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Blockchain in Industries: A Survey

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ABSTRACT Blockchain technologies have recently come to the forefront of the research and industrial communities as they bring potential benefits for many industries. This is due to their practical capabilities in solving many issues currently inhibiting further advances in various industrial domains. Securely recording and sharing transactional data, establishing automated and efficient supply chain processes, and enhancing transparency across the whole value chain are some examples of these issues. Blockchain offers an effective way to tackle these issues using distributed, shared, secure, and permissioned transactional ledgers. The employment of blockchain technologies and the possibility of applying them in different situations enables many industrial applications through increased efficiency and security; enhanced traceability and transparency; and reduced costs. In this paper, different industrial application domains where the use of blockchain technologies has been proposed are reviewed. This paper explores the opportunities, benefits, and challenges of incorporating blockchain in different industrial applications. Furthermore, the paper attempts to identify the requirements that support the implementation of blockchain for different industrial applications. The review reveals that several opportunities are available for utilizing blockchain in various industrial sectors; however, there are still some challenges to be addressed to achieve better utilization of this technology.

INDEX TERMS Blockchain, industrial applications, smart contracts, secure transactional ledgers, smart systems, technological impact.

I. INTRODUCTION

Blockchain establishes new advanced features for the business and industrial world [1]. These features help enhance, optimize, secure and streamline many existing business and industrial processes. In addition, they enable the creation of new business models that were impossible to form a few years ago. These new business models impact many industrial sectors such as finance, healthcare, manufacturing, and logistics. While the Internet opened the door for the creation of many currently deployed business and service models, there are always concerns regarding how to securely register and ensure agreements among different parties involved in some business deals. With the introduction of blockchain, businesses and individuals can record and secure their conducted agreements among themselves.

Blockchain incorporates various techniques to support a shared ledger among a group of users (organizations, businesses, individuals, software agents, etc.) such that everyone involved agrees on its content and all transactions are secure and cannot be altered after being added. In addition, it allows for detailed tracking, measurement and tracing of transactions. Blockchain enables a group of entities to reach an agreement on a certain activity and register that agreement without the requirement for a regulatory authority. Their agreed upon activities can be registered, secured and shared using blockchain. The agreed upon activity can be a payment transaction from one of the members to another, a purchase activity, a voting activity, or a medical lab test entry for a patient. Other activities may also involve multi-party collaboration on a specific task, contract agreements, supply chain logistics to name a few.

Blockchain as a technology combines the advantages of both peer-to-peer networks and cryptographic algorithms to ensure the validity of the conducted agreements. None of the participating entities can change an approved and registered activity without involving the other participating entities. This feature is well suited for conducting different business agreements among a group of entities from different places. Blockchain can also preserve the order of events and ensure the correctness of logged transactions over time. Since no one can individually alter any of the recorded transactions, it is nearly impossible to fake records or repudiate from an agreement. As a result, many industries and businesses are

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considering its utilization and more research is being done to effectively apply blockchain in these domains.

This paper investigates blockchain usage in different industries. This includes surveying blockchain's industrial applications, their benefits, and their challenges. The applications covered are categorized based on the different industrial domains they serve including financial, healthcare, logistics, manufacturing, energy, agriculture and food, robotics, entertainment as well as other industrial domains. The paper also covers the key requirements for enabling the utilization of blockchain in industrial applications and some open issues in the field.

While there are several good survey papers on blockchain, our scope and aims in this paper are different as we identify the challenges and discuss the requirements for effective incorporation of blockchain in industrial applications. Examples of surveys on general blockchain concepts, opportunities, and applications are [72]–[75]. Other papers focused on surveying specific aspects of blockchain such as security [79]–[83], consensus protocols and algorithms [84], [101], [108], scalability [89], [103], software engineering issues [92], [93], and current research in the field [88]. Furthermore, some focused on surveying specific applications of blockchain like cryptocurrencies [85]–[87], healthcare [94], big data [90], governmental applications [104]–[107], intrusion detection [91], and Internet of Things (IoT) [95]–[100]. Unlike these papers, we focus on the industrial aspects of blockchain including industrial applications, benefits of employing blockchain in various industries, challenges of utilizing blockchain in these industries, requirements for effective utilization in these industries, and some of the current open issues in the field. In addition, this paper will not cover the concept of blockchain in details as it can be found in many other sources. However, it will cover the concepts that are directly related to industry.

The rest of the paper is organized as follows. Section II provides background information about blockchain with its fundamental features and functions that enable industrial applications. Section III discusses blockchain industrial applications in different domains. Section IV discusses the challenges of utilizing blockchain in industrial applications, while Section V discusses the key requirements of deploying such applications. Section VI provides general discussion and open issues in the field, while Section VII concludes the paper.

II. BLOCKCHAIN

Blockchain is a growing list of linked records, named blocks, which are connected and secured using encryption algorithms [2]. The key to the effectiveness of this list is the links that are created from one block to the next, thus making it difficult to change any block after it is added to the list. Hence, we get the name ''blockchain'' as it is virtually a chain of blocks of data. This list represents a protected online registry for stating some agreed on and conducted transactions among different entities or organizations. The recorded transactions are usually generated as a result of certain activities such as financial, business, industrial, or system activities. The blocks that store the transactions are usually timestamped, encrypted and replicated on multiple sites, and cannot be altered.

A group of people or organizations on a network can use blockchain to record some transactions (activities) among them. The members of the group can generally review the previously recorded transactions; however, none of them can modify or remove any of the previously recorded transactions. This makes blockchain maintain immutable history of the activities of the group's members. This history is shared among all or selected group members. This offers high levels of traceability of any and all recorded transactions and transparency that allows everyone involved to view these transactions. Yet, it also provides assurances that these records (or blocks) cannot be altered by anyone in the group who created it or anyone else, for that matter. The logical links created between the transactions are agreed upon by the group; yet, they are irreversible, thus making it impossible to change.

One of the main features that was introduced with blockchain is the enabling of two or more entities to securely record an agreement of certain actions over a public network such as the Internet without including a third party like an authorization entity or government office. The involved entities may or may not know each other and they do not even have to trust each other. Yet, they can still make the agreement, document it and have that transaction record appended to the chain. Hence, the record of the agreement after it is appended to the chain cannot be altered, canceled, or denied by any of the entities involved in the agreement. A process called ''mining'' is used to guarantee the validity and consistency of the conducted agreements appended to the chain. This important feature was not available before introducing blockchain. Therefore, blockchain is the main enabler of the Internet of Transactions [3], [4], which is needed to support many industrial applications.

