ANALYSIS OF LARGE-SCALE DECISION MAKING TOOLS USING A DECENTRALIZED ARCHITECTURE TO GOVERN COMMON POOL RESOURCES

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This paper analyses the status quo of large-scale decision making combined with the possibility of blockchain as an underlying decentralized architecture to govern common pool resources in a collective manner and evaluates them according to their requirements and features (technical and non-technical). Due to an increasing trend in the distribution of knowledge and an increasing amount of information, the combination of these decentralized technologies and approaches, can not only be beneficial for consortial governance using blockchain but can also help communities to govern common goods and resources. Blockchain and its trust-enhancing properties can potenitally be a catalysator for more collaborative behavior among participants and may lead to new insights about collective action and CPRs.

1. Introduction

Blockchain is mostly known as the technical infrastructure for cryptocurrencies and the financial industry, however, there are more applications which can have a sustainable and ethical application as well as an impact, like large-scale and collective decision making in combination with collective action theory and common pool resources (CPRs) [1]. Due to an increasing trend in the distribution of knowledge and an increasing amount of information, the combination of these decentralized technologies and approaches, can not only be beneficial for consortial governance using blockchain but can also help communities to govern common goods and resources [1]. Thomas W. Malone explores on the other side the many applications of information technology and human-machine interaction and how they enable us to decide together in order to solve complex problems and form smarter communities, markets, companies and eventually societies. Therefore, it provides the opportunity to overcome outdated inefficient economic models [2]. This paper analyses the status quo of large-scale decision making combined with the possibility of blockchain as an underlying decentralized architecture and evaluates them according to their requirements and features (technical and non-technical), potential impact and ethical implications. Further research questions and suggestions for further implementation are elaborated as a summary and final conclusion of the analysis. Besides, the well-known applications of blockchain, decentralized technologies can potentially be an engine for large-scale and collective decision-making. Hence, technical features and properties of blockchain have the potential to accelerate collective action approaches [1] that were e.g. elaborated by Elinor Ostrom in 1990 in her book about governing common goods and collective action [3]. Features of blockchain can enable new forms of decision-making and hence new forms of organizations, communities and societies. The decentralized set up and distributed storage of the database can enable trust and increase collaboration, due to transparency and immutability of the data [4]. At the same time, decentralized identities can provide solutions for compliance with data privacy laws and standards [5].The combination of these approaches and technologies may prevent depletion and conflicts over Common Pool Resources (CPRs), possibly public goods, as well, and therefore lead to self-governed, more sustainable and ethical decisions for communities, societies, including the environment [6].

2. Methodology and Limitations

Within this context the paper aims to analyze to which extent large-scale decision-making approaches are researched to govern common goods as suggested by Liv Ostrom via technological solutions such as Blockchain. Furthermore, we analyze if there are common features or requirements that can enable collective action and decision-making. Hence, our paper aims to identify the combined application of collective and large-scale decision-making with blockchain as a possible infrastructure to govern common resources in a more efficient, sustainable and moral manner. Therefore, we performed an interdisciplinary qualitative literature survey, based on surveys of each discipline, to understand if Ostrom‘s approach is already combined with these emerging topics. The literature sources examined for this survey are widely varied and include databases, research papers, book chapters, journal papers, web resources, conference papers, and whitepapers published by various blockchain, organizations, companies and forums.
To lower the complexity of the paper and increase comprehensibility, the following section provides a brief description and context of the terms used and also points out limitations of the paper and methodology.
Firstly, the terms public goods and common pool resources are distinguished. Goods and services are often classified based on two criteria: the cost and possibility to exclude free-riders (people who consume but do not pay) and the level of subtractability of a good or service (how rivalrous the good or service is) [3]
Ostrom concludes that public goods are usually underproduced and common-pool resources are usually both underproduced and over consumed. for example fish in the ocean. Reasons are missing compensations and free-riding. The initial focus of the paper is on the well researched common-pool resources (CPRs). Given the similarities between many CPRs and public

