PUBLIC BLOCKCHAIN – A SYSTEMATIC LITERATURE REVIEW ON THE SUSTAINABILITY OF CONSENSUS ALGORITHMS

Research paper

Eigelshoven, Felix, Chair of Business Informatics, esp. Processes and Systems, University of Potsdam, Potsdam, Germany, feigelshoven@lswi.de

Ullrich, André, Chair of Business Informatics, esp. Processes and Systems, University of Potsdam, Potsdam, Germany, aullrich@lswi.de

Bender, Benedict, Chair of Business Informatics, esp. Processes and Systems, University of Potsdam, Potsdam, Germany, bbender@lswi.de

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Abstract

Blockchain has the potential to change business transactions to a major extent. Thereby, underlying consensus algorithms are the core mechanism to achieve consistency in distributed infrastructures. Their application aims for transparency and accountability in societal transactions. As a result of missing reviews holistically covering consensus algorithms, we aim to (1) identify prevalent consensus algorithms for public blockchains, and (2) address the resource perspective with a sustainability consideration, whereby we address the three spheres of sustainability. Our systematic literature review identified 33 different consensus algorithms for public blockchains. Our contribution is twofold: first, we provide a systematic summary of consensus algorithms for public blockchains derived from the scientific literature as well as real-world applications and systematize them according to their research focus; second, we assess the sustainability of consensus algorithms using a representative sample and thereby highlight the gaps in literature to address the holistic sustainability of consensus algorithms.

Keywords: Blockchain, Consensus Algorithms, Sustainability, Systematic Literature Review.

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1 Introduction

More than a decade after its emergence, blockchain is reinventing the digital artifacts that we use to conduct daily transactions, thereby changing the way in which we store data, information, and financial assets. Beneficiary effects will reach businesses, governments, and consumers (Kewell *et al.*, 2017), when unlocking its full potential. Following the work of Zheng *et al.* (2017), a public blockchain is understood as a decentralized distributed ledger where every record (e.g. a transaction) is available for publicity and everyone can take part in the consensus process. Reaching consensus in a fully decentralized infrastructure is the core challenge of the blockchain infrastructure and achieved by the use of consensus algorithms (Viriyasitavat & Hoonsopon, 2018). Consensus algorithms originating from the field of distributed systems and "allow a collection of machines to work as a coherent group that can survive the failures of some of its members" (Ongaro and Ousterhout, 2014). In the case of blockchain, consensus algorithms provide rules that allow peers to reach a common agreement on the current state of the distributed ledger.

Recently blockchains gained attention and existing architectures revealed issues regarding their scalability, whereby their consensus algorithm is one of the primarily limiting elements (Chaudhry and Yousaf, 2019). Especially due to their open nature, consensus algorithms are crucial for public blockchains and significantly affect the reliability and efficiency of the network. While different types of consensus algorithm emerged, research lacks a recent overview of existing consensus algorithm as well as their key characteristics as a basis for a classification. Addressing issues in their architectural approach is key to systematically develop new approaches or improve existing consensus algorithm as a basis for more efficient blockchains (Mingxiao *et al.*, 2017). As such, this paper addresses this research gap by systematically identifying exisiting consensus algorithms for public blockchains through a literature survey in the information systems domain. The results benefit research and practice in a similar way, since they allow to systematically improve blockchain architectures from a research perspective and thereby overcome current barriers in practice and allow to develop new applications with appropriate consensus algorithms. As such, we aim to answer:

RQ1: Which consensus algorithms exist in the field of public blockchains?

Consensus algorithm aim to provide transparency and accountability and thus security, e.g. by avoiding corruption attempts (Zwitter and Herman, 2018). Aiming at achieving higher levels of consistency is one of the design principles in blockchain architectures. However, there is a trade-off between the security level (i.e. consistency) and computing resources required. The level of security has recently been associated with extensive resource demands. To guide future developments, we aim to address the resource perspective with a holistic sustainability consideration of consensus algorithms. Considering IT artifacts (such as blockchains) from a sustainability perspective, they are usually characterized as instruments for achieving sustainability (cf. Chen *et al.*, 2008; Stuermer *et al.*, 2018). Sustainability generally refers to the characteristic of an entity to endure time and change, and is commonly deconstructed into the *social*, *environmental*, and *economic* sustainability spheres (cf. Barbier, 1987; Hansmann *et al.*, 2012). Addressing the social sphere, blockchain is exemplarily being applied in humanitarian and development sectors to fight corruption, improve property rights, create digital identities, or tackle gender inequality (Zwitter and Herman, 2018). The consensus finding of Bitcoin consumes at least 2.55 gigawatts of electricity per year (Ireland's annual electricity consumption in 2018 was 3.1 gigawatts), with a strong upward trend (de Vries, 2018), affecting both the ecological and economic sphere of sustainability. The importance of sustainability is twofold (Rodriguez *et al.*, 2002): first, realizing sustainability minimizes the negative costs of social, environmental, and economic systems; and second, sustainability aims to improve the rate and extent of human development and quality of life, realized by the usage of digital artifacts. Stuermer *et al.* (2018) argue that digital artifacts need to be seen as resources that should be sustainable themselves. In this line, we aim to answer:

RQ2: How sustainable are existing consensus algorithms for public blockchains?

In order to explore these research questions, this study provides a systematic literature review (SLR) following the approach from vom Brocke *et al.* (2009, 2015). During the study, we identified 818 con-

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tributions from 25 journals, seven conferences, two databases and 25 white papers. We identified 33 different consensus algorithms for public blockchains and five different research perspectives, and synthesized them in a concept matrix. Furthermore, a categorial assessment of the consensus algorithms regarding their sustainability is the second main result. To the best of our knowledge, our study is the first to provide a systematic summary of existing consensus algorithms for public blockchains derived from the scientific literature as well as real-world blockchain applications. This study contributes with a recent overview of prevalent consensus algorithm for public blockchains. Furthermore, identified consensus algorithms are assessed concerning their sustainability characteristics.

The paper is structured as follows. Section two provides an overview of consensus algorithms and sustainability. Section three describes the underlying methodology. Section four presents the results, including the derived concept matrix. Section five adds the sustainability-focused assessment. Finally, section six concludes the aspects covered, discusses the limitations, and areas for future research.