Blockchain is an evolving technology initially invented in the Bitcoin arena [5]; however, it is applicable in many industrial applications, some of which we survey and discuss in this paper. One of the strong believers of blockchain and its viability in the general business and industrial domain is IBM, as they are investing heavily in the field and working on various enhancements and applications [6]. Before, we start to discuss these applications, we will discuss the fundamental features and functions of blockchain that are the main enablers of the surveyed industrial applications.

A. DIGITAL IDENTITIES

We use a driver's license or passport issued by a governmental organization to prove our identity for conducting different official activities such as performing some banking transaction or buying a property. Blockchain can offer a digital equivalent that can be used to identify not only people but also organizations [7]. This feature enables authenticating different people, organizations, and entities of various types involved in any business or industrial activities over a public

network such as the Internet. In addition, a digital identity can be expanded to include property, possessions and object identities. These digital identities can be issued by a governmental organization in a way like issuing driver's licenses, passports, company registrations, and property titles. This feature had already been under consideration in many countries and many are working on the methodologies and logistics of creating and protecting these identities.

B. DISTRIBUTED SECURITY

One of the key success factors of blockchain is its ability to protect the data and transactions recorded in the shared ledger using a compartmentalized and distributed approach [8]. This protection may be offered through the capability to support different levels of encryption and hash features that blockchain users can employ. In addition, it includes high levels of replications and chained series of content that make it impossible to alter any record that has already been appended to the chain. Every newly added transaction, after being validated by the participating entities, is linked with the chain of previous transactions, thus no one record can be altered in any way. In addition, relying on the verified digital identities and that each transaction is recorded with a full agreement among all entities involved, it becomes practically impossible for any of these entities to later deny being involved or in agreement [9].

C. SMART CONTRACTS

The recording, validation and security features of blockchain in addition to the digital identity support enable smart contracts [10]. Smart contracts permit the conducting of a credible contract over a public network without a third party. This contract is trackable, secure and unalterable. Blockchain-based smart contracts have the prospective to advance many industrial sectors in different ways. One of these advancements is by automating agreement processes between companies and their partners and between companies and their customers. This will considerably reduce the processing time and the administrative costs and create a more efficient model to initiate, negotiate and finalize contracts without the need to rely on third party registrations or heavy documentation.

D. MICRO-CONTROLS

Another area where blockchain features can positively impact industries is the ability to facilitate micro-metering, micro-measurements and dynamic pricing and adjustment at fine grain levels of detail. The ability to securely record events and activities without the need for third party confirmations and external assurances, will increase the amount of recorded data and activities and will allow organizations to build detailed ledgers of their activities and processes. These can be easily analyzed to provide measurements and quality controls at any level of detail. In addition, it allows for accurate records that can be easily used as audit trails and evaluation factors of an organization's activities, market position, financial standing for example [11].

III. INDUSTRIAL APPLICATIONS

Blockchain took hold as a promising technology with the introduction and wide use of cryptocurrency [12]. However, it is showing signs as a promising technology enabling many applications in various domains. In this section, we discuss several blockchain industrial applications that provide many business and industrial benefits. We categorize these applications based on their domains. Table 1, at the end of this section, summarizes the main benefits of using blockchain in the various industrial domains discussed.

A. FINANCIAL INDUSTRY

Driven by the success of blockchain in supporting the cryptocurrencies, it was logical for the financial industry to follow it with applications of blockchain in other financial domains. In general, trusted third parties are used to conduct financial activities among people and organizations. These third parties provide four functions [13]:

1. Confirming the reality of trades
2. Avoiding financial transactions duplications
3. Registering and validating financial activities
4. Functioning as agents in support of clients or associates

Blockchain can generally replace two of these roles: avoiding transaction duplicates and registering and validating financial activities. With blockchain it is easy to prevent, for example, a client from performing multiple payments with a total amount that exceeds what they owe. Actually, it is possible to illegally perform this act with regular cheques. However, it is impossible to achieve this with blockchain as all financial activities must be collectively verified before they are performed. At the same time, blockchain can act as a secure registry for the conducted financial transactions. This registry cannot be modified by any entity involved after being appended to the chain. It can also be used to validate the conducted transactions through collective checks and verifications. These two features enable many financial applications such as the following examples.

1) DIGITAL CURRENCIES (a.k.a. CRYPTOCURRENCY)

There are more than 500 digital currencies available worldwide as of January 2015 [14]. These currencies are mainly based on blockchain. Blockchain is used to record and validate digital money ownership and to conduct, register, and verify digital money payments. Bitcoin was the first cryptocurrency initially released in 2009. A recent study in 2017 estimated that there were 2.9 to 5.8 million unique users using cryptocurrencies, most of them are Bitcoin users [15].

2) STOCK TRADING

Stock trading is usually done through a centralized authority such as an exchange market that keeps track of all trades and settlements. However, this process is usually associated

with extra costs and settlement delays. To avoid these issues, tZERO [16] designed a platform based on blockchain to reduce costs and settlement time while at the same time increase transparency and auditability. This platform is integrated with cryptographically secure distributed ledgers to facilities settlement processes. Another successful effort in utilizing blockchain to facilitate stock trading is created by Chain [17]. Chain developed a live blockchain integration to link NASDAQ's stock exchange and Citi's banking systems.

3) INSURANCE MARKETPLACE

Blockchain can be used to support the insurance marketplace transactions between different clients, policyholders, and insurance companies. Blockchain can be used to negotiate, buy and register insurance policies; submit and process claims; and support reinsurance activities among insurance companies. Different insurance policies can be automated using smart contracts [18], which can significantly reduce administration costs. For example, there is a high administration cost associated with processing insurance claims. In many cases, the administration of claims can be very complex processes due to disagreements and misinterpretations of the terms. Smart contracts can evade these problems by structuring insurance policies in more precise ''if-then'' relationships [18]. This allows for the automation of executing the terms by digital protocols that exactly implement the agreed upon insurance policies, thus reducing the effort needed and the costs of execution. With this reduction, insurance companies can also reduce the cost of their insurance products and be more competitive to attract more customers. At the same time, it allows insurance companies to launch new automated insurance products for their clients without worrying too much about their administration overhead and costs. Furthermore, blockchain enables insurance companies to be expanded globally [13].