good problems, insights may be applicable to some extent to even small-scale public goods. Example of CPRs are the ocean, fishery and forestry [3] Secondly, the context of collective and large-scale decision-making is provided. Due to the nature of the problem with CPRs the scope of the paper excludes classical multi-person or Group-Decision Making (GDM) approaches for smaller groups. In current Large-Scale Decision Making (LSDM) Studies, there is no common definition to outline the key characteristics of LSDM. However, one of the most important ones can be argued to be the higher complexity of decision-making processes in the scenarios of LSDM. Moreover, these kinds of events and decisions are important for certain societies, communities and citizens living in cities. Additionally, they should include as many affected participants and stakeholders as possible. These parties are participating directly and not via a representative, as it is the case in most classical group-decision making approaches [1]. Due to the complexity and many levels of different stakeholders, LSDM can be seen as a possible approach to collectively govern CPRs. Thirdly, the taxonomy of distributed ledger technology and blockchain are explained to provide a common understanding of the terms used. Since the introduction of Bitcoin in 2008 by Satoshi Nakamoto, Blockchain Technology has been well known for its application in the financial industries and in cryptocurrency trading, it has moved far beyond this and is researched, discussed and applied by many different fields within academic discourse. industries and public services [7]. The diversity of research and development creates potential for cross fertilisation of ideas and creativity, but also the risk of fragmentation due to no common taxonomy of blockchain technologies and distributed ledger technologie. Reasons are consistent progress in engineering large and complex blockchain systems at a rapid pace [8]. In order to decrease the complexity further and since there is no uniformed definition at this point, blockchain is understood to be a part of distributed ledger technologies, which also include other technologies like Iota, which uses a directed acyclic graph (DAG or Tangle), instead of a linear blockchain data structure. In the context of this paper, these technologies are still accounted as a blockchain, even though some researchers and practitioners may refer to them as distributed ledger technologies only [8] [9]. Consequently, the following limitations of this analysis need to be pointed out.

Due to the novelty of the topics and the interdisciplinary character of this paper very strict definitions are not applied within this paper. The definitions are rather to be understood as descriptions of phenomena which are currently arising and hence are not well defined and classified in literature by a standardized manner. Since, there is not a distinguished taxonomy for the mentioned disciplines a quantitative survey of the combined topics does not seem appropriate, since there has to be a discourse about the clear distinction of certain terminology. The focus on CPRs in this paper are due to the recognition and well-discussed approach by Ostrom in combination with collective action and hence decision-making. Her work was even rewarded with the Nobel Prize in 2009 [10]. However, she also pointed out that comparable data and experiments are still missing to test the theories to make better assumptions and models that can find different rules for various scenarios, goods and stakeholders [10]. One reason may be the interdisciplinarity and thus very different terms of approaches and language. Moreover, it has to be acknowledged that neither this paper nor Ostrom claims that collective action is the only way to govern public goods and CPRs, in certain circumstances it may be one possible way. Therefore, a more common taxonomy is needed in the social-ecological framework and now combined with new technological possibilities that can help in the long-term to do more empirical research, which can refine and improve these theories to find better economic models.

3. Collective Action Theory and Self-Governance of CPRs

Within recent years many researchers started to pay attention to the approach of commons again. It refers to the research on people working commonly in the pursuit of the common good and the development of collective forms of common goods production, distribution management and ownership [11] Within this paper one of the most fundamental theories by Elinor Ostrom serves as an example for collective action. Her work can be broadly categorized within the rational-choice tradition within the fields of politics and economics and describes a collective way of CPR management to avoid the tragedy of the commons, free-riding and move beyond privatisation and government regulations. She acknowledged that agents are dealing with incomplete information and cognitive limitations, but are still agents responding to incentives [10]. Hence, she developed new game theories based on her studies that allow cooperative behavior within a non-cooperative framework. Since, she calls out for new forms of economics further classification of her theory from a heuristic point of view is not provided. The main discovery of her empirical studies was that despite recognized economic theories communities indeed create and enforce rules against free-riding and even ensure long-term sustainability of communal properties. Her 'design principles' explain under what conditions this happens and when it fails [10]. Similarly, she aims to provide a framework that can guide decisions about when to rely on spontaneous processes of governance and when to rely on the external generation of rules [10].

