing user reputation.

There are several decentralised reputation systems (Hendrikx, 2015), most relying either on maintaining a personal list of trusted and untrusted nodes; aggregating such reputation information from other trusted nodes (with certain degree of transitivity such as in web-of-trust); or using Distributed Hash Tables to manage a global directory of semi-trusted nodes (Chawathe et al., 2003).

Blockchain technology introduces the possibility for a next generation of reputation systems that utilise persistent global state and immutable transaction histories. This allows for transparency and security guarantees that were unavailable in previous distributed systems. Furthermore, the openness and persistence of blockchains makes them a valuable tool to support shared data stores that can be leveraged by multiple services, thereby enhancing reputation portability and interoperability.

B. Evolution

Bitcoin (Nakamoro, 2009) relied on blockchain technology to create a distributed payment system operating on top of a peer-to-peer network. The operations of Bitcoin did not rely on trust or reputation. Instead, the influence of every network node is determined by the amount of resources engaged into the network: the greater the amount of resources, the more influence one has in the network. Many of the other blockchain-based networks that followed suit relied on similar protocols, also based on a resource-driven model (i.e. the amount of hashing power in the case of Proof-of-Work or the amount of tokens holding in the case of Proof-of-Stake).

Early reputation systems have been implemented at the infrastructure layer, as trust-based alternatives to the **Proof-of-Work** or **Proof-of-Stake** consensus algorithm. For instance, delegated **Proof-of-Stake** (Larimer, 2014) allows for a more meritocratic system, based on merit or perceived trustworthiness. As a result, anyone holding a particular amount of reputation within a blockchain community will have influence in proportion to the amount of reputation they hold.

At the application layer, the introduction of "reputation" in the blockchain space was also an attempt to move away from the perception of blockchain technology as a purely trustless system, to enable the establishment of more sophisticated systems where some actors *can* be trusted. As argued by Hawlitschek and colleagues (Hawlitschek et al., 2018), the introduction of "reputation" is necessary for the establishment of trustless systems that operationally rely on trust. On the one hand, trustless systems such as Bitcoin are based on the assumption that no one *can* or *shall* be trusted. Hence, these systems are designed to entirely eliminate the need for trust, relying on cryptographic primitives and proofs in order to ensure that people behave according to the rules (Ali et al., 2016). On the other hand, there are many human-sensitive services (e.g., peer-to-peer marketplaces like Uber, Airbnb, or eBay) based on the assumption that some actors can be trusted to behave honestly. These systems rely on "reputation" in order to help users assess the trustworthiness of the other users interacting on these platforms. In order to provide these types of human-sensitive mediation services, blockchain-based applications need to also rely on some kind of reputation system.

C. Coexisting uses/meanings

Existing blockchain reputation systems vary widely in how reputation is earned and utilised. In many blockchain-based marketplaces, reputation does not have an explicit or software-defined role, but acts as a signal of trustworthiness. For instance, in service marketplaces (Gitcoin, Bounties Network), users can decide who to hire or work for based on transaction histories and summary statistics. Similarly, in digital goods marketplaces (Rarible, OpenSea), a buyer can review the seller's transaction history to evaluate the quality of goods for sale before making a purchase.

In blockchain-based social media (Steemit, Hive, Sapien, Relevant) and work networks (Colony, Sourcecred), reputation represents a user's evaluation weight on other users' contributions. Reputation can be global in scope or limited to a specific community or domain. Evaluation-weighting alters reputation dynamically, as users continuously influence each other's reputation scores in proportion to their own reputation. Some systems also incorporate time-based mechanisms to decay reputation with inactivity.

In blockchain-based governance frameworks (Aragon, DAOstack, Moloch), reputation often determines a user's voting weight on proposals in a given organisation. Reputation can also entitle the user to a proportional claim of the organisation's assets or ongoing revenues. Reputation is often modified through community voting, where the votes of community members are weighted by their reputation (e.g. a community can vote whether to give 50 reputation points to Alice or remove 100 reputation points from Bob). Just as in social media cases, reputation can also be modified by dynamic criteria stipulated by the community, such as reputation rewards for voting with the majority, creating proposals that pass, or reputation penalties for the reverse.

Issues currently associated with the term

A. Different types of reputation

First of all, it is important to distinguish between two different types of reputation systems: "personal" and "global" reputation systems (Hendrikx, 2015).

- **Personal reputation** systems are specific to an individual. They represent the standard mechanism of peer-to-peer reputation assignment. These systems are designed to assign a personal reputation score to each member of a particular network or community, although such a score will ultimately be relevant only to one specific individual. Hence, these systems necessarily rely on direct user input: users are expected to score each of their interactions with other community members, in order to help the system compute their corresponding reputation score. However, these systems often suffer from scalability issues. Indeed, the purpose of a reputation system is to provide information about the qualities of different users in a given domain, so that other users can make informed decisions about who they wish to interact with. Yet, a personal reputation system has limited capacity to do so, because it is not possible (or too costly) for a single user to evaluate the qualities of all the users in the system. In order to overcome this limitations, many of these reputation systems often implement a "web of trust" mechanism, leveraging the information submitted by other people (who are regarded as trustworthy by the user) in order to compute the personal reputation score of those with whom such user did not yet have a sufficient amount of interaction.

- **Global reputation** systems are not specific to any community member, but rather to the community as a whole. These systems assign a single and unique reputation score to the different actors in a particular community or network, which will be regarded by all community members as the sole and legitimate score. These reputation systems are rather easy to implement in a centralised platform; they are much more difficult to implement in a decentralised setting, since they require highly sophisticated mechanisms of reputation transfer that will not fall prey to Sybil attacks, where anyone can create multiple pseudonymous accounts to gain disproportionate influence over the system.

It is important to note that both personal and global reputation systems suffer from specific limitations, although to different degrees. First of all, there is the problem of reputation being reduced to a single measure or score, which might not properly reflect the preferences of individual communities. Such a problem is particularly relevant in the context of global reputation systems, which are designed to average reputation into a particular score, even if values are highly heterogeneous within the community of reference. Yet, it also subsists in the context of personal reputation systems that rely on a broader web-of-trust mechanism. Second, both global and personal reputation systems might suffer from an excessive lack of granularity, to the extent that they do not differentiate between defined characteristics or properties (e.g., reputation associated with a particular skillest, as opposed to a generic reputation score). Finally—and relatedly—reputation valuations can be based on objectively quantifiable facts, as much as subjective opinions. Mixing the two can lead to misleading aggregate reputation signals.

B. Sybill attacks and identity

Unlike popular online services, decentralised systems have no central party to verify user identities, ban fake accounts, or patrol spam. While beneficial for privacy, this opens the door to Sybil attacks. While decentralised sybil-proof reputation systems have long been regarded as a theoretical impossibility (Cheng & Friedman, 2005), blockchain-based reputation systems might overcome these challenges (Almasoud et al., 2020).

One approach is to minimise the possibility of users leveraging multiple accounts by relying on centralised or decentralised identity systems—also known as "proof of personhood" (Siddarth et al., 2020). Decentralised identity systems often rely on web-of-trust models, where a small set of users slowly invites more users to be peer-verified over time (Liu et al., 2020), or on credential-based models, where users can prove their uniqueness by collecting attestations about their identity from trusted third parties (Wang & De Filippi, 2020).

Alternatively, reputation systems can be leveraged to avoid the need of identifying users. In that model, users need to accumulate a certain degree of reputation within a particular blockchain-based system in order to influence the operation of that system (in proportion to the reputation they hold), and—potentially—assign reputation to other users of the system (Almasoud et al., 2020). Because of the proportionality between reputation and influence, an individual has to contribute just as much value, regardless of how many accounts they spread the effort over, so there is no added incentive for Sybil attacks (Pazaitis et al., 2017).

C. Privacy

In light of its attributes of transparency, censor-resistance, and immutability, blockchain technology can be instrumental to the operations of both personal and global reputation systems, enabling anyone to access and retrieve these scores, in order to compute both a personal and a global reputation score.

However, in order to protect the privacy of users, the reputation system should avoid permanently registering in a blockchain the association between real-world identities and the identities of the reputation system. In addition, users should be aware of the risks of linking real-world identities to their blockchain accounts. Maintaining this separation makes it possible for users to protect their privacy while allowing for anyone interacting within their blockchain-based identity to evaluate the risks of each user in that domain.

This is especially relevant in light of the new European General Data Protection Regulation, which provides users with the possibility to request the erasure of specific information deemed inaccurate, inappropriate, or obsolete. Given the immutability of a blockchain, the recording of any type of data that can affect the reputation of a particular persona would potentially violate the provisions of the law, insofar as the persona can be linked back to a real-world identity.

D. Oligarchies and power distribution

The use of reputation systems also raises concerns about power concentration. The creation and consolidation of oligarchies are common in online communities. However, reputation systems might reinforce inequalities in such communities, as powerful actors are more likely to be trusted and increase their reputation while those with low reputation will have fewer opportunities to increase their reputation. Blockchain systems use reputation as a source of economic or political power: these options are explicitly made available in many governance frameworks (Aragon, DaoStack, Moloch). Thus, the accumulation of reputation in such blockchain systems might result in even stronger power inequalities than in other online communities.

E. Amplification of social inequalities

It is worth considering the potential biases reputation systems incorporate and reproduce. First, not all activities or contributions are a source of reputation in online communities (Rozas & Gilbert, 2015). Some activities, such as contributing source code in free software projects are explicitly valued in these systems, while others such as community organising, or affective labour, typically carried by women (Iosub et al., 2014) are often invisible to these reputation systems. These types of biases can trigger new forms of inequalities incorporated directly into the algorithms managing a platform, such as higher work time and lower average wage for women in the so-called gig economy (Barzilay, 2016). We have briefly considered the reproduction of gender inequalities by reputation systems. However, other dimensions of social injustice such as race or class, and their interactions, should also be considered when studying how reputation systems reproduce them.

Conclusion

Reputation in a blockchain-based system is a digital representation of an entity's standing or status in a specific domain. Reputation is usually derived from aggregated peer-evaluation of the entity's past actions. It can be leveraged both explicitly through functions in the code (voting power, economic rights) or implicitly as a means of signalling an entity's trustworthiness.

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5.4 Towards an Agent-supported Online Assembly: Prototyping a Collaborative Decision-Making Tool

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Abstract

The promise of online assemblies has been present for years already, and a diversity of tools have attempted to fulfill it. This work aims to reapproach the issue from a novel standpoint that relies on a federated architecture, a real-time collaborative environment, goal-oriented software agents and a consensus-based methodology. Consensuall is a prototype of consensual decision-making collaborative webtool that allows the elaboration, rating and commenting proposals in order to build consensus among a group. The webtool design follows the Agent- Oriented Software Engineering paradigm. Thus, it proposes the use of software agents as complementary automatic participants fulfilling specific roles, as a way to address decision-making common issues. The article presents Consensuall, a prototype of an agent-based collaborative decision-making webtool within the distributed real-time collaborative platform Apache Wave, providing a proof-of-concept of the adopted approach

Towards an Agent-supported Online Assembly: Prototyping a Collaborative Decision-Making Tool

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***Abstract*—The promise of online assemblies has been present for years already, and a diversity of tools have attempted to fulfill it. This work aims to reapproach the issue from a novel standpoint that relies on a federated architecture, a real-time collaborative environment, goal-oriented software agents and a consensus-based methodology. Consensuall is a prototype of consensual decision-making collaborative webtool that allows the elaboration, rating and commenting proposals in order to build consensus among a group. The webtool design follows the Agent-Oriented Software Engineering paradigm. Thus, it proposes the use of software agents as complementary automatic participants fulfilling specific roles, as a way to address decision-making common issues. The article presents Consensuall, a prototype of an agent-based collaborative decision-making webtool within the distributed real-time collaborative platform Apache Wave, providing a proof-of-concept of the adopted approach.**

***Keywords*–Collaborative Decision-making; Apache Wave; Consensus; Agent-Oriented Software Engineering; Multi-Agent System.**

I. INTRODUCTION

Post-industrial social movements (also coined "new social movements") emerged since the 1960's in the Western societies [1], and, nowadays, have reached a global impact. These movements are increasingly embracing different forms of consensus decision-making as an organizational principle [2]. This is guided by the belief that this model has the potential to empower participants, acknowledge their great internal diversity, and commit to the ideals of participation, democracy and decentralization [3].

Consensus decision-making covers a broad spectrum of implementations [4], and generally it is not understood as a synonym for unanimity, but as aiming to collaboratively reach an acceptable resolution for all the group members. Consensus-driven group assemblies may have multiple lacks and issues, and multiple methodologies have been proposed to address them, successfully doing so for most of them [5]. Still, it is frequently considered that online tools should boost this model, facilitating both scaling up and speed, while not losing its legitimacy and user participation.

The promise of "online assemblies" has been present for years already, and a diversity of tools have attempted to fulfill it. Besides, the emerging Commons-based peer production online communities do not follow traditional hierarchical organizations, and frequently adopt modified forms of consensus decision-making [6]. Popular examples may be found in free/libre/open source software (FLOSS) [7] or Wikipedia [8]. Still, the forms of achieving consensus through online means still have multiple issues and in some cases are rather rudimentary (such as a mailing lists with "+1" in Apache or a simple Discussion page in Wikipedia).

Multiple online group decision-making tools have been built in order to fulfill this gap (see Section II). This work aims to reapproach the issue from a novel standpoint that relies on a federated architecture, a real-time collaborative environment, software agents and a consensus-based methodology. CONSENSUALL is a prototype of consensual decision-making webtool that allows the elaboration, rating and commenting proposals in order to build consensus among a group. This webtool is developed from an Agent-Oriented Software Engineering (AOSE) approach [9], and proposes the use of software agents as complementary automatic participants. Such agents are inspired by the formal (or informal) roles found in offline assemblies, and aim to facilitate the debate and solve certain flaws of the consensus decision-making process.

This work is structured as follows. Section II introduces different decision-making methods and software tools, with a special focus on consensual decision-making processes and applications. Afterwards, Section III explains the adopted methodology, including the concepts of *software agent* and *AOSE* and the technologies used. The prototype design is presented in Section IV, where the concept of the tool, its functionality and the behavior of the designed agents are introduced. Section V presents the developed prototype, showing the use of the tool through an example, and illustrating the agents' behavior with a sequence of their interactions. Finally, Section VI summarizes the contributions and presents future work.

II. REVIEWING CONSENSUS DECISION-MAKING

This section explores different group decision-making methodologies and software tools that intend to boost participation and agreement in democratic decision-making and compares them with CONSENSUALL proposal.

A. Group Decision-Making Methods

1) Consensual decision-making: In general, a group decision is a consensual decision if all members of the group are willing to commit to a proposal [10]. Consensus building or consensual decision-making is the collaborative process where a group aims to find a consensual decision. This process may be formal [11][12][4] or informal [13].

As discussed in Section I, forms of consensus decision-making are the preferred by different groups, including FLOSS projects [13][8], social movements [14], groups of unrelated experts [11], or many other communities [15]. These groups tend to see the consensual decision-making process as a method to obtain synergistic output, not achievable by single participants [16] and as an extremely democratic and participatory technique [3].

2) Other group decision-making methods: There are other group decision-making methods that attempt to boost participation and agreement further than traditional majority voting. Some relevant examples follow.

- *Liquid Democracy* also referred as *Delegated Democracy* or *Proxy voting* is a decision-making method that enables both direct democracy and revocable, topic-based, transitive delegation [17]. This method has been adopted by some political parties [18] and other groups and communities [19] and has been implemented in several online applications [17][20].
- *Dotmocracy* is a participatory large group decision-making method. Participants can write ideas in paper "dotmocracy sheets" and rate these ideas with the values {"Strong Agreement", "Agreement", "Neutral", "Disagreement", "Strong Disagreement", "Confusion"}, together with some qualitative comments [12].
- *Dynamically Distributed Democracy* is a method to approximate a group opinion when not all members of the group participate. It uses a social network of the transitive relations of trust within the group to calculate the opinion of non participants by the opinion of their trusted participants [21].

B. Group Decision-Making Software Applications

There are different online group decision-making tools. These software tools differ in the target groups and group sizes, the methods they implement (see Section II-A), the collaboration degree, the required level of agreement, or might have a wider or more concrete scope of application. These and other dimensions are considered in the comparison among some of the most important decision-making tools or resources and the CONSENSUALL proposal.

1) E-voting & Polls: There are plenty of software tools implementing majority voting and polls. These tools are used by different kinds of groups for democratic decision-making. Generally, e-voting and polls do not allow a high degree of collaboration, they usually lack discussion support and proposal modification/addition. Among these tools there are voting platforms [22][23] and poll extensions integrated in software platforms such as forums, social networks (e.g., Facebook) or collaborative environments (e.g., Apache Wave). There are also domain-specific voting tools, such as "Date matchers" (e.g., Doodle [24]), software systems to collectively decide appointment dates.

2) Adhocracy: is a participatory platform for democratic decision-making. It targets communities, organizations and citizens [20]. Users can make proposals, add an alternative proposal to an established proposal, comment proposals, and vote proposals with either +1 or -1 vote. The tool implements liquid democracy (see Section II-A), allowing users to delegate their votes for specific topics to a trusted user.

3) LiquidFeedback: is a liquid democracy (see Section II-A) decision-making tool for communities and citizens [17][19]. As in Adhocracy, a user can propose, make an alternative proposal, rate, and comment. It uses preferential voting (i.e., Schulze method [25]) to boost collaboration and avoid rival competitive voting.

4) Delphi: is a formal consensual decision-making method consisting of an iterative process of elaboration and response of questionnaires [11]. This method is commonly used to obtain expert opinions and forecasting, although it can be applied for other purposes [11].

5) Loomio: is an online consensus decision-making tool for communities [15]. It allows users to create topics, to propose and rate proposals with the values {"Agree", "Abstention", "Disagree", "Block"}; comments are allowed during the topic main discussion, the proposal discussion and the rating of proposals, which enhance collaboration to achieve consensus.

Lommio is the most similar to this paper's proposal. However, there are several differences: CONSENSUALL uses software agents interacting within the tool as a way of improving consensus decision-making process. It takes advantage of a real-time environment, together with a federated architecture (see Section III-B); besides, CONSENSUALL enables the parallel discussion and rating of more than one proposal while Loomio only allows the rating and discussion of a proposal at a time, which mimics offline assemblies behavior.

Other general purpose tools are also used for decision-making (e.g., mindmapping, videoconference, collaborative writing). However, those fall out of the scope of this paper.

C. Multi-Agent Systems for decision-making

MAS have been applied to assist decision-making. In decision support systems, some MAS provide information aiding to choose a decision [26]. In the negotiation process, MAS may help to obtain favorable deals [27]. However, these systems focus on decision-making scenarios such as business negotiations and domain-specific decisions. Moreover, within these negotiation systems (as in market environments) parties are usually considered competitive, rational and self-interested (i.e., following Rational Choice Theory (RCT) [28]). CONSENSUALL is a general-purpose decision-making tool, and designed for a collaborative context with group aims and emotional links among members, far from a RCT approach.

III. METHODOLOGICAL APPROACH

This section introduces the methodological approach of the proposal. Explaining its AOSE perspective and technologies.

A. Agent-Oriented Perspective

The software has been designed and developed with an AOSE perspective [9].

Software Agents are software systems that possess: *autonomy*, *social ability*, *reactivity* and *pro-activeness* [29].

AOSE is devoted to the development of Multi-Agent Systems (MAS). AOSE uses software agents and their interaction as the basis for the specification of its systems. It is frequent in AOSE works to follow a Model-Driven Engineering (MDE) methodology [30], which implies the use of intermediate languages between the conceptualization and the implementation of models, facilitating the model description and replicability.

The introduction of agents in order to extend the decision-making tool is one of the main contributions of CONSENSUALL. In offline consensual decision-making, many issues are addressed by specific participants that play a formal (or informal) role, through interventions in the assembly [4]. This inspires the conception of automatic participants (agents) addressing specific roles within the system.

On top of the use of agents, the use of Agent-Oriented design has been a useful tool to conceive the prototype. Objects as agents (also used as Actors in the prototype design), roles, goals and actions, have been helpful abstractions for the design purposes.

B. Technologies

The INGENIAS [31] methodology, a software development methodology for MAS, have been used for the design of the tool. It adopts a MDE approach with two basic components: a modeling language and software tools. A metamodel specifies the INGENIAS modeling language. It defines the available concepts and relationships, together with their properties and constraints. Within this framework, an agent is mainly characterized in terms of its goals and the capabilities it has to accomplish them. Besides, agents participate in interactions with other agents to achieve global goals.

Thus, CONSENSUALL follows an Agent-Oriented perspective, using the metamodels provided by the INGENIAS tool, i.e., an intermediate graphical language to design the tool.

The webtool CONSENSUALL has been conceived as an *app* running on top of a FLOSS federated real-time collaborative platform, being Apache Wave [32] or Kune [33]. Wave is a technology that was initially developed by Google (and known as Google Wave [34]), and later transferred to the Apache Foundation and released as FLOSS. The Wave Federation Protocol [35] is the first protocol for full federation of contents in multiple servers with real-time transparent synchronization among them. Kune is a Wave-based federated collaborative platform which integrates social-networking features, and is under the umbrella of the Comunes Nonprofit [36].

The Wave technology allows the development of *Gadgets* or applications embedded into conversations [37] and *Robots* or automatic participants [38] that can perceive changes in gadgets and conversations and participate in them. CONSENSUALL takes full benefits of the potentials of this technology: the decision-making space where users and agents interact by building, rating and commenting proposals is implemented as a Gadget. Finally, agents are implemented as Wave Robots.

Gadgets and Robots have been developed using Java and the Google Web Toolkit (GWT) [39], which allows the automatic generation of JavaScript code from Java code.

IV. THE WEBTOOL DESIGN

The proposed prototype has been designed using the AOSE methodology INGENIAS [31]. This section explains such design using the INGENIAS “Agents”, “Interactions” and “Goals and Tasks” viewpoints, illustrated with INGENIAS metamodel diagrams in Figures 1, 2 and 3.

A. Concept

CONSENSUALL is a prototype of a collaborative consensus decision-making tool. It is inspired in offline consensual assemblies but takes advantage of online real-time collaboration provided by its technology (see Section III-B). The decision-making webtool, developed as a Wave Gadget [37], can be introduced in any part of a wave document or wave conversation and is conceived as a generic tool for any Wave [32]/Kune [33] community.

The proposal introduces software agents (see Section III-A) as a way of extending the decision-making webtool. These agents, automatic participants in wave conversations [38], interact with the user and the webtool as other participants: posting comments, adding or rating proposals. This feature is inspired by the roles and interactions in offline assemblies to solve some of the most common issues in the consensus seeking process. Two agents have been developed to prove the appropriateness of this approach: a “consensus seeker” agent and a “participation seeker” agent; the definition of these agents (Section IV-E) and an example of their interaction with the users and the tool (Section V-A) are detailed below.

B. User and Agent Participants

The introduction of software agents as an extension of the decision-making webtool is one of CONSENSUALL’s main contributions. This inclusion of agents in the tool provides a modular solution to address a variety of issues in decision-making processes (see Section VI-B for other interesting new agents). Thus, each group may invite the agents they find useful and could develop new agents to solve their problems without modifying the decision-making tool.

Both software agents and users have been considered to play the *role* of Participants of the tool (see Figure 1). These participants are able to perform different *actions*, described below.

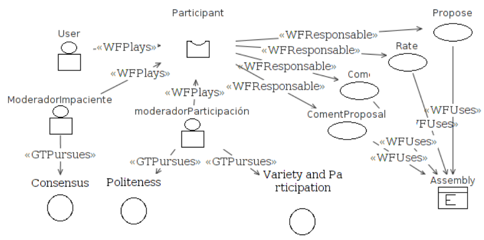

Figure 1. INGENIAS diagram of the Agent viewpoint in Consensuall

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C. Actions

Consensus decision-making is a process that involves deliberation, to make proposals, rate these proposals and reformulate or make new proposals [10]. In CONSENSUALL, each participant, (either user or agent) can post a general comment, make a proposal, comment proposals and rate proposals. These interactions are depicted as the *actions* "Comment", "CommentProposal", "Rate", "Propose" in Figure 1. These actions facilitate the deliberation (performed through messages and comments in the real-time collaborative environment) and allow the easy creation and rating of proposals.

The diagram in Figure 2 shows the design of the interaction triggered by one of these actions ("Proposal") in an INGENIAS "Interaction" viewpoint. That figure shows that a proposal interaction contains an initiator participant and many participants that collaborates in the interaction, meaning that a specific participant (either user or agent) makes a proposal and the others receive it and interact within this conversation ("ProposalConv").

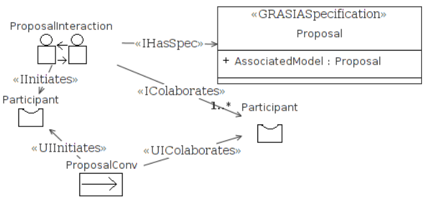

Figure 2. INGENIAS diagram of the "Interaction" viewpoint within a Proposal interaction.

The mentioned action *Rate* deserves special attention, and thus it is discussed in the following subsection.

D. Proposal rating

The possible ratings users can give to proposals have been chosen to facilitate consensus building. Similar to the options provided in Loomio [15] or dotmocracy [12], CONSENSUALL provides 5 rating options: *"Agree"*, *"Do not care"*, *"Do not agree"*, *"Block"* and *"Not decided yet"*. This set of options allows users to express their opinion about an specific proposal better than with a binary rating used by other tools. Among the rating options, distinguishing the block or veto [4] (different than "Do not agree") is a desirable feature in consensus building, since without it, a user cannot express that consensus has not been obtained yet. That is, a proposal is considered blocked just if one or more participants select the "Block" rating. A proposal with no Blocks is considered a valid resolution even if it contains "Do not agree" ratings, as by default consensus does not require unanimity. It should be noted that, as consensus is a collaborative process where opinions change, the ratings can be modified at any moment.

E. Proposed Agents

Two agent prototypes have been implemented to illustrate the interest of this resource in decision-making tools. One of the agents pursues the achievement of consensus while the other aims to encourage participation and good manners (Figure 1). The development of other interesting agents is discussed as future work (Section VI-B).

1) Consensus seeker: The "consensus seeker" agent (*ModeradorImpaciente* in Figure 1) aims to obtain consensus. To improve the odds of obtaining its goal, this agent writes a generic comment to participants *blocking* a proposal (see Section IV-D), in the case that such participant is the only one blocking the proposal. The design of this behavior can be observed in Figure 3.

2) Participation seeker: The "participation seeker" agent (*ModeradorParticipacion* in Figure 1) aims to boost participation in the decision-making process and to keep a polite discussion. In order to increase participation, it makes generic comments encouraging users that have not participated yet to vote and comment. In order to keep a polite discussion, it blocks proposals which have either rude words or orthographic mistakes, explaining in a proposal comment its reasons for blocking. When the "participation seeker" agent is asked to unblock a proposal by the "consensus seeker" agent, the former may tolerate orthographic mistakes (and thus it will unblock if requested) but will not tolerate rude words (and thus it will remain blocking until they are removed). See Figure 3 for a design diagram representing this behavior.

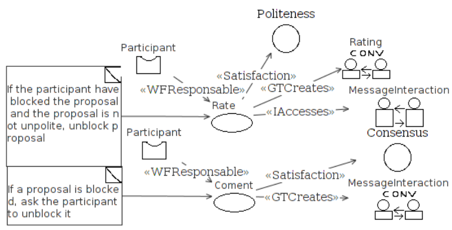

Figure 3. Part of the INGENIAS diagram of the "Goals/Tasks" viewpoint.

F. Agents and Webtool integration

Both Wave Robots (agents) and Wave Gadgets (decision-making webtool) are aware and react to changes in Gadgets state. Considering this, the integration among the agents and the decision-making tool is done through a shared data model of the state of the consensus decision-making process. Being aware of the data model and being able to perceive and create changes in the state, robots can, for instance, interpret a new proposal when it is inserted, or insert a proposal by themselves. Similarly, the webtool can also perceive when an agent performs an action and it may refresh its displayed information.

V. THE PROTOTYPE AT WORK

The presented design (see Section IV) has been implemented in an available working prototype [40]. This section presents the prototype, showing an example where the users and agents (Section III-A) interactions are explained.

A. Example of use

This section explores the users and agents interactions with the decision-making tool.

1) Starting: To start a decision-making process using CONSENSUALL, the prototype has to be included in a wave document/conversation as a gadget. In order to do so, its URL [40] has to be inserted in the Gadget Selector pop-up of any wave document/conversation. Participants of the wave can then invite agents as if she was inviting any other user (these agents must be previously registered with their own username in any Wave server).