4) FINANCIAL SETTLEMENTS

Blockchain can be used among companies and organizations for recording, validating, and processing financial settlements without involving a clearing house. It facilities clearing processes which involve adjusting the financial commitments so as to enable payments. One of the early uses of such application is when the Royal Bank of Canada (RBC) started to utilize blockchain for its US-Canada interbank financial settlements [71]. The bank started using an application implemented with the Hyperledger platform in September 2017. Blockchain based financial settlement systems can be integrated with other blockchain based applications such as blockchain based stock trading applications or blockchain based logistics applications to enable financial settlement processes in these applications.

5) PEER-TO-PEER GLOBAL FINANCIAL TRANSACTIONS

Traditionally any financial transaction performed between people must go through some form of authoritative entity of financial institution for verification and guarantees. This entity needs to verify finances and ensure accurate execution of these transactions. However, many of these transactions can now be digitized and verified through blockchain. As a result, the middleman is cut from the process and people can collectively verify and ensure correct execution and recording of these transactions. Following in the footsteps of cryptocurrency, these transactions can be performed with any available currency as long as it can be backed correctly across all entities involved. The additional benefit here is these transactions will also be open for use globally since there will be no restrictions on where entities performing the transactions are and what currencies are in use.

B. HEALTHCARE INDUSTRY

One of the most sensitive and critical components in healthcare is patients' data. A patient's medical record is usually scattered across multiple systems owned and operated by one or more healthcare providers. The digital evolution has created the capability to digitize patient information into what is usually referred to as the electronic medical record (EMR). There are many obstacles in sharing EMRs among multiple healthcare providers and healthcare related organizations due to many issues including security and privacy. Blockchain can be used to enable secure EMRs and other healthcare information sharing among multiple providers. A startup company called Gem developed a blockchain based network for developing healthcare applications and universal healthcare data infrastructure [19]. In addition, another startup company Tierion developed a platform for healthcare data storage [20]. This platform also supports verification and audit processes of healthcare records and processes.

In another research work, Health Data Gateway (HDG) is proposed [21] as an App architecture based on blockchain used to allow patients to control and securely share their health data while maintaining their privacy. This architecture guarantees that while patients own and control access to their health records, they cannot alter, delete, or add any health-related information to these records. In such architecture, access policies can be defined using software services while different entities can use other services to access the EMRs. As EMRs can be updated by multiple authorized entities, Blockchain technology can be also used to record all these updates to maintain a trustable audit trail that can provide step by step records of all update history for the EMRs.

Secure sharing of EMRs and related healthcare information can also facilitate fine grain analysis of patients' data, medical innovations and research results in addition to data collected on treatments, diagnostics and related work securely and anonymously when necessary [102]. In addition, blockchain can be used to enable other healthcare related industries such as pharmaceuticals. One example is using blockchain to enhance the pharmaceutical supply chain management [37]. All this blockchain healthcare related data can enable better access for analysis and research to discover

and manage trends as they arise and support better and more useful healthcare solutions. In these cases, blockchain will facilitate access and reduce the need to rely on third parties and owners to authorize and export the required data. Thus, saving a lot of time and effort and reducing costs of research and development.

C. LOGISTICS INDUSTRY

Logistics management applications are software systems that help manage the delivery of raw material, products, and services between the producers/sellers and the consumer destinations. These can all be part of a single organization or run across multiple organizations and entities. Blockchain can provide powerful support to enable these applications. One of the complexities in logistics management is the involvement of multiple companies in the activities. This may also include a number of synchronized sub-activities performed by different companies such as factories, storage companies, shipping companies, and regularity authorities. It is important for any logistics management application to provide a set of functions to plan, schedule, coordinate, monitor, and validate the performed activities. Such functions can be efficiently and securely supported by blockchain. Using the shared distributed ledgers in blockchain to verify, store and audit logistics transactions will help reduce time delays, management costs, and human errors. In addition, applying smart contracts will facilitate agreements between the companies involved and create binding contracts faster and with lower costs.

With these benefits blockchain is anticipated to have a substantial impact on the logistics industry [22]. There are many startup companies in this area that offer blockchain based logistics management platforms and applications. One example is Provenance [23], which provides a traceability system that links consumers and suppliers together for different logistics activities. Another example is Hijro [24], which offers an application platform for supporting global supply chain management.

D. MANUFACTURING INDUSTRY

The manufacturing sector is taking long strides towards smart manufacturing and automated/autonomized operations and thus can benefit from blockchain in different areas. One important area is for logistics management which we discussed earlier. Logistic management is extremely important for any manufacturer to ensure fair pricing and timely delivery of row material and supplies for its productions. In addition, it helps ensure efficient and timely delivery of their products to satisfy the needs of customers. Like any logistics management application, using blockchain for manufacturing logistics management can reduce time delays, management costs, and human errors [3]. This enables the manufacturers to reduce manufacturing costs and to be more agile and competitive.

In addition, blockchain can be used to enable social manufacturing networks (SMNs) among manufacturing enterprises to support sharing and utilizing their social manufacturing resources effectively, fairly, and securely. Social manufacturing is a new evolving manufacturing approach and business practice that aims to build more personalized products and individualized services for customers. Adopting of this approach, manufacturing enterprises can enhance their competitive capabilities. This approach can be more effective if multiple manufacturing enterprises cooperate in sharing their social manufacturing resources and forming a social manufacturing network among them for the benefits of all participators. A manufacturing enterprise with access to more social manufacturing resources in this network can produce more precise and professional products tailored to the specific demands of the consumers [47]. Nevertheless, there are always high concerns of security, fairness, and effectiveness in this collaborative network. One possible resolution is addressed in [27], where Liu *et al.* developed a blockchain-based Product Credit Mechanism (PCM) to securely, fairly, and effectively manage the cross-enterprise collaborations within their social manufacturing network. This management is achieved in a peer-to-peer fashion, without involving a third party, using smart contracts and a credit system.

Blockchain can also be utilized to support cloud manufacturing operations. Cloud manufacturing is a new manufacturing model proposed to utilize concepts from cloud computing, Internet of Things (IoT), service-oriented computing, and virtualization to convert manufacturing resources and operations into a set of manufacturing services that can be smartly integrated and managed [48]. In this regard, blockchain is proposed to be used to enable secure decentralized cloud manufacturing architecture [28] and secure knowledge sharing for manufacturing design such as designing and redesigning injection molding [29].

Another area where blockchain is used is to improve anti-counterfeiting and copyright protection procedures for additive manufacturing. Kennedy *et al.* [25] developed a physical anti-counterfeiting approach that can verify the authenticity and quality of 3D-printed parts. In this approach nanomaterial chemical signatures are added to these parts, while blockchain is used to ensure the origins of the parts based on the added nanomaterial chemical signatures. Some of the main advantages of using blockchain to verify the originality of parts in manufacturing are to enable healthier supply chains in manufacturing and to reduce the risks associated with using imitative parts [26]. Here, the authentication of each individual part can be done through an automated process before being used to build other products.