3.1 Core requirements for Collective Action

In 1990 she published her work and the eight design principles to ensure sustainability in self-organized CPRs. Since the principles have been slightly adapted over the years (The Future of the Commons, Beyond Market Failure and Government Regulation, which was published in 2012.) In the following, the eight core principles of a socio-ecological systems and design principles for CPRS are briefly described in order to understand how distributed technologies like blockchain and large-scale collective decision-making rules are able to represent these conditions to set rules as software and protocols. The eight underlying principles for self-organized governance systems are: 1) Boundaries to facilitate exclusion; 2) The importance of internal rules 3) The importance of locally adapted rules; 4) The importance of monitoring and enforcement; 5) Dispute Resolution 6) Interaction between system of rules 7) The presumption against centralized natural planning and 8) The role of the state in environmental resource management [10]. In 1990 she summarized them as the following: "*All efforts to organize collective action. whether by an external ruler, an entrepreneur. or a set of principals who wish to gain collective benefit. must address a common set of problems. These have to do with coping with free-riding, solving commitment problems, arranging for the supply of new institutions, and monitoring individual compliance with sets of rules. A study that focuses on how individuals avoid free-riding, achieve high levels of commitment, arrange for new institutions, and monitor conformity to a set of rules in CPR environments should contribute to an understanding of how governing the commons dividuals address these crucial problems in some other settings as well"* [3]. Besides these eight principles she defined other variables and criteria that influence successful collective action such the number of participants involved, whether benefits are subtractive or fully shared, the heterogeneity of participants, face-to-face communication, the shape of the production function (factors independent from repetition) and other variables that depend on repetition. These include information about past actions, how individuals are linked and whether individuals can enter and exit voluntarily*. Moreover, she points out that the core relationships of reputation, trust and reciprocity affect cooperation. Systems where people are encouraged to cooperate seem to have a higher social outcome than the non-cooperative game theory commonly represented with the Nash-Equilibrium. She *concludes that this relationship is so fundamental that at the core of an evolving theoretical explanation of a successful or unsuccessful collective action are the links between the trust that one participant (Pi) has in others (Pj….Pn) involved in a collective action situation, the investment others make in the trustworthy reputations, and the probability of all participants using reciprocity norms* [12]. Since, she points out trust and reputation as the fundamental successor of collective action, decentralized architectures like blockchain that promise digital trust are analyzed as a possible underlying infrastructure. The possibilities of many participants to decide together via digital (collective) decision-making approaches is reviewed in the subsequent part.

4. Large-Scale Decision-making and Information Technology

Since Ostrom published her research on collective action a lot of progress has been made in communication and information technology. E-Democracy, citizen participation and social media are only a few examples of possible ways to connect and decide together these days [1]. Large-Scale Decision-Making in this context are tools which enable stakeholders to decide via computer-based systems together on different topics. In the following their application to CPRs and usage of Blockchain Technology is evaluated. Firstly, an overview of the current status quo of this discipline is presented in order to understand potential, opportunities and progress within research and real-world applications.

In their recent study Ding et al. point out the tremendous increase of Large Scale Decision-Making within the recent decade, with 2014 and 2018 as a turning point. In 2018, a high impact factor was found for the following journals and it's related publications: IEEE Transactions on Fuzzy Systems, IEEE Transactions on Industrial Informatics, IEEE Transactions on Systems, Man and Cybernetic Systems, Man and Cybernetic Systems, Information Fusion. This also proves the strong fusion of decision-making disciplines with IT and new technologies [1]. Moreover, four key elements were identified that commonly appear in literature and are in most cases stages of the Consensus-Reaching Process (CRP) within LSDM. It is essential since it helps to make consensual decisions as the number of participants and diversity can increase rapidly. and can be summarized as follows: 1) consensus measurement; 2) subgroup clustering; 3) behavior management and 4) feedback and preference modification [1].