2) Proposing: To insert a proposal, participants should provide a title of the proposal and a description. Once a proposal is done, participant can rate it as discussed below. The proposal insertion dialog is located in the upper part of the GUI (see Figure 4).

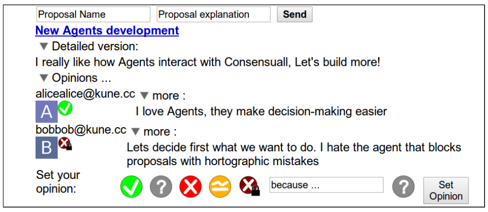

Figure 4. CONSENSUALL User Interface of a new proposal

3) Rating and commenting a proposal: Participants can rate and comment a proposal. Participants should select their rating to the proposal and may insert an optional comment. Figures 6 and 7 show ratings and opinions by one of the agents.

4) General comments: Comments can be added in the wave conversation as it is usual in waves. Figure 5 shows a comment done by "Consensus seeker" agent reacting to previous user interactions in Figure 4.

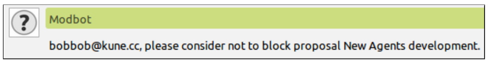

Figure 5. "Consensus seeker" agent asking a user not to block a proposal.

B. Agents interaction

This section presents an example of a non-trivial agent interaction and is illustrated by image captures of the prototype. A description of the behavior of the developed agents can be found in Section IV-E. Both "consensus seeker" and "participation seeker" agents are used in this interaction example.

The interaction starts when a participant makes a proposal with orthographic mistakes. This triggers the following sequence of agent interactions:

1) "Participation seeker" agent, in order to achieve the goal "politeness"(see Figure 1), blocks the proposal, writing a comment in the proposal requesting to rewrite it.
2) "Consensus seeker" writes a comment (analogous to comment of Figure 5) asking "participation seeker" not to block the proposal (as it is the only participant blocking it).
3) "Participation seeker" agent unblocks the proposal after "consensus seeker" agent's message and changes its comment to the proposal (see Figure 7).

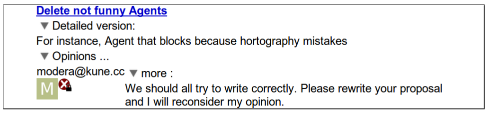

Figure 6. "Participation seeker" agent blocking a proposal.

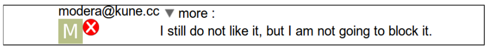

Figure 7. "Participation seeker" agent rating a proposal.

Direct communication among agents, such as the shown message asking other agent to unblock the proposal, could be enhanced by the definition of an *agent communication language* for the proposal domain. This feature is considered as future work (Section VI-A).

VI. CONCLUDING REMARKS

A. Conclusion

The article presented CONSENSUALL, a prototype of a collaborative consensual decision-making webtool. CONSENSUALL provides a decision-making environment where users can elaborate, rate and comment proposals. Additionally, the application allows the introduction of software agents as automatic participants to address common consensus decision-making issues, inspired by the roles adopted in offline assemblies.

The webtool has been designed with an AOSE [9] perspective and software tools (INGENIAS). The use of such tools and methodology have facilitated the development, providing useful concepts and abstractions for the design and conception of the application.

The technology used fits the needs of CONSENSUALL approach. Apache Wave [32] provides a real-time collaborative environment that favors collaboration, needed in a deliberative decision-making process. Wave Gadgets [37] facilitate the development of webtools that may be inserted in wave conversations and shared among participants, and thus it is suitable to build the decision-making prototype. Wave Robots [38] allow the development of software agents as participants, as the article shows with two examples. Their easy development and insertion in the environment makes them a valuable option for a modular improvement of the application.

The results state the feasibility of the proposal, constituting a proof of concept for the future development and research identified in the next subsection.

B. Future Work

The most obvious future research lines point towards scaling consensual decision-making [8][41] and exploring the implementation of different forms of consensus [4] or even other decision-making methods (see Section II-A).

As proposed above, the tool may be extended by the development of new agents, that can be identified in collaboration with users and communities. Examples of some other agents may be: elaborated versions of the two proposed agents; an "egalitarian participation moderator" that points out unbalances in participation (i.e., low participation of female participants or minorities) and encourage the group to solve this issue. The development of an *Agent Communication Language* (for instance, compliant with the FIPA ACL standard [42]), as proposed in Section V-B, would allow interesting interactions among agents.

Some additional improvements, such as its GUI or wave integration or the use of visualization tools, may transform this prototype in a usable webtool for standard users, allowing to make experimentation in real communities. Thus, this would allow further exploration of the potentials of the CONSENSUALL consensus decision-making webtool and its associated software agents, allowing to asset the adequacy of the tool and agents to improve the desired characteristics of consensus decision-making such as democracy, diversity, quality of the decision or required time.

ACKNOWLEDGMENTS

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Chapter 6

Distributed Technologies

6.1 Peer-to-Peer System Design Trade-Offs: A Framework Exploring the Balance between Blockchain and IPFS

Reference

Á. Tenorio-Fornés, S. Hassan, and J. Pavón, “Peer-to-peer system design trade-offs: A framework exploring the balance between blockchain and ipfs,” *Applied Sciences*, vol. 11, no. 21, p. 10012, 2021

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Abstract

The current state of the Web, which is dominated by centralized cloud services, raises several concerns on different aspects such as governance, privacy, surveillance, and security. A way to address these issues is to decentralize the platforms by adopting new distributed technologies, such as IPFS and Blockchain, which follow a full peer-to-peer model. This work proposes a set of guidelines to design decentralized systems, taking into consideration the different trade-offs these technologies face with regard to their consistency requirements. These guidelines are then illustrated with the design of a decentralized questions and answers system. This system serves to illustrate a framework to create decentralized services and applications, that uses IPFS and Blockchain technologies and incorporates the discussion and guidelines of the paper, providing solutions for data access, data provenance and data discovery. Thus, this work proposes a framework to assist in the design of new decentralized systems, proposing a set of guidelines to choose the appropriate technologies depending on their requirements, e.g. considering if Blockchain technology may be required or IPFS might be sufficient.

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Article

Peer-to-Peer System Design Trade-Offs: A Framework Exploring the Balance between Blockchain and IPFS

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Abstract: The current state of the web, which is dominated by centralized cloud services, raises several concerns regarding different aspects such as governance, privacy, surveillance, and security. A way to address these issues is to decentralize the platforms by adopting new distributed technologies, such as IPFS and Blockchain, which follow a full peer-to-peer model. This work proposes a set of guidelines to design decentralized systems, taking the different trade-offs these technologies face with regard to their consistency requirements into consideration. These guidelines are then illustrated with the design of a decentralized questions and answers system. This system serves to illustrate a framework to create decentralized services and applications that uses IPFS and Blockchain technologies and incorporates the discussion and guidelines of the paper, providing solutions for data access, data provenance, and data discovery. Thus, this work proposes a framework to assist in the design of new decentralized systems, proposing a set of guidelines to choose the appropriate technologies depending on the relevant requirements; e.g., considering if Blockchain technology may be required or IPFS might be sufficient.

Keywords: decentralization; distributed systems; P2P systems; IPFS; Blockchain; multi-agent systems

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1. Introduction

Centralized cloud web services now represent an increasingly large portion of the internet [1]. This trend has been significantly accelerated since the emergence of the Web 2.0 model [2], in which web applications enable user participation and user-generated content. Thus, today's internet activity is concentrated on highly successful web services which have dominance over their respective markets [3,4]. During recent years, concerns have been increasing on the multiple issues caused by this situation, with respect to, e.g., privacy [5], governance [3,6], legislation [1], surveillance [7], or security [8]. Consequently, there have been several proposals to tackle some of these issues through new legislation [9,10] or through recommendations for platform developers [11]. In parallel, these issues have triggered the emergence of a wide range of technical solutions through different forms of decentralization.

We may divide the proposed decentralized solutions into three waves. The first wave involved the use of "federated" technology [12–14]—i.e., multiple central nodes communicating with each other—where users are free to choose the node with which to interact . Email is a classic example of an open protocol that is federated, together with the more recent XMPP for chatting [15], OStatus for microblogging [16], ActivityPub for social networking [17], OAuth for authentication [18], or SwellRT for real-time collaboration [19]. This approach is based on interoperability across services and servers [12,20,21]. However, many of these technologies are still hindered by several drawbacks, such as the existence of points of failure [22] and control [23], or the lack of interoperability of the data beyond a few applications [14,21].

The second wave of decentralized solutions was achieved through fully distributed technology; i.e., P2P networks without classical servers but instead using ordinary computers (different from classical cluster/grid parallel computing). There have been multiple attempts to offer P2P web services [24,25], such as Freenet for censorship-resistant communication [26], although broad adoption has mostly been limited to the field of file sharing; e.g., eDonkey, BitTorrent [27].

The third wave began when some unresolved technical challenges with P2P solutions [28,29] became more evident. This opened the door to a new generation of solutions, most of which rely on cryptographic hashes organized in Merkle trees [30]. The advent of the first fully decentralized digital currency, Bitcoin [31], triggered a plethora of decentralized solutions based on its underlying technology: the Blockchain. In addition, another groundbreaking technology emerged around P2P storage: the IPFS, or Inter-Planetary File System [32]. These two new decentralized technologies, often combined, enable a wide range of applications [33–37]. Furthermore, CRDT (refer to Abbreviations for a list of acronyms and their meanings) [38] technology enabled real-time collaboration for P2P systems.

Exploring the synergies of these technologies may unveil new decentralization possibilities. IPFS is frequently used as a decentralized storage for Blockchain applications. However, other non trivial combinations of these technologies may enable new, decentralized system designs.

Therefore, there is a need for frameworks and models to explore the limitations and synergies of these recent innovations. This work proposes a combination of IPFS and Blockchain technologies for the design and implementation of open distributed systems. Concretely, it presents the trade-offs that decentralized technologies face and proposes design guidelines to assess the adequacy of the different considered technologies. Moreover, this paper attempts to assist computer scientists and software engineers in the design of novel distributed systems, proposing a set of guidelines to choose appropriate technologies depending on the relevant requirements. For instance, this framework would enable researchers to decide if Blockchain technology is really needed or if other alternative peer-to-peer technologies (such as IPFS) may be sufficient for the given use case.

The rest of the paper is structured as follows. Section 3 defines characteristics of the considered distributed systems. Then, Section 2 introduces the used decentralization technologies. Section 4 discusses the trade-offs of open distributed system design, discusses the tensions and approaches for consistency in such systems, and provides design guidelines to assess whether a system may require the use of Blockchain technology. Afterwards, Section 6 applies the previous section's discussions and design guidelines to propose a distributed system design, using a distributed questions and answers (Q&A) system as an example. The conclusions follow in Section 7.

2. Decentralization Technologies

Our proposal relies on Blockchain [31] and IPFS [32] decentralization technologies. This section describes these technologies and some of their underlying concepts and properties, such as content-addressability and Merkle linked structures.

Content Addressability: In centralized and federated systems, content is frequently referenced with addresses that include location information: Uniform Resource Locators (URLs) [39]. However, references to content can also be independent from their location, using Universal Resource Identifiers (URIs) [40]. In peer-to-peer systems, agents cannot rely on the location of other agents to access content because the content could be provided by any agent. The hash of any content can be used as its URI (hash functions are one-way collision-free functions; i.e., functions that result in a negligible probability of guessing which input produced an output). Thus, these hash URIs are used in multiple distributed systems such as IPFS to build scalable content-addressable networks [32,41–43].

Merkle Links and Structures: The use of hash values (see previous subsection) to reference data in data structures was first introduced in 1987 by Merkle [30]. Complex data structures can use these links (See Figure 1 for an example). Merkle-linked structures are key to the building of technologies such as Git [44], Blockchain [31], and IPFS [32], among others. Section 6.2 proposes the use of these structures for the data representation of the system.

Blockchain: Blockchain was the first technology that enabled a fully distributed digital currency (Bitcoin) [31], solving the double-spending problem in distributed systems (see Figure 2). It uses a Merkle-linked list of blocks of transactions (a Blockchain) to build a distributed ledger of transactions. To address the double-spending problem, it made it computationally difficult to propose a candidate for the next block in the distributed ledger and incentivized nodes to try to propose those blocks with valid transactions. Then, the protocol considers the largest observed chain the actual ledger to trust. Therefore, in order to forge a Blockchain, an actor would need half of the computing power of the system, bringing security to the consistency of the data recorded in the ledger. Section 4.4 proposes the use of the Blockchain to provide consistency to open distributed systems.

IPFS: Some peer-to-peer systems such as P2P sharing software [41] use a hash of the content to address it (See Figure 3). Other technologies such as Git use complex Merkle-linked structures [44]. IPFS integrates both the use of complex Merkle-linked structures with the data-addressability of P2P file-sharing systems. The content is distributed over a peer-to-peer network. Section 6.1 proposes the use of IPFS for the storage and distribution of data in the framework.

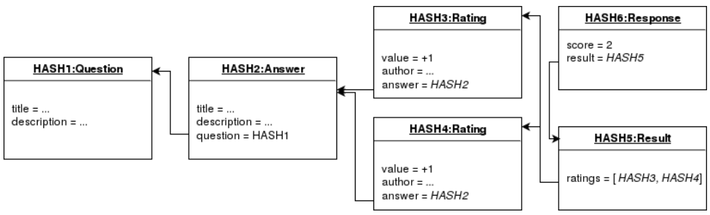

Figure 1. Merkle-linked data of an example Q&A system (such as Stack Overflow).

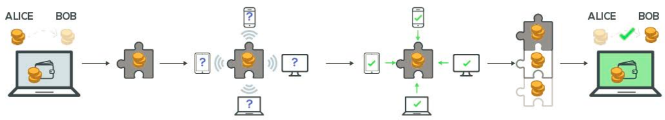

Figure 2. A brief Bitcoin overview: when Alice sends Bitcoin to Bob, her transaction is represented by a block, which is broadcasted to the network. When it is validated, the block is attached to the Blockchain, the transaction is performed, and Bob gets the Bitcoin.

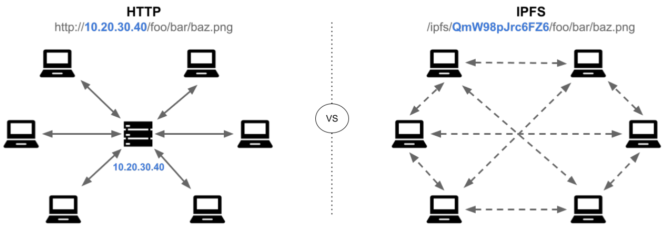

Figure 3. A brief IPFS overview: the classical HTTP protocol used in the web uses location addresses, relying on a centralized architecture in which users connect to the central server (location) which provides the file. Instead, IPFS uses content addresses, where users can retrieve files that are uniquely identified from any node in a distributed network that stores that file.

3. The Open Distributed Systems Considered

The main purpose of this work is to provide a framework and set of guidelines that may facilitate the design of open peer-to-peer services and applications that maintain a shared state and common agreed rules. This work focuses on *open* and *fully distributed peer to peer systems*, especially those enabled by the recent third wave of peer-to-peer solutions such as the Blockchain and IPFS (see Section 1). The kind of systems that are best suited for the given guidelines are defined in this section.

3.1. Shared State and Agreed Rules

Blockchain technology enabled a new generation of distributed systems. For the first time, distributed systems were able to maintain a consistent shared state and trust that the rules to change this state were strictly followed. This may be easily understood when considering the first application of the Blockchain: cryptocurrencies. In this context, there is a need for a consistent shared state: the amount of currency owned by each account. Similarly, nobody should be able to spend the same coin twice, and nobody should obtain money without either receiving it from a transaction or "mining" it for their contribution to the maintenance of the infrastructure.

To achieve this consistent shared state and strict rules, the Blockchain relies on the following building blocks:

- Agreed rules: A consensus on the rules of the system across the network. Thus, the participants on the network agree on how the shared state can change and who can change it. Cryptographic identities are used to ensure that the people who are performing the operations are allowed to do so. For instance, they may agree that only the owner of a cryptocurrency account can send money from that account.
- Trusted state: This is achieved using a tamper-proof, cryptographically-linked data structure named the Blockchain. Thus, every agent can access the complete history of transactions (the chain of blocks) and verify that the rules have been respected (e.g., that no one has sent more money than they initially had).
- Incentivized consistency: This ensures the maintenance required for the consistency of the shared state is performed appropriately. This is achieved by rewarding the "miners" for their maintenance work, typically through a Proof of Work or Proof of Stake algorithm.

This work studies the possibilities of new decentralized systems that rely on similar building blocks. We consider systems in which agreed rules can update the system state in a way that every agent can trust; i.e., it can be verified that the rules have been followed. This paper challenges two typical assumptions in Blockchain systems:

- The hard requirement of a single data structure (such as the blockchain) to maintain all the information is not suitable for multiple distributed systems. Thus, this paper proposes that other distributed architectures such as an IPFS network may store and distribute such information.

- Similarly, maintaining consistency through an elaborate incentive system (such as the famous Proof of Work algorithm) is not a must for multiple distributed systems. Thus, the proposed design guidelines help users to assess whether a Blockchain is needed or if other consistency strategies may be followed (namely, consistency as logical monotonicity, or CRDTs).

Note that other kinds of distributed systems with purposes different than those defined (to maintain a shared state and agreed rules) fall outside the scope of this paper. Thus, classical distributed computing (as in grid computing) or Content Delivery Networks (CDNs) are not considered.

3.2. Openness

Open systems should provide the means for autonomous agents to enter, interact, and leave the system.

The concept of an open system has been widely applied in computing and telecommunications for a long time (see, for instance, standardization efforts such as the OSI model [45]). Its main idea is that services (with well-specified interfaces) can be provided by different entities with their own implementation. An open system, therefore, specifies the means for the communication of its entities, which can enter, interact, and leave the system [46,47].

The evolution of the open system is therefore highly dynamic, which makes it quite complex to obtain complete knowledge of the whole system state at any time. Entities only have a partial knowledge of their environment (the open system), and the only aspect that all entities hold in common is their ability to communicate with each other [47]. In this sense, the paradigm of multi-agent systems (MASs), which assume autonomy and the ability for distributed entities—the *agents*—to communicate to be fundamental, is a proper model for the development of open systems. An agent is an autonomous entity, with the assumption that its knowledge of the world is partial [48], so it tries to take the best decision (principle of rationality [49]) and interacts with other agents.

3.3. Peer-to-Peer Full Distribution

Fully distributed peer-to-peer systems are composed of a network of interconnected agents that communicate and coordinate their actions without a central control entity.

Systems such as the web and P2P file-sharing programs are distributed systems composed of web servers and computers sharing files, respectively [41,50]. While centralized systems depend on a single component for their operation, distributed systems are resilient to the disconnection of some of their components; e.g., if a web server is disconnected, the web will still be a functional system. However, some distributed systems still depend on single components for parts of the system to work. For instance, if a web server disconnects, their web pages will become unavailable. This work refers to *peer-to-peer systems* when referring to distributed systems that are independent from any single node.

4. Design Trade-Offs of Distributed Open Systems

The design of decentralized open systems faces some challenges. Unlike centralized systems, they lack a single entity to determine the consistency of the state of the system. This work focuses on the different strategies that decentralized systems can adopt to achieve consistency. Indeed, Blockchain technology was a solution for a specific problem (the design of a decentralized currency system) with a very strong consistency requirement: users should be able to know who owns money in the system and be sure that each transaction follows the agreed rules. However, not all distributed open systems have such strong consistency requirements.

Fortunately, the existing literature has extensively studied the issue of consistency in decentralized systems. This section builds upon some of the most relevant literature on the consistency of distributed systems and provides a set of four guidelines to design distributed open systems.

First, Section 4.1 introduces the *CAP Theorem* [51], which provides a framework that states the unavoidable compromises between data consistency, availability, and partition resistance in distributed systems. Then, Section 4.2 explains the *CALM Principle*, which offers tools to discover if an open distributed system needs coordination technology for consistent behavior or if alternatively it can be achieved through *Logical Monotonicity*. Finally, Section 4.3 introduces Conflict-Free Replicated Data Types (*CRDTs*), which provide a solution to achieve *eventual consistency* for these systems without needing coordination technologies. Finally, Section 4.4 explains that using *Blockchain* enables such coordination technology to maintain consistency while preserving decentralization when CRDTs cannot be used or when the system has stronger consistency requirements.

4.1. CAP Theorem

The *CAP* Theorem [51] states that a networked data system can only hold two of these three desirable properties:

1. Consistency: The requests of the distributed system should behave as if they were handled by a single node with updated information.
2. Availability: Every request should be responded to.
3. Partition resistance: The system should be able to operate in the presence of network partitions.

Given that the framework considers open systems where agents with partial information can join or leave at any moment, partition resistance is a necessary property for our proposal. Therefore, one of the most important design decisions for the systems built within this framework is to find the best balance between consistency and availability.

4.2. CALM Principle

Some queries are impossible to resolve in distributed open systems. Intuitively, in a distributed open system, some data may not be accessible; therefore, queries that need to take into account all the information of the system such as those that count the data that satisfy some constraints (e.g., counting the exact number of web pages that include a certain word) are impossible to resolve.

The Consistency as Logical Monotonicity (CALM) principle describes those queries that can be resolved in a distributed system without coordination [52]. A system is considered to be *logically monotonic* if the truth of a given statement cannot change by considering new information. In such systems, the responses to distributed queries are consistent.

The designer of a distributed system can check the monotonicity of its queries as follows:

Order independence: This is a needed condition for logical monotonicity [52]; i.e., if the system behavior depends on the order in which the information is received, then it is non-monotonic. For instance, in the double-spending problem, where an agent tries to spend "the same coin" twice, the state depends on which payment was made first. Therefore, it is a non-monotonic problem.

Monotonicity: By definition, if new information may revoke a previously valid response to a query, the query is non-monotonic. For instance, counting the number of positive votes for an answer in a Q&A system is non-monotonic, since new votes would change the response.

Formal analysis: This can prove the logical monotonicity of a system [52].

In distributed open systems, non-monotonic queries may produce non-consistent results without a coordination mechanism. Thus, in the presence of non-monotonic queries, the designer should decide on the consistency requirements of the system.

Guideline 1. *Monotonic queries can be consistently resolved in open distributed systems without coordination technologies.*

Thus, in the presence of network partitions, choosing perfect consistency over availability can be implemented without coordination using logically monotonic systems. If inconsistent behavior, such as missing some votes in a Q&A system, is acceptable for the system, then coordination mechanisms are still not needed.

Guideline 2. *Consistency requirements are a design decision. If inconsistent behavior is acceptable for the non-monotonic queries of the system, coordination technologies are not required for open distributed systems.*

Moreover, some non-monotonic open distributed systems may achieve eventual consistency without coordination, as explored in the next subsection.

4.3. Eventual Consistency

Eventual consistency is defined as consistency among the nodes of a distributed system once all messages have been delivered. The proposed Conflict-Free Replicated Data Types (CRDTs) enable eventual consistency without coordination, such as reaching consensus or rolling back [38]. A data type is said to be a CRDT if the possible concurrent operations are commutative.

Guideline 3. *Eventual consistency can be achieved without coordination in open distributed systems by ensuring that concurrent operations are commutative.*

Note that with eventual consistency, statements that are considered true in a given time can become false after receiving new messages. Thus, this consistency may not be sufficient for systems with strong consistency requirements, such as crypto-currencies.

CRDTs achieve eventual consistency once all messages have been delivered. Different systems may tolerate different delays of these messages. For instance, while a Q&A system may ignore a vote for a long period of time, for a collaborative document, incorporating relatively old updates may be problematic, regardless of eventual consistency.

4.4. Blockchain for Distributed Consistency

Some non-monotonic problems, such as the double-spending problem in distributed currencies, require strong consistency. Thus, a coordination mechanism is needed to provide that consistency. Blockchain technology enabled the implementation of Bitcoin [31], the first distributed digital currency. It proposed a fully distributed coordination mechanism to establish a consensus on the order of valid transactions. Thus, it provided consistency to a non-monotonic problem in a fully decentralized system. Indeed, the Blockchain can be used to provide consistency to other non-monotonic systems by establishing a consensus on the order in which the information should be considered.

Guideline 4. *The non-monotonic queries of an open distributed system with strong consistency requirements should be supported by a coordination technology such as the Blockchain.*

The guidelines are summarized in Table 1.

Table 1. Guidelines summary.

	Weak Consistency	Eventual Consistency	Strong Consistency
Weak availability	No need for coordination technologies (Guideline 2)		Logical Monotonicity or Blockchain (Guidelines 1, 4)
Strong availability		CRDTs (Guideline 3)	*Not possible, considering CAP Theorem*

5. Applying the Guidelines to Well-Known Decentralized Systems

To illustrate the use of the proposed guidelines, we briefly discuss how they would be applied to two well-known but very different decentralized systems: PGP [53] cryptographic key servers and the Git [44] version control system.

5.1. PGP Keyservers

Pretty Good Privacy (PGP) [53] is a de-facto standard for cryptographic identities used to secure email, providing cryptographic signatures and encryption. These identities are often uploaded and shared at PGP keyservers. These keyservers form a decentralized network in which users upload their key to one of the servers, but the servers need to update each other in order to keep the global set of public keys available for any user that requests keys from other users. Moreover, users validate (sign) each other's keys in a distributed manner, forming a "web of trust". Below, we describe how each of the guidelines applies to this system.

When Alice receives a signed message from Bob, she needs to verify that the signature indeed belongs to Bob. A first approach for this verification is to find a signed message from a person Alice trusts stating they trust that the key belongs to Bob. This is the basis of the web of trust for PGP identities. In this simplified first approach, this is a non-monotonic query, since if a signature from a trusted person says that the key belongs to Bob, no new information would override that statement. Following Guideline 1, if we do not need strong availability, we do not need coordination technologies. This is true for many uses of PGP, where users simply share their keys with the few relevant people that they use PGP to communicate with. Still, public keyservers have emerged for convenience, and in these systems, users could upload their public keys with the signatures of the keys they trust.

However, people soon realized that keys could be compromised or that people could revoke the trust they shared about a public key. Thus, the question of whether to trust a key can change in the face of new information, making the system non-monotonic. Facing this issue and following Guideline 2, the system designer should chose whether consistent behavior is acceptable or not (i.e. if it is required to stop trusting a key as soon as the owner or the trusted parties revoke their trust). Many PGP users believe this is a strong requirement and therefore use keyservers to share and update information about trusted keys. With respect to the operations of trusting and revoking trust of a key, Guideline 3 ensures that we will eventually achieve consistency (e.g., once the user receives meaningful revocations). However, trusting cryptographic keys is considered by many to be an issue with strong consistency requirements, as it is dangerous to trust a key that has been compromised. Thus, as Guideline 4 states, there is a need for coordination technologies. In the case of the PGP web of trust, this is achieved by a network of keyservers that update each other and that users can query whenever they need to verify the status of a public identity. Indeed, some have proposed the use of the Blockchain for this strong consistency requirement [54]. However, as we have discussed above when referring to Guideline 3, we are considering a problem in which meaningful consistency is eventually achieved. Thus, we might argue that the Blockchain is actually not needed, and a network of public keyservers that keeps updated information might be sufficient.

5.2. Git

Git [44] is distributed version control software that is widely used to facilitate collaboration and maintenance in software repositories. Similar to the Blockchain, users can verify that changes were made by authorized actors and see the whole history of the version of the repository to which they have access. Multiple different versions of a Git repository coexist on many different computers. Typically, there is an official version maintained by the official contributors, but each of these contributors might have changes that they have not shared yet, and many unofficial versions of the repository with different versions of the software might exist. One of the most common queries in Git is to know the current status of a specific version of the repository (this is a non-monotonic query, as new changes would change the response, as explained in Guideline 1).

Git is a fully decentralized system. Each user (Git instance) may query the changes performed by other users from other known instances in order to keep their information up to date. Thus, this semi-manual update process is the proposed "coordination" mechanism used to obtain an updated state of the system. However, and for convenience, many developers started to use a single repository for coordination purposes, and centralized services for that purpose, such as Github or Gitlab, gained popularity. To re-decentralize Git repositories and maintain the convenience of a single source of consistent information given by centralized services, some have proposed the use of the Blockchain [55]. Git obtains eventual consistency by design (Guideline 3), since it maintains a strict order of operations. Thus, the Blockchain is not needed as a coordination mechanism, since other systems to share updated information may be sufficient.