A startup company, Genesis of Things [30], is developing a platform to combine 3D printing, blockchain, and Internet of Things to make more innovative manufacturing processes. This enables lowering the costs of custom products created by 3D printing and automating several manufacturing and related activities for more efficient customization.

Another area of benefit is the enabling of secure exchange and sharing of manufacturing information among collaborating manufacturers. In situations like these, data must be secured, but must also be tracked and controlled to ensure appropriate access and prohibit any unwanted changes or tampering.

E. ENERGY INDUSTRY

One of the main uses of blockchain in energy related applications is in microgrids. A microgrid is a localized set of electric power sources and loads integrated and managed with the objective of enhancing energy production and consumption efficiencies and reliabilities [31]. The electric power sources can be distributed power generators, renewable energy stations, and energy storage components in facilities created and owned by different organizations or energy providers. One of the main advantages of the microgrid technology is that it does not only allow residents and other electric power consumers such as factories to have access to the needed energy, but they can also produce and sell excess energy to the grid. Blockchain can be used to facilitate, record, and validate power selling and buying transactions in microgrids [18]. This allows for applying power exchange restrictions and regulations, managing payments and fairly and efficiently making shared decisions among the participants without the need for a centralized microgrid controller [51]. As an example, blockchain is used in a microgrid that groups 130 buildings in Brooklyn, New York [18], [50]. This minimizes or eliminates the need for intermediaries among these buildings to complete their energy selling and buying transactions. In addition, blockchain can be used in islanded microgrids to track energy losses produced by energy transactions. This leads to a better matching between the physical position and losses of power across the grid network and the resulting costs attributed to participants [49].

In a similar way, blockchain can be used at larger scales to enable energy trading in smart grids. In smart grids equipped with bi-directional communication flow, blockchain can be used to support secure and privacy-maintained consumption monitoring and energy trading [52] without a need for a central intermediary. It can also be used to support the management of demand response programs [53]. Smart contracts can be used to ensure the programmatic descriptions of anticipated power flexibility degrees, the validation and tractability of demand response agreements, and the balance between power needs and generation.

Furthermore, blockchain can be used to enable energy trading in Industrial Internet of Things (IIoT) [54]. This allows for better power supply negotiations and agreements among providers and consumers in various industries. This will help reduce total production costs of these industries, thus making them more flexible and competitive within challenging market environments. Generally, utilizing blockchain for energy-related applications has the potential to reduce energy costs [55] as well as increase resiliency [56].

F. AGRICULTURE AND FOOD INDUSTRY

Generally, Information and Communication Technology (ICT) play an important role in enhancing both agricultural and food industry applications. ICT enables e-agriculture which is a farming system that supports market efficiencies, food safety and security, and decreases uncertainty and risks. E-agriculture relies on enabling agriculture knowledge sharing to help farms be more productive, safer, and to avoid potential risks. This knowledge sharing can be better utilized and enabled by blockchain. Applying blockchain in e-agriculture systems helps establish trust among participants sharing their knowledge and utilizing the provided e-agriculture servers in improving their farming operations [36]. These services will improve cost-effectiveness, enhance food safety, and reduce uncertainty and risks. In addition to the main agriculture operations, blockchain technology can also be used in agriculture related industries such as bee industry to record the activities of honey adulteration, support smart pollination contracts, and enhance the beehive insurance market [57].

In the food industry, blockchain can be used with ICT to ensure food safety. For example, it can be used with RFID (Radio-Frequency Identification) to build an agri-food supply chain traceability system [59]. Such a system can provide trusted information through secure data collection and communication processes in the agri-food supply chain to ensure the safety of food in all production, manufacturing, warehousing, delivery, and sales stages. In addition to RFID, blockchain can be integrated with other IoT technologies and other developed concepts used to ensure food safety such as Hazard Analysis and Critical Control Points to further maintain and guarantee food quality and safety through the supply chain [60].

Walmart is working with IBM and Tsinghua University of Beijing to create blockchain-based supply chain applications in China, with a specific focus on the pork market [61]. They reported an encouraging result in reducing the time needed to track food from days to minutes. This enables more effective monitoring for food safety which can increase the customers' trusts in their products. Generally, there are many benefits for using blockchain in the food industry including improving transparency in food systems, enhancing food flows, reducing food waste, helping in deterring food fraud, and offering new tools for increasing trust in food [62].

G. ROBOTICS INDUSTRY

Swarm robotics have many potential industrial applications including material transport and precision farming. However, there are many challenges obstructing such technologies from being practically developed and employed including autonomous capabilities, decentralized controls, and collaborative behaviors. As blockchain technology can be used among multiple distributed entities to reach agreements without the need for a controlling authority, it can be used in swarm robotics applications for the same purpose and to

add security, autonomy, and flexibility features [32]. This helps build more secure swarm robotics applications that are capable of better decision making in a distributed manner for efficient operations. Using blockchain can also enable managing byzantine robots in a swarm robotics collective decision-making scenario [33]. With all these capabilities, new business and industrial models for swarm robotics applications can easily be created. Each robot subtask can be represented as a transaction. A set of synchronized and coordinated transactions are usually needed to complete a mission. Using blockchain to manage these transactions can provide some advantages [32]:

1. New security measures can be applied to protect swarm robotics applications. Since all coordination and synchronization efforts must be communicated over a network, secure communication and verification of messages are essential. Blockchain enables swarm robotics communications and transactions verification thus facilitating more applications including mission critical applications.
2. A specific mission application can be effortlessly designed, implemented, and executed by negotiating and agreeing on specific transactions necessary for the mission and then having them recorded in a blockchain ledger for verification, execution, and future reference.
3. Using blockchain adds high flexibility in using swarm robotics for different applications through the additional capabilities introduced.
4. Blockchain can be used to offer a facility for confirming that robots will only execute agreed transactions within acceptable legal responsibilities and safety measures.

