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A Review of Distributed Ledger Technologies in the Machine Economy: Challenges and Opportunities in Industry and Research

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Abstract

Blockchain Technology has gained prominence since 2008 with trust, reliability, speed, and transparency becoming major advantages. It has also been applied and researched within a multitude of industry applications ranging from manufacturing to financial transactions through to real estate. In addition to Artificial Intelligence (AI) and Internet of Things (IoT), Distributed Ledger Technology (DLT) such as blockchain serves as the backbone to the Machine Economy, which is a relatively recent concept in which machines can communicate and exchange data with each other autonomously, allowing manufacturing companies to become more competitive. However, using blockchain for exchanging large volumes of data requires significant fees and energy due to its use of miners to validate transactions which is a barrier for manufacturing companies to implement. Directed Acyclic Graph (DAG), which is a different type of DLT is an example of an alternative to blockchain which aims to overcome most of the problems currently on the blockchain and promises to enable fee-less transactions with much lower power requirements than blockchain. In this paper, the authors explore the DLT aspect of the machine economy within the manufacturing context. Firstly, the enabling DLT technical attributes of the machine economy are analysed. This is followed by an evaluation of all DLT's, focusing on the challenges and benefits of each alternative. Following on from this, a cross comparison of each DLT type is done which leads into a discussion and future directions to be drawn.

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Keywords: Machine Economy; Distributed Ledger Technology; Blockchain; Machine Communication; Smart Manufacturing

1. Introduction

The fourth industrial revolution of evolving digitalization and smart connectivity has led to businesses discovering new ways of reducing costs and increasing performance. The manufacturing sector in most western economies is facing challenges from the Far East due to their lower cost of labor and along with the decline of manufacturing employment [4], this places an emphasis on newer ways to increase competitiveness and reduce costs through automation.

The advancements made in Internet of Things (IoT) technology in which its total economic impact by 2025 is estimated to be $11.1 trillion per year [5], along with Artificial Intelligence (AI) and Distributed Ledger Technology(DLT), the attention in industry and research has shifted towards machine communication [6]. Machines are becoming smarter with the introduction of new emerging technologies, where they can communicate with each other, make decisions autonomously and conduct transactions with each other. This concept is termed as the "Machine Economy" and can be defined as "Smart, autonomous, networked and economically independent machines or devices that act as the participants, carrying on the necessary activities of production, distribution, and allocation with little to no human intervention" [7]. Trust, speed, transparency, and reliability of data are key ingredients within machine automation [8]. Contrasting with the current economy of centralization and intermediaries the Machine

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Economy aims for decentralization and autonomy for all its participants, without the need for human interference. This can be seen in a multitude of application areas such as manufacturing where machines in a factory can sell their services during downtime, communicate with other machines in the factory and self-maintain themselves by re-ordering spare parts, all without the need for human presence [9]. In the preceding example a machine is turned into an economic agent which facilitates microtransactions between other agents and entities to create a microservice ecosystem in which services become commoditized[10]. Hence, each machine will have its own identity, history and (bank) account to store digital tokens to pay for services e.g., replacement parts. With automation becoming a key initiative within manufacturing production systems, factories will need machines to self-optimize and communicate with each other. This is further evidenced in a report by [9] where the Smart Manufacturing market is estimated to reach $480 billion by 2023. Other industry examples include smart cities and mobility [11, 12].

Internet of Things (IoT), Distributed Ledger Technology(DLT) and Artificial Intelligence (AI) are seen as major pillars of the Machine Economy [6]. However, with the potential of millions of transactions occurring each second between machines, providing a platform for an efficient, safe, and fast communication system is needed. This is provided by DLT which acts as the backbone of the Machine Economy by facilitating interactions of machines. Blockchain, the most prominent DLT type has been met with criticism over its high energy consumption, high fees involved during communication and lack of scalability [3]. Therefore, alternative DLT types must be explored to overcome these problems. In this paper, the authors analyze the DLT aspect of the Machine Economy by evaluating its enabling requirements along with cross comparison of alternative DLT's.

The remainder of this paper is organized as follows. In Section 2 the DLT requirements needed for the Machine Economy to function are presented. In Section 3, the different types of DLT in terms of their structure, strengths, and limitations are presented. This is followed by an overview of comparative results focusing on how DLT types compare against each in Section 4. Finally, in Section 5 a discussion and final conclusions are drawn presenting future directions.