6. Designing a Distributed Questions and Answers System

In this section, the trade-offs and design guidelines introduced in this paper are presented through a running example of a simple Q&A system, such as the well-known Stack Overflow [56]. The balance between availability and consistency in the system is discussed, and the need for Blockchain technology is assessed.

The proposed system architecture relies on IPFS for fully distributed data storage, public-key identities for data provenance, and a peer-to-peer network for communication. This section introduces how data access, data provenance, and data discovery are provided by the proposal.

6.1. Accessing Data

In centralized Q&A systems such as Stack Overflow, data are addressed and accessed using a location-centric model; i.e., a server is responsible for providing the data. For instance, a user may search for responses to a programming problem on the Stack Overflow website.

The use of content-addressable models for data access provides a fully distributed alternative. Our architecture relies on the IPFS network to distribute the data as Merkle-linked structures. These data structures provide both a Merkle-linked structure and data addressability [32]. Concretely, the data in the system are composed of key–value records and by named, directed Merkle-links to other data (as depicted in Figure 1). This data may be provided by any agent of the system.

6.2. Data Provenance

In centralized and federated systems, the trustworthiness of the data is provided through a direct connection to trusted servers; e.g., the user of a centralized Q&A system trusts a server not to hide or alter the information of the system. Fully decentralized alternatives can also be considered to obtain trustworthy data.

We propose the use of asymmetric cryptography identities to ensure the trustworthy provenance of data. Data that are digitally signed by trusted identities are trusted in the system. Following the technological choices of the architecture, the use of IPNS [32] or the Ethereum [57] identity infrastructure can be used.

Following our Q&A system example, every question, answer, and vote is digitally signed by the authors. Replicating the behavior of Stack Overflow, every user can submit questions and answers to the system. Thus, every signed question or answer is consider valid. A simple version of the system may consider every question, answer, and vote valid, thus having weak consistency requirements. Such a system would not need coordination technologies (Guideline 2) to work. However, systems such as Stack Overflow implement strategies to avoid system abuses; for instance, the system only allows authors with at least 15 reputation points to vote. Five reputation points are earned with each positive vote to a question or answer. Thus, to implement such strategies, our system should only allow the votes of users with at least three positive votes. Since these votes also have to be valid, the vote verification is recursive, until it reaches a trusted base case; e.g., identities that were initially allowed to vote without reputation in the system.

If negative votes are not considered in the system, answering whether a vote is valid is a non-monotonic problem. Thus, it can be implemented in a distributed system with strong consistency without coordination mechanisms (Guideline 1). However, the recursive nature of the example shows that the size and complexity of the data needed to trust a response may not be trivial.

The consideration of negative votes to questions and answers that would decrease the reputation of the authors adds complexity to the problem. The question of whether an identity has at least 15 reputation points is no longer monotonic, since observing new negative votes may change the results. Fortunately, adding and subtracting values to a number are commutative operations. Thus, and following the proposal of CRDTs, we could chose availability over consistency and be able to operate in the system while not knowing all the up and down votes, trusting that eventual consistency will be achieved (Guideline 3).

Furthermore, digital signatures may not be enough to prove authorship in the system. A malicious agent may sign data previously authored by other agents. Deciding the identity of the first author is therefore a non-monotonic problem that cannot be resolved with strong consistency without coordination. This problem is similar to the double-spending problem and could be resolved using the Blockchain if the designer considers that the system requires such strong consistency (Authors could use blockchain to claim authorship by registering a fingerprint of their content in the blockchain before publishing it.) (Guideline 4).

Non-monotonic searches (see Section 4.2) with strong consistency requirements, such as determining the exact number of votes for a question, may need the use of the Blockchain as a coordination mechanism. For instance, the votes of a Q&A system or the authorship of questions and answers could be registered in a Blockchain to provide consistency to those queries. Our architecture proposes the development of smart contracts using Ethereum [57] to provide such consistency for these systems.

6.3. Data Discovery Using a Trustless Distributed Protocol

To discover data in our open and distributed system, we propose the use of a query protocol. The queries of the system state the constraint that the responses must satisfy. For instance, a question that contains a given text can be searched in a Q&A system. The query can also constrain the structure of the response (e.g., it has more than one answer and more than one positive vote).

Additionally, a score function can be defined to sort the valid responses. For instance, the questions containing some text can be ranked by the number of positive votes.

Next, the protocol interactions (Figure 4) are described as follows:

1. An agent sends a query (with constraints and a score function).
2. Any agent can reply, with a response consisting of a content-centric link to the data satisfying the query and its corresponding score.
3. The querying agent accesses the data and verifies the responses and scores.

This protocol presents the following characteristics:

1. Lightweight communication: Responses consist of a short link and a numeric value. Their length is then a few bytes long, even though they may represent complex, large data structures.
2. Early distributed ranking: Responses may be ranked without accessing their data.
3. Trustless ranking and validity: Similarly to how any node can verify that all the transactions in a Blockchain are valid without needing to trust a third party, the validity and ranking of the responses in the proposed protocol can be assessed without trusting the agents providing the responses or the data (e.g., checking the digital signatures for authorship and the validity of the linked votes).

The protocol can be implemented using the following: (1) Merkle-linked data distributed over IPFS; (2) JavaScript pure functions to express query constraints and score functions, using the JavaScript implementation of IPFS; and (3) a bus model for distributed systems communication [58] over IPFS pub–sub channels. Thus, the protocol would enable the implementation of distributed open systems with different consistency and availability requirements (see Table 1 for a summary of the guidelines for those different requirements).

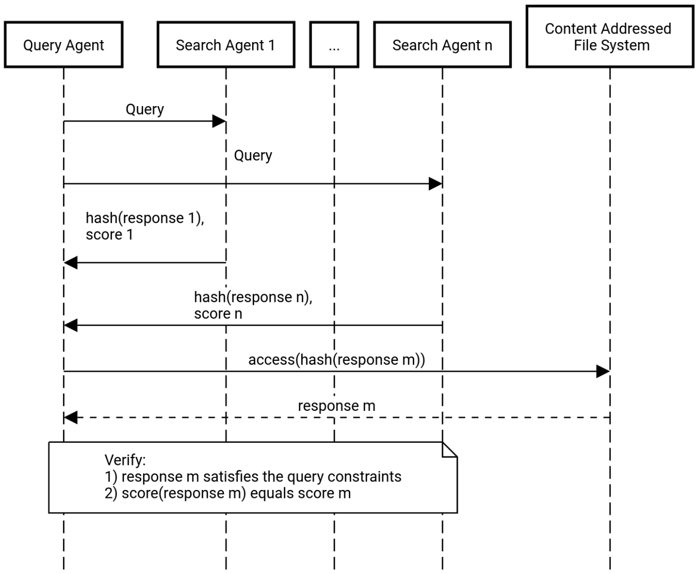

Figure 4. Distributed discovery protocol UML sequence diagram.

7. Discussion and Conclusions

This work introduces the tensions between consistency, availability, and partition resistance in fully distributed systems using current technologies such as the Blockchain and IPFS. It explores the possibilities and limitations of different approaches and technologies, providing guidelines to design these fully distributed systems. The guidelines help to assess whether blockchain technology may be needed for a distributed system. Four guidelines provide alternatives depending on the consistency and availability requirements of the system. The paper claims that these consistency and availability requirements are design decisions and that some systems may not have strong requirements for either of them, thus removing the need for advanced technologies to enhance coordination or availability (Guideline 2). For solutions that require strong consistency, logical monotonic systems can provide such consistency without coordination (Guideline 1). However, not all problems are non-monotonic, and in that case, a Blockchain is required to provide such consistency and maintain the system decentralization (Guildeline 4). For systems with weaker consistency requirements, CRDTs offer an alternative that favor high availability while relaxing their consistency requirements to eventual consistency (Guideline 3).

The paper presents an architecture that is illustrated with a running example of a Q&A system. In this proposal, the data are represented as Merkle-linked structures and distributed with IPFS. Asymmetric cryptography provides trust to the data provenance of the distributed system. Ethereum technology is proposed as the Blockchain-based coordination framework to support the non-monotonic strong consistency requirements that these systems may have. A query communication protocol enables the data discovery in the open distributed system, providing ranked responses and the trustless verification of responses.

This proposal faces some limitations and challenges, as with other Blockchain-based and distributed technologies, such as privacy [59,60], sustainability [61], and scalability [62]. Ultimately, these challenges, which are not covered by our guidelines, could determine which distributed systems are viable. Furthermore, the design of distributed systems following our proposal should consider security concerns faced by similar distributed systems such as *sybil attacks* [31] and *generation attacks* [63]. Still, the sustainability and privacy of decentralized technologies is often better than the centralized alternatives [20].

Future work would help to consolidate and validate the contributions of this paper. Studying the efficiency and performance of the system, the proposal and implementation of new applications, the identification of more suitable network topologies and protocols, or the use of specialized agents such as search agents for specific applications are some of the opportunities to explore.

Decentralization technologies offer an opportunity to solve some of the challenges of the current internet. This paper has introduced design guidelines and a framework to design and build these systems using the potentials of new decentralizing technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

CALM	Consistency as Logical Monotonicity
CAP	Consistency, Availability, Partition resistance
CDN	Content Delivery Network
CRDT	Conflict-Free Replicated Data Types
IPFS	Inter-Planetary File System
IPNS	Peer-to-peer
MAS	Multi-Agent System
OAuth	Originally "Open Authorization", open standard for access delegation
OStatus	Originally "Open Status", open standard for federated microblogging
P2P	Peer-to-peer
PGP	Pretty Good Privacy
Q&A	Questions and answers
URI	Universal Resource Identifier
URL	Uniform Resource Allocator
XMPP	Extensible Messaging and Presence Protocol (originally, *Jabber*)

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6.2 Open Peer-to-Peer Systems over Blockchain and IPFS: an Agent Oriented Framework

Reference

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Abstract

In recent years, the increasing concerns around the centralized cloud web services (e.g. privacy, governance, surveillance, security) have triggered the emergence of new distributed technologies, such as IPFS or the Blockchain. These innovations have tackled technical challenges that were unresolved until their appearance. Existing models of peer-to-peer systems need a revision to cover the spectrum of potential systems that can be now implemented as peer-to-peer systems. This work presents a framework to build these systems. It uses an agent-oriented approach in an open environment where agents have only partial information of the system data. The proposal covers data access, data discovery and data trust in peer-to-peer systems where different actors may interact. Moreover, the framework proposes a distributed architecture for these open systems, and provides guidelines to decide in which cases Blockchain technology may be required, or when other technologies may be sufficient.

Open Peer-to-Peer Systems over Blockchain and IPFS: an Agent Oriented Framework

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ABSTRACT

In recent years, the increasing concerns around the centralized cloud web services (e.g. privacy, governance, surveillance, security) have triggered the emergence of new distributed technologies, such as IPFS or the Blockchain. These innovations have tackled technical challenges that were unresolved until their appearance. Existing models of peer-to-peer systems need a revision to cover the spectrum of potential systems that can be now implemented as peer-to-peer systems. This work presents a framework to build these systems. It uses an agent-oriented approach in an open environment where agents have only partial information of the system data. The proposal covers data access, data discovery and data trust in peer-to-peer systems where different actors may interact. Moreover, the framework proposes a distributed architecture for these open systems, and provides guidelines to decide in which cases Blockchain technology may be required, or when other technologies may be sufficient.

CCS CONCEPTS

• Computing methodologies → Multi-agent systems; **• Computer systems organization → Peer-to-peer architectures**;

KEYWORDS

Decentralization, Distributed Systems, P2P Systems, Framework, IPFS, Blockchain, Multi-Agent Systems

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1 INTRODUCTION

Nowadays, centralized cloud web services represent a large portion of the Internet [14, 24]. In the last years, there are increasing concerns on the multiple issues this situation arises, with respect to e.g. privacy [43], governance [20], legislation [14] , surveillance [36] or security [29].

Decentralized systems have tried to tackle these issues through interoperability [10, 44, 46] and federation [1, 10]. However, they are still hindered by several drawbacks, such as the existence of points of failure [41] and control [34], or the lack of interoperability of the data beyond specific applications [44].

Full decentralization would be certainly useful, especially for certain applications [30]. However, it was not until recently that some unresolved technical challenges [33, 45] have become more evident, which have been the driving forces to innovations such as Blockchain [39] and IPFS [3].

These new decentralized technologies enable multiple applications [4, 17, 18]. Nevertheless, there is a need for models and frameworks that explore how this technologies may be combined and what are their limitations and synergies in order to unveil the decentralization possibilities of recent innovations.

This work proposes a framework for the design and development of open distributed systems. The proposed model uses an agent-oriented approach, and, aiming to focus on real systems, the model assumes open systems (an open environment in which agents can join or leave freely [15, 23]) and where agents have partial information of the system data [22].

The rest of the paper is structured as follows. In Section 2, it defines the requirements of the considered systems, then it introduces the used decentralization technologies (Section 3). Section 4 discusses the consistency and search challenges of open distributed systems and provides design guidelines to asses whether those challenges may require using blockchain technology. Afterwards we proceed to provide an architecture to implement the proposed framework, in Section 5, where we use a distributed Questions and Answer system as example. The conclusions follows in Section 6.

2 SYSTEM REQUIREMENTS

This paper proposes a framework for distributed open systems with the following requirements:

(1) Open system: An open system is a system that enables external autonomous agents to freely join, leave and interact within it [15, 23]. Systems such as the World Wide Web (the Web) or Operating Systems are examples of open systems where new web servers or new programs can freely join and interact [5]. Such systems operate with certain degrees of uncertainty [7], as external actors can interfere in any given moment, and existing actors may leave. These open systems rely on interfaces, protocols and data types to enable the

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interactions within the system. The framework considers open systems to support the construction of heterogeneous and complex systems.

(2) Peer-to-peer system: Distributed systems are composed by a network of interconnected nodes that communicate and coordinate their actions (where such nodes may be e.g. computers or software agents) [12]. Systems such as the Web and P2P File sharing programs are distributed systems composed by web servers, and computers sharing files, respectively [5, 42]. While centralized systems depend on a single component for their operation, distributed systems are resilient to the disconnection of some of their components, e.g. if a web server is disconnected, the Web will still be a functional system. However, some distributed systems still depends on single components for parts of the system to work. For instance, if a web server disconnects, their web pages will become unavailable. This paper refers to *peer-to-peer systems* when referring to distributed systems that are independent from any single node.
(3) Agents with partial information: agents in open and distributed systems have access to just local knowledge of the system [22]. For instance, a web service may just have local knowledge about the resources it serves to the network. This model considers agents with local information that interact solely by 1) sharing new information in the system, 2) querying for information, and 3) responding to queries with their local information.
(4) Communication through a query protocol: Communication among agents of distributed systems is typically enabled through communication protocols [16, 19, 40]. These protocols enable agents to read (syntax) and understand (semantics) the messages involved in the communication. Moreover, they provide the sequence in which these messages must be exchanged. Although a wide variety of interactions can be enabled by communication protocols [40], this model proposes the use of a communication protocol that just allows to *share* information and to *query* for information (as other distributed systems do [47]).

The system proposes the use of queries that can be verified. Thus, an agent does not need to trust the agents providing the responses since these responses can be verified with regard to the query. This shared communication protocol also aims to enhance the interoperability of the proposed framework. The communication protocol is further described in Subsection 5.3.

3 DECENTRALIZATION TECHNOLOGY

This section introduces a technological background for the proposed framework. It describes Blockchain [39] and IPFS [3], the technological innovations that enable the development of new peer-to-peer systems previously unfeasible that this paper studies [3, 11, 25, 31, 35, 39] and some of its underlying concepts such as content-addressability and merkle linked structures.

Content Addressability In centralized and federated systems, content is frequently referred with addresses that include location information, the Uniform Resource Locators (URLs) [6]. However, references to content can also be independent from their location, using Universal Resource Identifiers (URIs) [26]. In peer-to-peer systems, agents cannot rely on the location of other agents for accessing content, because the content could be provided by any agent. The hash[1] of any content can be used as its URI. Thus, these hash URIs are used in multiple distributed systems such as IPFS to build scalable content-addressable networks [3, 27, 38, 42].

Merkle Links and Structures The use of hash values (see previous subsection) to reference data in data structures was first introduced by [37]. Complex data structures can use these links (See Figure 1 for a Merkle structure example). This Merkle linked structures are key to build technologies such as Git [35], Blockchain [39] and IPFS [3] among others. Section 5.2 propose the use of these structures for the data representation of the system.

Blockchain Blockchain was the first technology that enabled a fully distributed digital currency[39]. It uses a Merkle Linked list of blocks of transactions (a Blockchain) to build a distributed ledger of transactions. It made computationally difficult to propose a candidate for the next block in the distributed ledger and incentives nodes to try to build those candidates with valid transactions. Then, the protocol requires that honest nodes will consider the largest chain they have observed in a given time as the actual ledger to trust. Therefore, in order to forge a blockchain, an actor would need half of the computing power of the system. Section 4.3 proposes the use of Blockchain to provide consistency to open distributed systems.

IPFS Some peer-to-peer systems like P2P sharing software [42] use hash of the content to address it. Other technologies such as Git use complex Merkle-Linked Structures[35]. IPFS integrates both the use of complex Merkle-Linked structure with the data-addressability of P2P file sharing systems. The content is distributed over a peer-to-peer network. Section 5.1 proposes the use of IPFS for the storage and distribution of data in the framework.

4 CHALLENGES OF DISTRIBUTED OPEN SYSTEMS: CONSISTENCY AND SEARCH

Data discovery in decentralized open systems is a challenge [23]. This section frames this challenge in the following three subsections:

- CAP Theorem [8] (Subsection 4.1) introduces the compromises between *C*onsistency, *A*vailability and *P*artition resistance in distributed systems.
- CALM Principle [2] (Subsection 4.2) provides analysis tools to assess whether a distributed system (or search) needs coordination
- Blockchain technology provides the first peer-to-peer coordination mechanism for distributed systems requiring trustless strong consistency such as cryptocurrencies (Subsection 4.3).

[1] Hash functions are one-way collision-free functions, i.e. functions that, given their output, the probability to guess which input produced it is negligible.

4.1 CAP Theorem

CAP Theorem [8] states that a networked data system can only provide two out of these three desirable properties:

(1) *C*onsistency: The requests of the distributed system behaves as if handled by a single node with updated information.
(2) *A*vailability: every request should be responded.
(3) *P*artition resistance: the system is able to operate in presence of network partitions.

Given that the framework considers open systems, the *P*artition resistance is a needed property for our proposal. Therefore, one of the most important design decisions for the systems built within the framework is to find the best balance between *C*onsistency and *A*vailability.

4.2 CALM Principle

Discovering information within a distributed network is a challenge, since the information may be scattered among many nodes. In fact, some requests are impossible to resolve within distributed open systems. Intuitively, in an open system we cannot know all the data. Therefore, queries that need to take into account all the information of the system such as those counting the data that satisfy some constraints are impossible to resolve.

*C*onsistency *As L*ogical *M*onotonicity (CALM) principle provides a tool to describe which queries can be resolved in a distributed system without coordination [2]. In a system with logical monotonicity, a true statement remains to be true with the addition of new axioms. The results of a distributed search will be consistent if the query is monotonic, i.e. if considering new information, the results cannot change.

The designer of a distributed system can check the monotonicity of its queries as follows:

(1) A sufficient condition for monotonicity is order independence [2]. For instance, the double spend problem where an agent tries to spend "the same coin" twice in distributed currencies arises from the impossibility to know which payment was done earlier without a coordination mechanism: it is a non-monotonic problem.
(2) If adding new information may change the validity of a response to a query, then it is non-monotonic, e.g. the search of the most voted answer in a Q&A system is non-monotonic, since new votes to an alternative answer would change the response.
(3) Formal analysis of the queries can be done to assess logical monotonicity [2].

Non-monotonic queries produce non consistent results in distributed systems without coordination (e.g. the double spending problem). Thus, in the presence of non-monotonic queries, the designer should decide on the consistency requirements of the system.

Guideline 1. *Monotonic queries can be implemented without using Blockchain or other coordination technologies.*

If inconsistent behaviour, like missing some votes in a Q&A system, is acceptable for the system, then coordination mechanisms are still not needed. If inconsistent behaviour is unacceptable, for instance the double-spend problem in distributed currencies then a coordination mechanism is needed. Blockchain technology is a coordination mechanism that provides consistency while maintaining the system distributed.

Guideline 2. *Consistency requirements are a design decision. If inconsistent behaviour is acceptable for the non-monotonic queries of the system, coordination technologies such as Blockchain are not required.*

Guideline 3. *The non-monotonic queries of the system with strong consistency requirements should be supported by a coordination technology such as Blockchain.*

4.3 Blockchain for distributed consistency

Blockchain was indeed proposed as a way of coordinating a non-monotonic problem for an open distributed system: the double-expend problem, where a malicious actor may try to simultaneously pay twice with the same coin in a distributed payment system. The order in which these payments are processed matters, since the second payment would not be considered valid.

Recording and validating the interactions of a distributed system in a Blockchain (a distributed ledger) provides consistency for non-monotonic systems. Note that in open systems, full partition recoveries and explicit partition management are not expected, and therefore solutions that rely on them such as CRDTs [8] are not applicable.

5 ARCHITECTURE

The architecture of the proposed framework is presented with an example of the implementation of a simple Questions and Answers (Q&A) system, similar to the popular Stack Exchange[2] and its most famous instance Stack Overflow[3].

The architecture uses IPFS as a distributed data store, public-key identities for data trust, and a generic P2P network for communication. Based in the design guidelines presented in previous section, it proposes the use of Blockchain technology when strong consistency is a requirement. The discussion of data access, data trust and data discovery of the system structures the presentation of this open and distributed architecture.

5.1 Tackling Data access

Traditional Q&A systems such as Stack Exchange use a location-centric model for data access. In these systems, specific nodes called hosts are responsible for data provision and are trusted for providing the requested data. For instance, when a user has a programming question, she may search in Stack Overflow website for answers.

Our architecture proposes the use of content-addressable data as alternative to distribute the systems data provision and access. Concretely, it proposes the use of Merkle-linked structures distributed over the IPFS newtwork. Structuring the information as IPFS objects provide both the Merkle-linked structure and the data-addressability of the information [3]. The nodes of this structures are objects composed 1) by key-value pairs representing their attributes and 2) by named directed Merkle-links to other nodes. A

[2] https://stackexchange.com
[3] https://stackoverflow.com

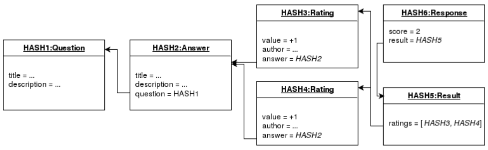

Figure 1: Merkle linked data of an example Question and Answers system (such as Stack Overflow)

representation of linked questions, answers, and votes of a Q&A system is depicted in Figure 1.

The data will be distributed through IPFS. Any agent with system information can act as *data provider* of that information. Moreover, specialized provider agents can be deployed to ensure the availability of information.

5.2 Tackling Data Trust

Both centralized and federated systems use direct communication with trusted hosts to obtain trustworthy data. For instance, centralized Q&A systems trust a web server. However, peer-to-peer alternatives can be explored to enable other nodes to provide trusted data.

This architecture proposes trusting cryptographic identities instead of hosts for providing trustworthy data. Data signed by valid identities is then trusted in the system. In order to enable an easier integration with other parts of the framework, the architecture suggest the use of IPNS [3] or Ethereum [9] identity infrastructure.

Considering our running example, questions, answers and votes would be signed by their authors. Following Stack Exchange rules, new identities can ask questions or provide answers. Thus, in a distributed implementation, any identity could sign questions and answers. However, Stack Exchange requires at least 15 reputation points to be able to vote. Thus, our system would only trust a vote signed by an identity with at least that reputation. Reputation is given for the quality of the user's contributions, for instance, each positive vote in a question or answer gives the user 5 reputation points (as in Stack Exchange).

Thus, the information needed to trust an answer with one vote would be: 1) the question, signed by any identity, 2) the vote signed by an identity that have signed questions and answers that have received three valid votes. 3) recursively validate the new three votes.

With this example we observe that although it is possible to replicate the logic of some centralized systems, the complexity and size of the data needed to trust some information may not be trivial.

Non-monotonic searches (see Section 4.2), such as getting exact number of votes of a question or knowing if a question was reported as spam, may need the use of a blockchain as coordination mechanism. For instance, votes may be registered in a blockchain, enabling verifiable responses to non-monotonic searches. This work proposes the use of Ethereum [9] for the development of blockchain-based smart contracts that govern the logic and consistency of such systems.

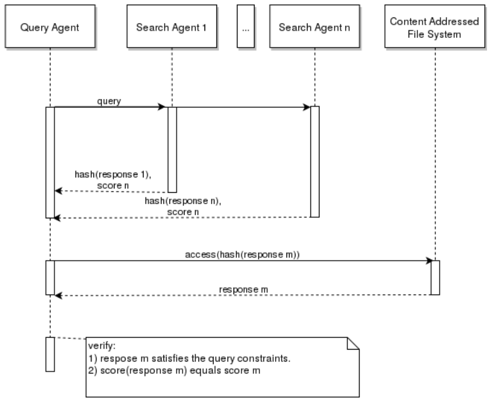

Figure 2: Distributed Discovery Protocol UML Sequence Diagram

5.3 A Trustless Distributed Data Discovery Protocol

The protocol proposes the definitions of queries as constraints to be satisfied by data responses. For instance, a question in a Q&A system can be searched and constraints over its content (e.g. it contains a list of words) and over its structure (e.g. has at least one answer) can be requested.

In addition, the protocol allows the definition of *score* functions for the responses satisfying the queries constraints. This is later used to rank the responses. For instance, the number of votes can be used to sort the searches.

Finally, the protocol interactions (Figure 2) are defined as follows:

(1) An agent sends a query consisting of the constraints and score function.
(2) Any agent can reply with a content-centric link to the data satisfying the query and the result of the score function applied to the data.
(3) The agent can then access the data of the responses. The response can be verified to satisfy the constraints and to score the provided score value.

The protocol as described above has the following advantages:

(1) Lightweight communication: responses consist of a short link and a numeric value. Their length is then a few bytes long while they may represent complex large data structures.
(2) Early distributed comparison/verification: Allows the comparison of responses before even knowing the responses content, in a trustless manner.
(3) Trustless ranking and validity: Responses can be checked to satisfy both the constraints (and thus their validity) and the score function (and thus their ranking with respect to other responses).

The proposed implementation of the protocol relies in: 1) IPFS merkle-linked objects to represent the data and provide the responses. 2) Javascript pure functions to express query constraints and score functions, using the JavaScript implementation of IPFS, and 3) A bus model for distributed systems communication [28] over IPFS pub-sub channels.

6 DISCUSSION AND CONCLUSIONS

This work presents a framework to build peer-to-peer open systems as a multi-agent systems. It enables the data access, data discovery and data trust in a decentralized infrastructure, targeting some of the challenges of fully distributed systems.

The framework studies recent technologies such as IPFS and Blockchain that enable previously unfeasible distributed systems (such as crypto-currencies[39]). It proposes design guidelines to asses whether a coordination tool is needed to provide strong consistency in distributed open system and proposes the use of Blockchain for such cases.

A distributed architecture is proposed for the implementation of the studied systems. IPFS and its merkle linked structures are proposed for data representation and distribution, Public key cryptography is used to provide trust to the distributed data, and Ethereum Blockchain technology is proposed as coordination tool to support the non-monotonic consistency requirements of the systems. A simple channelled flooding algorithm over the IPFS infrastructure is proposed as sample communication infrastructure. The framework also proposes the use of a query communication protocol which enables data discovery in open distributed systems and support both ranked responses and trust-less verification of the responses.

Thus, the presented framework supports the design and implementation of peer-to-peer systems using the innovations introduced by Blockchain and IPFS. The theoretical limitations of these technologies inform the propposed design guidelines, providing tools to asses whether using Blockchain is recommended for the system.

The proposal inherits the challenges and limitations of Blockchain-based and distributed technology such as privacy [13, 21] and sustainability [11]. Moreover, some security issues such as *sybil attacks* [39] and *generation attacks* [32] deserves special consideration in the systems designed with the framework. Still, distributed technologies most frequently provide better privacy than their centralized counterparts [46].

The performance and efficiency of the proposed framework remains to be studied in future work. The deployment of specialized agents, such as search agents for specific applications, or the proposal of improved network topologies and protocols are some of the performance improvement opportunities to explore.

The implementation of new open decentralized systems as interoperable multi-agent systems may enable the growth of a new family of complex and heterogeneous peer-to-peer systems. This paper have introduced a framework to build these systems using the potentials of new decentralizing technologies.