H. ENTERTAINMENT INDUSTRY

Blockchain technologies can support the entertainment industry in many ways. Online entertainment applications such as online video games can gain many benefits as blockchain can be used to offer new and advanced mechanisms for players to interact with the gaming platforms [63]. These mechanisms offer better controls over virtual assets. Unlike in traditional platforms, players can own virtual assets that can be used across different gaming platforms. The players are not restricted with specific platforms to own their virtual assets. This allows players to have more flexible and better entertainment experiences. In addition, blockchain can be used to build different reward mechanisms for interactions, security mechanisms for protecting the ownership of virtual goods on the gaming platforms to stop any illegal transactions, hacking, and thieving of the goods, and as fast payment methods between players and game providers [63]. Furthermore, the peer-to-peer structure of blockchain can be utilized to offer real-time cheat prevention and robustness for multi-player online games [64]. Several companies are developing a blockchain enabled gaming platform named the Aura Network [65]. This platform is designed to provide an infrastructure with blockchain capabilities to support decentralized games and virtual worlds. This infrastructure is enabled by a new protocol named the Aura Protocol that offer scalability solutions to simultaneously support millions of players.

Another entertainment industry that can benefit from blockchain is online gambling. Distributed ledgers and cryptocurrencies have the capability to change how these gaming businesses are handled [66]. These provide many advantages for facilitating the online gambling industry; however, there are many issues in such applications such as whether providers accept cryptocurrency and permitting clients to play outside of regulatory jurisdictions as cryptocurrencies are not dependent on the regulations of specific countries.

Blockchain can also be used to register, verify and control entertainment content licensing using smart contracts between the content providers and the consumers [67]–[69]. Furthermore, blockchain can enable new business models for the entertainment industry. One of these new models can eliminate the need for the middleman between entertainment creators and consumers. For example, we as consumers use on-demand streaming platforms such as Apple Music, Tidal, and Spotify to listen to some music. These companies add a level of intermediation between consumers and music creators which may add some costs and restrictions [70]. Using blockchain, such transactions can be executed and managed directly between the producers and consumers. Although, this model may have some limitations such as marketing and payment issues, it allows music producers to generate and gain more value and income from their own entertainment products by increasing their bargaining power [70]. Like any new business model, this model for entertainment needs to be further studied in terms of challenges, threats, and benefits.

I. OTHER INDUSTRIAL DOMAINS

In addition to the applications discussed earlier, there are other useful applications in domains like construction and telecommunication industries. In the construction industry, blockchain can be used for construction management through enhancing the current processes of contract creation, registration, monitoring, control, and management. In addition, blockchain services can support better construction supply chain management, and construction equipment leasing [34]. In the telecommunication industry, blockchain can enhance telecommunication services management [35]. Blockchain can improve traceability, contract management, and governance processes in the telecommunication industry. Furthermore, blockchain can be used to support Industry 4.0 applications [38] as they usually need to integrate several systems and components that may not always be owned by a single entity. Blockchain can help create more secure, trusted, and controlled processes for Industry 4.0 applications.

TABLE 1. Benefits of utilizing blockchain in different industrial application domains.

Application Domain	Benefits of Utilizing Blockchain Technologies in Application Domain
Financial Domain	• Reduce financial activities costs • Reduce transactional and operational errors • Enable the use of digital currencies • Enhance insurance policies and related activities such as negotiations, agreements and claims handling • Enable stock exchanges without involving a third party • Enable financial settlements without involving a third party
Healthcare Domain	• Enable controlled sharing of EMRs among multiple healthcare providers and related industries • Facilitate patients' ownership of their EMRs, while inhibiting their ability to alter them • Allow patients to control and securely share their health data while maintaining their privacy. • Enhance pharmaceutical supply chain management processes. • Facilitate fine grain analysis of patients' data, medical innovations and research results
Logistics Domain	• Help reduce time delays, management costs, and human errors • Facilitate faster and more efficient agreements between companies involved in logistics activities. • Securely and efficiently support planning, scheduling, coordinating, monitoring, and validating logistics activities
Manufacturing Domain	• Reduce manufacturing costs by improving manufacturing supply chain management • Enhance anti-counterfeiting and copyright protection procedures for additive manufacturing • Enable social manufacturing networks • Support cloud manufacturing • Enhance energy supply agreements and scheduling
Energy Domain	• Support power exchanges by enabling buying/selling activities in microgrids • Support energy trading in smart grids and IIoT • Support demand response programs in smart grids • Support tracking energy losses and enhance cost distributions
Agriculture and Food Domain	• Improve cost-effectiveness • Enhance food safety and reduce food waste • Enhance agriculture-related insurance support • Enable trusted food safety tracking in food supply chain management and help deter food fraud • Improve transparency in food systems and processes
Robotics Domain	• Improve security measures in swarm robotics applications • Enable swarm robotics to better negotiate, agree on, and execute mission activities • Facilitate adding new functions • Facilitate recording and verifying robots' actions
Entertainment Domain	• Offer better controls for online players over virtual assets and allows them to use these assets across different gaming platforms
	• Offer security mechanisms for protecting the ownership of virtual goods on the gaming platforms • Offer fast payment methods between clients and entertainment providers • Enable peer-to-peer online gambling • Enable verifying and controlling entertainment content licensing • Enable new business models for the entertainment industry
Construction Domain	• Enhance current construction processes like contract creation, registration, monitoring, and control • Support more efficient construction supply chain management processes • Support better construction equipment leasing and usage procedures
Telecommunication Domain	• Enhance telecommunication services management • Improve traceability and transparency • Enable efficient contract management • Support more cost-effective governance processes

IV. CHALLENGES

The promise of blockchain benefits is appealing; however, many challenges face the adaptation and deployment of blockchain in industrial applications. Here we will highlight some key challenges in using blockchain in this context. These challenges are both technical and non-technical. The technical challenges are related to security, integration, and scalability, while the non-technical challenges relate to privacy, professional preparation, and government regulations.

A. SECURITY

One of the main concerns of utilizing blockchain is security. As blockchain applications are connected and available over the Internet, they are vulnerable for various cyber-attacks including stealing, spy attempts, and Denial-of-Service (DoS) attacks, which can make blockchain services unavailable. One of the stealing attacks was against MtGox, a bitcoin exchange based in Tokyo, Japan, in 2014 that resulted in a loss of $600 million [42]. Another example was against Ether digital currency that values around $55 million.

One of the attacks that can compromise a cryptocurrency network is the 51% attack. It is also called a majority attack or >50% attack. If most miners (computers processing the network transactions) in such networks are managed by a single entity, they would have the ability to select which transactions get approved. This permits them to reject other transactions and permit their own coins to be spent multiple times, which is called a double spend [76]. This type of attack occurred more in cryptocurrencies with small communities of miners while cryptocurrencies with large communities of miners, such as Bitcoin, are more resistant to this type of attack. It was found that more than $20 million worth of cryptocurrency theft was accomplished with this attack in the first 10 months of 2018 [77]. Although this type of attacks has occurred mainly for cryptocurrency applications, it could also occur for other blockchain applications with small communities of miners.