2. DLT Requirements

For the Machine Economy to prosper it requires the DLT to have the following key attributes of Scalability, Validation, Immutability, Interoperability, Security, Fees and Energy. These are further detailed below. This paper considers all attributes mentioned in publications pertaining to the machine economy [8, 10, 13].

Scalability. Within the Machine Economy are potentially billions of transactions occurring each second and with the ever-increasing number of machines participating in the Machine Economy, the system must handle this load. In addition to the existing number of participants in the system, new machines will be entering the DLT system over time which requires the DLT to be scalable i.e., the transactions per second (TPS) to be constant or increase as the system size increases. When a new transaction needs to be added and validated onto the chain, the time taken to validate it also increases, which is a major bottleneck for new machines entering the ecosystem[8].

Validation. In a decentralized infrastructure with many independent machines exchanging data with each other, it is important that there are built in trust mechanisms within the system and have tamper-proof records of every transaction which allows immutability and ensures auditability. Validation of a transaction occurs differently depending on the DLT type[8].

Interoperability. Each machine will have its own operating language and therefore the system must allow different machine systems to connect and interact with each other seamlessly, for data exchange to take place. This requires certain standards to be created within each specific industry e.g., manufacturing interface standard for machine equipment[8, 10].

Security. Data security is a major requirement of the system and protects the participants in the Machine Economy from cyber-attacks or attacks to software through viruses[8, 10].

Fees. For a machine to participate in the Machine Economy by exchanging data, normally a fee is attached depending on the DLT. This is because validating a transaction requires powerful computers to solve complex mathematical problems and validate the transaction. The fee is also dependent on the network conditions at the time, data size that needs to be sent and received and gas energy consumed for that transaction[14]. The larger the data size and the higher number of machines sending data, the higher the fee involved. Hence, having a very low, if not feeless transaction is a key requirement for the Machine Economy[13].

Energy. During the validation process in blockchain, miners need to solve a complex mathematical equation which requires huge energy resources therefore emitting large quantities of C02 emissions[15]. The lower the energy required during the validation process the more desirable.

3. DLT Comparison

This section will provide comparisons between different types of DLT in terms of the six technical attributes mentioned in section 2. The list of DLT's analyzed in this section have been compiled through examination of all literature [3, 13, 16-18] on cross comparison of DLT's, not just pertaining to the machine economy.

3.1. Blockchain

Blockchain technology has gained great significance since 2011[19] and was initially used as the technology behind peer-to-peer(P2P) cash systems and ever since its greatest use case has been in the world of cryptocurrencies. There are many platforms that use blockchain technology. Bitcoin is the most prominent example, however Ethereum and Hyperledger Fabric are other major examples. Hyperledger Fabric though is a private blockchain [3] which is a problem for machine communication as preferably the platform must be public allowing many other machines to enter and participate.

3.1.1. Structure

To understand how a data transaction is sent and stored on the blockchain, the ledger is explained below in the context of the machine economy and can be seen in Figure 1.

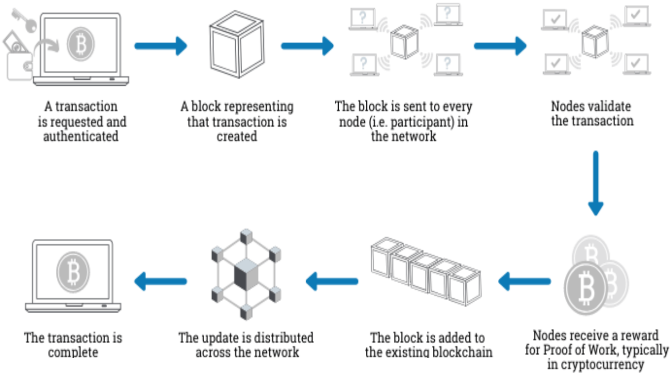

Figure 1-How Blockchain Transaction Works

1. Firstly, data is to be sent from machine A to machine B.
2. A block which represents that data transaction is created.
3. A copy of the data transaction is then sent to every machine (node) in the blockchain network.
4. Every machine then must validate the data transaction. which involves solving complex algorithms, in a process labelled "mining".
5. The machines then receive their "fees" for validating the transaction.
6. Once the validation has occurred the "block" is then added to the existing blockchain.
7. This update in the blockchain is then sent to every machine in the network and data transaction is complete.
8. The data transaction is complete.