These key elements vary through the literature and use different approaches. However, there were still trends that could be identified within the stages: "Most of the LSDM approaches analyzed within their study included a CRP in them , *with the measurement of the agreement level being a key aspect in defining such models* [1]. The consensus level CD is most widely adopted via an approach which determines the similarity degree among participants, based on a distance function. It can be understood as the supporting rate of participants for a certain alternative. This distance-based approach can be further classified into two consensus measurements: 1) CD is based on the distances to the collective assessment (aggregated collective opinion of all the participants) 2) CD is calculated by distances between pairs of DMs. If a consensus cannot be reached sub clustering can be useful to emerge to a consensus with fewer iterations. Most of these subcluserting methods are based on the distance of participants to collective opinion. Behavior Detection and Management deals with the part of establishing decision weights for participants which is however not mandatory in every LSDM scenario. Feedback and recommendation processes are on the other side of great importance since they make CRPs more efficient [1]. The main challenges for further progress within LSDM approaches are the following: There is a growing demand for software, e.g. mobile apps, that facilitate distributed LSDM and consensus building processes in real-world scenarios where the decision group structure is decentralized. Blockchain and Distributed Ledger Technologies can provide these decision-making tools with certain advantages, since they enforce more security, integrity and and most importantly can enhance trust and represent reputation in these distributed decision making processes [1].

In this setting, blockchain technologies can provide a tool that enforces security, integrity and cost-effectiveness in these distributed federated decision processes [13]. Blockchain is a decentralized network capable of providing immutability, security, privacy and transparency without a third central authority. It allows tracking of the whole decision-making process, thereby making it more transparent. Conversely, federated blockchain technologies could also benefit from ideas underlying consensus processes in LSDM, so as to reduce the costs of their commonly used consensus algorithms [14] while ensuring security and integrity of activities occurring in distributed networks of miners configuring a blockchain system [1]
Another interesting finding by Ding et is that *In many decision situations, it is no longer realistic nor accurate to make large-scale collective decisions that solely rely on subjective pref- erences of DMs. It has been demonstrated in part of the surveyed litera- ture, that most of such large-scale decisions are rarely made by groups where DMs are socially isolated from each other. Different forms of so- cial relationships between DMs can occur, with varying strength, such as: trust, distrust, influence, reputation, etc . Social data and So- cial Network-based approaches are therefore a valuable tool to better understand the background, motivations and attitude of (Decision Makers)DMs, not only towards the problem being tackled, but also towards each other* [1]. Hence, even these large-scale collective decision-tools need an underlying trust and reputation architecture to trigger a meaningful cooperation. Other problems that need to be addressed is governance of LSDM problems with overlapping communities (most models do not represent the possibility of one participant to be involved in different subgroups), a more comprehensive analysis of decision-maker in Consensus-Reaching Process (CPR) (e.g. to identify non-cooperative behavior), visualizing of the LSDM problem (multiple evaluation criteria, diversity of stakeholders background, conflict and trust relationships etc.). They also state that there is an increasing trend to apply machine learning, computational neuroscience, deep learning, complex system simulation and decision support tools based on AI and statistical methods in order to effectively cope with scenarios where evaluation criteria is interdependent and a decision is collective and large-scale [1]. The biggest potential of innovation is seen in model validation in real-world problems, so far the nature of these tools have been far more theoretical and lack experimental studies to validate new models. They also assume that Smart Cities and Internet of Things (IOT) may influence collective decisions due to active information sharing. The aggregation and usage of the data can enable citizen data scientists to share new information and insights about the environment [1]. Similar insights are provided by Tang et al. which also point out the importance of trust and social relationships, since most theories assume that agents act indepently [15]. Empirical research suggests that trust and reputation are far more important for collaboration than so far assumed by common economic models. Hence, not only the collective action theory by Ostrom recognizes the importance of trust and reputation, but also scholars from LSDM found that trust is a core requirement to enable stakeholders to decide together. The following parts describes the core features of blockchain and explains how it can solve some of the fundamental challenges of collective action and LSDM.

5. Common features of Blockchain Technologies

This part highlights common features of blockchain and further classifies them according to contemporary approaches. A very significant innovation of blockchain technology is that blockchain technologies (not by Bitcoin itself though) have minimized two of the major risks connected to digital currency transactions: 1) The Byztantine General Problem and 2) Double Spending (in Proof of Work Consensus) [7]. Via an univerisial state layer that every actor can trust, even though they may not know each other, the need for centralized verifying third-party authority is removed. Instead protocols are used to reach consensus within the decentralized network. The technical specifications of DLT systems and their consensus mechanisms are becoming increasingly varied in nature [16]. Zwitter et al. show that often-highlighted features of blockchain technologies, such as immutability, transparency, and trustlessness, are in fact design features rather than a given property [16] In the following, the core features are explained, however not discussed in detail, since it would be out of scope. Consequently the opportunities arising with these new features are pointed out with focus on LSDM and the governance of CPRs.
A common classification of blockchain types is based on the access rights to read and write on the distributed ledger. Buterin classified “blockchain-like databases” into the following categories: 1) public blockchains 2) consortium blockchain and 3) Fully private blockchains [17]. The difference is described in the consensus process within the network. In a public blockchain anyone can read, send transactions and participate in the consensus process(e.g Bitcoin and Ethereum). In a consortium blockchain the consensus process is controlled by a preselected set of nodes (e.g. Bloxberg). Fully private blockchains are