2 Background

From first mention of Bitcoin and the associated *proof of work* (PoW) consensus algorithm in 2008, interest in blockchain research has significantly increased and various consensus algorithms have emerged (Wang et al., 2019). Blockchains can be classified as private, consortium or public (Zheng *et al.*, 2017). These three types differ inter alia in number and rights of participants, degree of centrality and their consensus process as well as respectively impose diverse requirements on the algorithms that guarantee consensus within the network. Consensus algorithms provide certain rules or protocols that define the procedure of consensus reaching within distributed nodes of a chain (Sankar *et al.*, 2017), and ultimately enable consensus through these rules and proofs in a network. Although there is a wide variety of algorithms, there is no algorithm that meets all requirements different blockchain application impose. With regard to the importance of consensus algorithms in public blockchains and the increasing number of blockchain-based applications, especially cryptocurrencies, this study focuses on the systematic analysis of consensus algorithms of public blockchains.

In a public blockchain, algorithms deal with two problems to reach a robust consensus between untrustworthy nodes. First, cryptocurrencies have to solve the *double spending problem*, describing the phenomenon that a digital currency is re-used for two different transactions (Mingxiao *et al.*, 2017). Therefore, a consensus algorithm has to ensure that only one block is added to the chain and in the case of cryptocurrencies that the same coin cannot be spent twice. Second, the process of reaching consensus within a public blockchain can be considered as a *byzantine general problem* (cf. Lamport, 1982), in which a distributed group of byzantine generals and their troops surround a city for conquering it by attack. Each general can decide whether to attack or retreat. However, the conquest will only succeed if the attack is mutually coordinated and simultaneously conducted. Along with the fact that there are traitors in their own ranks, this can lead to a reduced level of trust among the generals. The problem of finding consensus in a decentralized environment is applicable to all distributed system, like a public blockchain. Therefore, consensus algorithms are used to reach a common agreement of the current state between the untrusted nodes of the chain (Cachin and Vukolić, 2017).

Two categories of algorithms can be differentiated: proof-based algorithms and voting-based algorithms (Alsunaidi and Alhaidari 2019). The former is characterized by the principle "that among many nodes joining the netwotk, the node that performs sufficient proof will get the right to append a new block to the chain, and receive the reward" (Nguyen and Kim, 2018). The latter "requires the identification of the nodes that will participate in the verification process" before beginning the work and "all network nodes will together verify the transaction" (Alsunaidi and Alhaidari 2019).

Previous reviews on consensus mechanisms in the blockchains have been carried out. Zheng *et al.* (2017) present a general summary of the underlying technologies of the blockchain, focusing on six commonly-applied consensus algorithms. Similarly, Mingxiao *et al.* (2017) conducted a comparison of five commonly-applied algorithms and proposed a technical guidance for choosing the suitable algorithm. Chalaemwongwan and Kurutach (2018) summarized and compared seventeen consensus algorithms based on saving energy, node identity, tolerated power of adversary, data model, language,

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execution, application/example. Alsunaidi and Alhaidari (2019) compared proof- and voting-based algorithms and highlighted that public algorithms need improvement in the form of a lightweight process of identification for nodes. Chaudhry and Yousaf (2019) as well as Phalajani *et al.* (2019) provided a comparative analysis of consensus algorithms, focussing on the algorithms used in private and consortium blockchains. Chaudhry and Yousef's analysis resulted in the identification of nine parameters – e.g. consensus finality and attacks – that are used for a comparison of consensus algorithms.

Although a large variety of consensus algorithms is presented and compared in previous studies, it remains unclear how the algorithms were selected and to what extent they are representative for the research field. Prior studies primarily focused on specific consensus algorithms but failed to address all available approaches. For example, Zheng *et al.* (2017) and Alsunaidi and Alhaidari (2019) declare that they compare typical and popular algorithms, although the number and selection of algorithms compared differs. Comparing the algorithms from the aforementioned studies, it becomes apparent that the intersection of the analyzed algorithms is smaller than the symmetric difference.

While previous studies have considered the aspect of power consumption (cf. Alsunaidi and Alhaidari, 2019; Zheng *et al.*, 2017; Chalaemwongwan and Kurutach, 2018), prior studies fail to address the aspect of sustainability in a whole. This holistic perspective on blockchain and especially consensus algorithms is important for unlocking positive effects like green consumption and reducing negative effects such as environmental degradation or social exclusion and, thereby, offers considerable opportunities for society, business and their sustainable development (Bai and Sarkis, 2019). We could not identify literature comparing consensus algorithms with respect to the three spheres of sustainability following Barbier (1987). 1) The *environmental* sphere primarily affects the usage of natural resources, whereby not only the consumption should be considered but also the residuals and waste that possibly result from using technologies. In this light, pollution prevention includes natural resources such as air, water, land and waste. Therefore, environmental sustainability addresses both production and consumption (Lozano and Huizingh, 2011). Thus, e.g. energy efficiency and resource efficiency of algorithms are in focus within this sphere. 2) *Social* sustainability deals with crucial aspects such as the standard of living, education and community supporting opportunities, including in terms of equity and equality. Furthermore, environmental justice as well as stewardship of natural resources both locally and globally link social sustainability to the environment. However, as Goodland (1995) highlights, social and environmental sustainability are connected in a quite more fundamental way, since "environmental sustainability or maintenance of life-support systems is a prerequisite for social sustainability". Algorithm-specific aspects of social sphere are inter alia fairness of the algorithm, node competition, syndicate probability, validator selection, tolerated adversary power, the ability of participation in the consensus process and the level of decentrality provided. 3) Following a market-based view of production and consumption, profit, cost savings, economic growth as well as research and development are all crucial aspects of *economic* sustainability. In this vein, economic sustainability refers to the capacity of fostering the mentioned aspects, thereby enabling an entity to endure on the market over time. A more specific view of economic sustainability claims that "economic sustainability focuses on that portion of the natural resource base that provides physical inputs, both renewable (e.g. forests) and exhaustible (e.g. minerals)" (Goodland, 1995) into the production and application processes. Economic and social sustainability converge when it comes to considering business ethics, workers' rights or fair-trade, whereby all of these aspects can be placed into perspective from the community up to the global level. Aspects like monetary incentives for taking part in the consensus process, scalability of the algorithms and investment costs in the form of hardware fall into this sphere when comparing algorithms.