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6.3 Building Real-Time Collaborative Applications with a Federated Architecture

Reference

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Abstract

Real-time collaboration is being offered by multiple libraries and APIs (Google Drive Real-time API, Microsoft Real-Time Communications API, TogetherJS, ShareJS), rapidly becoming a mainstream option for webservices developers. However, they are offered as centralised services running in a single server, regardless if they are free/open source or proprietary software. After re-engineering Apache Wave (former Google Wave), we can now provide the first decentralized and federated free/open source alternative. The new API allows to develop new real-time collaborative web applications in both JavaScript and Java environments.

Building Real-Time Collaborative Applications with a Federated Architecture

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***Abstract* —Real-time collaboration is being offered by multiple libraries and APIs (Google Drive Real-time API, Microsoft Real-Time Communications API, TogetherJS, ShareJS), rapidly becoming a mainstream option for web-services developers. However, they are offered as centralised services running in a single server, regardless if they are free/open source or proprietary software. After re-engineering Apache Wave (former Google Wave), we can now provide the first decentralised and federated free/open source alternative. The new API allows to develop new real-time collaborative web applications in both JavaScript and Java environments.**

***Keywords—Apache* Wave, API, Collaborative Edition, Federation, Operational Transformation, Real-time**

I. Introduction

Since the early 2000s, with the release and growth of Wikipedia, collaborative text editing increasingly gained relevance in the Web . The wiki software [1] (such as MediaWiki, TikiWiki and others), which enabled scalable collaborative edition of documents, rapidly became popular. Nowadays, we can see thousands of wikis used by researchers, institutions, enterprises, and a wide diversity of communities to crowdsource the knowledge of the participants. Just Wikia [2], a wiki service provider, accounts for 300K wiki communities with 135M monthly visitors.

Writing texts in a collaborative manner implies multiple challenges, especially those concerning the management and resolution of conflicting changes: those performed by different participants over the same part of the document. That is, if Alice and Bob edit the same sentences at the same time, we should make sure none of their contributions is lost. In fact, in a scenario where we have hundreds or thousands or contributors over the same pages, such conflict is not rare. These conflicts are usually handled with asynchronous techniques as in version control systems for software development [3] (e.g. SVN, GIT), resembled by the popular wikis. In these environments, the software automatically merges contributions over different sections, but users are forced to “take turns” to edit the same sentences (or otherwise manually merge the others’ contributions to theirs).

However, some synchronous services for collaborative text editing have arisen during the past decade. These allow users to write the same document in real-time collaboration (simultaneously), as in Google Docs [4] and Etherpad [5]. They tend to sort out the conflict resolution issue through the Operational Transformation [6] technology which has grown to become the de-facto standard in real-time collaborative systems. These services are typically centralised: users editing the same content must belong to the same service provider. However, if these services were federated, users from different providers would be able to edit contents simultaneously. Federated architectures provide multiple advantages concerning privacy and power distribution between users and owners, and avoid the isolation of both users and information in silos [7].

The rest of this paper is organised as follows: first, the state of the art of Operational Transformation frameworks is outlined in Section 2. Section 3 depicts the re-engineering approach and the technologies and tools that were used. Section 4 covers the main concepts of the original Wave Platform, and the changes that were performed are explained in detail. Afterwards, the results are discussed in Section 5. Finally, conclusions and next steps are presented in Section 6.

II. State of the Art of Real-time Collaboration

The development of Operational Transformation (OT) algorithms started in 1989 with the GROVE System [8]. During the next decade many improvements were added to the original work and an International Special Interest Group on Collaborative Editing (SIGCE) was set up in 1998. During the 2000s, OT algorithms were improved as long as mainstream applications started using them [9].

In 2009, Google announced the launch of Wave [10] as a new service for live collaboration where people could participate in conversation threads with collaborative edition based on the Jupiter OT system [11]. The Wave platform also included a federation protocol [12] and extension capabilities with robots and gadgets [13]. Allegedly because of lack of fast user adoption, in 2010 Google shut down the Wave service. However, as initially promised, Google released the main portions of the source code to the Free/Open Source community, and handed its ownership to the Apache Foundation. Since then, the project belongs to the Apache Incubator program and it is referred as Apache Wave [14]. Eventually, Google has included Wave’s technology on several products, such as Google Docs and Google Plus. Despite its high technological potential, the original final product had a constrained purpose and a hardly reusable implementation.

Other web applications became relevant during that time, such as the Free/Libre/Open Source Software (FLOSS) Etherpad. However, it was mostly after the Google Wave period when FLOSS OT-based frameworks appeared, allowing the integration of real-time collaborative edition of text and data within third-party applications. The most relevant examples are outlined as follows.

TogetherJS [15] is a Mozilla FLOSS project that uses the WebRTC protocol for peer-to-peer communication among web browsers, together with OTs for concurrency control of text fields. It does not provide storage and it needs a server in order to establish communications. It is a JavaScript library and uses JSON notation for messages.

ShareJS [16] is a server-client FLOSS platform for collaborative edition of JSON objects as well as plain text fields. It provides a client API through a JavaScript library.

Goodow [17], is a recent FLOSS framework replicating the Google Drive Real-Time API with additional clients for Android and iOS, while providing its own server implementation.

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On the other hand, *Google provides a Real-Time API* as part of its Google Drive SDK . It is a centralised (non-FLOSS) service handling simple data structures and plain text.

In general, these solutions are highly centralised. Despite they claim collaboration, users from different servers cannot work or share content. Besides, they mostly provide concurrency control features without added value services like storage and content management. And all of them just allow collaborative edition of simple plain text format.

III. Re-engineering: technologies and tools

This section summarises the procedure followed to re-engineer and build a generic Wave-based collaborative platform, together with the technologies used. First, it introduces the software and technologies that have been generalised, Apache Wave and Wave in a Box, and afterwards the technologies used to develop and test the performed extensions. The description of how and where the results are shared and published conclude this section.

A. Assessment of Apache Wave & Wave in a Box

Wave in a Box is the FLOSS reference implementation of the Apache Wave platform, which supports all former Google Wave protocols and specifications [18] and includes both implementations of the Server and the Client user interface. Most of its source code is original from Google Wave and was provided by Google, although it was complemented with parts developed by community contributors. It enables real-time collaboration over rich-text conversations in a federated infrastructure. It was designed to be an extensible platform through the use of gadgets and robots.

The existing source code is written in Java and the Google Web Toolkit (GWT) [19]. GWT is a FLOSS framework which allows to write Java code and translate it to JavaScript in order to be used in a Web browser. This approach is used to write all Wave components shared between server and client. User interface components are developed in GWT and they are strongly coupled to the Wave's business logic.

The lack of technical documentation forced to perform a preliminary extensive source code inspection, identifying main packages and interfaces and developing text documentation and diagrams. It was concluded that from a logical point of view, Wave concepts could be reused for general purposes, and that technically the source code was organised in layers properly decoupled.

B. Development & Testing frameworks

Both, server and client components of the Wave in a Box software have been extended. In particular, extensions to the server's storage system have been added to support the NoSQL database MongoDB [20] and some HTTP RESTful services have been also created. Part of new source code in client components has been written avoiding GWT dependencies in order to be reused in any Java runtime environment without adaptations. On top of this code, the JavaScript client API has been developed with some GWT specific code.

Concerning software testing, the JavaScript framework Jasmine [21] was used in addition to existing Java unit tests. The test suite attacks all JavaScript API functions in a web browser environment. These are end-to-end tests where all components of the Wave architecture are verified, from client API methods, to server's storage routines.

C. Contributions

The development has been tracked and released in an open and public source code repository [22]. It includes documentation and different examples about how to use the API.

Besides, during the development process, several contributions have been made to the Apache Wave FLOSS community, in the form of source code patches, documentation and diagrams.

IV. Generalising the Wave Federated Collaborative Platform

This section shows the fundamentals of the Wave platform and how they have been used to turn Wave into a general-purpose platform unlike the former conversation-based one.

A. Original Wave Data Models & Architecture

This subsection describes how original Wave data models work from a logical point of view. This allows further understanding of the presented work.

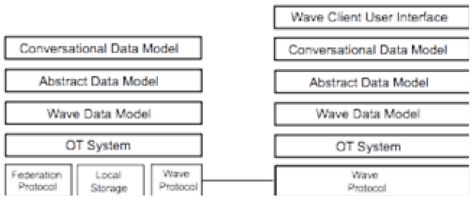

Fig. 1. Apache Wave Architecture, including data model layers.

1) The Wave Content Model

There are three different logical data models in the original Wave systems (Fig. 1). The Wave data model [23] is the basic level of data abstraction in the system providing a basic storage entity, Documents, and two aggregated entities: Wavelets and Waves.

Documents are XML documents where arbitrary data can be stored. They are logically grouped in a *Wavelet* which provides access control for the contained documents. Finally, Wavelets are grouped logically in *Waves*. A Wave is basically a unique identifier -for a particular domain- referencing a set of Wavelets which controls the access to a group of XML Documents.

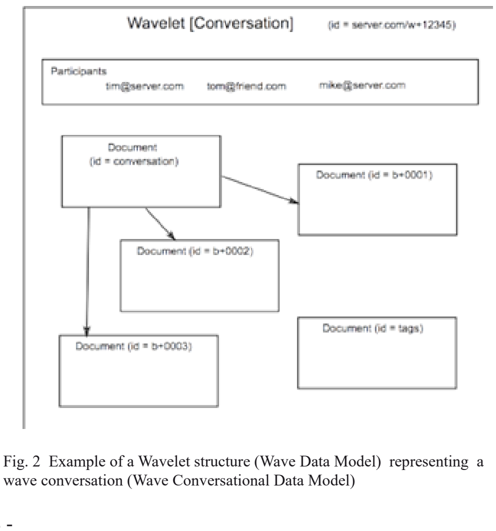

Fig. 2 Example of a Wavelet structure (Wave Data Model) representing a wave conversation (Wave Conversational Data Model)

The actual way to store these entities, and the Document's XML in particular, is through the historical set of changes performed to them. These changes are represented with a special set of character-based operations over a document: the Operational Transformations (OT) .

In the cases of having different users changing an entity at the same time, the OT's applied to the data entity through a special concurrency control algorithm ensures a consistent state of the entity, among all users, after all OT's have been applied. The OT system is responsible to implement such functionality. The implementation of the Wave Data Model allows to react when changes are performed over these entities thanks to this operation-based design.

2) The Abstract Data Model

In summary, the Wave Data Model enables only real-time collaborative editing of structured text (XML). However, it was convenient for the Wave system to handle non textual data as well. The Abstract Data Model provides a set of basic data structures –maps, lists and strings or Abstract Data Types (ADT)– which are represented as XML within Documents. This way, these data structures can be used by different users concurrently whereas they inherit the consistency properties of the underlaying OT system. Besides, the data model translates incoming OT's from the underlying data model in meaningful mutation events for data structures like "element is added", "element is removed", etc.

3) The Conversational Data Model

On top of these two layers, the Conversational Data Model [24] is placed. It provides the data entities and business logic of the original Google Wave product, focused on conversations.

A conversation is handled by a Wavelet, and each message is stored as a Document. The structure of messages is also stored in a Document but using the Abstract Data model instead: the logical structure of the thread can be seen as maps and lists of Documents' identifiers. The Conversational Data Model codifies the content's type of each Document within its identifier (Fig. 2).

These layers are deployed in a client-server architecture. The server side or "Service Provider" provides mainly OT history storage, OT system and federation control with other servers using the XMPP protocol [25]. Additional services like indexing and robots rely on the rest of already introduced data model layers. On the other hand, client side is responsible of the application logic and the user interface, therefore it handles all data layers as well.

The implementation of this architecture is a Java/GWT software originally developed by Google. This technology allows to use almost completely the same source code for all layers in both, server and client modules. Java source code is translated to optimised JavaScript by the GWT compiler. Just a few and specific parts tied to the execution environment are different between server and client, such as networking and random number generation. The server-client communication between follows the Wave Client-Server Protocol. It defines a set of operations and JSON data entities to exchange Operational Transformations for Waves, Wavelets and Documents.

B. General-Purpose Collaboration: Generalising the Wave Data Model & Architecture

Previous section outlined the original Wave's data models and architecture. This section introduces how they can be used in a generic way thanks to the new Wave Content Model, and the Wave Content API.

1) The Wave Content Model

The Wave Content Model is a new general-purpose data model built on top of both existing Wave and Abstract Data Models. It provides a more convenient set of data abstractions and relationships to work with Abstract Data Types. This new data model allows to see a Wavelet as a dynamic tree of nested data objects: maps, lists, text strings and rich text documents. These objects are stored in different Documents of the Wavelet whereas the new data model manages the organization of them and their relationships among the Documents properly (Fig. 3).

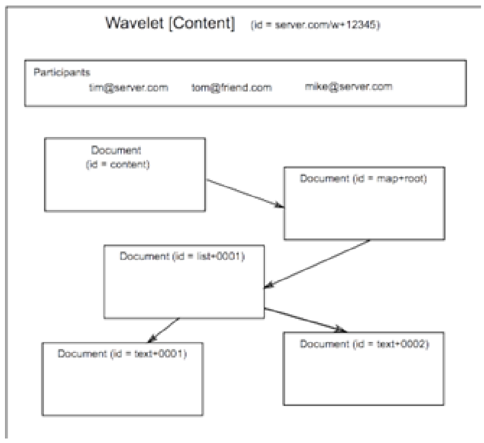

Fig. 3 Example of a Wavelet structure (Wave Data Model) representing a collaborative data object (Wave Content Model)

The Wave Content Model is implemented as a class hierarchy (Fig.4) controlling each possible data type –map, list, string and text– plus a controller class for the whole Wavelet, following the Composition Pattern [26].

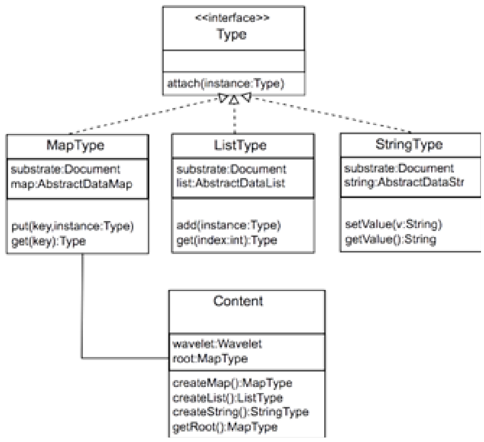

Fig. 4 Class hierarchy implementing the Wave Content Model.

A data class instance, or data objects, handles one single underlaying abstract data type instance over a single Document. New instances are initially unhooked from any Wavelet, so they must be attached to an existing parent instance. Attach process creates the underlying substrate Document, the right Abstract Data Type handler and stores the new Document identifier as reference in the parent instance. This classes allow to register callback methods to be notified on model mutations.

With this approach, Wavelets -and Waves- became generic and dynamic data containers where multiple users can create and modify a nested data structure at the same time ensuring its consistency over the time.

In comparison with the former architecture stack, in the presented approach the Conversational Data Model has been removed and replaced by the Wave Content Model. Of course, the existing user interface layer is also removed (Fig. 5).

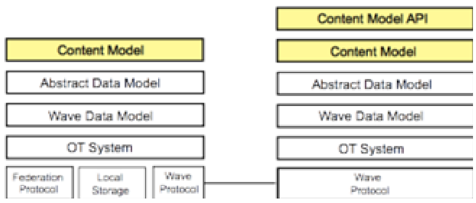

Fig. 5. New Apache Wave Architecture, including new content model

2) The Wave Content API

The new Wave Content Model allows to see Waves as real-time collaborative data structures. However, additional effort is required to expose this model to third-party applications in a handy manner.

According to the technology used in the Apache Wave implementation, just new Java or GWT web applications could use new content data model directly. With the aim of offering these new capabilities to any web application, a JavaScript API has been built.

Although GWT eventually translates Java code into JavaScript, this is not suitable to be consumed directly by non-GWT JavaScript code in a web-browser environment due to the following facts (among others): GWT-generated JavaScript, which is obfuscated by the compiler, does not provide references to objects with suitable names; GWT Exceptions do not flow out of the GWT code, so they must be translated and adapted to external code properly.

Java Script Native Interface (JSNI) and Overlay Types are features of GWT allowing to write arbitrary native JavaScript code integrated transparently within Java code. These features have been used to develop a native JavaScript layer which exposes functionality of the GWT-generated objects of the Wave Content Model. This is an implementation of the Proxy Pattern.

Additional functionality is also required in the JavaScript API. First, users no longer will use the former user interface to get registered or logged in. Therefore, the API provides replacement methods for making HTTP calls to create and authenticate users.

Management of the Wave life cycle now is provided through the API to clients. They can open or create Waves by calling API's methods. Moreover they can be aware of changes in the model registering callback functions in the API.

3) Content Search Index

Clients are able to query Waves stored in the Server Provider thanks to a new query service. Original Wave server implementation stores Wavelets as a sequence of OT's. This approach prevents to look into actual data of Documents to perform operations, for example executing search queries, regardless of the storage engine used.

A secondary storage is used now in order to provide a query service. Anytime the Server Provider commits a change to the main storage, an asynchronous indexing process takes care of the changed Wavelet: a full view of its Wave Content Model is generated in memory and a Visitor Pattern is used to transverse data objects generating an equivalent JSON document.

This process is optimised in two different ways: first, the number of times the indexing process runs is decreased by queuing committed changes sequentially and processing them in groups according their time closeness. Second, loading and transversing the full content model in memory is avoided by pruning. Each received change references to its target Document, which stores unequivocally one data object in the data model. This information is used to skip data model branches without changes in any of its data objects.

Finally, JSON documents are stored in the NoSQL database. The API encapsulates the database query interface and filters queries according to the current logged in user: a user cannot retrieve Wavelets where she is not a participant.

V. Discussion

This paper introduces the first federated platform for real-time collaboration available nowadays. However, using Wave involves some issues, mainly due to the limitations of the source code and its technologies.

There are several critiques concerning the complexity of the Wave OT system regarding two main issues: the complexity of the Operational Transformation system put in place [16] and the large length of the source code with around 500 thousand lines [27]. These facts together with the lack of good documentation causes the maintenance of the source code to be a tough task, requiring highly skilled developers in object-oriented programming with enough mathematical background. However, any OT system is inherently complex. To design a flexible and comprehensive set of operational transformations –such as Wave's– in order to provide an actually usable functionality is hard in any case. Besides, to implement control algorithms is a hard task, even if nowadays they are properly formalised.

Some existing OT implementations use a simpler approach. These OT systems are generally based in the JSON language, having a smaller set of OT operations just defined to operate at the language level. In contrast, Wave's OT system has significantly superior capabilities. It includes business logic operations in the system, such as add and remove participants to a Wavelet. But the most relevant features are to include XML tags and text annotations as part of the OT language. The first allows to handle any XML dialect, while the latter enables contextual meta data over that XML. These characteristics are used in the Wave's rich text format, which, for example, allows to embed arbitrary objects within the text, from images to widgets, just using new XML tags for them.

Operation's semantics and syntax of the introduced API follows the same style of the Google Drive Real-Time API: starting from a root map, new data objects must be created by a factory and then attached to the existing data tree. On the other hand, JSON based OT systems work seamlessly in JavaScript environments, allowing direct manipulation of the data. It is hard to conclude which approach is more appropriated, but the first seems more generic concerning the API implementation in different programming languages, as it is not as tied to JavaScript. Moreover, data structures of JSON documents and new Wavelet's inner structure are equivalent, so it would not be hard to develop adapters. However, currently there is no actual data about the developers preference, i.e. how comfortable are they with each approach.

Performance issues must be taken into account in the new Wave

Content Model. The first consideration is whether the new changes have a negative influence in the general performance of the platform in comparison with the original architecture. Regarding the client, no special impact in performance is expected as long as data objects of the new content model are created in memory only when access to them is required. On the server's side, no changes have been done affecting performance critical aspects of the OT system like in memory recreation of Wavelets and delta-based storage. However, current design of the JavaScript API duplicates some data structures of the underlaying data model to simplify the implementation. Internal improvements in this area could be performed, although they do not affect current or future use of the API.

The GWT development framework is sometimes seen as a disadvantage regarding efficiency and code complexity in comparison with development of native JavaScript software with modern native frameworks [28]. It is true that GWT was produced in a time when JavaScript tools and frameworks were not as advanced as today. However, it is a very stable and mature FLOSS project, and it is supported by Google. Moreover, the GWT compiler generates highly optimised code and it solves the issue of managing dual-language applications.

Client-Server communications relies massively on WebSockets [29] because changes in Wavelets are transmitted in both directions continuously. Protocol implementation is provided by an embedded Jetty HTTP server instance, a classic *Servlet* container which has been improved to support new HTTP features recently. It might be more efficient to use a non-blocking IO server [30] in order to improve vertical scalability. In addition, to use an embedded Jetty instance, prevents the deployment of the code into standard Java server containers.

Finally, it is necessary to assess the use of XMPP as a federated communication protocol among servers. It has been almost a standard for distributed communications in chat applications during more than a decade. However, the previous adoption from big players, such as Google and Facebook, has dropped. Moreover, it seems a heavy protocol to be used in small devices, and to support new features apart from chatting, especially in comparison with new decentralised protocols .

VI. Concluding Remarks and Future Work

A federated platform to develop web applications with real-time collaborative editing capabilities has been presented in the previous sections. It has been developed as a generalisation of the Apache Wave platform, the FLOSS project formerly known as Google Wave.

Nowadays there is no other federated (or distributed) platform for real-time collaboration of data and rich-text.

The provided API is a functional alternative to existing collaborative platforms. It provides a full-stack of software ready to be deployed, including functionalities only comparable with the proprietary Google Drive Real-Time API. Additional features such as the participation model, content storage and search index are part of the platform whereas they are missed in the rest of OT systems.

The API is offered in JavaScript and it can be used in any Web application. But thanks to the Java code base, it would be really easy to have versions for Java and Android applications. In such case, it would be an alternative to the lack of a Google Drive Real-Time API native client for Android.

From a wider perspective, this work opens new challenges in the context of decentralised collaboration:

In the introduced model, access and modification of content (and its structure) is granted to all participants in a Wavelet. However, this might not be enough for some sort of applications where read but not write permissions could be required for some users, e.g. a participant's profile information should not be written by anyone else whereas it must be readable by friend participants.

But also a fine-grain access control could be required beyond the current per-document access control. For instance, in a content Wavelet representing a poll, a user might be allowed to change her vote, but not to change others participants votes.

Under some circumstances integrity of the data model should be enforced, for instance allowing one and only one vote in the previous example. Or in a list of chess moves, enforcing the order and correctness of them.

Content Wavelets are highly flexible data entities for model application where the inner structure allows to define parent-child relationships of data elements. However, in any application, relationships among Wavelets or among inner objects of different Wavelets emerge naturally, so mechanisms to handle them must be explored, e.g. typifying Wavelets, object identification, etc.

Furthermore, in a scenario where several applications make use of the distributed data objects (for instance accessing profile information of users), the use of standard formats for data representation would be required. Technologies such as the Semantic Web [31] and Linked Data [32] provide an example of how distributed data can be organised and linked in a manner that allows further operations such as querying in a decentralised environment.

Current trends in software are driven by the mobile ecosystem. There, code and data are separated: *apps* running in devices, while retrieving data from a remote storage. Nowadays, it is easier to consider these apps managing data generated from different users and stored in different remote servers but eventually combining them in the device.

This work shows the unexplored high potentials of Google's original development, in spite of its complexity and lack of documentation. Thus, this work steps out engineering challenges for the reuse of parts of Apache Wave. The result is a platform ready to explore new challenges in decentralisation of data and services. We certainly hope this work will pave the way for other researchers and developers.

Acknowledgment

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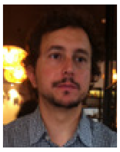

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6.4 Awakening decentralized Real-time Collaboration: Re-engineering Apache Wave into a General-purpose Federated & Collaborative Platform

Reference

P. Ojanguren-Menendez, A. Tenorio-Fornés, and S. Hassan, “Awakening decentralised real-time collaboration: Re-engineering apache wave into a general-purpose federated and collaborative platform,” in *Distributed Computing and Artificial Intelligence, 12th International Conference*, pp. 269–276, Springer, 2015

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Core (2014) C

Abstract

Real-time collaboration is being offered by plenty of libraries and APIs (Google Drive Real-time API, Microsoft Real-Time Communications API, TogetherJS, ShareJS), rapidly becoming a mainstream option for web-services developers. However, they are offered as centralised services running in a single server, regardless if they are free/open source or proprietary software. After re-engineering Apache Wave (former Google Wave), we can now provide the first decentralized and federated free/open source alternative. The new API allows to develop new real-time collaborative web applications in both JavaScript and Java environments

Awakening Decentralised Real-time Collaboration: Re-engineering Apache Wave into a General-purpose Federated & Collaborative Platform

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Abstract. Real-time collaboration is being offered by plenty of libraries and APIs (Google Drive Real-time API, Microsoft Real-Time Communications API, TogetherJS, ShareJS), rapidly becoming a mainstream option for web-services developers. However, they are offered as centralised services running in a single server, regardless if they are free/open source or proprietary software. After re-engineering Apache Wave (former Google Wave), we can now provide the first decentralised and federated free/open source alternative. The new API allows to develop new real-time collaborative web applications in both JavaScript and Java environments.

Keywords: Apache Wave, API, Collaborative Edition, Federation, Operational Transformation, Real-time

1 Introduction

Since the early 2000s, with the release and growth of Wikipedia, collaborative text editing increasingly gained relevance in the Web [1]. Writing texts in a collaborative manner implies multiple issues, especially those concerning the management and resolution of conflicting changes: those performed by different participants over the same part of the document. These are usually handled with asynchronous techniques as in version control systems for software development [2] (e.g. SVN, GIT), resembled by the popular wikis.

However, some synchronous services for collaborative text editing have arisen during the past decade. These allow users to write the same document in real-time, as in Google Docs and Etherpad. They sort out the conflict resolution issue through the Operational Transformation technology [3].

These services are typically centralised: users editing the same content must belong to the same service provider. However, if these services were federated, users from different providers would be able to edit contents simultaneously. Federated architectures provide multiple advantages concerning privacy and power distribution between users and owners, and avoid the isolation of both users and information in silos [4].

The rest of this paper is organised as follows: first, Operational Transformation frameworks' state of the art is outlined in Section 2. Section 3 depicts the reengineering approach and used technologies and tools. Concepts of the Wave Platform and changes made are explained in Section 4. Afterwards, the results are discussed in Section 5. Finally, conclusions and next steps are presented in Section 6.

2 State of the Art of Real-time Collaboration

The development of Operational Transformation algorithms started in 1989 with the GROVE System [5]. During the next decade many improvements were added to the original work and a *International Special Interest Group on Collaborative Editing* (SIGCE) was set up in 1998. During the 2000s, OT algorithms were improved as long as mainstream applications started using them [6].

In 2009, Google announced the launch of Wave [7] as a new service for live collaboration where people could participate in conversation threads with collaborative edition based on the Jupiter OT system [8]. The Wave platform also included a federation protocol [9] and extension capabilities with robots and gadgets. In 2010 Google shutted down the Wave service and released the main portions of the source code to the Free/Open Source community. Since then, the project belongs to the Apache Incubator program and it is referred as Apache Wave. Eventually, Google has included Wave's technology on some other products, such as Google Docs. Despite its huge technological potential, the final product had a very constrained purpose and hardly reusable implementation.

Other applications became relevant during that time, such as the Free Libre Open Source Software (FLOSS) Etherpad. However, it was mostly after the Google Wave period when several FLOSS OT client libraries appeared, allowing integration of real-time collaborative edition of text and data in applications. The most relevant examples are outlined as follows.

TogetherJS [10] is a Mozilla project that uses the WebRTC protocol for peer-to-peer communication between Web browsers in addition to OTs for concurrency control of text fields. It does not provide storage and it needs a server in order to establish communications. It is a JavaScript library and uses JSON notation for messages.

ShareJS [11], is a server-client platform for collaborative edition of JSON objects as well as plain text fields. It provides a client API through a JavaScript library.

Goodow [12], is a recent FLOSS framework copying the Google Drive Real-Time API with additional clients for Android and iOS, while providing its own server implementation.

On the other hand, Google provides a *Real-Time API* as part of its Google Drive SDK [13]. It is a centralised service handling simple data structures and plain text.

In general, these solutions are centralized. Despite their claim of focusing in collaboration, users from different servers cannot work or share content. They just provide concurrency control features without added value services like storage and content management. They mostly allow collaborative editing of simple plain text format.