Without suitable security measures to protect against such attacks, they can cripple the applications. Unfortunately, the very nature of blockchain and its usage models increases this vulnerability as it operates across multiple platforms, communicates using open networks, and involves multiple entities. Current security measures offer some answers, yet, there is a need to address the issues specifically within the context of blockchain to come up with more suitable and effective security models.

B. INTEGRATION

Blockchain solutions are not for standalone applications, they are usually integrated with multiple distributed applications used within the organizations and beyond. Blockchain will be used as an enabler to add new functions that are needed to support future business models. Integrating blockchain solutions with existing applications including legacy applications can be challenging. This challenge is mainly due to interoperability and security issues. For example, legacy applications may not be ready to be smoothly and securely integrated with newer systems and applications including blockchain solutions. Another example is the different platforms and operating environments that may need to interoperate with each other to operate blockchain based applications. In addition, old and new applications may have been developed by different vendors using different development methodologies, environments, and programming languages. Thus, the integration process becomes even more complex. Any integration model used should maintain the correctness and reliability of the existing applications' functions and the consistency of the business data among all integrated systems. Furthermore, any integration should maintain good security measures for all applications involved. This integration must not open any doors for security vulnerabilities, privacy concerns, or reliability and availability issues. Some work is underway to provide effective integration models that will incorporate blockchain in various integrated industrial applications. However, more useful and specific solutions are still to be found and developed.

C. SCALABILITY

The blockchain distributed ledger requires the involvement of multiple entities (involved in the transaction) to agree on the transaction that is then linked to the transactions in the ledger and appended to the blockchain. This process is relatively complex, yet effective given a limited sized blockchain. Unfortunately, current applications requiring blockchain generate huge amounts of transactions to be processed and linked, which could easily degrade the overall performance. Another issue arises when the blockchain is mined to find, verify, or use earlier transactions. This process involves various steps and the performance is inversely proportional to the size of the blockchain. Thus, the bigger the blockchain the slower the process gets. Scalability has become a pressing issue with the rapid growth in the size and number of entities involved and transactions being performed. One example to consider is that the rate of transactions that need to be recorded in a blockchain system can be higher than the capability rate of data synchronization in this system [43]. Others include the time needed to mine for specific transactions or to achieve consensus among all entities involved in an acceptable amount of time. These problems can create some business and operational issues to the industrial applications using blockchain as some business decisions could take too long to reach or be taken based on not up-to-date information.

D. PRIVACY

There are three types of blockchain: public, consortium, and private [44], each of which has different characteristics. In a public blockchain, all participants can view and verify the blockchain's transactions and contribute in the consensus process. In a consortium blockchain, some participants have the authority to view and verify the blockchain's transactions and contribute in the consensus process, while

others cannot. Participants are restricted based on strict agreed upon authorization policies. A private blockchain is owned, operated and controlled by a single entity that makes its own rules for access and use. Different blockchain types are used in different applications. For example, cryptocurrencies such as Bitcoin and Ethereum use public blockchains, while Hyperledger [45], an open source blockchain for different industry types, is a consortium blockchain. All blockchain types have different privacy concerns. Public blockchain can be viewed by all participants; therefore, it is difficult to maintain privacy of any participating industry entity and conduct some transactions in such blockchain. With a consortium blockchain, the privacy cannot be fully maintained as there are some selected participators who can view all transactions. A private blockchain can provide a relatively better degree of privacy; however, it is generally considered an unsecure environment as it is only controlled by a single entity [72].

E. PROFESSIONAL PREPARATION

Developing, deploying and utilizing blockchain technologies require prepared professionals in the field. Incorporating ICT in different industrial domains have taken great strides towards effective and efficient systems supporting the industries. Yet, there is a lot more to look forward to with the introduction of blockchain in the mix. ICT professionals are capable of creating and managing various types of applications; however, the relatively new area of blockchain and its integration in industrial applications poses new challenges. Although the underlying technologies used to create blockchain are in many ways common; transaction-based systems, ledgers, audit trails, digital signatures, and security models; the new integration and utilization methods are unique. To create fully integrated blockchain-based industrial applications, the design and development teams need to be knowledgeable in various areas. The industrial domain they are working for, the ICT to be used, the blockchain technologies and models, in addition to various software and system development processes. With the continuing shortages in technical and professional workforce, it is a challenge to find and train the required professionals for these projects. In addition, there is a pressing need for appropriate and effective training and development programs that can quickly produce the required professional workforce in this field.

F. REGULATIONS

Although blockchain technology can provide technical proofs of ownership, consensus, and responsibilities, these proofs need to be legally supported. The legal system is still struggling when it comes to technology and technical disputes. Although a smart contract, for example, technically binds the contractors, the legal system still does not recognize that directly. This leads to lengthy disputes and costly processes for all parties involved when a problem or legal issue occurs. Rules, laws and specific regulations are needed to address such issues directly and allow for flexible interpretations of the technical binding features in blockchain. Without regulations, it is difficult to use blockchain for some industries. For example, a manufacturer agrees with a supplier on material purchases and documents it using a smart contract approved by both parties and pays using digital currency. There may be an issue if the order was not delivered within the agreed time or required specifications. This issue may need to be solved with the support of the legal system. With the absence of an actual authenticated contract, this becomes a big problem since the legal system may not accept the smart contract as a binding agreement. This can be made less complicated if the law extends to accept the technical capabilities of blockchain features in creating binding agreements. Another aspect that could further complicate the issue is when the buyer and supplier are from different countries, then it is not only whether the laws apply, but also which country's laws should be used. It is imperative that the legal aspects of blockchain are studied and addressed from the law perspective and workable solutions and regulations are created to support it.

V. REQUIREMENTS

Aside from the challenges, to be addressed and resolved, there are specific and key requirements needed to enable utilizing blockchain in industrial applications. These requirements are necessary to facilitate the design, development and deployment of these applications.

A. SUPPORTING PLATFORMS AND TOOLS

It is important to use a good blockchain platform capable of providing the required services to implement and deploy blockchain applications for a specific business or industry. There are different blockchain platforms being developed. Some of these platforms are generic and can be used for different industrial domains while others are more specialized and developed for specific domains. An example of generic platforms is Ethereum [78], an open source public blockchain-based distributed computing platform. It provides some support for applications that need to use smart contracts. Smart contracts in Ethereum can be programmed to negotiate and sign contracts on behalf of a certain company or organization.