The work of Cole and Cheng (2018) investigates Proof of Work, XRP and STP algorithms regarding their energy consumption. They, however, solely focus on the identification of an algorithm that can be used efficiently in the IoT domain where electricity plays a critical role, rather than the identification of a most sustainable algorithm from a holistic perspective. Gaining a comprehensive understanding of consensus mechanisms is a necessary step for an holistic sustainability assessment. Furthermore, an organized identification and categorization would allow for a systematic overview, which enables solving the real world problem of selecting appropriate algorithms for specific problems, un-

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der the perspective of sustainability. Additionally, the classification enriches scientific knowledge. Therefore, we claim that there is an existing gap in the field of public blockchains and thus we call for a more systematic and transparent review of the existing consensus algorithms. Furthermore, we aim to close this gap by investigating the existing consensus algorithms in public blockchains regarding their consideration of sustainability.

3 Methodology

In order to answer the research questions, we conduct a SLR following vom Brocke *et al.* (2009, 2015), who proposed a systematic way to review and summarize literature in the field of IS research. Simultaneously, the SLR follows the taxonomy framework (table 1) by Cooper (1985) to provide an overview of the underlying scope. The gray-colored cells in table 1 represent the applicable categories within the SLR, which focuses on identifying research outcomes, theories and applications of consensus algorithms in public blockchains. This broad focus has been defined to avoid missing relevant research during the search. The SLR aims to identify central problems within the public consensus and integrate the results into the existing field of research. The organization of the SLR follows a conceptional approach and has been designed from a neutral perspective. Moreover, it addresses scholars specialized in the field of blockchains and in particular consensus algorithms. Finally, due to various fields and the resulting number of different journals and conferences that cover blockchain aspects, the SLR aims to cover a representative part of the blockchain literature based on high-quality publications. A backward search was conducted to include important literature from related fields. The body of literature was analyzed regarding the research questions. Based on the results, a concept-centric approach by Webster and Watson (2002) was applied to synthesize the findings in a concept matrix.

Characteristics	Categories			
Focus	research outcomes	research methods	theories	applications
Goal	integration	criticism	identification of central Issues	
Perspective	neutral representation		espousal of position	
Coverage	exhaustive	exhaustive /selective	representative	central/pivot
Organization	historical	conceptual	methodological	
Audience	specialized scholars	general scholars	practioners	general public

Table 1. Taxonomy of the SLR (following Cooper, 1985)

Phase 1 – Iterative keyword definition - In order to ensure a broad coverage of the relevant literature, seven different keywords were developed in an iterative process, which are ordered into three different categories. Table 2 shows the keywords, the scope and the assigned category. Keywords of category one were systematically derived from the central blockchain literature. Synonyms were included to ensure a profound search. In order to cover the application of public consensus algorithms, the most prominent application of "cryptocurrency" was included as a term. A first search was conducted to countercheck how many aspects of the relevant literature were covered by these keywords. Only a few hits were found in IS, blockchain and sustainability focusing outlets. We relaxed the key words (simplification and less strict concatenation) to counteract these shortcomings, resulting in the second category. A second search with the keywords of category two resulted in a broader range of hits results in the field of IS. Unfortunately, the number of hits in sustainability and blockchains focusing outlets remained low. Subsequently, key words of category three were generated and employed to outlets focusing on blockchain and sustainability. They were used to ensure appropriate coverage of specialized outlets and the reduced exclusion of potential hits.

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Category	Scope	No.	Search terms	Usage
1.	narrow	1.	"consensus algorithm" AND blockchain AND sustainability	in all outlets
		2.	"consensus mechanism" AND blockchain AND sustainability	in all outlets
		3.	cryptocurrency AND consensus AND sustainability	in all outlets
2.	focused	4.	"consensus algorithm" AND blockchain	in all outlets
		5.	"blockchain" AND "sustainability"	in all outlets
3.	broad	6.	"blockchain"	only sustainability focusing outlets
		7.	"sustainability"	only Blockchain focusing outlets

Table 2. Keywords defined for the search

Phase 2 - Journal and database selection - Table 3 shows the journals, databases and conferences that provide the source basis for this SLR. Major contributions are more likely to occur in the leading journals (Webster and Watson, 2002). Therefore, the selection of the literature basket is based on multiple top-ranked outlets in their respective field, aiming at reviewing a representative selection (vom Brocke et al., 2009). Overall, 25 journals, seven conferences and two databases were examined.

Based on the VHB-JOURQUAL 3 ranking for the IS field, we examined all journals ranked A+ and A. Furthermore, the first ten journals ranked in the B category were also considered. In order to account for results in the field of sustainability, we included the three leading journals in the category of "Renewable Energy, Sustainability and the Environment" from the Scimago Journal & Country Rank. Furthermore, in order to ensure a diverse view, we added the Sustainability Journal from MDPI. For the same adequate coverage in the field of blockchain, we included three blockchain journals based on their citation scores. Moreover, one leading journal with a focus on technical trends was added to the basket. Due to the high degree of coverage as well as the large number of highly-ranked diverse outlets, the IEEE and ACM databases were also examined. In order to cover the most recent research in the respective fields, we included the four leading IS conferences from the Association for Information Systems, two leading conferences in the field of cryptographic and one blockchain conference that emerged in 2018. For ensuring quality of the results, all outlets were required to be peer-reviewed.

Phase 3 - Search and hit definition - The search was carried out between August and October 2019. A hit is defined as any publication found within the search process. In order to check whether a hit fits the research scope, we examined the articles' title, abstract and author/database defined keywords. If the status of the article remained unclear, we examined the whole paper. A final hit is defined as a publication that focuses on public consensus algorithms or comprises a paragraph on public algorithms in which technical aspects, advantages and disadvantages and functionalities are explained below. If a publication matches the defined criteria, it was considered as a final hit and an in-depth analysis followed. In order to mitigate potential biases, the analysis was carried out individually by two different researchers and the results were jointly determined based on a consensus of their findings. We used cross-side validation following Forman and Damschroder (2007) for conducting codebooks.