3 Reengineering: technologies and tools

This section summarises the procedure followed to re-engineer and build a generic Wave-based collaborative platform, together with the technologies used.

Wave in a Box [14] is the FLOSS reference implementation of the Apache Wave platform, which supports all former Google Wave protocols and specifications [15] and includes both implementations of the Server and the Client user interface. Most of its source code is original from Google Wave and was provided by Google, although it was complemented with parts developed by community contributors.

In particular, the Client part has been used as ground to develop the new API, with same technologies: Java and the Google Web Toolkit (GWT) FLOSS framework [16]. The Client is written in Java but is compiled and translated into JavaScript by GWT in order to be executed in a web-browser.

The lack of technical documentation forced to perform a preliminar extensive source code analysis outcoming documentation and UML diagrams. Then, initial developments within the Wave client were performed to assess whether the Apache Wave implementation could be used to develop new applications within fair parameters of quality and cost.

New general functionality was added in separated components, on top of underneath layers such as the federation protocol and server storage system. This has proved the feasibility of reusing the original code and Wave core features. The new source code is GWT-agnostic in order to be reusable in Java platforms. GWT is used to generate just the top JavaScript layer.

Concerning software testing, the JavaScript framework Jasmine [17] was used in addition to existing unit tests. The developed test suite for the API attacks the public API functions in a web-browser environment testing new layers together with the rest of the architecture stack.

The development has been tracked and released in a public source code repository [18]. It includes documentation and examples on how to use the API. Besides, during the development process, several contributions have been made to the Apache Wave Open Source community, in the form of source code patches, documentation and diagrams.

4 Generalising the Wave Federated Collaborative Platform

This section shows the fundamentals of the Wave platform and how they have been used to turn Wave into a general-purpose platform unlike the former conversation-based one.

4.1 Conversations: Wave Data Models & Architecture

This subsection exposes the conversation approach of Apache Wave, its data models and general architecture. From a logical point of view, the Wave platform handles two data models: the *Wave Data Model* [19] and the *Wave Conversational Model* [20]. First, the Wave Data Model defines general data entities used within the platform:

- **Participant**: user of the platform. It may be a human or a robot [7].
- **Document**: recipient of collaborative real-time data.
- **Wavelet**: set of Documents shared by a set of Participants.
- **Wave**: set of Wavelets sharing the same unique identifier.

Documents are the smallest entity that can store data which can be edited in a collaborative way. Documents are logically grouped in Wavelets. In addition, a Wavelet has a set of participants, which are able to access –read and edit– those Documents. Finally, the Wave Data Model defines the Wave concept as just a group of Wavelets sharing the same Wave identifier.

Data is represented in XML and the Wave Operational Transformation (OT) system [21] provides the concurrency control and consistency maintenance for editing this XML in a Document by multiple users at the same time. It also generates events to notify changes to other parts of the system, locally or remotely. XML is used to represent two types of data: rich *Structured Text* in a HTML-like format and *Abstract Data Types* (ADTs) like maps, lists, sets, etc.

On the other hand, the Wave Conversational Model was defined to manage *Conversations*, the major concept of the Wave product. A Conversation is a Wavelet having a set of participants, and a set of Documents supporting the Conversation Thread. A Conversation Thread is compound of Documents storing paragraphs as Structured Text and a Document storing the tree-structure of those paragraphs using ADTs. Conversation Metadata is also stored as a Document using ADTs. This schema is summarised below in Figure 2.

Those data models are implemented in separated layers of the Wave Client architecture as it is shown in Figure 1. All the components of this architecture are developed, packaged and deployed as an unique Java/GWT application.

4.2 General-Purpose Collaboration: Generalising the Wave Data Model & Architecture

Last section outlined the Wave's general data model that could be used in alternative ways. This section introduces a general approach to use it (the Wave Content Model) and a mechanism to consume it (the Wave Content API).

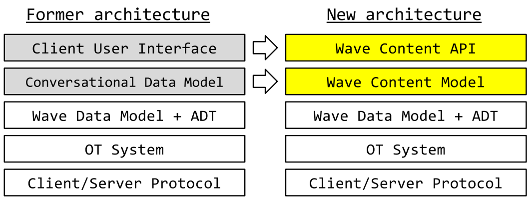

Fig. 1. Wave Client architecture

The Wave Content Model This is a new general-purpose and dynamic data model replacing the former Wave Conversational Model (see Figure 2). It allows to edit Abstract Data Types collaboratively on real-time by different users.

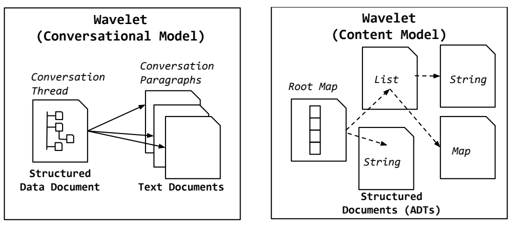

Fig. 2. Wave Data models

The main task was to develop a suitable layer that allows to dinamically create and handle ADTs within Documents of a Wavelet. ADTs are Java classes managing part of the Document content in a particular way. They can be combined declaring new compound types. The Conversation Thread implementation is an example of inmutable compound type as long as inner data structure can't be change on execution.

However, to provide a dynamic composition of ADTs, a Composite pattern [22] is applied. Such pattern defines a hierarchy of data types that can be combined and nested: map, list and string values. Each type is backed by the matching ADT; these new data types control where and how to create and handle ADTs instances within Documents:

This dynamic model is named the *Wave Content Model*. For the shake of clarity, a Wave is now called *Content Instance*, and it provides a main Wavelet where arbitrary data types can be stored dynamically starting from a provided root map. Applications can add new instances of lists and maps to this root or their nested lists and maps, and eventually store string values.

From the architecture perspective, all existing components related to Conversations have been discarded. In particular, the two top layers of the architecture have been replaced (see Figure 1). First, the Wave Conversational Model by the new Wave Content Model. Second, in order to consume the new model in a general way -not just by one single application- the old client is replaced by an API as it is depicted below.

The Wave Content API With the new Wave Content Model any application could use collaborative data structures. However, according to the technology used in the Apache Wave implementation, just new Java or GWT Web Applications could use them directly. With the aim of delivering these new capabilities to any Web Application developed in any technology, a JavaScript API has been built.

Although GWT eventually translates Java code into JavaScript, this is not suitable to be consumed directly by non-GWT JavaScript code in a web-browser environment, for several reasons: the exception handling is not understood by outer code, and GWT-generated JavaScript syntax is obfuscated.

JSNI and Overlay Types [16] are features of GWT allowing to write arbitrary native JavaScript code and objects integrated transparently with Java code. These features have been used to develop a native JavaScript layer, following the Proxy pattern, which exposes the Wave Content Model functionality as an API. A summary of the features provided by the API follows:

- **Session management**: controls user authentication and life cycle of content instances and
- **Content Instance management**: Maps, lists and strings are created through a provided factory and a root map is provided as a hook.
- **Data types management**: exposes type-specific operations such as the addition of an element to a list or getting map keys.

5 Discussion

This paper introduces the only federated platform for real-time collaboration available nowadays. However, using Wave as its starting point involves some issues.

There are several critiques concerning the complexity of the Wave OT system [11]. Its highly complex implementation –together with the lack of good documentation– causes the maintenance of the source code to be a hard task. However, OT systems are inherently complex and to design OT-based languages and control algorithms require knowledgeable people.

Some existing OT implementations are simpler, using the JSON language and a smaller set of OT operations [11] [12]. In contrast, Wave uses XML dialects that supports both, *rich text* edition straight away and structured data, instead of just plain text and JSON. Wave is the only open OT system providing full rich text and text annotations.

Regarding the API design, it works with data structures (map, list) –as the Google Drive Real-Time API–, in contrast with direct JSON objects. It is hard to conclude which approach is more appropriate for third-party developers since the lack of information about the adoption level and critics in both cases.

Java/GWT as implementation language and Jetty as the HTTP server [23], could be seen as a pitfall as long as nowadays trends are to develop using JavaScript directly and to use high-performance servers. However, GWT is still a highly adopted and mature project which a strong community. And from the server perspective, it would be easy to adapt the code to run in non-blocking IO servers [24], extending the life of the original source code.

6 Concluding Remarks

A federated platform to develop web applications with real-time collaborative editing capabilities has been presented in the previous sections. It has been developed as a generalisation of the Apache Wave platform, the FLOSS project formerly known as Google Wave.

Nowadays there is no other federated (or distributed) platform for real-time collaboration. Moreover, this work takes the Wave Federation Protocol further, making it a general protocol. Thus, now on top of the Wave Content Model anyone can define new inter-operable collaborative data formats for text documents, spreadsheets, drawings, games, social media, social activity, etc. New applications could adopt them using an existing provider or becoming a new one. Providers can scale on interoperability since OT storage system is agnostic from underlaying content. Clients just need to be aware of data formats.

The provided API is a functional alternative to existing collaborative platforms. It provides a full-stack of software ready to be deployed, with functionalities only comparable with the proprietary Google Drive Real-Time API. Features such as the participation model, content storage and capabilities to search and manage contents, are already included in the Apache Wave platform but not implemented in any alternative.

The API is offered in JavaScript, to be integrated in web applications. Besides, a Java version will be soon released, in order to allow also Android and Java applications to have collaborative capabilities.

This work shows the unexplored high potentials of Google's original development, in spite of its complexity and lack of documentation. Thus, this work steps out engineering challenges for reusing Apache Wave and we hope it paves the way for other researchers and developers.

Acknowledgments

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Chapter 7

Case Study: Decentralized Tools for academic publishing and peer reviewing

7.1 Towards a Decentralized Process for Scientific Publication and Peer Review Using Blockchain and IPFS

Reference

A. Tenorio-Fornés, V. Jacynycz, D. Llop, A. A. Sánchez-Ruiz, and S. Hassan, "Towards a Decentralized Process for Scientific Publication and Peer Review using Blockchain and IPFS," in *Proceedings of the 52st Hawaii International Conference on System Sciences*, 2019

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Abstract

The current processes of scientific publication and peer review raise concerns around fairness, quality, performance, cost, and accuracy. The Open Access movement has been unable to fulfill all its promises, and a few middlemen publishers can still impose policies and concentrate profits. This paper, using emerging distributed technologies such as Blockchain and IPFS, proposes a decentralized publication system for open science. The proposed system would provide 1) a distributed reviewer reputation system, 2) an Open Access by-design infrastructure, and 3) transparent governance processes. A survey is used to evaluate the problems, proposed solutions and possible adoption resistances, while a working prototype serves as a proof-of-concept. Additionally, the paper discusses the implementation, in a distributed context, of different privacy settings for both open peer review and reputation systems, introducing a novel approach supporting both anonymous and accountable reviews. The paper concludes reviewing the open challenges of this ambitious proposal.

Towards a Decentralized Process for Scientific Publication and Peer Review using Blockchain and IPFS

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Abstract

The current processes of scientific publication and peer review raise concerns around fairness, quality, performance, cost, and accuracy. The Open Access movement has been unable to fulfill all its promises, and a few middlemen publishers can still impose policies and concentrate profits. This paper, using emerging distributed technologies such as Blockchain and IPFS, proposes a decentralized publication system for open science. The proposed system would provide (1) a distributed reviewer reputation system, (2) an Open Access by-design infrastructure, and (3) transparent governance processes. A survey is used to evaluate the problems, proposed solutions and possible adoption resistances, while a working prototype serves as a proof-of-concept. Additionally, the paper discusses the implementation, in a distributed context, of different privacy settings for both open peer review and reputation systems, introducing a novel approach supporting both anonymous and accountable reviews. The paper concludes reviewing the open challenges of this ambitious proposal.

1. Introduction

Science publication and peer review are based on a paper-based paradigm that has not seen large changes in the last centuries [1]. Critics to current science publication and peer review systems include concerns about fairness [2], quality [3], performance [4], cost [5], and accuracy of the evaluation processes [6].

The development of the Internet enabled an expansion of the proposals for alternatives for both science dissemination [7] and evaluation [8]. The reduction of distribution costs enabled wider access to scientific knowledge, and questioned the role of traditional publishers [9].

It is acknowledged that the Open Access and Open Science movements have successfully reduced the economic cost of readers to access knowledge [10]. However it has not successfully challenged traditional publishers' business models [11] that are often charging both readers and authors [12].

Traditional peer review has suffered multiple criticisms, and yet only few alternatives have gathered success [13]. The literature provides multiple proposals around open peer review [14], and proposals of reputation networks for reviewers [15]. In fact, a start-up, Publons[1], provides a platform to acknowledge reviews and open them up.

In addition, other alternatives to the traditional science publication process have arisen in the last 20 years. *Preprints* are scientific papers that have not been peer-reviewed, therefore have not been published in a journal or conference. Platforms such as arXiv[2] and Preprints.org[3] have been successful within the scientific community, allowing these pre-published papers to gain more visibility [16].

Social networks have also carved a niche in the community. Platforms such as Academia[4] or Research Gate[5] are being used by more people every day, allowing researchers to upload their published papers, further connecting the scientific community.

Nevertheless, the mentioned platforms are centralized, with an infrastructure typically controlled by a sole private entity. This centralization has multiple implications [17, 18], for example, less control and self-management for the scientific community; a requirement of blind trust in a third-party that can change its terms or policies at anytime (e.g. in case of a buy-in); or problems related to for-profit business

[1]https://publons.com/
[2]https://arxiv.org/
[3]https://www.preprints.org/
[4]https://www.academia.edu/
[5]http://researchgate.com/

URI: https://hdl.handle.net/10125/59901
ISBN: 978-0-9981331-2-6

models which may affect users, or their data.

Decentralized alternatives, despite their promises [19], are still in their infancy. A few proposals, none of them functional to date, have appeared recently: a peer review proposal using cryptocurrencies [20], a blockchain-enabled app with voting and storage of publications, again using cryptocurrencies [21], or a peer review quality control through blockchain-based cohort trainings [22]. Additionally, the new Ledger[6] journal records the publication timestamps in the Bitcoin blockchain.

This paper proposes the development of a decentralized publication system for open science. It aims to challenge the technical infrastructure that supports the middleman role of the oligopoly of traditional publishers [11]. Due to the successes of the Open Access movement, some scientific knowledge is freely provided by publishers. However, the content is still mostly served from their infrastructure (i.e. servers, web platforms). This ownership of the infrastructure gives them power over the scientific community which produces the contents [23]. Such a central and oligopolistic position in science dissemination allows them to impose policies (e.g. copyright ownership, Open Access prices, embargo periods, dissemination restrictions) and concentrate profits.

The proposed system presents the ambitious aim to move the infrastructure control from the publishers to the scientific community. It entails the decentralization of three essential functions of science dissemination: 1) the selection and recognition of peer reviewers, proposing a peer reviewer reputation system where review reports can be rated 2) the distribution of scientific knowledge, through the distribution of scientific papers using the IPFS P2P network, providing an Open Access by-design infrastructure, and 3) peer review process communication, relying on Blockchain to provide a transparent and decentralized platform for open peer review process communications, such as paper submissions, reviewer proposals or review submissions. It specifically targets four issues of the peer review process: 1) the quality, and 2) fairness of peer review from authors' perspectives, 3) the fairness of recognition, reputation or rewards received for reviewing from reviewers' perspectives, and 4) the difficulty in finding good reviewers from editors' perspectives. Additionally, it proposes a decentralized solution aiming to reduce the control of publishers through their centralized infrastructure.

First, Section 2 offers a review of the state of decentralization technologies and introduces the concepts and technologies used in the paper. Then, Section 3 provides an overview of the system's requirements, with a design explained in Section 4 and an implemented prototype described in Section 5. In order to perform a preliminary evaluation of the detected problems and proposed solutions, we have performed a survey described in Section 6, including a discussion of its results. In addition, since the proposed open system raises multiple concerns around privacy, Section 7.1 discusses the opportunities and challenges around different privacy settings regarding peer review in an open and decentralized network. Furthermore, this section introduces a novel approach which enables both anonymous and accountable reviews, bringing together the promises of both blinded [24] and open review [14] models, addressing the concerns about the negative consequences for reviewers of a reputation system. Finally, Section 8 discusses the benefits, challenges, opportunities and open questions arising from the described proposal.

[6]https://ledgerjournal.org

2. Decentralization Technology

As further explored in Section 3, this paper proposes to use decentralized technologies to provide 1) a reputation system for reviewers, 2) an Open Access by-design infrastructure for paper distribution and 3) transparency for peer review governance. This section introduces the decentralization technologies on which the paper proposals to rely. Note the section follows the approach of Tenorio-Fornés et al. [25] which proposes a framework for distributed systems in which IPFS is used for distributing content and Blockchain to provide consistent behavior.

IPFS: IPFS is a decentralized file system which enables the distribution of content in a decentralized network of peers (such as some P2P sharing systems [26]). It also supports secure links among such contents (Merkle-links [27]), enabling the use of complex data structures such as those used in git [28] or blockchain. This paper proposes the use of IPFS to distribute the papers and reviews of the system (see Section 3.2). Thus, papers and reviews can be unambiguously identified in the network by the hash of their data.

Blockchain: Blockchain was the first technology that enabled a fully distributed digital currency, Bitcoin [29]. It solved the double-spending problem by which a dishonest actor may try to spend the same coin twice in decentralized currency systems. It relies on a ledger of transactions that is updated and maintained by a network of peers. The blockchain introduces incentives to maintain the security of the ledger, both rewarding nodes that contribute computational power for the security of the network, and requiring at least half of the computing power of the network to alter the state of the blockchain — i.e. the blockchain is secure if at least half of the computing power is provided by honest peers. This technology enabled a new wave of decentralization of applications such as domain name registries [30] or microblogging platforms[7] . A second wave of blockchain-based decentralization was started by Ethereum [31], as described below.

Ethereum and smart contracts: Ethereum is a blockchain-based distributed computing platform. It started the aforementioned second wave of decentralization [31], which enabled the deployment, on the blockchain, of small code snippets named *smart contracts* [32]. In this technology, the peers of the network execute the code of smart contracts. Similarly to Bitcoin, where a network of peers ensure the validity of a ledger of transactions, in Ethereum a network of peers ensures the execution of these smart contracts. Thus, a smart contract code will be executed as long as there are peers in the network, i.e. it cannot be stopped and it is autonomous from its creators. Also, its rules will be executed as defined by its code, i.e. its rules are self-enforced [33]. Each interaction with Ethereum is registered as a cryptographically signed *transaction*, similarly to Bitcoin. Examples of decentralized applications enabled by this technology include prediction markets [34], social networks [35] or a game to collect, breed, and sell virtual kitties[8]. This paper proposes the use of smart contracts to 1) implement a reviewer reputation system and 2) to enforce the transparency of the peer review rules, for example, who may assign reviewers, or who can submit a review (See Section 4).

3. Requirements

The proposed system aims to provide a distributed platform for open science, from submission to publication, including the peer review process communications. The system rests on three main pillars: a distributed reviewer reputation system, Open Access by-design, and transparent governance. These are outlined in the following subsections.

3.1. A Distributed Reviewer Reputation System

The information concerning the quality and reliability of reviewers is usually private to publishers and journals (and even editors). There is no easy way to predict the quality of a reviewer from factors such as training and experience [36]. Although this information is valuable, it is kept private, reinforcing the publishers' and journals' influential positions.

This proposal extends traditional peer review communication workflow with the possibility of rating peer reviews, building a reputation system for reviewers [37]. Reviewers are rewarded for worthy, fair, and timely reviews, or penalized otherwise.

This open reputation network of reviewers could increase the visibility and recognition of the reviewers [38]. In fact, such incentives could even be monetary, using cryptocurrencies [39]. In addition, creating a public reputation network for reviewers reduces, or at least exposes, unfair and biased reviews [2, 40].

3.2. Open Access By-Design

Open Access focuses on free access to scientific knowledge. While publishers provide Open Access content free of charge, their control of the science dissemination infrastructure allows them to impose certain rules, such as charging authors unreasonable fees to offer their work as Open Access (Gold Open Access) [41] or the temporary embargo and restrictions on the dissemination of the final version (Green Open access) [42], among others.

Our system proposes a decentralized infrastructure for science publications. Academic documents - from first drafts to final versions, including peer reviews - are shared through IPFS, an open P2P network [43] described in the previous section. In this type of P2P networks, it is substantially difficult to impose restrictions on content access and sharing. Thus, the system inherently (by-design) facilitates Open Access through its distributed infrastructure, circumventing publishers' dominant roles. Moreover, the access to these documents does not depend on the existence of our platform. Even if our platform ceases to exist, the documents could still be retrieved from the network.

3.3. Transparent Governance

Nowadays, the peer review process is digitally supported, yet some argue that the system remains feudal [9]. There are multiple proposals to improve peer reviews [8], yet communications and processes remain closed and under the control of journals and publishers, and thus depend on their specific infrastructures [40].

The proposed system aims to improve the transparency, speed and fairness of the peer review process. In order to do this, the system proposes to support the peer review interactions in an open and decentralized network. It registers, in a public

[7] http://twister.net.co/
[8] https://www.cryptokitties.co/

decentralized ledger, the following parts of the publication process: paper submission, assigning reviewers, review submission and paper publication. Thus, processes like the selection of reviewers, or the contents of the reviews, are open to the public. With interactions being time-stamped and tamper-proof thanks to blockchain technology, they can be monitored, audited, and held accountable. More complex iterations of the system may consider blind reviews (Section 7.1).

Opening the peer review process communications to the public could even change the acceptance dynamics within the system. Currently, high rejection rates are encouraged because the risk of rejecting a relevant paper is negligible, while the acceptance of less relevant content is penalized [9, 44]. However, within a more transparent system, the first may be penalized as well.

This transparency, combined with a distributed infrastructure for peer review, facilitates the exploration of new workflows [40].

4. Design using a Decentralized Infrastructure

The system provides a platform for the peer review process communications, from paper submission to paper acceptance or rejection, and supports the rating of peer reviews to build a reviewer reputation network.

The proposed system relies on the technologies mentioned in section 2. On one hand, the *Ethereum blockchain* provides a public decentralized ledger to record the system's interactions. Smart contracts are used to enforce the rules of the system, such as only accepting reviews of invited reviewers. On the other hand, *IPFS* provides a distributed file system to store the content of the peer review process. This ensures that the information registered in the platform will be persistent, free and accessible, and will not rely on a centralized server.

The sequence diagram of the system (Figure 1) describes the main interactions of supported peer review governance. Below we proceed to describe these interactions and the basic ideas to implement them.

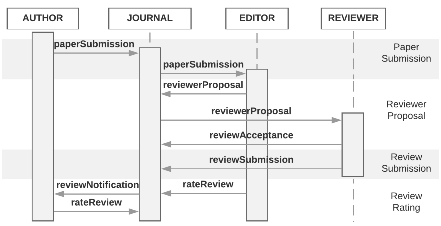

Figure 1. Sequence diagram of platform interaction

Paper submission: The submission process has three steps within the system. First, the paper is uploaded to the IPFS network, then the platform will recover the unique identifier of that paper, the IPFS address. Finally, the platform will create an Ethereum *smart contract* containing the file address and the addresses of the authors to record the submission on the blockchain. This creates a transaction in Ethereum that can be used to verify that the authors submitted the paper. Furthermore, this *smart contract* generates an Ethereum address that acts as a paper's unique identifier inside and outside the platform.

Reviewer proposal: A journal editor may invite a reviewer to review a specific paper, creating a *review task* in the paper's *smart contract*. The transaction will record the Ethereum address of the reviewer and, optionally, a deadline to submit the review. The invited reviewer may accept or reject the *review task* (which will also be recorded into the blockchain). If the task is rejected, the editor can assign another reviewer.

Submit review To submit a review, the reviewer should carry out a transaction that will record the acceptance/rejection and the IPFS address (i.e. the location) of the detailed review. In the event of a reviewer sending a review when the time has expired, a penalty is applied to the reviewer's reputation in the reputation system.

Rate review A novelty of the system discussed in Section 3.1 is the reputation system for reviews. A blockchain transaction will record the sender address and the rating as well as the rated review and reviewer addresses.

5. Implementation

In order to implement the system, we developed a proof-of-concept prototype that allowed us to perform preliminary testing of each interaction within the platform, exploring the feasibility of its implementation using the aforementioned decentralized technologies. Thus, this software implements a basic version of the requirements specified in Section 3, and follows the design of Section 4. The software is free/open source, available in Github[9].

The architecture relies on 1) IPFS for distributed storage of papers and review reports and 2) Ethereum Blockchain for the system's logic and state. The prototype proposes an HTML + JavaScript interface that connects to IPFS and Ethereum through JavaScript clients and uses Metamask[10] to provide an user-friendly management of Ethereum user identities.

[9] https://github.com/DecentralizedScience/Gateway
[10] https://metamask.io

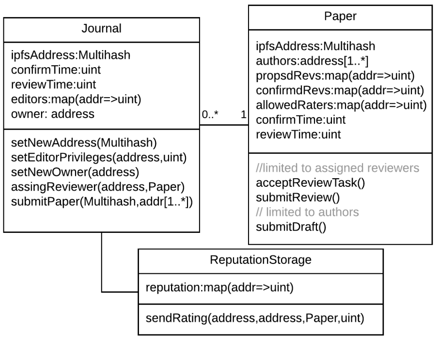

Figure 2. Smart contract diagram of the platform

This proof-of-concept prototype uses three different Ethereum smart contacts to run the platform's inner functioning. Figure 2 shows a diagram of this structure. The *Multihash* structure is used to store IPFS references in the system. The *Journal* contract controls the paper submission, the selection of editors, the assignment of reviewers, and the acceptance of reviewers. The *Paper* contract identifies a paper within the system, controls the review submissions, and shares who may rate a review. Finally, the *ReputationStorage* contract stores the ratings of the peer reviews, receive new rates, updating the reputation of reviewers if allowed by their Paper contract, and shares the reviewers' reputation.

6. Evaluation

A Likert scale survey [45] was conducted to assess (1) the importance for respondents of the tackled peer review process problems, (2) to which degree they believe a reviewer reputation system may help to improve them and (3) to which extent they would experience some resistance towards the solution. The survey constitutes an exploratory study of the validity of the proposed solution. It addresses academic researchers interested in the problems of peer review processes. Its design follows a convenience non-probability sampling: three different groups of academics that may be interested in the solution took part in the survey; namely 1) a Telegram group of 166 members ("Open Science Ecosystem") for projects building decentralized solutions for open science, 2) the Computer Science department the authors are members of, and 3) a list of 36 people who have subscribed to a newsletter available on our prototype website. Thus, the survey does not aim to generalize the results for the whole academic researcher population; its purpose is to explore the response of potentially interested users of different profiles. That is, would this proposal attract enough early adopters which would enable further exploration and validation? The survey is solely targeted for academic researchers, although the questions are intended to be answered from the perspective of three different roles: as authors, reviewers or editors.

The survey first collects data for the characterization of the population: age, gender, whether the respondent is (or has been) an academic, and current participation in research groups or open science projects.

Afterwards, the survey questions the perception of the importance of the peer review problems, the possible resistance to a reviewer reputation system, and the perceived adequacy of such a system to solve the explored problems. These perceptions are investigated using a 1 to 5 Likert scale to measure agreement with the statements, where 1 means 'strongly disagree' and 5 'strongly agree'.

Problem questions: The survey asked the following questions related to the problems of the review process: 1) As an author, I think that the quality of the review process can be sensibly improved. 2) As an author, I think that the fairness of the review process can be sensibly improved. 3) The recognition, reputation or rewards I receive as a reviewer feels fair in relation to the amount of work that I do. 4) As an editor, I have difficulties finding good reviewers (quality, relevance, timeliness).

Resistance responses: Afterwards, the survey enquires about the following possible resistance for the adoption of a reviewer reputation system: 5) As an author, I would prefer to submit my work to a journal in which reviews can be publicly rated (on a reviewer reputation system), 6) As a reviewer, I would prefer to submit a review to a journal in which my review would be publicly rated (on a reviewer reputation system), 7) As a reviewer, I would only submit a review to a journal which rates its reviews, if I remain anonymous. 9) As an author/editor/reviewer, I would like to be able to rate the reviews of the papers I am working with.

Problem/solution fit responses: Finally, the survey asks, for each of the four explored problems, if the respondents believe that a reputation system of reviewers may sensibly contribute to address them. 8) As an editor, I would find a reviewer system sensibly useful to find relevant, timely and/or high quality reviewers. 10) I believe that a reviewer reputation system could sensibly improve the quality and/or fairness of the peer review process. 11) I believe that a reviewer reputation system could sensibly improve the recognition, reputation or rewards I receive for my reviews.