3.1.2 Limitations

Scalability. Blockchain has an inherent problem in that whenever a new "block" is created as seen in Figure 1. This limits the transactions per second (TPS) even further meaning that as more "blocks" are created more and more machines in the network must verify and validate the transaction which leads to a slowdown in the number of transactions that can occur each second. Different blockchain platforms have different TPS rates. Bitcoin has the lowest rate of 7 TPS, whereas Ethereum is more than double with 15 TPS [20]. Hyperledger Fabric though can achieve much higher scalability with 3000 TPS [21].

Interoperability. Currently no universal standard exists and the interoperability landscape is immature for business use [22].

Energy Usage. Per transaction it is estimated that during validation with Bitcoin, the C02 emissions is estimated to be 451.6kg[23]. With Ethereum though this value is nearly four times lower with 126.4kg per transaction [24]. This is still a relatively high value with potentially millions of data transactions occurring each second between machines. With Hyperledger Fabric being a private blockchain it will have much lower energy usage per transaction; however, it cannot be seen as a feasible alternative due to its private setting.

Fees. If a data transaction is needed to be completed very quickly, this can involve a higher fee during the validation process as "miners" receive a reward/fee for using powerful computers to solve complex mathematical problems and validate the transaction. The fee is dependent on the network conditions at the time and data size that needs to be sent and received. The larger the data size and the more machines sending data, the higher the fee involved for the machine sending and receiving data. This is a big barrier for potential participants to be involved in the Machine Economy. In Section 3.2 an alternative DLT called DAG is presented.

3.2 Directed Acyclic Graph (DAG)

Directed Acyclic Graph (DAG) is a different type of DLT which has recently gained prominence as a major alternative to blockchain due its superiority in scalability, fees, and energy consumption. The IOTA foundation, which uses DAG for developing machine-to-machine communication, uses the DAG data structure as seen in Figure and rebranded it to "The Tangle"*[25]* which was proposed as an alternative to blockchain. The structure and the unique features of DAG are explained below.

3.2.1. Structure

When a new data transaction needs to be added onto the network it first needs to approve two previous transactions before it can be added. For example, in Figure Transaction 5 needs to approve Transactions 2 and 3 before it can be added. Transaction 6 is called a tip as it is not approved yet and each incoming transaction must choose two tips to approve. In comparison to the blockchain structure, DAG offers multiple sites for attaching a new transaction whereas in blockchain only one site is offered for attaching a new "block" which is commonly known as the "blockchain bottleneck" [14].

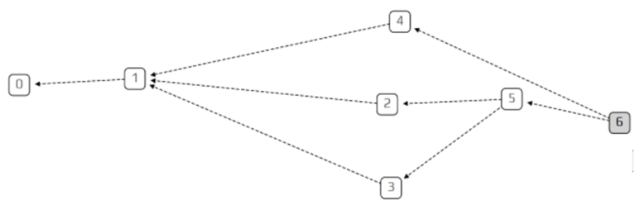

Figure 2-DAG Structure [1]

3.2.2. Unique Features

Scalability. DAG overcomes this issue as it offers multiple sites for attaching new transactions as seen in Figure . This effectively allows the DAG network to achieve much higher scalability [26] and TPS speeds when more participants join the network, which is ideal for fast machine-to-machine communication.

Energy. DAG does not need the use of miners to validate transactions nor require heavy calculations hence is much more environmentally friendly than blockchain [27].

Fees. There are no miners in the validation process hence there is no need for fees to pay for manufacturers or machines. In the following section the Hashgraph data structure and its unique features is presented.

3.3. Hashgraph
3.3.1. Structure

In order to validate a new transaction into the Hashgraph, the network participant is obliged to share all information relating to transaction with multiple randomly selected nodes in the network using “gossip” protocol [28]. The nodes which have received that information will then share the information with other randomly selected nodes and ultimately after some time all nodes will receive this information and validation of that transaction will be completed with the help of “virtual voting” protocol which can be further explained in [29]. The structure of Hashgraph can be seen in Figure 3. With energy per transaction related to whether miners are involved, as Hashgraph does not use miners the energy used per transaction is 0.00017 kwh [30]which is very low.

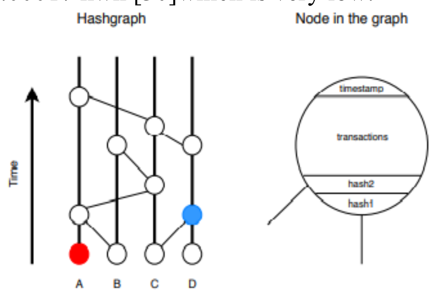

Figure 3-Hashgraph Data Structure [3]

3.3.2 Unique Features

Virtual Voting. Each participant in the network has a copy of the Hashgraph ledger containing the full history of all transactions that have occurred and therefore no participant must send their vote to other participants in the network. This occurs because each participant will know how the other participants will vote as they all have a copy of the same ledger, which helps to achieve validation much more effectively [3].