Phase 4 - White paper selection – White papers from the field of cryptocurrencies were analyzed to bridge the gap between real-world applications of public consensus algorithms and algorithms that are described in the literature. Against this background, we analyzed the website "Coinmarketcap.com" (CoinMarketCap OpCo, 2019), which evaluates and ranks existing cryptocurrencies based on their market capitalization. In the analysis process, the top 25 cryptocurrencies ranked by their market capitalization were analyzed. The valuation yardstick was the type of coin, the availability of the white paper, the existence of open source code, and whether the coin is a fork of another coin or not. The analysis results in thirteen white papers that were considered for further analysis.

Phase 5 - Backward search – Finally, we performed a backward search, which followed the selection search process for finals hits described in phase three. Therefore, the references of the previously identified final hits were examined with an emphasis on contributions in the fields of public consensus algorithms and sustainability. Each cited reference that fitted the defined criteria in phase three was added to the basket. During the backwards search, several citations frequently occurred in the various final hits, indicating that the review had reached a certain level of saturation (Boell and Cecez-

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Kecmanovic, 2014; Leedy and Ormrod, 2010). Furthermore, the repeated emergence of certain articles during the backward search points to the identification of pivotal literature.

4 Results

This section describes the results of the SLR. Overall, the search process yielded 818 hits, 199 of which originated from journal publications (~25%), 109 from conference proceedings (~13%), and 485 from the query applied in the ACM and IEEE database (~59%). In addition, 25 hits are a result of the analysis of the white paper of the top 25 cryptocurrencies ranked by coinmarketcap.com (~3%). After evaluating the 818 hits as well as undertaking a cleaning process of the duplicates, we obtained 84 unique final hits, which equals a relevance rate of ~10 %. The backward search resulted in 25 additional relevant publications, which were added to the final literature basket.

No.	Category	Outlet	Database	Search	Hits	Final Hits
1	Senior Scholar Basket	European Journal of Information Systems	EBSCOhost	"all fields"	0	0
2		Information Systems Journal	EBSCOhost	"all fields"	2	0
3		Information Systems Research	EBSCOhost	"all fields"	0	0
4		Journal of AIS	EBSCOhost	"all fields"	15	0
5		Journal of Information Technology	EBSCOhost	"all fields"	0	0
6		Journal of MIS	EBSCOhost	"all fields"	0	0
7		Journal of Strategic Information Systems	ScienceDirect	"all fields"	3	0
8		MIS Quarterly	EBSCOhost	"all fields"	0	0
9	VHB A ranked Outlets	Mathematical Programming	Spinger	"all fields"	0	0
10		European Journal of Information Systems (EJIS)	Springer	"all fields"	0	0
11		INFORMS Journal on Computing (JOC)	pubsonline.informs	"all fields"	0	0
12		SIAM Journal on Computing	Siam Library	"all fields"	0	0
13	VHB B ranked Outlets	Decision Support Systems (DSS)	ScienceDirect	"all fields"	2	0
14		Decision Sciences	Wiley Online Library	"all fields"	4	0
15		Computers & Operations Research	ScienceDirect	"all fields"	0	0
16		Business & Information Systems Engineering (BISE)	Springer	"all fields"	8	0
17		International Journal of Electronic Commerce (IJEC)	Taylor Framcis Online	"all fields"	0	0
18	Databases	IEEE Database	IEEE	"full Text & metadata"	444	51
19		ACM Database	ACM Digital Library	"any field" + "matches all"	41	9
20	AIS Conferences	Americas Conference on Information Systems (AMCIS)	AIS Electronic Library	"all fields"	49	0
21		European Conference on Information Systems (ECIS)	AIS Electronic Library	"all fields"	3	0
22		Pacific Asia Conference on Information System (PACIS)	AIS Electronic Library	"all fields"	7	0
23		International Conference on Information Systems (ICIS)	AIS Electronic Library	"all fields"	44	2
24	Sustain-ability Outlets	Sustainability Journal	MDPi Open Acess	"all fields"	22	1
25		Energy & Environmental Science	RSC library	"all fields"	0	0
26		Advanced Energy Materials	Wiley Online Library	"all fields"	0	0
27		Nature Energy	nature	"all fields"	4	0
28	Blockchain Outlets	Frontiers of Blockchain	frontiersin	"articles"	55	0
29		The Journal of The British Blockchain Association	jbba.scholasticahq.com	"articles"	0	0
30		EUROCRYPT	Springer	"all fields"	0	0
31		CRYPTO : International Cryptology Conference	Springer	"all fields"	6	1
32		Ledger Journal	ledgerjournal.org	"all fields"	11	3
33		International Conference on Blockchain Technology and Application	ACM Digital Library	"all fields"	0	0
34	Tech. Outlet	Future Generation Computer Systems	ScienceDirect	"all fields"	73	4
35	White-paper	Top 25 Blockchains ranked by market Capitalization	Coinmarketcap	-	25	13
Total Number of Hits and Final Hits					818	84
Hits from the Backward Search					25	

Table 3. Summary of the results from the literature search

Table 3 summarizes the results of the search process in aggregated form. The table contains the examined outlet and the database in which all of the mentioned outlets can be found. Moreover, the table provides information about specifications in the search as well as the number of hits and final hits of the respective outlet. The additional information should ensure that scholars can replicate this work and contributes to the overall transparency of this study.

4.1 Concept matrix

Based on the results from table 3, the concept matrix (table 4) was derived, which synthesizes the findings. The matrix categorizes the content of the examined publications by two dimensions. The algorithms of the respective publication can be found on the horizontal axis, whereby a "X" marked field indicates that the focus of the publication was set on the respective algorithm. "O" indicates that the algorithm is addressed – e.g. briefly explained or used for a comparison – but is not the main focus of the contribution. Finally, white indicates that the algorithm was not addressed at all. On the vertical axis, research perspectives are shown. Overall, we were able to identify five most prevalent perspectives. The first perspective aims to summarize and *compare* existing consensus algorithms via different categories. Publications of the second perspective deal with the *application* of public consensus algorithms and the development of possible use cases. In this context, it could be identified that a large number of studies are concerned with the application of consensus algorithms in the field of IoT. Publications that can be assigned to the third perspective deal with the *optimization* of existing consensus algorithms, such as the introduction of a new election mechanism for *DPoS* (Luo et al., 2019). The fourth research perspective deals with the profound *analysis* of public consensus algorithms. Finally, publications of the fifth research perspective primarily deal with the *conceptualization* of the algorithms and include – among others – the introduction of new algorithms.