Question	#Answers	mean*	mode
1) quality	35	4.2	4
2) fairness	36	4.4	5
3) rev. fairness**	34	2.4	2
4) finding reviewers	30	3.9	3 or 4
5) author resistance	36	3.9	4
6) reviewer resistance	34	3.6	4
7) anon. rev. resistance	34	3.1	3
8) improve rev. search	30	3.9	4
9) want to rate	36	4.3	5
10) improve qual./fair.	36	4.1	4
11) improve recog.	35	3.9	4

*Max of 5. **Perceived fairness, i.e. lower the better

Table 1. Summary of Likert scale 1 to 5 responses

6.1. Results

The survey was responded to by 37 people, of which one was filtered out as a non-researcher. The results of the survey are summarized below.

33 of the participants are academic researchers, while 3 have been academic researchers in the past. 8 responded that they do not participate in a research group or a project related to open science or did not responded to that question. The age ranges 18-24, 25-34, 35-44 and 45+ are distributed as 1, 11, 14 and 10 participants respectively. 10 are female and 26 male (none chose other or not responded).

The responses to the 11 likert scale questions with the 1 to 5 scale are summarized in Table 1.

6.2. Results discussion

The four explored problems seem to be relevant for the participants. Note that question 3 is inversed with respect to the other questions, as it asks for the perceived fairness of the current process (and not unfairness). Questions 1 and 2 present the strongest results, as their means are between agreement and strong agreement. Questions 3 and 4 have an average between (dis)agreement and neutral, thus, the perceived relevance of these problems is relatively smaller than the former.

The three questions assessing possible resistances for the adoption of the solution show that both authors and reviewers would prefer to use the proposed solution. In fact, only 4 participants disagree in their preference of the proposed system in each question. With regards to anonymity, 14 reviewers agree or strongly agree that anonymity is a needed condition for their participation in the system, while most respondents remain neutral or disagree with this need. Participants agree that they would like to rate reviews (average between agree and strongly agree).

Finally, the use of a reputation system for reviewers is perceived as a relevant solution for the explored problems with averages close to agreement: 3.9 for finding reviewers, 4.1 for improving quality or fairness and 3.9 for recognition and reputation of peer reviewers.

Overall, it is considered that this small survey provides a preliminary evaluation which invites further exploration of the proposed solution. It is also an indication that such a system could attract early adopters with whom to perform further testing.

7. Privacy requirements

Given the concerns around privacy in the proposed system, and following the feedback received, we have explored an extension of this system, taking into account different privacy settings and their potential implementations.

In traditional peer review, there are several privacy settings that can be adopted, allegedly to improve the fairness of the process [24, 46]: (1) Blind reviews, which keeps reviewers anonymous, protecting their freedom to criticize. (2) Double blind reviews, which keeps both authors and reviewers anonymous, to prevent social bias. (3) Open reviews, in which both authors and reviewers are known, with effects under debate [47, 48]

7.1. Privacy requirements for Reviewer Reputation Systems

	Public Reviewer	**Anon. Reviewer**
Public Rater	Signed rate of open review	Signed rate of blind review
Anon. Rater	Anonymous rate of open review	Anonymous rate of blind review

Table 2. Different configurations to rate a review

This section builds on the described traditional privacy settings, adding a new layer of complexity: we not only deal with reviews, but with both reviews and ratings. As already proposed in Section 3.1, the construction of a reputation network of reviewers may improve the accountability of the peer review process. Thus, this section explores different privacy settings such reputation systems may have. One of these settings, the rating of blind reviews, is explored in more detail. Challenges of such systems are identified, and will later guide the discussion in subsection 7.2 on how this may be achieved.

Signed Rating. Similarly to the open peer review (explained above), signed ratings are both public and verified ratings of a review. It is straightforward to implement by maintaining a public identity for the raters.

Anonymous Rating. Protecting the identity of raters is interesting in several reputation systems [49]. We can support this anonymity feature using *blinded tokens* [49] that grant permission to rate without revealing the identity of the rater. People authorized to rate a review in the system, e.g. authors, editors and other reviewers of the paper involved in the process, may each get one of these tokens.

Rating Blind Reviews. The question of whether we can keep the benefits of blind reviews while providing accountability and recognition to reviewers (and thus rating their reviews) deserves special consideration, and thus it is explored below.

The following challenges must be considered in order to provide the Rating Blind Reviews privacy setting:

Challenge 1 (Anonymity) *The reviewer should be able to claim the rating received in her review (e.g. to receive a positive reputation) without revealing that she is the author of the review.*

Challenge 2 (Accountability) *The reviewer should not be able to avoid the effect of negative reviews (e.g. only claiming the positive ratings).*

Challenge 3 (Authorization) *The ratings should come from authorized raters (i.e. minimizing cheating).*

Challenge 4 (Sybil resistance) *Having several identities in the system should not provide advantages. Note that blockchain systems such as Ethereum allow the creation of multiple identities per user.*

Challenge 5 (System abuses) *The anonymity of interactions may hinder the detection and prevention of system abuses. For instance, malicious actors may try to submit fake reviews to be rated by accounts they control in order to obtain unfair good ratings. Detecting this behavior would not be trivial since reviews and ratings may be anonymous.*

A system allowing an anonymous yet accountable reputation system for peer reviewing would enable a new privacy and accountability model for peer reviews. However, its implementation faces important challenges such as those described above. The next section provides an overview of how existing techniques may be applied to tackle the identified challenges.

7.2. Achieving Accountable Anonymous Reviews

The previous section identifies challenges that an anonymous yet accountable reputation system for peer reviews faces. Some existing technologies have been applied to similar challenges, and others may help to combine their advantages. This section explains these technologies and how they may be used to tackle the challenges of this system. First it provides an overview of how the technologies may be combined, and a description of the technologies follows.

A simple way of protecting the identity of users is the use of different virtual identities for each interaction, i.e. *single-use identities*. However, linking the reputation received by these single-use identities to their real identity, both providing accountability (Chlg. 2) and preserving anonymity (Chlg.1), requires the use of other technologies.

In order to provide accountability (Chlg. 2), the system may try to detect when an identity has not received a bad reputation. For this purpose, a reputation deposit or *collateral* could be requested for each rating a reviewer may receive. This way, users could compare the number of claimed ratings and the number of unclaimed ratings, and assume bad ratings for those that are missing. This collateral-based technique should be applied carefully, avoiding abuses such as trying to use the same collateral for different ratings. Advanced cryptographic techniques such as *zk-SNARKs* (explained below) may help to prove that these requirements are met without compromising a reviewer's identity. These techniques may be used to allow a reviewer to claim a rating from a review she carried out without revealing her identity but proving her authorship (Chlg. 1).

A different issue is to allow ratings to come solely from authorized raters (Chlg. 3). To fulfil these authorization requirements, several techniques such as *blind signatures* or *blind tokens* may be used. These would enable permission to be granted to a collection of identities to perform an action, e.g. rate a review, without revealing which of them voted, or which voted for what. As previously mentioned, *single-use identities* may be used to provide anonymity; in this case, for raters.

Allowing only authorized rates, as previously explained, may help to prevent Sybil attacks (Chlg. 4). Moreover, the cost of losing a reputable identity may reduce the attractiveness of creating a new identity simply to gain a reputation.

The use of the mentioned zk-SNARKs may also help to prevent some system abuses. For instance by enabling the use of cryptographic proofs that verify that the ratings come from reviews submitted to reputable journals, would prevent fake reviews and ratings.

Next, the mentioned technologies are explained.

Single-use identities: New single-use identities may be used as a simple technique to support anonymous interactions (Chlg. 1). However, supporting the authorization rules of the system (Chlg. 3) and providing accountability (Chlg. 2) for those identities are challenges that require consideration.

Ring signatures: Ring signatures [50] are a cryptographic technique that allows the authorization of a collection of identities to perform an action, while maintaining the privacy of the specific identity that performed the action. They may be used to authorize rates to a group of identities without revealing who rated what or who rated. Thus, this technique may be used to support the authorization requirements of the system (Chlg. 3), while providing some anonymity to the users (Chlg. 1). Note that with this technique, the identities of those who may have signed are known, so the combination with other anonymity measures could be of interest.

Blind tokens: In the context of an election and using a cryptographic technique called blind signatures [51], it is possible to create ballots for authorized actors that preserve the anonymity of the vote (both hiding who casted a vote and what each actor voted) but ensuring that only authorized voters participated. Note that, as with ring signatures, the identities of those who may have signed are known, and thus complementary anonymity measures could be used. This technique has been also used to anonymize a distributed reputation system [49]. Thus, it could be used to provide anonymity to reviewers and raters (Chlg. 1) while supporting the authorization rules of the system (Chlg. 3).

Collateral pattern: In order to secure the funds needed for a blockchain application to function, it is common that the application requires the participants to pay for the assets they may lose as collateral. For instance, a betting smart contract will first ask all participants to pay their bets and afterwards distribute the prices. This paper calls this technique "collateral pattern", and proposes its use to provide accountability (Chlg. 2) to the reviewers of the reputation system (Section 3.1). For each rating a reviewer may obtain, the reviewer must spend as much reputation as she may lose. This encourages the claiming of bad ratings, since not claiming them may result in a bigger loss.

zk-SNARK: is a cryptographic procedure enabling a statement to be proved without revealing anything else; that is, apart from the evaluation if the statement is in fact true (zero-knowledge proof of knowledge) [52] . The same authors also provide this property in a succinct and non-interactive fashion, for example, using a relatively small proof and not requiring further communication between prover and verifier. In fact, the popular Zcash project uses this technology to build an anonymous cryptocurrency [53]. Proving statements in this privacy preserving manner is of great interest for several challenges of the proposed accountable anonymous review system. For instance, proving that a user controls a single-use identity may allow the user to claim the reputation given to that identity (Chlg. 1). Additionally, a reviewer may prove that she paid the reputation collateral needed to submit a review without revealing her identity and without being able to use the same collateral for another review (Chlg. 2). Finally, proving that the reputation comes from a review submitted to a collection of honest journals that do not allow abuses, may help to mitigate the abuses that fake reviews and ratings represent for the system (Chlg. 5).

8. Discussion and Concluding Remarks

This paper proposes the opening and decentralization of three of the peer review and publication functions: 1) the selection and recognition of peer reviewers, 2) the distribution of scientific knowledge, and 3) the peer review process communication. Arguably, this decentralization of the infrastructure could help to challenge the central role of middlemen such as traditional publishers.

Distributed technologies such as blockchain and IPFS may finally realize the promise of Open Access, while enabling new models of science dissemination. Opening and decentralizing the infrastructure enhances the transparency and accountability of the system, and may provide a new arena to foster innovation. Note that the proposed system does not rely on the use of cryptocurrencies, since it is focused on a not-for-profit approach, far from the startup-driven commercial approaches common in the blockchain space.

The transparency provided by opening the peer review process allows the construction of a reputation system of reviewers, but also raises concerns about privacy and fairness. Furthermore, the introduction of a new public metric (reviewers' reputation) may also affect researcher careers, adding pressure to the already straining processes for academic survival [54]. A working prototype was developed as a proof-of-concept of the reviewer reputation system proposal. This work uses a survey to evaluate the perceived importance of four peer review process problems and if a reviewer reputation system is perceived as a solution for them, as well as the possible resistance to adoption that the proposal may suffer. The results suggest that the four problems are relevant, especially peer review quality and peer review fairness. The studied resistance to adoption seems low while the participants agree they would like to use the proposal. Additionally, the participants seem to agree that the solution addresses the studied problem.

Still, some challenges of the system remain open as future work, such as the detection and prevention of fake science, journals, and conferences or the detection and prevention of fake reviews, or revenge ratings to game the reputation system.

Blockchain technologies can be used to replicate the privacy settings currently used in peer review processes. However, Blockchain can also be used to introduce a new review model that supports the accountability of peer reviewing while maintaining the anonymity of blind and double blind reviews to improve fairness. The implications of such accountable, open and anonymous review models are still to be revealed, since an incentive based reputation system it could also support negative dynamic changes such as increasing competitive dynamics, or gender bias.

Additionally, the proposed system's infrastructure relies on new technologies with their own challenges. Blockchain technologies face scalability issues, transaction costs, inclusiveness and usability problems that remain open and under discussion. On the other hand, distributed file systems such as IPFS may be more resilient, but they still need somebody in charge of preserving and providing data, since without that responsible actor, it may result in an unpredictable loss of content. Considering these archiving issues, whether this new technologies will allow the creation of durable science repositories able to interoperate with legacy, current and future systems remain open.

Other open issues that require further research and may be explored in future work are the implementation of the proposed privacy settings, the exploration of different copyright regimes, the challenging of traditional journal-centered metrics to rate publication quality, different reputation algorithms, different levels of openness, and the exploration of decentralized autonomous journals.

Despite the existing challenges, we are confident that decentralizing the processes that Science relies on, would open up a whole new playing field, with implications we cannot possibly foresee. Will its benefits outweigh its risks? We believe it is a conversation worth having.

Acknowledgments

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7.2 Decentralizing science: Towards an interoperable open peer review ecosystem using blockchain

Reference

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Abstract

Science publication and its Peer Review system strongly rely on a few major industry players controlling most journals (e.g. Elsevier), databases (e.g. Scopus) and metrics (e.g. JCR Impact Factor), while keeping most articles behind paywalls. Critics to such system include concerns about fairness, quality, performance, cost, unpaid labor, transparency, and accuracy of the evaluation process. The Open Access movement has tried to provide free access to the published research articles, but most of the aforementioned issues remain. In such context, decentralized technologies such as blockchain offer an opportunity to experiment with new models for science production and dissemination relying on a decentralized infrastructure, aiming to tackle multiple of the current system shortcomings. This paper makes a proposal for an interoperable decentralized system for an open peer review ecosystem, relying on emerging distributed technologies such as blockchain and IPFS. Such system aims to enable a decentralized reviewer reputation system, which relies on an Open Access by-design infrastructure, together with transparent governance processes. Two prototypes have been implemented: a proof-of-concept prototype to validate DecSci's technological feasibility, and a Minimum Viable Product (MVP) prototype co-designed with journal editors. In addition, three evaluations have been carried out: an exploratory survey to assess interest on the issues tackled, a set of interviews to confirm the main problems for editors, and another set of interviews to validate the MVP prototype. Additionally, the paper discusses the multiple interoperability challenges such proposal faces, including an architecture to tackle them. This work finishes with a review of some of the open challenges that this ambitious proposal may face.

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Decentralizing science: Towards an interoperable open peer review ecosystem using blockchain

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ABSTRACT

Scientific publication and its Peer Review system strongly rely on a few major industry players controlling most journals (e.g. Elsevier), databases (e.g. Scopus) and metrics (e.g. JCR Impact Factor), while keeping most articles behind paywalls. Critics to such system include concerns about fairness, quality, performance, cost, unpaid labor, transparency, and accuracy of the evaluation process. The Open Access movement has tried to provide free access to the published research articles, but most of the aforementioned issues remain. In such context, decentralized technologies such as blockchain offer an opportunity to experiment with new models for scientific production and dissemination relying on a decentralized infrastructure, aiming to tackle multiple of the current system shortcomings. This paper makes a proposal for an interoperable decentralized system for an open peer review ecosystem, relying on emerging distributed technologies such as blockchain and IPFS. Such system, named "Decentralized Science" (DecSci), aims to enable a decentralized reviewer reputation system, which relies on an Open Access by-design infrastructure, together with transparent governance processes. Two prototypes have been implemented: a proof-of-concept prototype to validate DecSci's technological feasibility, and a Minimum Viable Product (MVP) prototype co-designed with journal editors. In addition, three evaluations have been carried out: an exploratory survey to assess interest on the issues tackled; two sets of interviews to confirm both the main problems for editors and to validate the MVP prototype; and a cost analysis of the main operations, both execution cost and actual price. Additionally, the paper discusses the multiple interoperability challenges such proposal faces, including an architecture to tackle them. This work finishes with a review of some of the open challenges that this ambitious proposal may face.

1. Introduction

Blockchain has raised in recent years as a novel and promising technology that might have a great impact in classical information systems (Berdik, Otoum, Schmidt, Porter, & Jararweh, 2021) in well-established fields such as finance, health, media, commerce, supply chains, IoT, etc. Its decentralized architecture (Sai, Buckley, Fitzgerald, & Gear, 2021) allows new governance models

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based on different consensus mechanisms, encourages collaboration and promotes transparency, and, at the same time, imposes strict security features that makes incredibly difficult to create fraudulent records. However, this technology also raises new concerns (Casino, Dasaklis, & Patsakis, 2019) regarding suitability, scalability, interoperability, security and data privacy issues.

Nevertheless, the potential of blockchain does not only promise to change industry but also other fields like academia. For example, blockchain can be used to mitigate the existing security issues concerning the sharing of students' credentials (Mishra, Kalla, Braeken, & Liyanage, 2021) or to check code copyright and combat plagiarism (Jing, Liu, & Sugumaran, 2021). In this paper we introduce "Decentralized Science" (DecSci), a decentralized and interoperable system that relies on emerging distributed technologies such as blockchain and IPFS, to mitigate problems identified in the processes of peer review and publication of scientific articles.

1.1. Innovations in the scientific process

In the last decades, the Internet has revolutionized multiple fields. However, the production of science and its peer review process have not seen large changes with respect to the traditional paper-based publication and review practices (Spier, 2002). The communication of knowledge still relies on academic articles, that journals collect and publish with certain periodicity for the consumption of scholars in academic institutions. The criticisms to nowadays scientific publication and peer review processes include concerns with respect to quality (Goldbeck-Wood, 1999), fairness (Wenneras & Wold, 2001), cost (Bergstrom & Bergstrom, 2004), performance (Huisman & Smits, 2017), and evaluation metrics accuracy (E., 2006).

Still, the advent of the Internet brought some changes to the scientific process. Its reduction of distribution costs allowed for broader access to scientific knowledge, and thus further questioning of the role of traditional publishers which previously assumed the distribution effort (Whitworth & Friedman, 2009a). Thus, alternatives emerged, especially with respect to scientific dissemination, grouped around the "Open Access" movement (Eysenbach, 2006). The Open Access (OA) movement, leveraging the replicability of digital content, aims to provide free access to the published research articles. And even though it is far from universal, it is generally recognized that the Open Access movement has reduced the economic cost for readers to access knowledge (Evans & Reimer, 2009).

However, despite its partial success, Open Access potential to democratize access to knowledge has been questioned (Knöchelmann, 2020). In fact, OA has not successfully challenged traditional publishers' business models (Larivière, Haustein, & Mongeon, 2015) which are often charging both readers and authors (Van Noorden et al., 2013).

With respect to the traditional peer review system, despite the multiple criticisms received mentioned above, only few alternatives have gathered success (Walker & Rocha da Silva, 2015; Ware, 2008). The literature provides multiple proposals around "open" peer review (Ford, 2013), which would enable transparent and public reviews, versus the traditional blind and private reviews (Lee, Sugimoto, Zhang, & Cronin, 2013). In fact, relying on such open peer review models, we can find some proposals of reputation networks for reviewers (Song, Hu, & Gehringer, 2015), which may provide new quality control processes for the reviewers, authors and editors. It is worth noting that the start-up Publons,[1] provides a platform to acknowledge reviews and open them up. The project reached quickly a large reviewer community, and it was recently absorbed by Clarivate Analytics publishing conglomerate.

In the last decades, other initiatives that challenge the traditional science publication process have emerged. *Preprints* are versions of scientific articles which have undertaken formal peer review, and have not been published formally in a journal or conference proceedings. Today, there are multiple widely successful platforms to host preprints and provide them visibility, like arXiv[2] or Preprints.org[3] (Shuai, Pepe, & Bollen, 2012).

Besides, social networks crafted for the scientific community have also found their niche. These enable scientists to upload their authored published articles, sharing them with fellow scientists whom they can connect. Example successful platforms include Academia[4] or Research Gate.[5]

These platforms are all centralized, that is, relying on a single platform owner which controls the infrastructure. Such centralization has multiple consequences (Benkler, 2016; Berners-Lee, 2010; Chaudhry et al., 2015) such as: problems related to monopolistic business models which affect users and their data; the need to depend on and trust a third-party which may change its policies anytime (e.g. in case of a change of business model, or a buy-in); market dominance over derived services such as metrics (e.g. JCR Impact Factor) or databases (e.g. Scopus); paywalls and the derived need of subscription packages for research institutions; and overall, issues related with the lesser control of the researcher community over their data and processes.

1.2. Decentralized alternatives

Decentralized alternatives aim to tackle issues from a different standpoint, aiming to avoid the traditional issues with centralized systems. In particular, the new generation of decentralized technologies that have emerged in recent years, such as blockchain and IPFS (see Section 2), have enabled a broad spectrum of emergent projects tackling multiple fields, including Finance, Internet of Things, supply chains, education, or governance (Hassan et al., 2020). These projects aim to take benefit from blockchain

[1] https://publons.com/
[2] https://arxiv.org/
[3] https://www.preprints.org/
[4] https://www.academia.edu/
[5] http://researchgate.com/

affordances (Rozas, Tenorio-Fornés, Díaz-Molina, & Hassan, 2021), such as its transparency, tokenization, codification of trust, or decentralized infrastructure. And in particular, there is an emergent diversity of projects aiming to tackle issues concerning scientific publication and peer review (Bartling, 2019; Leible, Schlager, Schubotz, & Gipp, 2019).

The literature covers multiple applications of blockchain (and related technologies) for improving the Open Science process. The most straight forward applications concern the use of time-stamping using blockchain, to assert authorship and provenance relying on the transparency and immutability of the ledger (Gipp, Breitinger, Meuschke, & Beel, 2017; Sivagnanam, Nandigam, & Lin, 2019). However, the most common application is the use of blockchain capabilities of managing crypto-tokens, i.e. transferable electronic representations of value, such as crypto-currencies or embedded permissions. Thus, there are multiple proposals to reward activities using tokens, such as incentive collaboration (Duh et al., 2019), management of data access permissions (Mamoshina et al., 2018), reproducibility of studies (Kochalko, Morris, & Rollins, 2018), endorsement of publications (b8d5ad9d974a44e7e2882f986467f4d3, 2016), peer reviewing (Kosmarski & Gordiychuk, 2020; Spearpoint, 2017), or as novel methods of funding research (Lehner, Hunzeker, & Ziegler, 2017).

Other works rely on the capabilities of blockchain to facilitate transparency and openness, e.g. enhancing the Open Access process (Tenorio-Fornés, Jacynycz, Llop-Vila, Sánchez-Ruiz, & Hassan, 2019) or Open Science integrity (Bell, LaToza, Baldmitsi, & Stavrou, 2017). Finally, other works rely on *smart contracts*, i.e. software that is automatically executed in a decentralized blockchain network, e.g. to provide automatic processes for scientific publication (Dhillon, 2016; Duh et al., 2019), or reproducibility of studies and experiments (Dhillon, 2020).

1.3. A proposal for open peer review

This paper proposes the development of a decentralized publication and peer review system relying on an Open Access and open review model. It focuses on improving the peer review system, relying on an open review model, and on rewards for reviewers. However, it does not rely on a crypto-currency like many of the reviewed works, but on a reputation system to evaluate both reviews and reviewers. The proposal benefits from multiple of the mentioned blockchain characteristics, including transparency, new reward models, smart contract automatization, time-stamping, and decentralization.

Thus, this work joins other mentioned initiatives in challenging the current infrastructure that supports what it is considered an oligopoly of traditional publishers (Larivière et al., 2015). As mentioned above, the Open Access movement has enabled a portion of academic publications to remain freely available. However, these publications are still mostly served from infrastructure controlled by a few industry players (Elsevier, Springer, Clarivate). Thus, infrastructure ownership enables them to exert control, impose policies (e.g. limitations to dissemination, copyright transfer, Open Access fees price, embargo periods) and concentrate profits (Fuster Morell, 2010).

The system proposed in this work, named "Decentralized Science" aims to enable the scientific community to hold higher control over their infrastructure. Thus, the proposal involves the decentralization of 3 main parts of the scientific process:

- The process of selecting reviewers and recognizing their work, through the use of a reviewer reputation system in which review reports may be rated.
- The (server-less) research dissemination, by distributing academic articles through the IPFS peer-to-peer network, and by default provisioning an Open Access by-design infrastructure.
- The transparency of the whole peer review process, through the use of blockchain technologies. Thus, review reports will be public following the open peer review model (Ford, 2013), together with the communication flow from paper submission to reviewer proposals and review submissions.

Concerning specifically with the peer review process, the proposed system tackles four issues: the overall quality of the reviews; the fairness of the process for the authors; the fairness of recognition (and payment) for reviewers; and the challenges associated with the search and selection of good reviewers for the journal editors.

To achieve such an ambitious goal and taking into account that our proposal uses distributed technologies that are not mature yet, we have decided to use an iterative and incremental approach building partial prototypes that allow us to validate their viability. These prototypes are the result of various interviews with other interested parties, that have subsequently participated in their validation. Furthermore, for our proposal to be successful, it must be able to inter-operate with other existing platforms (centralized or decentralized), which represents significant challenges. This paper extends our previous work (Tenorio-Fornés et al., 2019) in several ways: (1) it delves into the fundamental requirements that give value to our proposal, (2) it extends the system architecture and describes a first prototype search tool to find reviewers that has been co-designed and validated with journal editors, and (3) it analyzes the interoperability challenges faced by our platform to integrate and collaborate with other existing platforms and technologies.

The rest of the paper is organized as follows. First, Section 2 reviews the main decentralized technologies used, together with related concepts. Section 3 describes the main requirements for the system, which is later designed in Section 4. Following, Section 5 describes two software prototypes: (1) a proof of concept to assess the technological feasibility of the proposal (Section 5.1) and (2) a minimum viable product for the management of peer reviewing (Section 5.2). Section 6 presents the evaluation of the system, consisting of three studies: a survey to evaluate the perception of the problems and proposed solutions (Section 6.1), a series of interviews to evaluate the relevance of the problem and adequacy of the prototype to solve them (Section 6.2), and a cost analysis with regards to execution cost and price of the major operations, including a related scalability analysis (Section 6.3). Additionally, Section 7 discusses the challenges to integrate decentralized applications with existing technologies and online communities. To conclude, Section 8 tackles the main challenges and open questions that this proposal entails.

2. The decentralized technologies used

The use of decentralized technologies is an essential part of our proposal to provide transparency and accountability throughout the scientific paper publication process (submission, revision, publication and access) and, at the same time, avoid the concentration of power in a few actors. Using these technologies to implement the core of the platform we ensure that every fundamental transaction in the system will be publicly recorded and validated by a majority of the network participants according to a pre-established set of rules. This way, none of the participants has more decision power than the others because the transactions in the platform are accepted or rejected using a majority consensus mechanism. Furthermore, the public and permanent log of these transactions promotes transparency and trust in the process. Next, we introduce the main distributed technologies on which our proposal is based.

IPFS (Benet, 2014) is a peer-to-peer hypermedia protocol that enables the distribution of files using a decentralized network. Files are divided in blocks that are indexed using cryptographic hashes. These blocks are then distributed (and possibly replicated) among the network nodes. When a file needs to be retrieved, its blocks can be downloaded simultaneously from different peers. Note that new participants can add new nodes to the network and replicate the content they are interested in. We propose the use of IPFS to store and share the different versions of the papers, from first drafts to final versions, and peer review reports.

Blockchain is the underlying technology that supports Bitcoin (Nakamoto, 2008), the first fully distributed digital currency. Monetary transactions are collected in blocks that are accepted or rejected by the peer-to-peer network using a consensus mechanism in which at least half of the network needs to agree. Each new block is then linked to the previous one creating an immutable chain of blocks (blockchain) or public ledger that contains all the historical transactions performed. It is interesting to mention that each node of the network stores a full copy of the blockchain so that it can autonomously accept or reject future transactions. The order in which transactions are recorded in the public ledger is decided by the node (miner) that produces the next valid block. In order to produce new blocks, the nodes compete against each other to solve a computationally expensive problem. This computational effort is rewarded by the protocol with incentives (new bitcoins) to maintain the security of the ledger.