Another general industrial blockchain platform is Hyperledger [45]. Hyperledger is an open source blockchain platform project initiated by the Linux Foundation in the end of 2015. The objective of this project is to provide good performance and reliability support for blockchain industrial applications in different domains including financial, logistics, and manufacturing. Another objective of Hyperledger is including open protocols and standards developed by individual efforts to allow for collecting and integrating different types of blockchain services for consensus, data management, identity management, access control management, and smart contracts in one platform.

Examples of specific domain blockchain platforms are Gem [19] and Tierion [20] for healthcare applications, Provenance [23] and Hijro [24] for logistics applications, and

Genesis of things [30] for manufacturing 3D applications. These platforms provide specific facilities and tools that are designed to support the specific domain they serve. These facilities and tools can provide rapid development and/or deployment for blockchain applications supporting the requirements of these domains. However, these platforms are usually have restrictions in flexibility and openness.

Generally, the selection of a blockchain platform is completely dependent on the needs of the industry and the industry collaborative chain in blockchain. For example, a group of healthcare providers can use one platform like Gem that supports healthcare applications, while multiple collaborative diverse companies (from different domains) can use a platform like Ethereum to implement smart contracts capabilities over their network.

B. BLOCKCHAIN MANAGEMENT

An important requirement for different industries deploying blockchain for their applications is blockchain management. As an industry deploys a blockchain node to be involved in a blockchain network, it is important to provide the necessary management capabilities for the availability and accessibility of this node. As some operations start to rely on the availability of a blockchain network, these operations can be affected such that they may negatively degrade the reputation and credibility of the industry and its business. In such industries, the blockchain node and the connectivity to the blockchain network should be reliable and highly available. Therefore, it is important to manage the scalability, performance, quality-of-service, security, and fault tolerance issues in such networks. This requires the availability of effective monitoring, configuration and adaptation capabilities within the network. In addition, the resources used for blockchain should provide good scalability abilities to support the required loads. Furthermore, it is important to manage the future scalability and performance requirements through proper and accurate capacity planning processes. In addition, it is important to identify and manage the associated risks and provide alternative solutions to handle problems and continue operations without interruptions.

C. OPEN STANDARD TECHNOLOGY

As each industrial organization has different types of businesses, operations, and partners, it is advantageous to have open standards for developing and deploying blockchain solutions. This will include good flexibility for upgrading, maintaining, and adding more application features for the industry. Moreover, this will smooth the integration among blockchain components and other enterprise applications components within a single industrial enterprise and among collaborative multiple industrial enterprises. Furthermore, it is crucial to set standards and rules for new applications to achieve easy integration between the available enterprise infrastructures and systems and the introduced blockchain applications. This can be achieved by performing a full study of the industrial entities, stakeholder, and the infrastructure to assess the readiness to incorporate blockchain applications. Based on such study, regulations, standard models of design and integration rules can be developed for blockchain applications development and operations for different industries.

One important approach for having open standards is to use other well-known standards for enabling integration among blockchain components within a blockchain network and between different industrial systems and blockchain networks. For example, this can be enabled by the service-oriented approach [46], [109]. With this approach, blockchain networks are viewed as services that can easily be integrated with other services from other industrial systems using an integration standard such as a web service standard.

Furthermore, there are many standardizing efforts in progress for blockchain technologies conducted by professional and standards organizations including efforts from IEEE Standards Associations [39], the International Organization for Standardization (ISO) [40], and Standards Australia [41]. Creating these standards will help facilitate smoother integrations and better utilization of blockchain features. As these standards emerge and get accepted in the industrial and business domains, a wider spread of blockchain based applications in these domains will be a reality.

D. SECURITY AND PRIVACY

In many industrial applications like healthcare applications, sensitive and/or private information is generally involved, it is important to guarantee that all technologies and applications in use include and maintain acceptable levels of security and privacy measures. Although blockchain provides many positive advantages for different industries, it also poses several threats to their security, safety, reliability, and privacy by relying heavily on their features. In addition, as blockchain solutions will be integrated with other industrial systems solutions, this integration should also be secure.

The possibility of illegal access or malicious attacks on such infrastructures can lead to catastrophic outcomes affecting the industry's operations and infrastructure, its customers and partners. Industrial blockchain applications designers and developers must include security and privacy policies and procedures as an integral part of the design and implementation of their applications. Clear guidelines and requirements must be recognized from the various users to be enforced in the applications.

Furthermore, as different industries have different needs in terms of security and privacy, it is important to select blockchain types and technologies that meet these specific requirement. For example, some domains deal directly with personal information such as financial and health records, thus require very strict ownership, privacy and data protection capabilities and must meet the required regulations and compliance policies. Other domains may only deal with generic public data, but include some private industrial information. In this case the policies and regulations will be more focused on the segments requiring protection, but can be relaxed for the others. The security and privacy requirements should be

studied and defined well at the initial stage of any blockchain applications. In additions, provisions to include various levels of protections must be made available to these applications.

E. GOVERNMENT SUPPORT

Like many applications that span large numbers of stakeholders, and span multiple regions and authorities, there is a need for regulatory governmental support. In addition, blockchain-based applications also provide a new dimension that has not been commonly used and that is the features enabling trust, traceability and smart contracts. Therefore, blockchain-based industrial applications require additional levels of governmental support in various ways and capacities. One example is an overall support to adopt blockchain as an integral component of different applications and recognize its binding capabilities across all entities involved. Part of this includes willingness to adapt and create new laws, rules, and regulations that account for blockchain and help support transactions made through it in addition to swiftly resolving any arising legal issues.

Another area of support is providing the necessary infrastructure and capabilities to create, manage and control basic blockchain features like the digital identity. Establishing proper mechanisms to issue and authenticate digital identities will help different entities to initiate and trust blockchain transactions when they are able to authenticate the others involved in these transactions. This also allows government bodies to track and verify transactions, determine the legality of agreements and eventually create and apply suitable laws to control the processes based on blockchain. Furthermore, governmental support comes in the form of providing the necessary resources to help train qualified professionals in all blockchain related fields, STEM, law, healthcare, and business to name a few. Educational and training programs supported by to government will streamline the process and create an efficient pipeline of professionals in the field. Another important requirement is for the government to support research and development efforts to enhance and better utilize blockchain capabilities in different industries. Research grants, support for standardization efforts, better management and control regulations are examples.