kept centralized with one organization. Its permission to read may still be public. These different set ups lead to different levels of centralization and trust within the network and hence community. Buterin also argues that fully-private blockchains are not the best technology choice and may be better implemented with generalized zero knowledge proof technology (e.g.https://github.com/scipr-lab/libsnark). Therefore, this paper focuses on public and consortium blockchains, the latter one is a hybrid model of the low-trust public version and the high-trust single party approach [17]. Blockchain does not only provide a decentralized and transparent way to reach consensus, but can also leverage trust due these features and a commonly agreed consensus process within the entire network [18]. Compensation for the used resources to provide such an infrastructure are provided in forms of incentives via tokens (e.g. Bitcoin or Ether). Which are not only incentives for economic agents and are a missing component in the tragedy of the commons, but also according to Buterin the reason why blockchains are more robust and may solve problems other technologies cannot due to missing incentivisation layer [6]. Möhlmann et al, also analyzed trust and found that it can be one of the key drivers for more sustainable behavior and that blockchain can be an appropriate solution to represent trust digitally and therefore trigger collaboration. [19]. Moreover Blockchain can be used for digital identities which provide great opportunities in terms of data privacy for consumers and citizens. One approach was for example published by w3c which provides an entire guideline for a trust model using not only but also underlying blockchain solutions [20]. Even distributed storage solutions are becoming possible. Examples for decentralized storage solutions are using Blockchain are e.g. Ocean Protocol [21]. Hence, applications reach from industry and automation processes to more ethical and customer-centric approaches, that are not only profitable for companies but also beneficial for customers, citizens, communities, governments and NGOs [6] The following part combines the features and requirements of the presented approaches and explains why they have a great potential to trigger collective action and help to protect the environment at the same time.