Scalability. Hashgraph has high scalability and TPS as it uses “gossip-about-gossip protocol meaning it randomly selects another participant and sends the message with any conditions [17]. The TPS rate however varies in literature with 100,000 in [17], >200,000 in [3] and >250,000 in [16]. However even if the actual TPS is at the lower end of 100,000 ,this still represents a huge increase compared to blockchain which has a TPS range from 3-20 TPS [3]. The focus in the next following section will focus is on Sidechain DLT type.

3.4 Sidechain
3.4.1. Structure

Sidechain uses the same structure as blockchain however its novelty lies in that it can combine multiple blockchains which can overcome existing limitations of a single blockchain of security, privacy, and scalability. The mechanics of validating data transactions and storing data is the same as blockchain. In Figure 4 the architecture of Sidechain is presented.

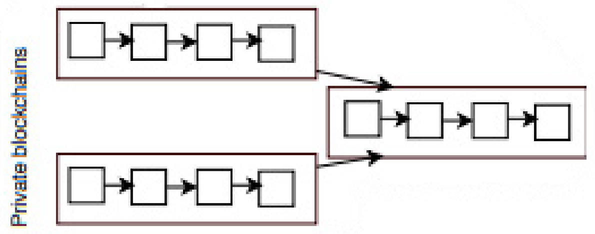

Figure 4-Sidechain Structure [2].

3.4.2. Unique Features

Scalability. Within blockchain as the number of participants grows, the TPS rate decreases. Therefore to counter this limitation the Sidechain structure of dividing the main blockchain into segments means any validation that needs to be done is done locally rather than globally [17].

Security. Privacy of data is increased as the Sidechain configuration of sub-networks creates private channels and constraints on who can access the data.

Even though Sidechain has been identified as a blockchain alternative, we cannot yet consider this as an effective alternative. This is because in relation to scalability, nothing is mentioned in current literature on how local validations of transactions in the blockchain segments can produce a global consensus system for validating all data transaction. In the next section the Holochain DLT is presented.

3.5. Holochain
3.5.1. Structure

Within Holochain every participant on the network has their own ledger which they maintain. In this way there is no global validation process, however the network has a set of rules called “DNA” which verifies each individual ledger for validation. Figure 5 shows the overall architecture of Holochain.

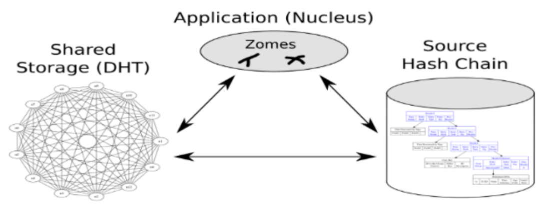

Figure 5- Holochain Structure [2]

3.5.2. Unique Features

Scalability. As previously described, each participant will hold their own ledger and will have the freedom to operate autonomously and data that is shared from them will be distributed through different locations in the world [31]. This makes the network low risk of over loading when new participants join the network and hence the network becomes highly scalable and in theory limitless scalability [16].

There is limited literature related to Holochain, especially within the context of the machine economy as it is one of the least mature DLT's [16] . as it is Holochain has been presented as a DLT which supports social coherence [2], in which groups who want to collaborate and co-ordinate together by sharing data can do in a reliable and scalable manner. However as seen Table 1, it does have features which makes it a suitable option for the Machine Economy. In the next section the identified DLT's are compared and discussed.

4. Comparison

Each DLT included in Table 1 has its pros and cons. Blockchain and Sidechain are made up of the same data structure. Therefore, the analysis is also very similar when compared with each other barring minor differences in scalability. Within Blockchain there are other platforms alongside Bitcoin as mentioned in section 3.1. However, Hyperledger Fabric cannot be considered as a solution as it works only on a private network, forbidding new machines entering the network which is a significant limitation in the context of the machine economy.

Scalability: In terms of solving the "blockchain bottleneck" of scalability, DAG, Hashgraph and Holochain can be viewed as solutions with DAG having multiple attachment sites for new transactions whereas Hashgraph uses the "gossip" protocol meaning much quicker validation of transactions. The TPS rate for Hashgraph varies when analyzing current literature. However, it is much greater than Blockchain, Sidechain and DAG [13]. Holochain does have the highest theoretical scalability, however no experiment has been done to confirm the theory.