Some governments have already recognized the capabilities and advantages of blockchain technology in reducing fraud, corruption, errors, and operational costs. In addition, many already acknowledge blockchain's ability to improve trust levels among collaborating entities; streamline, protect and simplify information sharing; and providing high levels of transparency and traceability between involved entities and the government [58]. This is the first step towards ensuring the required support from the government for blockchain-based industrial applications.

VI. DISCUSSION AND OPEN ISSUES

Blockchain can add significant economical and operational values to many applications in different industrial domains. These values can be improvements in operational procedures, reduction of operations and administration costs, reduction of operations time delays, and reduction of human errors. In addition, blockchain features such as digital identity for humans, companies, organizations, and properties can enable many new business models. Along with the digital identities, the distributed security and consensus-type agreements will allow for completing and trusting transactions among entities without the need for an authoritative body. Thus, the middleman can be eliminated from a lot of processes that currently cannot be completed otherwise. Leveraging both the added values and the capability of establishing new business models will lead to enhancing the competitive capabilities and flexibility of many industries.

There are many startup companies offering different blockchain solutions for different industries and business sectors. Some of these solutions are already in use in their respective sectors, while others are still under development or being further researched. While most of these solutions provided by different companies offer advanced features to support industrial applications, there are many opportunities for enhancing these features and adding more useful ones. It is important for these products and solutions to be flexible, useable, scalable, secure, reliable, and efficient. As discussed earlier, the different challenges need to be addressed to provide solutions that make blockchain more attractive and easier to incorporate in industrial applications. Achieving the requirements we discussed will help take us several steps closer to achieving the main objectives.

As many offer blockchain solutions, there are many issues to address. For example, any blockchain application over the Internet is vulnerable for various cyber-attacks including Distributed Denial-of-Service (DDoS) attacks, which can make blockchain services unavailable. Without suitable security measures to protect against such attacks they can cripple the application. Beyond security, there are several other challenges facing the practical use of blockchain in industrial applications as illustrated in Section IV. There are ongoing efforts addressing some of these challenges like security. However, other challenges like integration, scalability, and regulations compliance are still not being adequately investigated and developed. In addition, there are key requirements, as discussed in Section V, to be considered for any development and deployment of industrial blockchain applications. These requirements are important to put blockchain at the center of attention and bring its useful features to the different industry and business domains through usable and flexible models.

Furthermore, there are various areas within blockchain that are still in their infancy and need to be further researched and developed. The promise of blockchain benefits is strong, however it is still difficult to realize these benefits to their full potential. Several of these issues are dictated by the requirements discussed earlier. A major concern with any industrial applications is security and privacy and the

introduction of blockchain in the mix further complicates the possible solutions. Despite the considerable efforts made in this area, it is still very difficult to achieve security at acceptable levels to all types of blockchain industrial applications. Various constraints and issues must be addressed such as resources availability, performance and levels of protection needed.

Another area to consider is using blockchain to enable new business models that have not been possible before. In such cases, it is important to consider how these new models will be developed, deployed and measured. There are various areas of uncertainty that must be considered and since there are no current models to measure against, many industries are reluctant to move into new business models. Researchers and industrial communities have a lot to consider in this regard and many aspects in management, control, measurement and quality need to be carefully analyzed for new business models enabled by blockchain.

Moreover, deploying blockchain industrial applications will always involve integration with currently operational systems. Some of these systems are modern and could be adapted to integrate easily with new applications. However, there are many legacy applications still in use in many organizations and industries. These will create another issue when the new applications will need to use or interact with these legacy systems. Effective integration between the two, considerably, different types of applications and systems is problematic and require careful analysis and effective approaches that will facilitate the integration, while preserving the original operational standards of the legacy system.

Another major issue associated with blockchain industrial applications is scalability. The way blockchain is implemented relies heavily on the wide distribution of the created ledgers and the community of miners that will update, validate and use these distributed ledgers. In addition, as we discussed earlier, when blockchain communities are small, we run into various reliability, security and trust issues. Therefore, to achieve better protection and reliability, the blockchain needs to have a large community. This alone will lead to performance issues as more entities will be involved in every step. Over time and as the blockchain grows bigger, using it will also become more resources-intensive. Updating and mining the data will require a lot of resources and will slowly grow slower. This issue have not been adequately tested and addressed. In industrial applications, it is expected to have large communities collaborating and using blockchain and a huge number of transactions will be generated, recorded and mined as the uses for blockchain grow. Therefore, more effort is needed to find better ways to use blockchain and optimize the techniques used for access, management and mining.

Several other issues are also possible such as the need to create a more acceptable model for the creation and management of digital identities; the rules and policies for blockchain access controls and ownership issues; addressing the legal issues related to the use of blockchain; and creating a more inclusive model that allows different industries to safely and easily get involved and use blockchain applications for their benefits without exposing their private operations and data to the other participants. Moreover, as in any other application that may relate to privacy and protection, the general awareness of what blockchain can and cannot do is important. Educating the industries, the professionals and the general public about the capabilities of blockchain is important and creating the awareness of its benefits and shortcomings will help create a more understanding community that will further support the effective use of blockchain in different industrial applications.

VII. CONCLUSION

Blockchain demonstrated its usefulness through the widespread use of cryptocurrencies and its support for the operations needed to achieve digital currency. However, the same features are promising to enable and support other industrial applications in many domains. A wide range of industrial domains are starting to adopt or consider adopting blockchain to facilitate their operations in hopes of streamlining processes, enhancing security and data sharing, increasing efficiency and ultimately reducing costs to gain a competitive advantage. The main enablers for using blockchain in these applications are the introduction of digital identities, distributed security, smart contracts and micro-metering through the distributed blockchain ledgers. As a result, applications in the financial, energy, logistics, healthcare and manufacturing domains are emerging and proving to be very useful.

In this paper we demonstrated the possibilities and benefits of blockchain by surveying different industrial domains and the applications used in these domains. We also highlighted the main benefits of these applications. In addition, through the study of these applications we were able to identify the main requirements for effective utilization of blockchain applications in the industrial domains and the main challenges facing them. Some of these challenges have been addressed by the introduction of new features or use of current techniques available in other application techniques. Consequently a lot of work have been done and many features were introduced to increase the usability and effectiveness of blockchain in these applications. Nevertheless, there are still many open issues that need to be further researched and analyzed to create more workable and effective industrial applications that can fully benefit of the use of blockchain and achieve the intended goals. Examples of these open issues include security, privacy, scalability, integration with other systems and, more specifically with legacy systems, and regulatory and acceptance issues. Future work in the field is required to address these issues and close the gaps for more efficient, scalable and secure blockchain industrial applications.

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