6. Technology Fusion: Common Features and Requirements

By combining theories in economics and design mechanisms with progress in cryptographic mechanisms a new and interdisciplinary field emerged: Cryptoeconomics. The founder of Ethereum understood this potential of this combination early and added not only Smart Contracts to the technology stack of blockchains (which is not easily available in bitcoin) but is also one of the Pioneers in Cryptoeconomics [6]. Buterin explains within an extensive interview on better ways to fund public goods, blockchain failures, and effective giving, that a lot of problems like the increasing meat consumption and the related CO2 productions are collective actions problems that are very complex and international in their nature, which makes it impossible for all the stakeholders to meet, interact and decide [6]. Hence, he refers mostly to problems and approaches recognized already by Ostrom, but now combines these economic approaches with cryptographic features and interconnectivity. Even though Buterin talks about public goods and not CPRs, the provided description is valid for some examples as the common-resource pool and addresses problems like climate change which ultimately impact common resources. He suggests a general purpose infrastructure for funding public goods just as money is a tool for funding private goods. pool [6]. Therefore, he suggests a quadratic funding approach that computes the optimum level of social optimum with utility functions to fulfil the Nash Equilibrium. Ostrom stated that there are even more efficient ways than the Nash Equilibrium, however it may be more realistic to start with a well-known model to test different tools and approaches and then shift long-term to new economic approaches, onces insights have been validated. However, they agree in order to make these infractures work, large-scale participation is needed. Buterin also suggests a concrete enforcement or sanction mechanism that may be implemented with Escrow smart contracts [6] that can be run on Ethereum, which is in comparison to Bitcoin turing-complete. Escrow contracts may keep a certain amount of money of governments which will for example not be repaid in case of violation or war e.g. over a certain resource. On the other side, he also points out that there are certain security issues that have not been fixed [6]. Since Buterin is one of the pioneers in incentives designs to increase cooperation, aiming also to provide an infrastructure for public goods with Ethereum, the implementation of smart contracts, given the active community of Ethereum and hence it open-source character, Ethereum may be an appropriate technology choice for further research and experiments, since it is likely that technical developments will consider new forms of decision-making and recognize collective action as opportunity in combination with decentralization, transparency and interconnectivity. Not only Buterin paid attention to this topic, but also other researchers are working on this topic. The research institute of crypto economics published a report about Blockchain and its potential to enhance sustainability and contribute to Sustainable Development Goals by the UN. It is also acknowledged that also purpose-driven Token and hence a fair incentive can trigger value driven collective creation and contribution [22]. Consortial Blockchains seem to be a promising solution to create more experiments with collective action and CPRs in combination with LSDM. Compared to public blockchain they offer certain advantages that are more compliant with Ostrom's principles. The exclusion of participants is given due to the restricted character. Moreover, it provides an easier management of internal rules and less external disturbance. The level of trust medium, since it is a hybrid solution of low-level trust public model and high-level trust private version. Dib et al. point out that they are especially suitable for highly regulated business (known identities, legal standards, etc.), since there are quite efficient transactions throughput, transactions without fees are also possible [23]. Moreover, recently the TrustoveIP Foundation was found by the linux foundation in order to provide an architecture of Internet-scale digital trust by combining cryptographic trust at the machine layer and human trust at business, legal and social layers. The biggest promises with regards to Collective Action and CPRs is that it will help to verify origins and prove every step of the journey through a supply and ownership chain and potentially help organizations to form and maintain lifetime private digital connections with customers and suppliers with full audit trails for regulatory compliance [24]. Even though there are several issues connected to these promises, it makes it more possible and feasible to test these theories empirically in order to understand which rules will trigger a greater collective outcome for different scenarios. Not only Ostrom pointed out how important trust and reputation are, also researchers in the field of large-scale decision-making, as well as researchers and foundations within the field of blockchain point out the potential of trust to enhance collaboration and hence trigger innovation. At the same time blockchain technologies do not only increase transparency about past actions but also provide a community to monitor resources, users and the network as a whole to a certain extent. Hence, it could be applied to the monitoring part of resources, users and the network even as whole. Monitoring of these networks is already a big research area within the field of blockchains and behavior detection within other consortia and communities [7].

7. Conclusion and Further Research

Since Ostrom published her theories based on observation and studies of real use cases decentralized technologies emerged and humans started to be interconnected. As pointed out by Buterin and Ostrom one of the collective action problems is that it is difficult for all included stakeholders to organize and decide together [6] [10]. Blockchain in Combination with Large-Scale Decision-Making Tools can be a possible infrastructure to test Ostorm’s theory further, since technological progress made a lot of the principles less costly and hence feasible. Consortial Blockchains and Ethereum seem to be a good test infrastructure for now, since it enables smart contracts and consortial governance provides some features in alliance with the collective action theory. Therefore, more research on the potential of consortial blockchain governance in combination with CPRs has to be done. Furthermore, Ethereum as a possible test environment should be evaluated in more details with regards to its technical properties and possible implementations also in combination with other technologies and systems. It may lead to a suitable infrastructure which can help to test real world scenarios; and predict with new data analysis tools such as computational neuroscience and machine learning, the outcome while changing one variable at the time and hence refining rules suggested by Ostrom and other experts and interdisciplinary researchers. Moreover, more research needs to be done on consensus-reaching processes that are less costly, then the ones currently used in LSDM [15]. Blockchain Technologies like Ethereum provide already less costly options for Consensus Reaching Processes (e.g. Aura, Clique and IBFT) than the well-known but expensive Proof-of-Work in Bitcoin.. However, researchers, legislators and also entrepreneurs are still facing a lot of challenges within each discipline that needs to be addressed to make further progress with this fairly new field. The combination of these technologies can potentially provide solutions for decentralized self-governance within a centrally organized system that prevents free-riding and depletion of CPRs. Furthermore, it needs to be highlighted that trust is addressed as one of the core requirements for collective action. Therefore, blockchain and its trust-enhancing properties can potenitally be a catalysator for more collaborative behavior among participants and may lead to new insights about collective action and CPRs.

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