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		Consensus algorithm																																
Consensus Algorithm / Research Perspective	Author	PoW	PoS	DPoS	PoSp / PoC	PoET	RPCA	SCP	PoI	dBFT	PoA	PoB	PoR	LPoS	PoBe	PoP	PoE	Fast	PoPT	Trinity	Albatross	PoAc	PoPF	POL	PoX	PoAh	PoRe	MOCA	HDPoR	PoDL	CoT	PoV	PoO	PoPu
Analyzation	Gao, Hatcher and Yu, 2018	O	O			O					O	O																						
	Nærland *et al.,* 2018	O	O																															
	Saberhagen, 2013	O																																
	Delliere and Grange, 2018	X																																
	Tasca and Tessone, 2019	O	O		O						O	O																						
	Abe *et al.,* 2018	X																																
	Popov, 2016	O	X																															
	Yun *et al.,* 2019	X																																
	Zhang *et al.,* 2019	X	X	X		O					O	O																						
	Gramoli, 2017	X																																
	Cai *et al.,* 2018	O	O	O																														
	Shen and Pena-Mora, 2018	O	O						O																									
	Wang *et al.,* 2019	O	O	O		O					O	O										O												
	Reyna *et al.* , 2018	O	O	O	O	O			O			O		O								O												
	Boneh *et al.,* 2018	O	O		O																													
	Wang *et al.,* 2018	O	O										O																					
	Huynh *et al.,* 2019	O	O																			O												
	Patel *et al.,* 2018	O	O																				O											
	Yoo *et al.,* 2019							O																										
	Balogun and Zhang, 2019	O	O																															
	Zorzo *et al.,* 2018	O	O																															
	Maung Thin *et al.,* 2018	O	X	O																														
	Liaskos and Wang, 2018	X																																
	Jaoude and Saade, 2019	O	O																															
Comparison	Zhao *et al.* , 2019	X	X		X	X																												
	Chalaemwongwan and Kurutach, 2018	X	X	X	X	X	X		X		O	X	X									X											X	X
	Alsunaidi and Alhaidari, 2019	X	X	X					X													X		X										
	Mingxiao *et al.,* 2017	X	X	X																														
	Bach *et al.,* 2018	X	X	X			X	X	X															X	X									
	Chaudhry and Yousaf, 2019	X	X				X																X		X							X		
	Masood and Faridi, 2019	X	X	X	X	X	X	X				X																						
	Zoican *et al.,* 2018	X																																
	Cole and Cheng, 2018	X					X	X																										
	Xiao *et al.,* 2019	X	X			X	X																											

Conception	Nakamoto, 2008	O																																	
	Chase and MacBrough, 2018						O																											
	Mazieres, 2016							O																										
	Kiayias *et al.,* 2017	O	X																															
	Nem Foundation, 2018								X																									
	NEO Foundation, 2017									X																								
	Kang *et al.,* 2019			O																													
	Abramowicz, 2016	O	O												X																			
	Yuen *et al.,* 2019	O	O	O											X	O															O		
	Khan, 2018																	X																
	Xiang *et al.,* 2019	O	O																X															
	Zhidanov *et al.,* 2019	X	X																	X		X												
	Berrang *et al.,* 2019	O	O																		X														
	Xiang *et al.,* 2018	O	O	O																			X											
	Puthal *et al.,* 2019	O																									X								
	Sarda *et al.,* 2019	O	O									O																							
	Wang, 2019																											X						
	Shoker, 2017	O	O			O							O									O			X									
	Zhou *et al.,* 2019	O	O	X																													
	Ehara and Tada, 2019	O																																	
	Paillisse *et al.,* 2018	O	X																															
	Chenli *et al.,* 2019	O	O		O																									X				
	Zamani *et al.,* 2018	O																																	
	Huh & Kim, 2019	O	O	O																									X					
	Ravindran, 2019	O																													X			
Improvement/ Optimization	Pianese *et al.,* 2018)	O	O																			O												
	Zhen *et al.,* 2017	X	O	O						O																								
	Xian *et al.* , 2019	X	X																															
	Luo *et al.,* 2019	O	O	X																													
	Niya *et al.,* 2019	O	X																															
	Tang *et al.,* 2019	X																																	
	Yang *et al.,* 2019	O	O	X				O				O										O	O											
	Košťál *et al.,* 2018	X	X																															
	Chou *et al.,* 2018	X																																	
	Lin *et al.,* 2018	O																																	
	Vangulick *et al.,* 2019	O	O																															
	Mei *et al.,* 2019	O																																	
	Hari *et al.,* 2019	O																																	
	Saito and Iwamura, 2019	X																																	
	Wang *et al.,* 2020	O	O			O																O					O							
Application	Buterin, 2014	O	O																															
	Awalu *et al.,* 2019	O	O	O								O										O												
	Frederick and Jaiswal, 2019	O	X																															
	Tron Foundation, 2018			O																													
	Huang *et al.,* 2018	O	O	O																												O		
	Xie *et al.,* 2018	O																																	
	Goodman, 2016		O																														
	Grigg, 2017	O	O	O																													
	Duffield and Diaz, 2018	O																																	
	Kwon and Buchman, 2018	O	O																															

Table 4. Concept matrix consensus algorithms in public blockchains

4.2 Consensus algorithms

Overall, we identified 33 different consensus algorithms for public blockchains, which are briefly summarized in table 5. Overarching categories are used to structure the results. The two categories proof-based algorithm and voting-based algorithm were derived from the work of Alsunaidi and Alhaidari (2019), while the category experimental consensus algortihm was added by us. Proof-based algorithms use a pre-defined qualification – like coin stake or diskspace – to elect the next node who will attach the next block to the blockchain (Nguyen and Kim, 2018). Voting-based consensus algorithms reach consensus by votes, whereby a pre-defined threshold has to be reached to reach a consensus (Alsunaidi and Alhaidari, 2019). An algorithm was classified as experimental if it follows a different, new and unusual approach. Such algorithms require additional research and field tests. By extending the existing two categories, we were able to include new theoretical constructs as well as novel algorithms in our analysis and provide a more comprehensive picture of the current state of research.