Ethereum (Buterin, 2014) extends the blockchain technology to enable to execution of small programs or *smart contracts* creating the first blockchain-based distributed computing platform. These smart contracts are stored in the blockchain (so they are immutable) and triggered using transactions that define which part of the program must be executed. Its functioning is similar to the Bitcoin blockchain in which all the nodes validate the bitcoin transactions. In the Ethereum network, all the nodes execute the same smart contracts to reach a majority consensus, regarding the changes they produce in the public ledger that defines the state of the network. Each smart contract, therefore, defines a set of rules based on its code and once they are deployed they can be executed autonomously (De Filippi & Hassan, 2016). In summary, smart contracts are relevant because they allow the transparent execution of immutable programs in a trustless network. Some examples of Ethereum-based decentralized applications are prediction markets (Jacynycz, Calvo, Hassan, & Sánchez-Ruiz, 2016; Peterson & Krug, 2015) or social networks (Larimer et al., 2016). We propose the use of smart contracts to enforce transparency through the peer review process, and to implement a reviewer reputation system.

3. The proposal requirements

The proposed system, named “Decentralized Science” (abbreviated DecSci), aims to provide a decentralized platform for the scientific process, from submission to publication, with a special attention to the peer review process. It relies on three pillars, which are covered in this section: a decentralized reviewer reputation system, an Open Access by-design infrastructure, and a transparent governance.

3.1. A distributed reviewer reputation system

Typically, a major issue for editors and journals is accumulating the knowledge on the reliability and quality of reviewers. This valuable data is often kept private to publishers and their journals, reinforcing their influential positions. In fact, it is hard to predict the quality of a potential reviewer, even with knowledge on their training and past experience (Callaham & Tercier, 2007).

DecSci incorporates a new element to the traditional peer review communication work-flow: the option to rate the reviews, and then building metrics around those ratings, providing a reviewer reputation system (Resnick, Kuwabara, Zeckhauser, & Friedman, 2000). Thus, this opens the possibility for reviewers to be rewarded or penalized depending on the quality, fairness or speed of their reviews.

Building an open and public reputation system has multiple benefits for reviewers, including recognition and visibility (Rajpert-De Meyts, Losito, & Carrell, 2016), but also monetary incentives e.g. through cryptocurrencies (Jan et al., 2018). Besides, such open system is expected to reduce biased and unfair reviews, due to public exposure (Wenneras & Wold, 2001; Whitworth & Friedman, 2009b).

3.2. Open access by-design

Open Access refers to the principles and practices in which research outputs are distributed online, free of cost or other access barriers.[6] Thus, through the growth of Open Access, publishers provide research articles freely to readers. However, as mentioned above, since publishers are also the owners of the dissemination infrastructure, they are capable to establish certain rules and restrictions. For instance, they may charge authors unreasonable fees to opt for the Open Access option (Solomon & Björk, 2012), or demand restrictions or year-long embargoes for disseminating the final version (Björk, Laakso, Welling, & Paetau, 2014).

The DecSci proposal involves a decentralized infrastructure also to store and host all the documents involved in the scientific process. Thus, the different versions of the research paper, together with its reviews, are deployed publicly through the IPFS peer-to-peer network (Benet, 2014) (see Section 2). In such network, it is significantly hard to restrict access to the provided documents. Therefore, the proposed system implicitly enables unrestricted Open Access, facilitated by its decentralized infrastructure. This is designed in order to avoid dominant market positions such as those mentioned by current publishers. In fact, in case DecSci stopped working, the uploaded documents would still remain available in the IPFS distributed network, and links to them would still work as usual.

3.3. Transparent governance

As mentioned above, among the multiple issues of the current scientific process, there is a lack of transparency. That is, processes are typically private and closed, controlled by publishers, and depending on their infrastructure. Similarly, communications across authors, reviewers and editors remain private, and may enable arbitrary or biased results. Whitworth and Friedman (2009b).

DecSci aims to surpass these limitations through significantly increasing the transparency of the processes involved, hoping to improve speed and fairness in parallel. Thus, it proposes to record in a public blockchain, i.e. a distributed ledger, the interactions concerning article submission/publication, reviewer assignment or review submission. Therefore, previously obscure processes such as the reviewer selection or the review reports, would be open publicly. In addition, blockchain time-stamps every interaction and provides a theoretically tamper-proof mechanism, and thus the processes can be monitored by third-parties, audited, and eventually held accountable.

More research would be needed concerning the effects of both open reviews and open communication process, since it may influence the dynamics and incentives for journals and not just for authors or reviewers. Nowadays, journals are penalized for accepting irrelevant papers (i.e. which will not be cited, or have low quality), but are not penalized for rejecting valuable papers (Garfield, 2007; Whitworth & Friedman, 2009a). Thus, high rejection rates are typically encouraged. Within DecSci though, the latter would be also penalized, potentially triggering different dynamics for quality control and filtering.

Overall, we believe the transparent governance processes, combined with the decentralized infrastructure, enables experimentation and the emergence of novel work-flows (Whitworth & Friedman, 2009b).

4. System design using a decentralized architecture

The DecSci platform aims to support the whole peer review process, from paper submission to acceptance or rejection, as well as the rating of peer reviews to build a reviewer reputation network. Our platform relies on the two decentralized technologies introduced in Section 2: IPFS and Ethereum Smart Contracts, leveraging on recommendations from literature combining both (Chen, Li, Li, & Zhang, 2017; Nizamuddin, Hasan, & Salah, 2018; Tenorio-Fornés, Hassan, & Pavón, 2018). Both are peer-to-peer networks that provide the foundations of our proposed system.

On the one hand, *IPFS* provides a distributed file system to store and share documents such as the different versions of the paper, from first drafts to final versions, as well as the peer reviews generated during the revision process. On the other hand, *Ethereum Smart Contracts* are used to implement the rules of the system with transparency, such as only accepting reviews from invited reviewers, and register all the interactions in the blockchain. Note that the interactions are automatically time-stamped depending on the block in which they are accepted and cannot be tampered or deleted afterwards, creating a reliable log of the peer review process.

Each article and review stored in the IPFS network has a unique identifier (its address) which is stored in the blockchain, facilitating integration and direct access. The IPFS nodes storing the information may be provided by those actors deploying the system (such as publishers) or by third-party services such as Pinata.[7] Thus, this architecture provides free access and persistence to the registered information, and ensures its independence from centralized servers.

It is important to remark that, although DecSci relies on these novel technologies, users are not required to have any technical knowledge about them. Users interact with the platform using a web application that handles all this technical details for them, and users only need to have a valid identity in the network (an Ethereum address). For example, the sequence diagram shown in Fig. 1 describes the main interactions during a peer review process and below we describe the basic ideas to implement them.

[6] We do not refer here to the Open Access strict definition in which it is required that the article is not only freely accessible, but also open-licensed, removing further barriers to copying or reuse (e.g. as in PLoS journals).

[7] https://pinata.cloud

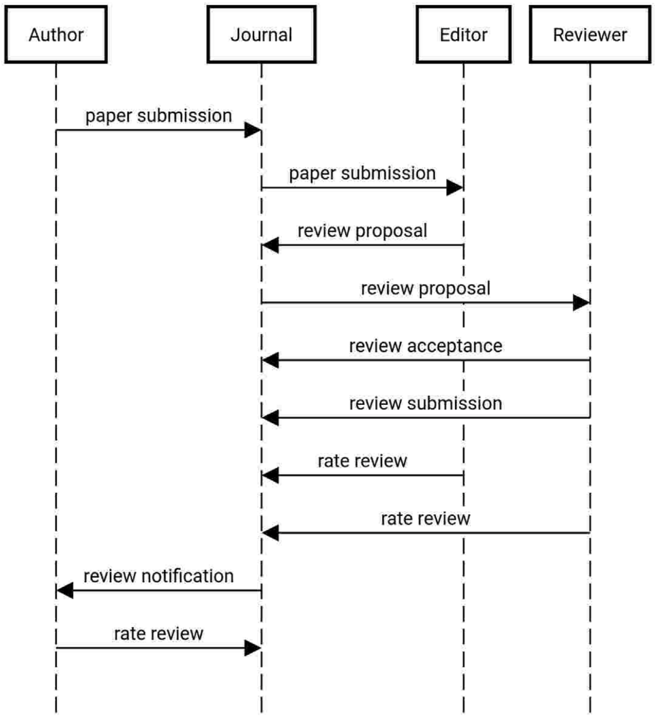

Fig. 1. Sequence diagram of a peer review process.

Paper submission When an author submits a new paper to the platform, the paper is automatically uploaded to the IPFS network so the IPFS address can be used as an unique identifier of the document. Next, the platform creates an Ethereum *smart contract* that will manage and record the peer review process for that specific paper. Note that the Ethereum transaction that creates the smart contact can be used to verify that the authors submitted the paper at some specific time. This smart contract will record the Ethereum addresses of the authors and journal editors.

Review proposal Journal editors may invite reviewers to review a specific paper, adding this *review request* to the paper's *smart contract*. This interaction records the reviewer's Ethereum address as well as an optional submission deadline for the review. The reviewer may respond accepting or rejecting the review request, in which case the editor can invite another reviewer.

Review submission When a reviewer submits a review, the document is automatically uploaded to the IPFS network. Then, the reviewer carries out an Ethereum transaction to the smart contract using the IPFS address of the review as well as her verdict (acceptance of rejection of the paper). In the event of a missing review or delay, a penalty can be applied to the reviewer's reputation in the reputation system.

Review rating Our proposal introduces a reputation system for reviews (Section 3.1). The actors involved in a peer reviewing process, i.e. the authors, editors and other reviewers, can rate the submitted review reports. These ratings are recorded in the blockchain.

One of the most important aspects to guarantee that the review process works correctly is to have a good base of reviewers who are willing to collaborate and whose knowledge and interests covers the different topics of the journal. In order to create better matches between reviewers and submission and, therefore, increase the quality of the revision process, DecSci incorporates a reputation system for reviewers and provides a search tool for the editors. This search tool can be use to find good candidates according to their interests, previous reviews and reputation rates. Below we describe this interactions in the platform, Fig. 2 provides a sequence diagram of these interactions.

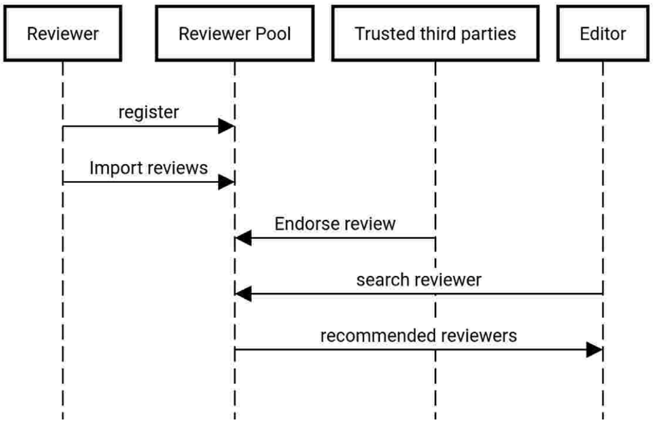

Fig. 2. Sequence diagram of reviewer registration, endorsement and search.

Register as reviewer Interested reviewers only need an Ethereum address to register in the system. Their interests and areas of expertise are also stored in the blockchain and can be updated at any time.

Import review Reviewers can import their previous reviews to the system. Several reviewers already have profiles and reviews stored in other online communities such as Publons, post-publication peer review services such as F1000Research or Peerage of Science and Academic databases such as ORCID or Crossref. As explored in Section 7.3, integrations with such systems are being developed.

Endorse review As anybody can freely import their previous peer reviews, there is a need for applications to decide if these reviews can be trusted or not. The system enables a way for other actors to endorse the validity of the imported reviews. Section 7.4 offers a detailed discussion on how this system would be implemented.

Search reviewer Journal editors should be able to find the most relevant and better reviewers for each paper. In Section 5 we describe our work to provide a useful and intuitive web interface to facilitate this task and find reviewers with relevant research interests, showing relevant information about them such as their reputation, acceptance rate, timelines and previous reviews.

5. Implementation

In order to realize our system proposal, we have developed two distinct prototypes:

- First, a proof-of-concept prototype to validate the technological feasibility of the proposal. Such implementation enabled the performance of preliminary tests of each of the platform's interactions, and to validate the feasibility of our decentralized architecture for the implementation of the system. Thus, this prototype provides a simple version of the requirements specified in Section 3, and the interaction design from Section 4.
- Second, a Minimum Viable Product prototype for Reviewer Management, co-designed with journal editors. This functional software is focused on the most relevant functionalities that current journals require, and facilitate its integration with existing journal infrastructure. Thus, it focuses on a subset of Section 4 interactions, in particular those relevant for reviewer search and reviewer data (in order to extract quality metrics).

5.1. A proof-of-concept to validate technical feasibility

As explained above, this proof-of-concept prototype allows us to test the main interactions using the aforementioned decentralized technologies, namely Ethereum, Smart Contracts and IPFS. This software implements a basic version of Section 3 requirements and Section 4 design. The software is publicly available as free/open source, publicly available in Github.[8]

[8] https://github.com/DecentralizedScience/Gateway

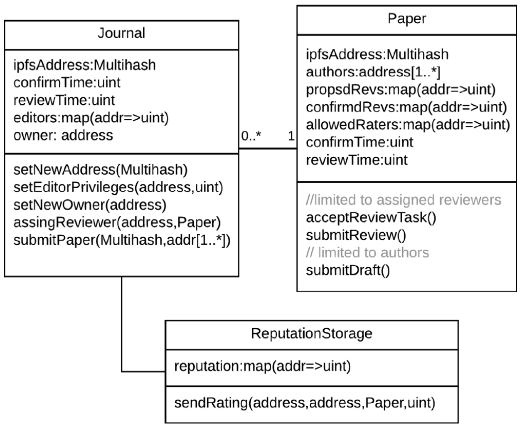

Fig. 3. Proof-of-concept UML architecture diagram.

Thus, this prototype architecture uses IPFS as a distributed file system to store and share the review reports and papers, and the Ethereum Blockchain to implement the logic of the system and to manage its state. The prototype uses a web interface that communicates with IPFS and Ethereum networks using JavaScript libraries. It proposes the use of Metamask[9] to provide user-friendly management of Ethereum identities.

This proof-of-concept prototype uses three different Ethereum smart contacts to run the platform's inner functioning, as shown in Fig. 3. The *Journal* smart contract provides functionality for the submission of papers, the selection of editors, and the management of review requests. The *Paper* smart contract serves to provide a digital id for the papers, manages the submission of review reports, and specifies who is allowed to rate a review report. Finally, the *ReputationStorage* smart contract manages the ratings of the peer reviews, updating the rating of reviewers upon receiving new ratings, if these ratings are allowed by their Paper contract.

The data structures of these Smart Contracts are optimized for Ethereum performance using data types such as maps instead of arrays and Ethereum addresses. Thus, (1) the Journal smart contract maintains a map of journal editors addresses; (2) each paper stores a map of proposed and accepted reviewers, as well as who is allowed to rate the reviews; and (3) the reputation contract stores a mapping of the reputation of each reviewer. The relationships between papers and journals that are not crucial to store in the blockchain are shared in events, thus reducing the cost of these operations. The events used in this smart contract are the following[10]: PaperCreated, ReviewerProposed, ReviewerConfirmed, ReviewReceived, NewDraft, JournalAdress, NewOwner, PrivilegeChange, PaperSubmitted, RatingReceived.

Note that, for each rating, the system registers the rater and modifies the reviewer's reputation, performing an exponential smoothing[11] of the score received (Gardner Jr, 2006). In this case, exponential smoothing is used to calculate the average of the score without knowing the total number of raters.

This prototype does not cover advanced reviewer interactions (register, import, search and endorse) which is the focus of the second prototype, explained in the following subsection.

5.2. A minimum viable product for reviewer management

This functional prototype was designed with participatory methodologies (Lean Design and User-Centered Design), in close collaboration with journal editors (Tirador & Tenorio-Fornés, 2019). Thus, it is designed to respond to their needs. The principal value proposition (Osterwalder, Pigneur, Bernarda, & Smith, 2014) for these journal editors is (1) a tool to find reviewers that (2) provides relevant metrics about them such as their timeliness or acceptance ratio, and (3) access to the open peer reviews of these reviewers. Fig. 4 shows a detail of the Graphic User Interface (GUI). The interface allows journal editors to find relevant reviewers in the system. As further explained in Section 7.1, the prototype is integrated with the well-known publication management software Open Journal System (OJS), enabling journal editors to see the journal's reviewers, and request a review using their peer review management system. The GUI offers additional functionalities for the selection of peer reviewers currently unavailable at

9 https://metamask.io

10 The events are not described in detail for the sake of brevity, although most are self-explanatory. They can be seen in detail in the Solidity smart contract https://github.com/DecentralizedScience/Gateway/blob/master/contract/decentralizedScienceContract.sol

11 The alpha value used in the exponential smoothing is 0.2.

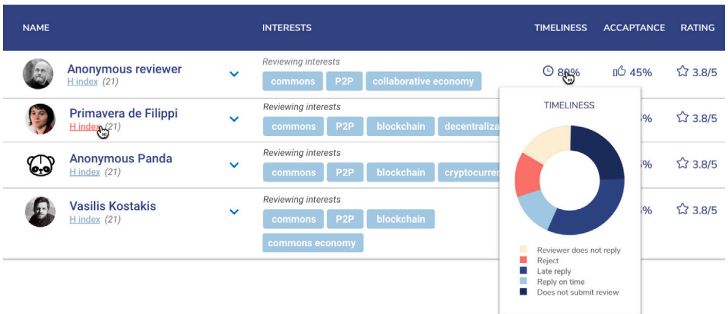

Fig. 4. Decentralized Science Reviewer search GUI.

OJS GUI (Tenorio-Fornés & Pérez Tirador, 2020). Concretely, it provides information about reviewers such as the acceptance ratio, the reputation, or the timelines, and facilitates access to their previous review reports.

However, this prototype does not just rely on centralized legacy software, but combines both centralized and decentralized technologies. In particular, (1) it uses Ethereum smart contracts to provide a decentralized management of the logic and state of the system, and (2) uses IPFS to store in a decentralized network larger files such as academic papers or the content of peer review reports. This way, using decentralized technologies we aim to promote the transparency of the peer reviewing process (Section 3.3) and provide an open access by design infrastructure (Section 3.2) for such information. Furthermore, maximizing interoperability and decentralization, we enable the participation of other third parties and prevent the enclosure of the information in data silos or walled gardens (Berners-Lee, 2010).

The implemented application interacts with these decentralized technologies to store, update and retrieve the needed information about the peer reviews managed by the system. Currently, the interaction with these decentralized technologies is done via a NodeJS implementation of the public GraphQL API (explained in Section 7.2). Such implementation accesses both the existing centralized and private information of journals, and the publicly shared and decentralized information Decentralized Science promotes. Thus, the software provides a web search interface that access both centralized and decentralized data, abstracting the technological differences for a better user experience.

6. Evaluation

We have performed three different and complementary evaluations. The first one consists on a survey to collect quantitative information regarding the response of potentially interested users with different profiles in a platform like DecSci. That is, an exploratory study to assess whether our proposal would attract enough early adopters to enable further exploration and validation.

The second evaluation consists on a set of interviews to validate both the problem and the solution. Thus, we performed interviews to better understand the problems faced by the editors during the peer review process, and we interviewed reviewers to validate our search tool for its relevant audience.

The third evaluation consists on a cost analysis, both in execution cost and price cost (in dollars), to assess the scalability of the proposed system, especially when relying on the Ethereum network.

In the first two evaluations, which rely on social research, our methods followed the guidelines and ethical considerations of the International Sociological Association.[12] Thus, we required standard written informed consent of the volunteer participants, which allowed the use of the data gathered. To ensure the right to privacy, individuals were anonymized in field notes.

6.1. Exploratory study to assess the interest in DecSci

6.1.1. Goals

The main goal of this exploratory study is to evaluate whether a platform like DecSci sparks enough interest among researchers and editors. In particular, we will assess (1) if there is a shared feeling about the need to improve the current article review process, (2) whether the different actors involved think that a reputation system could help, and (3) possible resistances regarding the use of such a reputation system.

[12] https://www.isa-sociology.org/en/about-isa/code-of-ethics

Table 1
Exploratory study survey to assess the interest in DecSci.

1. As an author, I think that the quality of the review process can be sensibly improved.
2. As an author, I think that the fairness of the review process can be sensibly improved.
3. As a reviewer, the recognition, reputation or rewards I receive feels fair in relation to the amount of work that I do.
4. As an editor, I have difficulties finding good reviewers (quality, relevance, timeliness).
5. As an author, I would prefer to submit my work to a journal in which reviews can be publicly rated (on a reviewer reputation system).
6. As a reviewer, I would prefer to submit a review to a journal in which my review would be publicly rated (on a reviewer reputation system).
7. As a reviewer, I would only submit a review to a journal which rates its reviews, if I remain anonymous.
8. As an author/editor/reviewer, I would like to be able to rate the reviews of the papers I am working with.
9. As an editor, I would find a reviewer system sensibly useful to find relevant, timely and/or high quality reviewers.
10. I believe that a reviewer reputation system could sensibly improve the quality and/or fairness of the peer review process.
11. I believe that a reviewer reputation system could sensibly improve the recognition, reputation or rewards I receive for my reviews.

Table 2
Exploratory study survey results using a Likert scale from 1 (strongly disagree) to 5 (strongly agree).

Statement	#Answers	Mean	Mode
(1) Quality	35	4.2	4
(2) Fairness	36	4.4	5
(3) Recognition	34	2.4	2
(4) Finding reviewers	30	3.9	3-4
(5) Author resistance	36	3.9	4
(6) Reviewer resistance	34	3.6	4
(7) Anon. reviewer resistance	34	3.1	3
(8) Want to rate	36	4.3	5
(9) Improve reviewers search	30	3.9	4
(10) Improve quality/fairness	36	4.1	4
(11) Improve recognition	35	3.9	4

6.1.2. Target population

Representatives of the 3 main actors involved in the review process, namely authors, reviewers, and editors. Given the exploratory nature of this study, we only intent to target a small group of researchers and the conclusions will not necessarily represent the opinion of the whole academic community. Additionally, most researchers have experience at least in 2 roles, as authors and reviewers.

We collected answers to our survey from 3 different academic groups: an ‘‘Open Science Ecosystem’’ Telegram group with more than 150 participants from different projects involved in the development of decentralized and open-source software solutions for open science; our faculty department that comprises more than 40 full time researchers and professors of Computer Science; and 36 subscribers to the DecSci’s newsletter from our website.

6.1.3. Survey

The survey is shown in Table 1 and consists of 11 statements that must be rated using a 1 to 5 Likert scale, where 1 means ‘‘strongly disagree’’ and 5 ‘‘strongly agree’’. The first 4 statements deal with the *need to improve* the current review process. Statements 5–8 assess possible *resistances* for the adoption of a reviewer reputation system. Finally, statements 9–11 evaluate whether the participants think that *a reputation system* might mitigate some of the issues.

6.1.4. Results and discussion

The survey was filled out by 36 researchers and the results are summarized in Table 2. Note that not all the statements have the same number of answers since participants only had to rate the statements regarding the roles in which they had experience (as authors, reviewers and/or editors).

As we expected, authors feel that the quality and fairness of the review process can be sensibly improved. Reviewers seem to think their work is not correctly rewarded or acknowledged, and editors have difficulties finding good reviewers, but these results are not as strong as the former ones.

Regarding resistances, both authors and reviewers support the idea of a reputation system. There is more controversy regarding anonymity: 14 reviewers agree or strongly agree that they would need anonymity to participate in the system, while 22 remain neutral or disagree. However, all participants strongly agree they would like to rate other’s reviews.

Finally, all participants believe that a reviewer reputation system could have a positive impact in the review process. Editors would have an additional source of information to find better reviewers; the quality and fairness of the reviews could be sensible improved; and the work of the reviewers would be properly recognized.

Overall, these results, although preliminary, encouraged us to further explore our idea and perform the interviews that we describe in the following section.

6.2. Editors interviews

After assessing the interest in our proposal, we performed a series of interviews to different types of editors following the Lean Startup methodology (Maurya, 2012). The goal of the *Problem Interviews* is to better understand the problem editors face during a peer review process and how they deal with them. This information is essential as a first step to define the functional requirements of our software solution. *Solution Interviews*, on the other hand, are used to validate the value propositions of the different iterations of the design and development of our system with a user centered approach.

Methodologically, the interviews were semi-structured, aiding a better understanding of the topic at hand. They were selected using snowball sampling. It was concluded that this method was the most suitable approach since the context, particularly at the institutional level (e.g. journal editorial office, academic associations, university press), required the interviewer to gain access via personal recommendations to ensure the participation of institutional actors.

6.2.1. Problem interviews

We performed 19 problem interviews and obtained information about 5 journals, 6 conferences, 3 academic associations, 4 reviewers and 1 university press.

We identified that the most important problems editors face in the peer reviewing process (the ones mentioned more frequently or with a stronger emphasis) are:

- Finding suitable reviewers for each paper.
- Getting reviewers to accept the review task.
- Receiving the reviews on time.
- Obtaining good quality reviews.

We also found out that editors use different strategies to deal with these issues. For example, a conference organizer shared that, to deal with bad quality reviews and slow reviewers, they keep a list of reviewers to avoid. And a journal editor explained that he usually needs to send at least ten invitations to get enough reviewers for a paper.

6.2.2. Solution interviews

We carried out some initial usability sessions and interviews with two potential interested organizations: Ediciones Complutense[13] and Iberamia.[14] During these sessions, they tested our prototypes and helped us to improve our search tool for finding reviewers. The current state of the tool, that was introduced in Section 5, provides three main functionalities:

1. **An interface to search reviewers** who meet some criteria.
2. **Reviewer reliability statistics** such as how often they review on time, reputation ratings and acceptance ratio.
3. **Access to previous review reports** if they are publicly available (open reviews).

We have also identified new requirements aimed at reducing even more the effort required to find suitable reviewers such as getting access to a larger pool of reviewers or getting automatic recommendations. We will deal with these requests in future versions of DecSci.

6.3. Scalability and cost analysis

We have performed a third kind of evaluation: a cost analysis of the main activities performed by the system. Thus, we can see in Table 3 the five main operations analyzed, and the cost of running those operations over the Ethereum network. Note that other metrics such as the latency are not dependent on our code. Instead, they depend on the Ethereum network congestion and on the commission the user is willing to pay to prioritize their transaction.

In Ethereum, every operation performed implies a cost, i.e. a commission to be paid by the user, for the miners to perform the requested operation. In practice, validating and performing those operations requires a certain amount of computational work performed by miners (see Section 2). The amount of computation required by an operation is named *gas*, and it is paid in cryptocurrency; in Ethereum, with its token Ether (abbreviated ETH). From the user approach, gas ultimately translates into money and the amount of gas depends on the size and type of each operation.

The five operations analyzed are:

[13] https://www.ucm.es/ediciones-complutense
[14] https://www.iberamia.org/iberamia/

Table 3
Cost analysis.

Function	Gas	Cost (ETH)[a]	Cost ($)[b]
Send Paper	114,812	0.0016	$3.86
Assign Reviewers	58,707	0.0009	$2.15
Accept Review	23,971	0.0004	$0.92
Send Review	149,760	0.0025	$6.12
Send Rating	94,122	0.0017	$4.08

[a]Using the recommended slow gas price at https://www.ethgasstation.info/.
[b]ETH price (June 16th 2021) $2400.

- Send Paper: to submit an article by the author
- Assign Reviewers: to assign potential reviewers to a certain article, by the editor
- Accept Review: to accept the invitation to review a certain article, by the reviewer
- Send Review: to submit the finished review of the article, by the reviewer
- Send Rating: to submit a rating of a review, by any actor qualified to assess reviews (which may be any user)

Thus, we can observe that some operations may have an excessive price for certain users, which may deter them from using the system. For instance, spending $6 to submit a review may be unacceptable, unless the reviewer is monetarily rewarded by the review. Similarly, submitting a review rating for $4 may limit the ratings received.

There are multiple paths to tackle the excessive transaction cost. First, the issue of excessive transaction cost is a well-known issue within the Ethereum community, which affects all Ethereum-powered apps. This damages adoption and limits scalability for the whole ecosystem. In order to tackle it, a new version of the system, named Ethereum 2.0, is expected to facilitate scalability and notably reduce the price of transactions.

The price of transactions varies depending on multiple factors, such as Gas price (which depends on network congestion) and Ethereum price (which depends on the cryptocurrency market). Thus, both factors are highly volatile and difficult to predict. Code optimization, to reduce gas cost per operation, could reduce transaction cost if scalability or price issues where a concern. However, our software can be deployed in alternative Ethereum-based networks such as Bloxberg. Bloxberg[15] (Kleinfercher, Vengadasalam, & Lawton, 2020) is a research infrastructure relying on a global blockchain maintained by a consortium of universities and research organizations. In the Bloxberg blockchain, gas price is free, since the block validation operations (“mining”) is performed by the consortium academic institutions.