Table 1-DLT Overall Comparison

Technical Criteria	Blockchain	DAG	Hashgraph	SideChain	Holochain
Scalability (TPS)	Low (4-28)	Medium (800-1000)	High (150,000 to >250,000)	Low (Similar to blockchain)	High (Limitless)
Interoperability	Medium	Low	Low	Low	Low
Energy Consumption	High (885 kwh)	Low (0.00011 kwh)	Low (0.00017 Khw)	High (885 kwh)	Low
Security	High	High	High	High	High
Fees	Yes	No	No	Yes	-
Validation Time	Order of minutes	Order of seconds	Order of Seconds	Order of minutes	Order of minutes
Platforms	Bitcoin, Ethereum, Hyperledger Fabric	IOTA	Hedera	Monax	Holochain

Interoperability. As stated in section 3.1, Blockchain which is the most mature DLT type currently has no universal standard and interoperability is still immature for business use. The alternative DLT's are therefore still at a very early stage of creating any standards for industrial use.

Energy Consumption. As seen in Section 3.1, blockchain has the highest energy consumption even if Ethereum is considered alongside Bitcoin. In literature, "energy consumption" in relation to Holochain is not frequently mentioned. However, using the inference of scalability being linked to energy consumption, it can be assumed it has low if not zero energy consumption. As seen in Table 1, IOTA uses the least amount of energy (0.00011kwh) per transaction [32] and Hashgraph is also not far off with 0.00017kwh [30]. Sidechain is composed of multiple blockchains; hence energy usage will be similar.

Security. All DLT's analyzed in Table 1 have very high security features. For Blockchain and SideChain, an attacker must attain 51% or more of the total mining power to prevent new data transactions from occurring which is very difficult to achieve. With Hashgraph all participants are known before, and the network is not open for non-registered participants [13] resulting in lower chance of attack.

Fees. Blockchain and SideChain will have high fees as they are both made of the same data structure. Hashgraph and DAG exhibit no fees as no "mining" is needed to validate the data transactions in the network. Not much information is given within literature on whether Holochain exhibits fees during validation.

Validation Time. Validation Time is indirectly linked scalability TPS, so the higher the TPS the quicker it takes to validate a transaction. In a study done by [20] Blockchain validation time ranges from 10 minutes (Bitcoin) to 0.25 minutes on Ethereum. DAG on the other hand has instant validation due to no mining involved. As seen in section 3.3.1 Hashgraph uses virtual voting protocol, where all nodes validate themselves resulting in very quick validation times.

Platforms. DAG has recently been adopted by the IOTA foundation, who have rebranded it as "The Tangle" in 2017[25] and are mainly at the experimental stage currently, with IOTA forming partnerships with Jaguar Land Rover (JLR)[33], Dell [34] and many others [35] to develop and test the Tangle framework. Hashgraph along with Holochain are the least mature DLT with both being introduced in 2018 by Hedera and the Holochain foundation respectively. However, Hedera has also built partnerships with major firms such as Boeing, IBM, Tata and major educational establishments e.g. University College London (UCL) and London School of Economics (LSE) [30].

5.Discussion and Conclusion

With product customization becoming increasingly important and governments and manufacturing businesses pushing towards developing "greener" solutions[36], manufacturers must react quickly to satisfy customer demands which places an emphasis on reducing costs and lead times through machine automation. As DLT is assumed to be a vital component in developing the Machine Economy, the impact on manufacturing, along with the enabling technical requirements are stated. This is followed by an in-depth analysis on alternative DLT's that can overcome the limitations that Blockchain currently has.

IOTA and Hashgraph have been presented as the most promising alternatives for the Machine Economy due to their very low energy and cost requirements as well as very high scalability allowing a greater number of machines to join the network. IOTA, in particular is one of seven DLT companies chosen by the European Union (EU) to participate in the European Blockchain Services Infrastructure's (EBSI) project due to its energy efficiency and feeless transactions [37].The problem with IOTA, Hashgraph and Holochain is that they are mostly in the experimental phases of developing test programmes with governmental and private agencies. This test period is likely to take a few years before being implemented on a global scale due to the problems discussed in this paper.

Over the next 5-10 years it is envisaged that many more partnerships will be created between private and public (governmental) entities. For the Machine Economy to prosper in manufacturing, governments will have to collaborate with manufacturing industries in setting standards for different DLTs to operate together as it may not just be a single DLT type that will fully become the backbone of a global Machine Economy.

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