5 Sustainability of consensus algorithms

Examining the hits regarding their contribution to the research field of sustainability, only a few hits could be identified that primarily deal with resource consumption; rather, it was not possible to identify a single paper that holistically analyses consensus algorithms against all spheres of sustainability.

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For our sustainability assessment we included five proof-based algorithms and one voting-based algorithm as being present and relevant in prevalent research and applicability for blockchain application.

No.	Category	Consensus algorithm	Abbreviation	Description
1	Voting-based algorithm	Distributed byzantine fault tolerance 2.0	DBFT 2.0	DBFT 2.0 was proposed by the Neo Foundation and is the successor of the first version of the consensus algorithms based on PBFT used in Antshares. DBFT reaches consensus by a real-time voting system that elects validators who verify the next block (Neo Foundation, 2017).
2		Fast	Fast	Novel consensus algorithm where consensus is reached though an adaption of map reduce for adding and aggregating transactions (Khan, 2018).
3		Ripple consensus protocol	RPCA	Voting-based consensus algorithm that relies on a the relevance of nodes and their votes. Every node can vote for an agreed transaction inside a block. The algorithm consists of multiple voting rounds (Chase and MacBrough, 2018).
4		Proof of vote	PoV	Partial decentalized consensus algorithm, which devides its nodes in butler candidate nodes, housekeeper nodes and comittee nodes. Rights in the consensus process are devided into billing rights voting rights and verification/signature rights (Huang *et al.,* 2018).
5		Stellar consensus protocol	SPT	Voting-based algorithm that is based on byzantine fault tolerance and can be divided into the nomination, balloting and timeout phases (Mazieres, 2016).
6	Experimental algorithm	Proof of belief	PoBE	Proof of belief (PoBE) is a novel consensus algorithm based on Autonocoin (Abramowicz, 2016). A formal tacit coordination game based on cryptocurrency investments is used for reaching consensus within the network.
7		Albatross	Albatross	Consensus algorithm that was proposed by Berrang *et al.* (2019). It is inspired by PBFT algorithms, although it differentiates itself by being permissionless. Furthermore, Albatross distinguishes active and potential validators who are chosen proportionally by the size of their stake.
8		Proof of previous transaction	PoPT	Consensus algorithm for JC Ledger, which is based on practical byzantine fault tolerance consensus (PBFT). The selection of the accountants for the next block is based on both a pre-defined hash function as well as a ranking based on participation in previous transactions (Xiang *et al.* , 2019).
9		Proof of participation and fees	PoPF	Consensus algorithm for JC Ledger. In supplements the idea of the PoPT by adding the amount of spent fees to the ranking of the accountant. Furthermore, the consensus itself is based on PoW instead of PBFT (Fu *et al.* , 2018).
10		Proof of authentication	PoAh	Consensus algorithm which is designed for lightweight Blockchains. The algorithm is based on block authentication, where there are only updates in the network during block validation (Puthal *et al.,* 2018).
11		Moca	Moca	Consensus algorithm based on the origins from the zero-temperature Ising model. Moca reaches consensus through voting system (Wang, 2018).
12		Proof of reputation	PoRe	Agreement about consensus is fully based on reputation, completely abandoning the token incentives (Wang *et al.* ,2020).
13		Hyper Delegation Proof of Randomness	HDPoR	Consensus algorithm which attempts to reach consensus in the network in a sustainable way by a p2p transaction approach (Huh & Kim, 2019).
14		Circle of trust	CoT	Novel consensus algorithm which is based on hierarchy of a circle of trust and votes (Ravindran, 2019).
15	Proof-based algorithm	Proof of work	PoW	Participants (Miner) must solve a complex mathematical problem in order to create a new block and to be authorized to sign it. Miners are confronted with costs in terms of time and resources (Satoshi Nakamoto, 2008).
16		Proof of stake	PoS	Offers a resource-saving variant of consensus finding in which the next validator is selected based on the height of the stake and the coinage (King and Nadal, 2012).
17		Leased proof of stake	LPoS	Variation of PoS where participants can borrow coins from other participants to increase their chances of being selected to verify the next block (Reyna *et al.* , 2018).
18		Delegated proof of stake	DPoS	Extension of PoS and introduces reputation values by allowing stakeholders to elect witnesses who decide on consensus on the behalf of the stakeholder (Bach *et al.,* 2018).
19		Proof of luck	PoL	Consensus algorithm based on randomly-assigned luck values [0-1] to each block. Miners that work on the verification of blocks therefore prefer to add blocks to the chain with the highest luck value (Bach *et al.* , 2018).
20		Proof of importance	PoI	Introduced by the Cryptocurrency NEM, the next block validator is not only selected by the height of its stakes, but also by its relevance to the network, whereby an importance score is calculated (Nem Foundation, 2018).
21		Proof of authority	PoA	Reputation-based algorithm that selects the next block verifier by the degree of valence of its identities. As a result, validators do not use coins or resources but rather their own reputation as a proof (Tasca and Tessone, 2019).
22		Proof of space/proof of capacity	PoSP / PoC	Proof of space – also called proof of capacity (Reyna *et al* ., 2018) – is very similar to PoW's approach, except that disk space is the resource used, and not CPU/GPU power (Zhao et al., 2019).
23		Proof of deep learning	PoDL	Consensus algorithm where consensus is reached by producing a proper deeep learning model (Chenli *et al.,* 2019).
24		Proof of burn	PoB	Follows the idea that participants have to burn a certain amount of resources, e.g. coins to be selected to verify the next block (Tasca and Tessone, 2019).
25		Proof of retrievability	PoR	Proof of retrievability (PoR) follows a similar concept as PoB, but dis-tinguishes itself by also taking bandwidth and retrievability into ac-count and therefore it increases the ability to provide provable com-mitment (Miller et al.,
26		Proof of elapsed time	PoET	Each participant has to wait for a randomly-assigned time slot, which follows a random distribution. The participant who first completes the allocated time is allowed to sign the next block (Zhao *et al.* , 2019).
27		Proof of activity	PoAc	Hybrid of PoS and PoW that combines the creation of new blocks based on solving mathematical problems (mining) with a randomized selection of validators – based on their size of stack – who sign the blocks (Bentov *et al.* , 2014).
28		Trinity	Trinity	Trinity is a hybrid consensus algorithm that combines aspects of PoW, PoA and PoS introduced by Zhidanov *et al.* (2019).
29		Proof of play	PoP	Proposed by Yuen *et al.* (2019), PoP is a novel consensus algorithm addressed at P2P games based on blockchain technology, where consensus is reached by creating consensus data based on their game results.
30		Proof of publication	PoPu	Consensus algorithm which takes timestamps of digital records into account. For the timestamps exists various techniques (Chalaemwongwan and Kurutach, 2018).
31		Proof of ownership	PoO	Consensus algorithm which considers ownership/right to use as a proof. PoO is not limited to value-related informations (Chalaemwongwan and Kurutach, 2018).
32		Proof of exercise	PoX	Adaption of Pow where the computing power is directed to real world Problems. Miners must "bid" on a problem provided by so-called employers (Bach et al., 2018).
33		Proof of excellence	PoET	Proof of excellence (PoE) follows a similar game-centric approach based on periodically-held tournaments and the performance of the participants (King and Nadal, 2012; Yuen *et al.* , 2019).