There is still the question if, regardless of price, the Ethereum network could handle the expected throughput of the proposed system. Ethereum has a throughput of more than 1M transactions per day (de Azevedo Sousa et al., 2021), and that is before the expected improvements of the forthcoming Ethereum 2.0. Moreover, the limit of transactions and gas per block can be increased by miners. Nowadays, the limit is 15M gas per block (MyCrypto, 2021), i.e. more that a hundred of our most expensive transactions every block (or 13 s). Every year 14M reviews are performed (Johnson, Watkinson, & Mabe, 2018), so the equivalent number per day (38 K) could be reasonable handled by the current version of Ethereum, even as one of the many applications available in the network. Still, Bloxberg, as mentioned above, does not suffer the mining limitations of the Ethereum network (Kleinfercher et al., 2020), as its expected throughput is calculated as hundreds of time higher than current Ethereum. Thus, scalability should not be a serious matter for the proposed system, especially in blockchain networks dedicated to academic purposes.

7. Interoperability challenges

The Decentralized Science system proposal, as described in Sections 3 and 4 , and implemented in the proof-of-concept from Section 5.1, is overly ambitious. In practical terms, information systems are not built on the void, but on an existing context of platforms, technologies, third-parties and legacy systems. In fact, one of the criticisms made to blockchain and decentralized technologies is their lack of interoperability with both existing centralized systems, and other decentralized applications. Thus, there are multiple interoperability challenges related to the Decentralized Science ecosystem:

- Integration with Publication Management Software
- Facilitate adoption by third-party web applications
- Interoperability with other reviewer platforms
- Interoperability with other blockchain applications

In this section, we explain how the architecture of the proposed system is appropriate to overcome interoperability issues in all those aspects. These will be covered briefly in the following subsections.

[15] https://bloxberg.org

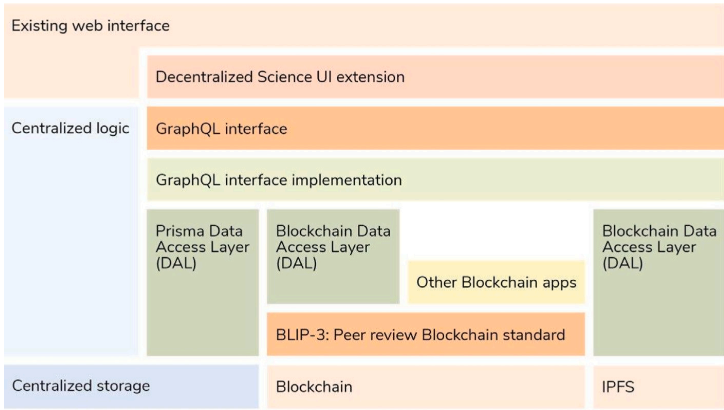

Fig. 5. Decentralized Science ecosystem's architecture (With BLIP3 standard).

7.1. Integration with publication management software

The submission, review and publishing of academic papers is currently supported by software Publication Management Systems. Big publishers such as Elsevier or Springer use their own proprietary software while OJS Open Source software is the most adopted solution among smaller publishers and independent journals accounting for tenths of thousands of journals.[16]

Our architecture proposal aims to facilitate the interoperability with such existing and widely used systems. It relies on providing a GUI for the search of relevant peer reviewers (Fig. 4), which can be integrated with the publication management software as a web component. Concretely, our software is integrated with OJS system. The database of this software (centralized storage in Fig. 5) is then accessed to get information about the reviewers. The left half of Fig. 5 depicts the interactions between the centralized software, storage and web interface (OJS), and DecSci GUI, logic and decentralized technologies. A public API (GraphQL interface in Fig. 5) to interact with the centralized and decentralized parts of the system is also provided, as described in the following section.

7.2. Enabling third-party adoption: GraphQL public API

Public APIs are often used by internet services to provide access and functionalities to third parties and promote interoperability among independent systems. Decentralized Science provides such API using a GraphQL interface.[17] This interface defines the data types of the system and how these data types can be composed.[18] For instance, providing the fields a peer review report record can have, or stating that users in our system have a list of such review reports that they authored.This GraphQL API enables other applications to interact with Decentralized Science. For instance, other GUIs could be implemented, as well as services such as enhanced reviewer search engines.

7.3. Integration with reviewer platforms

The publication of peer review reports and information is a key part of large online reviewer communities such as Publons (Rajpert-De Meyts et al., 2016) (with more than 200.000 reviewers) or post-publication peer review services such as Faculty of 1000 (F1000) (Wets, Weedon, & Velterop, 2003).

Our architecture proposes to inter-operate with such communities by allowing reviewers to import the reviews from Publons and F1000Research communities. The Bloxberg's blockchain peer-review-app implements such import functionality, bringing the needed interoperability to the system.

[16] e.g. being used by 44% of library-published, faculty-driven journals (Johnson et al., 2018)

[17] It is worth mentioning that the project The Graph (https://thegraph.com) is providing GraphQL APIs for existing Ethereum blockchain applications (Kaandorp, 2021)

[18] Details of DecSci's graphql schema can be found online in: https://github.com/DecentralizedScience/Prototype/blob/master/server/src/schema.graphql

7.4. Interoperability with other blockchain applications

There are several active blockchain projects that aim to share peer review information to improve recognition of reviewers' curriculum (e.g. Bloxberg's (Kleinfercher et al., 2020) peer-review-app (bloxberg, 2020)), provide incentives for peer reviewers (e.g. Eureka (Niya et al., 2019)), or enable post publication peer review (e.g. Orvium (Orvium, 2021)), among others (Mackey, Shah, Miyachi, Short, & Clauson, 2019). Several of these projects are collaborating in the definition of a standard for the registration of Peer Review information (Tenorio-Fornés et al., 2020) in Bloxberg's infrastructure. As mentioned above, Bloxberg is an Ethereum-based blockchain which provides infrastructure for scientific research.

Different blockchain projects such as Bitcoin or Ethereum have standardization processes to agree on shared libraries, interfaces and protocols. Some examples of these standards are the inclusion of Bitcoin multi-signature wallets (BIP[19] 67) or the standardization of Ethereum tokens (ERC[20]-20).

In the Bloxberg network, a blockchain for academic applications, such standards take the name of Bloxberg Improvement Proposals or BLIP. The standardization effort for registering peer reviews in the Bloxberg blockchain is named BLIP-3.[21] It aims to generalize the initial implementation of Bloxberg's peer-review-app to: enable a diversity of actors and applications to write and read the data; facilitate sharing information and avoid information silos; and promote interoperability with existing standards (such as ORCID, or Crossref), decentralized applications (such as Decentralized Science, peer-review-app, PeerMiles, or Orvium), and important peer reviewer communities (such as Publons or F1000Research). Fig. 5 shows how a shared blockchain interface would enable the interoperability across several decentralized applications.

8. Discussion and concluding remarks

8.1. Reviewing the proposal

There is a social consensus on the need to share and make scientific knowledge accessible, especially when it has been financed with public funds (Schiltz, 2018). Most researchers at universities and research centers do not charge for publishing their discoveries, and yet their institutions are forced to pay large amounts of money to publishers in order to access those same publications they produce. On the other hand, the evolution of technology has facilitated the distribution and access to scientific knowledge to the point of questioning the traditional role of publishers and other intermediaries in the chain of scientific publication.

In this work, we have presented *Decentralized Science* (DecSci), an interoperable platform based on decentralized technologies that aims to provide an alternative publication model to enhance the transparency and accountability of the peer review and publication processes. Overall, the main contributions of this work can be summarized in:

- We show how blockchain and IPFS technologies enable novel decentralized systems for managing the Peer Review process.
- An Open Access decentralized infrastructure for Peer Review is technically and practically feasible, after multiple evaluations and prototypes.
- We validate how the academic community (reviewers and journal editors) shows interest to improve quality, fairness and recognition through a system like the one proposed.
- We validate how the proposed MVP provides value to reviewers and journal editors, addressing their need to get recognition and improve their selection of peer reviewers respectively.
- A hybrid architecture tackles interoperability challenges of decentralized/centralized systems.

We proceed to detail the main contributions, followed by an overview of the main challenges this proposal and its underlying technologies may face.

In particular, we propose to decentralize three core parts of the Peer Review and publication process: (1) the selection and recognition of the peer reviewers using a transparent reputation model, (2) the distribution of the academic papers through the IPFS peer-to-peer network, and (3) the transparency of the whole peer review process, from submission to publication, using blockchain technologies.

We carried out a short survey to tentatively assess the possible interest and resistances that a transparent reputation system for reviewers could arise. The initial results were quite positive since most of the participants think the quality and fairness of the review process can be sensibly improved, and that a reputation model could be an interesting solution in which they would be willing to participate.

The core of the system is based on *smart contracts* that enforce a transparent review process, storing the different steps as time-stamped transactions in the blockchain: paper submission, review proposal and acceptance, review submission, author's resubmission of improved versions of the paper, and ratings of the reviewers. We have developed a proof-of-concept prototype based on Ethereum smart contracts to enable these interactions. We have also developed a minimum viable product of a search engine to find reviewers that provides relevant metrics (e.g. reviewer timeliness, acceptance ratio), and enables open access to previous peer review reports. Using our web interface, journal editors may be able to find suitable reviewers in different platforms (centralized and decentralized),

[19] Bitcoin Improvement Proposal
[20] Ethereum Request for Comments
[21] Bloxberg Improvement Proposal 3

using a unified interface. This interface was developed in collaboration with editors of academic journals by means of different interviews to identify and provide a solution to their needs.

We have also addressed the challenges that a decentralized platform such as DecSci must face to facilitate interoperability with existing software systems. These challenges include the integration with existing publication management software, the adoption by third-party applications, the interoperability with other reviewer platforms, and with other blockchain applications.

8.2. Open challenges

Furthermore, the use of decentralized technologies introduces additional scalability and cost challenges. The *scalability* of blockchain systems is an issue in very large systems and, in fact, the Ethereum network has already experience congestion episodes, leading to dramatic increases of latency and transaction costs (Faqir-Rhazoui, Ariza-Garzón, Arroyo, & Hassan, 2021). However, there are currently many different approaches being developed and adopted (Zhou, Huang, Zheng, & Bian, 2020) that make us feel optimistic about this matter. Besides, the Ethereum network currently handles hundreds of thousands of transactions daily, which is more than enough for our system requirements even in the long term. Blockchains are also often criticized for their transaction *costs*, but second layer solution should not only solve scalability issues in the future but also drastically reduce these costs.

Another important challenge for open and decentralized systems is the *management of identities*. Addressing potential problems by sybil identities (i.e. multiple identities controlled by a single entity) and identity verification (to avoid frauds and impersonations) are some of the most common issues to manage identities. To address them, there exist different strategies used in fields such as Social Networks (Al-Qurishi et al., 2017), Internet of Things (Zhang, Liang, Lu, & Shen, 2014), distributed currencies (Nakamoto, 2008), or Self-Sovereign identities (Mühle, Grüner, Gayvoronskaya, & Meinel, 2018), as well as from academic oriented services and applications such as ORCID (Bilder, 2011), or Peerage of Science (Hettyey et al., 2012).

The use of blockchain technologies can also bring transparency to peer reviewing and help to expose and reduce bad practices (Mohan, 2019) such as *fraud* and abuse in the peer review process to maximize profits (Bowman, 2014) or benefit academic curricula (Teixeira da Silva, 2017). However, it also introduces new concerns regarding the detection of fake identities and fake peer reviews that could break the integrity of the reviewing process, and damage the quality and fairness of academic publishing.

The low levels of *inclusiveness* and *usability* are other important limitations of current blockchain technologies. Reducing the complexities of decentralized systems to users is one of the biggest design challenges to reduce the barriers of adoption of blockchain solutions. *Data availability* and *stewardship* of decentralized information systems is an additional challenge, as without proper policies, important data could be lost.

Despite the existing challenges, the use of decentralized technologies can introduce disruptive innovations and improvements for academic publication and peer reviewing. Decentralized Science introduces a proposal of one of such systems, with a technological proof-of-concept and a minimum viable product implementations, evaluations of the proposal, and an architecture to facilitate the integration with existing and widely used technologies. The level of adoption of these decentralized technologies and their real impact remains to be seen. To support it, the paper introduces a perspective where an ecosystem of existing centralized technologies and emergent decentralized solutions work together to deliver the promises of blockchain applications for academia.

CRediT authorship contribution statement

Ámbar Tenorio-Fornés: Conceptualization, Software, Formal analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **Elena Pérez Tirador:** Conceptualization, Software, Formal analysis, Investigation, Writing – original draft. **Antonio A. Sánchez-Ruiz:** Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Samer Hassan:** Conceptualization, Formal analysis, Funding acquisition, Supervision, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

- The author Ámbar Tenorio-Fornés is sole owner of the enterprise Decentralized Academy Ltd.
- Elena Pérez Tirador is hired part-time at the same enterprise, Decentralized Academy Ltd.
- The enterprise Decentralized Academy Ltd. has received EU funding (Ledger Program grant 82526) to develop the project "Decentralized Science" (https://decentralized.science), whose architecture and MVP prototype are shown in this research article.
- Samer Hassan and Antonio A. Sánchez-Ruiz are external advisors of the "Decentralized Science" project.
- The Decentralized Science project is a spin-off from the ERC-funded project P2P Models (https://p2pmodels.eu) whose Principal Investigator is Samer Hassan.

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7.3 A Decentralized Publication System for Open Science using Blockchain and IPFS

Reference

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Abstract

Science publication and peer review raises concerns about fairness, quality, performance, cost or accuracy. The Open Access movements has been unable to fulfill all its promises, and middlemen publishers can still impose policies and concentrate profits. This paper, using emerging distributed technologies such as Blockchain and IPFS, proposes a decentralized publication system for open science. It provides transparent governance, a distributed reviewer reputation system, and open access by-design. The paper concludes reviewing the open challenges of such approach.

A Decentralized Publication System for Open Science using Blockchain and IPFS

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Abstract. Science publication and peer review raises concerns about fairness, quality, performance, cost or accuracy. The Open Access movements has been unable to fulfill all its promises, and middlemen publishers can still impose policies and concentrate profits. This paper, using emerging distributed technologies such as Blockchain and IPFS, proposes a decentralized publication system for open science. It provides transparent governance, a distributed reviewer reputation system, and open access by-design. The paper concludes reviewing the open challenges of such approach.

Keywords: blockchain, decentralized systems, distributed systems, open access, open science, peer review, P2P, publications, reputation

1 Introduction

Science publication and peer review are based in a paper-based paradigm, with few changes in the last centuries [1]. Critics to current science publication and peer review systems include concerns about its fairness [2], quality [3], performance [4], cost [5], and accuracy of its evaluation processes [6], among others.

The development of the Internet enabled the proposal of alternatives for science dissemination [7] and evaluation [8]. The reduction of distribution costs enabled wider access to scientific knowledge, and questioned the role of traditional publishers [9]. It is acknowledged that the Open Access and Open Science movements have successfully reduced the economic cost of readers to access knowledge [10]. However it has not successfully challenged traditional publishers business models [11] that are now combining charging readers and charging authors [12].

Peer review has suffered multiple criticism, and yet only marginal alternatives have gathered success [13]. The literature provides multiple proposals around open peer review [14], and proposals of reputation networks for reviewers [15]. In fact, a start-up, Publons[4], provides a platform to acknowledge reviews and open them up.

Decentralized alternatives, despite their promises [16], are still in their infancy. A few proposals, none of them functional to date, have appeared recently: a peer review proposal using cryptocurrencies [17], a blockchain-enabled app with voting and storage of publications, again using cryptocurrencies [18], or a peer review quality control through blockchain-based cohort trainings [19]. Additionally, Ledger[5] journal records the publication timestamps in the Bitcoin blockchain.

This paper proposes the development of a decentralized publication system for open science. It aims to challenge the technical infrastructure that supports the middlemen role of traditional publishers. Due to the successes of the Open Access movement, some of the scientific knowledge is today freely provided by the publishers. However, the content is still mostly served from their infrastructure (i.e. servers, web platforms). This ownership of the infrastructure gives them a power position over the scientific community which produces the contents [20]. Such central and oligopolistic position in science dissemination allows them to impose policies (e.g. copyright ownership, Open Access prices) and concentrate profits.

The proposed system aims to move the infrastructure control from the publishers to the scientific community. It entails the decentralization of three essential functions of science dissemination: 1)

[4] https://publons.com/
[5] https://ledgerjournal.org

the peer review process, 2) the selection and recognition of peer reviewers, and 3) the distribution of scientific knowledge. The following section provides an overview of the system features, while the final section discusses its challenges.

2 Decentralized publication system for open science

The proposed system relies upon two emerging distributed technologies. On the one hand, the Blockchain [21] provides a public decentralized ledger to record the system's interactions. On the other hand, IPFS [22] is a distributed file system to store all the papers and reviews sent to the platform. This ensures that all the information is persistent, free and accessible, and does not rely on a centralized server.

The proposed system provides a distributed platform for open science, from submission to publication, including the peer review process communications.

The system rests in three main pillars: a transparent governance, a distributed reviewer reputation system, and open access by design. These are outlined in the following subsections.

2.1 Transparent Governance

Peer review process communication nowadays is digitally supported, and yet some argue that its system remains feudal [9]. There are multiple proposals to improve peer review [8], however its communication and processes remain closed and in control of journals and publishers, and their infrastructure [23].

Distributing and opening peer review communication infrastructure, the proposed system aims to improve its transparency, empower the scientific community, and foster innovation. The system will support the peer review interactions in an open and decentralized network. Each interaction, from first submission to the final acceptance is registered in a public decentralized ledger. Thus, processes like the selection of reviewers, or the contents of the reviews, are open to the public eye. Thus, with interactions being time-stamped and tamper-proof, they can be monitored, audited, and held accountable. More complex iterations of the system can consider blind reviews, as discussed in section 3.

Opening the peer review process communications to the public could even change the acceptance dynamics of the system. Currently, high rejection ratios are encouraged because the risk of rejecting a relevant paper are negligible, while the acceptance of not so relevant content is penalized [9; 24]. However, within a more transparent system, the first may be penalized also.

This transparency, combined with a distributed infrastructure for peer review, facilitates the exploration of new workflows [23]. The following subsection explores one of these possibilities.

2.2 A distributed reviewer reputation system

The information concerning each reviewers quality and reliability is usually held private by publishers and journals (and even editors). There is no easy way to predict reviewer quality from reviewers training and experience factors [25]. This information is valuable, and yet it is kept private, reinforcing the publishers and journals influential positions.

This proposal extends traditional peer review communication workflow with the possibility of rating peer reviews, building a reputation system for reviewers [26]. Reviewers get rewarded for worthy, fair, and timely reviews, or penalized otherwise.

This open reputation network of reviewers would increase the visibility and recognition of the reviewing work [27]. In fact, they could be easily rewarded since third parties like founders could offer paid reviews to highly reputed reviewers. Moreover, creating a public reviewers reputation network reduces, or at least exposes, unfair and biased reviews [2; 23].

2.3 Open access by design

Open Access focuses in the free access to scientific knowledge. While publishers provide free of charge their Open Access content, their control of the science dissemination infrastructure allows them to impose certain rules, such as charging authors unreasonable fees to offer their work as Open

Access (Gold Open Access) [28] or the temporal embargo and restrictions on the dissemination of the final version (Green Open access) [29], among others.

The system proposes a decentralized infrastructure for science publication. Academic documents - from first drafts to final versions, including peer reviews- are shared in an open P2P network [22]. Thus, the system inherently grants Open Access by the design of its distributed infrastructure and circumvents the publishers dominant role.

3 Discussion and Conclusion

This paper proposes the opening and decentralization of three of the peer review and publication functions: 1) the peer review process communication, 2) the reputation of reviewers, and 3) the distribution of papers and peer reviews. Arguably, this decentralization of the infrastructure could help to challenge the central role of middlemen such as traditional publishers.

Distributed technologies such as Blockchain and IPFS may finally realize the promise of Open Access, while enabling new not-for-profit models of science dissemination. Opening and decentralizing the infrastructure enhances the transparency and accountability of the system, and fosters innovation.

Note the proposed system does not rely on the use of cryptocurrencies, since it is focused on a not-for-profit approach, far from the startup-driven commercial approaches common in the blockchain space.

This challenging proposal raises multiple issues. The opening of the peer review process may reduce the privacy of current closed system. Blind review relies in such privacy, and a lack of this protection can cause a great rejection by the community. Recent technical cryptographic innovations may be used to circumvent this issue [30] and allow transparency while still allowing double blind reviews.

The introduction of a new public metric (reviewers' reputation) may also affect researcher careers, adding pressure to the already straining processes for academic survival [31].

Additionally, the proposed system's infrastructure relies in new technologies with their own challenges. Blockchain technologies face scalability, transaction costs, inclusiveness and usability problems that remain open and under discussion. On the other hand, distributed file systems such as IPFS may be more resilient, but they still need somebody in charge of preserving and providing the data, since without that responsible actor, it may result in unpredictable loss of content.

Other open issues that may be explored in future work are the exploration of different copyright regimes, the challenging of traditional journal-centered metrics to rate publication quality, different reputation algorithms, different levels of openness, and the exploration of decentralized autonomous journals.

Despite the existing challenges, we are confident that decentralizing the processes that Science relies on, would open up a whole new playing field, with implications we cannot possibly foresee now. Will its benefits outweigh its risks? We believe it is a conversation worth having.

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7.4 The challenges of finding peer reviewers: insights from our product design research

Reference

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Impact metrics

Not Indexed

Abstract

Finding good peer reviewers is a difficult task. In Decentralized Science[1] project we are designing and developing a tool to improve the quality, fairness and reliability of academic peer reviewing. Our approach relies in opening peer review [151], giving transparency to the peer reviewing process using decentralized technologies such as Blockchain. During our ongoing product design research we gained interesting insights about the peer reviewing selection process, and how editors currently deal with it. Our research methods are oriented towards the development of a software tool. We use Lean Design and Agile development principles, favoring fast iterative learning over the precision and completeness of more formal approaches. This contribution shares what we learned in the process about how editors deal with peer reviewer selection: from their needs and complains to their tricks, including some of their confessions. It also explains how we embraced this insights to improve our current prototype design.

[1] https://decentralized.science

The challenges of finding peer reviewers: insights from our product design research

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Finding good peer reviewers is a difficult task. In Decentralized Science[1] project we are designing and developing a tool to improve the quality, fairness and reliability of academic peer reviewing. Our approach relies in opening peer review [1], giving transparency to the peer reviewing process using decentralized technologies such as Blockchain. During our ongoing product design research we gained interesting insights about the peer reviewing selection process, and how editors currently deal with it. Our research methods are oriented towards the development of a software tool. We use Lean Design and Agile development principles, favoring fast iterative learning over the precision and completeness of more formal approaches. This contribution shares what we learned in the process about how editors deal with peer reviewer selection: from their needs and complains to their tricks, including some of their confessions. It also explains how we embraced this insights to improve our current prototype design.

1 Research

This section introduces the product oriented design research we conducted to refine our knowledge about the peer reviewing process, as well as some of the insights we gain from this exploration. It starts introducing and contextualizing the origin and purpose of the work (Section 1.1), continues presenting how we focus the initial research on the editors' role (Section 1.2), presents the problems of peer reviewing from their perspective (Section 1.3), and finishes presenting the exploration of the proposed solutions (Section 1.4).

1.1 Point of departure

Our research start as an effort to find a "Minimum Viable Product" for Decentralized Science, a proposal to build a decentralized peer reviewing and publishing infrastructure, where articles and peer review reports can be publicly shared [2][3]. The project aimed to improve the quality, reliability and fairness

[1] https://decentralized.science

of academic peer reviewing for authors, reviewers and editors. Its approach consist in bringing transparency to the peer reviewing process using decentralized technologies such as Blockchain and IPFS.

The initial research already included a survey that explored the importance of some problems from the viewpoints of authors, reviewers and editors. However, it only provided an overall perspective of this problems and lacked qualitative information to refine these problems, and better understand how to solve them.

1.2 Framing the research

Our proposal aims to help authors, reviewers and journal editors. However, it is difficult to design a solution having in mind such diversity of actors in the initial design phases. Thus, this initial product research focuses on the journal editors' role. Therefore, important issues that our tool also aim to target, such as improving the recognition of peer reviewers or reducing the prices of open access publishing [4][5], are outside the scope of this study.

1.3 Discovering the problems

As suggested by the Lean Startup methodology introduced by [6], we conducted a series of "problem interviews" to start understanding our customers (i.e. the journal editors). In this interviews, our purpose was to identify the important problems of our customers, and learn how they currently deal with them.

We performed 19 problem interviews [6, 7] answered by 12 people (as some of them replied the interviews from different roles). These interviews gave us information about 5 journals, 6 conferences, 3 academic associations, 4 reviewers and 1 university press.

From these interviews we identified that the following were the most important problems for editors in the peer reviewing process (as they appeared with more frequency than other issues):

- Finding peer reviewers
- Get reviewers acceptance
- Reviewers' response time
- Quality of peer reviewing

We also found strategies that editors use to solve these issues despite not having easier tools. This contributes to find this problems important for them. For instance, to deal with bad quality reviews and slow reviewers, a conference organizer shared that they have a black list of reviewers, while to get reviewers to accept the invitations a journal editor shared that in order to get an acceptance, he should send at least ten invitations.

These findings were used to design our first prototype, that helped us continuing our research as explored in the following subsection.

1.4 Exploring the solutions

To address the identified problems (shared in previous section) we developed an initial Value Proposition [8], with three main functionalities:

1. **A specialized search for reviewers**: editors can search for reviewers
2. **Reviewers' reliability metrics**: the results of the search of reviewers include statistics about how often they reply on time.
3. **Transparent Peer Review processes**: the system encourages the publication of review reports (open peer review). These review reports can be shared among different journals.

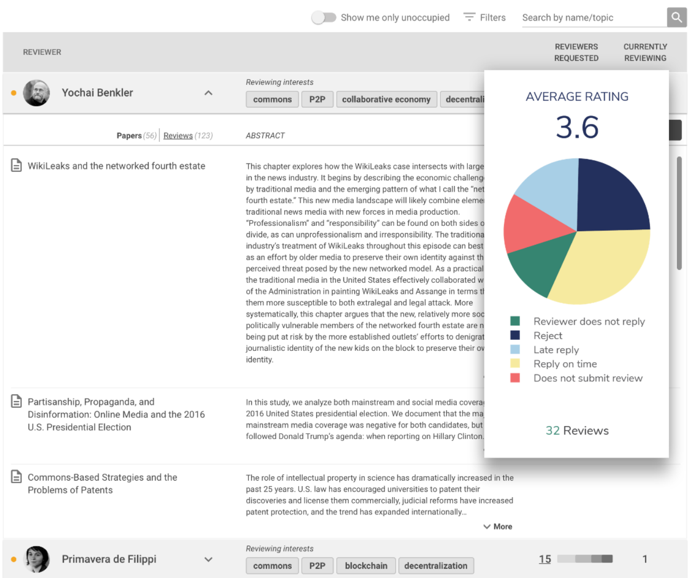

Fig. 1. Detail of the first version of the prototype Mock-up.

These functionalities were incorporated in a Mock-up prototype (Figure 1). It represents a search within a network of reviewers, with reputation metrics of reviewers that show their quality, and reliability. Thus, the system aims to provide a way for editors to find good reviewers.

This prototype has been tested within pilot projects by different customers. The development is following agile methodologies [9], gradually improving the proposal in short cycles (iterations) with customer participation. In these sessions, customer tested our prototypes. We learned from their reactions and feedback many relevant insights, such as what is important for them when they are searching a reviewer from the feature requests we received:

- Include reviewer's acceptance ratio statistics: It is important to know if a reviewer is especially strict.
- Include reviewer's h-index: The experience of the reviewer is an important factor.
- List also external reviewers: The journals' pool of reviewers is often not enough to find reviewers.
- Get automatic recommendations of reviewers: It is a costly process to find reviewers.

2 Results

As we learn from the recurrent solution interviews explained in previous section, we are developing a functional prototype, available under a Free Software license online[2]. The software is developed as an extension to existing peer reviewing software such as Open Journal Systems [10]. Interestingly, most of the needed information is already in the system, however it is not visible from the available interfaces. Thus, we can provide useful tools to journal editors using the information they already have. Additionally, our proposal aim to openly publish peer review reports, using decentralized technologies such as Blokchain and IPFS to provide transparency and Open Access. As some journals are already requesting, our tool will be able to offer information from peer reviewers of different journals, facilitating the search for the best and more reliable reviewers.

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