Table 5. Overview of identified consensus algorithms for public blockchains

Table 6 summarizes the findings. We conducted a categorial assessment for comparing the algorithms regarding the three spheres and their contribution towards sustainability. Therefore, we operationalized the spheres with aspects already considered in former studies or aspects related to the respective sphere. For the *environmental* spehere we considered *energy efficiency* (Alsunaidi and Alhaidari, 2019; Zheng *et al.*, 2017; Chalaemwongwan and Kurutach, 2018), and *resource efficiency* (Zhao, Yang and Luo, 2019; King and Nadal, 2012; Chase and MacBrough, 2018), which are both part of common understandings of sustainability. Additionally, we considered the specificity of *consensus resource* required, which is a part of many consensus algorithm definitions (cf. Nakamoto, 2008; King and Nadal, 2012; Zhao, Yang and Luo, 2019; Luo *et al.*, 2019).

The *economical sphere* is represented by incentives such as *block* and *transaction reward* (cf. Alsunaidi and Alhaidari, 2019; Chase and MacBrough, 2018), which summarize compensation for respective invested efforts, and *scalability* (Alsunaidi and Alhaidari, 2019; Chaudhry and Yousaf, 2019). Additionally, we introduced the aspect of *hardware cost* (cf. de Vries, 2018) to cover price of the resource required to compute the consensus algorithm.

The social sphere is operationalized by the structural *decentrality* (Nakamoto, 2008; Zheng *et al.*, 2017), the possibility to *partitipate* in the *consensus* process (cf. Luo *et al.*, 2019), the *tolerated adversary power* (Zheng *et al.*, 2017; Chaudhry and Yousaf, 2019), *miner/validator power* (cf. Alsunaidi and Alhaidari, 2019), *node consensus competition* (Zhao, Yang and Luo, 2019), and *consensus fairness*, which subsumes different aspects of fairness for participants in the consensus process. Furthermore, *syndicate power* is inspired by the number of pools in *PoW*, focusing on how high the underlying algorithm is exposed to possible syndicates. The level of measurement is an ordinal scale respectively. To ensure important consensus algorithms to be covered, the selection of the algorithms is based on both, the use in practice and the number of identifications within the publications studied.

5.1.1 Environmental sphere

The category is mostly concerned with the effective use of natural resources. In terms of the efficient use of electricity, *PoW* is classified as the most inefficient algorithm of the six compared in terms of electrical efficiency. This is based on the high difficulty of solving the hash functions, which is linked to the high number of possible validators that race to find the suitable hash value in a competitive environment. Taking a look at Bitcoin, with an electricity consumption of 2.55 gigawatts (in 2018), a transaction within the Bitcoin network costs approximately 300 kWh (de Vries, 2018). Furthermore, due to competitive mining of the same blocks, a lot of computing power is wasted and therefore the resource efficiency is also rated as low. *PoS* and *DPoS* achieve a lower degree of difficulty of the hash function to be solved by restricting the possible validators in the first place, which results in less required computer power and therefore less electrical consumption (Alsunaidi and Alhaidari, 2019). In case of resource efficiency, *PoS* and *DPoS*, only one validator verifies the new block. As downside, while locked away ("staked") coins cannot be used (King and Nadal, 2012). *PoAc* can be classified regarding its electricity and resource efficiency between *PoS* and *PoW* due to its hybrid character (Chalaemwongwan and Kurutach, 2018). *PoET* follows the limitation of validators by allocating a random waiting time to each validator. As long as the personal waiting time has not expired, a participant cannot verify a block. Only the participant whose time has expired first "wins" the next block and is allowed to verify it (Chalaemwongwan and Kurutach, 2018). RPCA differs from the other algorithms by using votes instead of a resource-based proof. Therefore, electricity consumption in *RPCA* can be classified as low, similar to the costs of running an e-mail server (Chase and MacBrough, 2018). All proof-based algorithms in the table are ultimately based on solving a mathematical problem and therefore on computational power. A distinction is drawn by side variables that influence the selection of validations, such as the height of the coin stake, coin age, type of CPU or time.

5.1.2 Economic sphere

Rewards can be divided into the sub-classes of block reward and transaction reward, which are defined in the protocol. A block reward is a payout given when mining a new block. *PoW* algorithms reward the first miner of a new block with a block reward as well as a transaction reward, while all other miners are left empty (Nakamoto, 2008; Koštál *et al.*, 2018). *PoS* and *DPoS* and *PoET* have no block reward. The participants who have been selected for verification receive the entire transaction fee. In the case of *DPoS*, witnesses may share the transaction fees with their voters (Snider et. al., 2018). *PoAc*

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was developed to give miners an incentive to participate in the finding of consensus through using block rewards when all coins are mined. *RPCA* has neither a block nor a transaction reward. Due to low cost of running a XRP ledger, no additional incentive is needed, which results in a less biased verification of blocks (Chase and MacBrough, 2018). Scalability addresses how the consensus algorithm scale in terms of efficiency and transaction speed. Apart from *RPCA*, all other algorithms require powerful hardware to efficiently participate in the consensus process. Analysis of the algorithms shows that hardware costs tend to be associated with increasing competition among possible verifiers.

		Consensus algorithm					
Pillars of sustain ability	**Category**	**PoW**	**PoS**	**DPoS**	**PoET**	**RPCA**	**PoAc**
Environmental	Energy efficiency	low	medium	medium	high	high	low
	Consensus resource	hash power	stake of coins / hash power	reputation/ stake of coins / hash power	time / Intel CPU power	ripple network / votum	hash power / stake
	Resource efficiency	low	medium	high	high	high	low
Economical	Block reward	first miner	no	no	no	no	first miner
	Transaction reward	first miner	validator	witness	validator	no	validator
	Scalability	low	medium	medium	low	high	low
	Hardware costs	high	medium	medium	low	low	medium
Social	Decentrality	high	high	high/medium	medium	medium/ low	high
	Ability of consensus participation	everyone	stake owner	elected witness	everyone with Intel CPU	relevant nodes/ master nodes	miner and stake owner
	Tolerated adversary power	< 25% hash power	< 51% coins stack	< 51% validators	unknown	<21% of faulty nodes	< 51 % of online stack
	Miner/ Validator election	hash power	coin stake	stake / votum	first whose time is up	relevance of the node	combination of PoW and PoS
	Syndicate Power	high	medium	medium	low	low	high
	Node consensus competition	yes	yes - locking coins	yes	no	no	yes
	Consensus fairness	low	low	medium	high	medium	low

Table 6. *Sustainability analysis*

5.1.3 Social sphere

PoW can be classified as the least restrictive algorithm in terms of participation in the consensus process. In case of *PoS*, nodes need a stake to take part in the consensus process, while in *DPoS* only elected witnesses can participate. *PoAc* algorithm have an open mining phase, combined with a validation phase, where the selection of the next verifier is stake-based. In order to be part of the consensus process of *PoET*, an Intel CPU is needed, while with *RPCA* consensus algorithm nodes have to be ranked as relevant. Decentrality is assessed in terms of how autonomously a network can operate and whether the network is dependent on a third verifying party. Furthermore, the concentration of decision-making power on individual parties is also important. In theory, *PoW* can be rated as highly decentralized, resulting from the network structure with no third party required and an open consensus process. However, due to high price increase as in the cases of Bitcoin and Litecoin, the competition among the miners is intensified. Due to increasing competition and the associated complexity increase of the hash function, miners have to upgrade their hardware to successfully participate in the consensus process. These arms race ultimately result in the merger of individual parties into so-called mining pools, which combine computing power to solve mathematical problems. At present, the four largest mining pools own more than 50% of the total computing power within the Bitcoin network (Alsunaidi and Alhaidari, 2019). For *PoS*, only nodes that stake coins can participate in the consensus-finding process. The higher the personal stake, the greater the probability of being selected for the next block verification. Therefore, *PoS* algorithms tend to favor owners of large quantities of coins (Thin et al., 2018). In the case of *DPoS* – as already described – only selected witnesses can participate in the consensus process. A merger of votes or witnesses into syndicates that manipulation blocks in their own interest would be conceivable. Due to the need of a centralized verificator server, like in the case of the cryptocurrency Ripple, *RPCA* consensus is classified as the least decentralized of these six algorithms. *PoET* requires a third party to allocate the slots, as in the case of Hyperledger Sawtooth. Although the allocated times are assigned randomly following a random distribution, the fully autonomous operation of the network is limited. The tolerated adversary power describes the degree to which faulty nodes can be tolerated while still reaching a consensus. Overall, we rate *PoW* due to high hardware costs and the existence of mining pools, *PoS* due to favoring rich over poor nodes, and the hybrid form *PoAc* as the lowest algorithm regarding the category fairness. *PoET* is based on a random time slot and has only a minor hardware limitation and is therefore rated as high in terms of fairness.

6 Conclusions, limitations, and future research

In this paper, we conducted a SLR on consensus algorithms for public blockchains and investigated exemplarily their contribution to the three spheres of sustainability. During the search phase, 84 final hits could be identified, of which only two relevant contributions were found in IS-centered outlets. Moreover, only a few contributions were found in journals, which might be a result of the emerging domain. Addressing RQ1, we investigated which consensus algorithms in the field of public blockchains exist. We identified 33 algorithms and systemized them in accordance with their research focuses in a concept matrix. Concerning RQ2, which addressed the sustainability (contribution) of existing consensus algorithms for public blockchains by conducting a categorial assessment of the consensus algorithms regarding the three spheres of sustainability. Thus far, only few publications address single facets of sustainability (primarily resource consumption). Nonetheless, our analysis revealed the existing consensus algorithms to differ concerning their sustainability contribution, e.g. energy consumption, scalability, and consensus fairness in the social sphere.

While we strive to provide a systematic analysis of existing literature in the field of public consensus algorithms, several limitations exist. *First,* by choosing a representative part of the literature, this SLR does not claim to be exhaustive and might miss important literature, especially emerging literature. We aimed to counteract this by combining high-ranked outlets from different fields, full database queries and literature focusing on applications. During a backward search, we noted a good level of saturation. Nonetheless, considering additional outlets will lead to new insights. *Second*, selecting relevant publications is subject to individual judgment. Although criteria were used for final hit selection and cross-validation by two independent researchers, a residual of the occurring subjective bias remains.

We identified avenues for conducting future research. An analysis of all consensus algorithms regarding the characteristics of the three sustainability spheres seems promising and allows designing consensus algorithms with a sustainability focus. A sustainability index for consensus algorithms allows selecting and applying algorithms for a broad range of transactions, reflecting transparency and fairness. Since we failed to find a contribution to holistically address all spheres of sustainability, we call for further research investigating this intersection to enable unfolding its full potential for society.

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