Blockchain for Diamond Industry: Opportunities and Challenges

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***Abstract*—In the recent years, the blockchain (BC) technology has been used in various applications ranging from financial sector to healthcare sector. Moreover, developing BC-based solutions for these applications has been an area of interest among the academia and industry professionals. Diamond has huge potential to become an investment asset, but there are some issues, which hinder the progress of the diamond industry, such as *provenance, supply chain traceability,* involvement of *third party in the verification process,* and reliability of *transactions*. BC seems to be a promising technology, which bridges the gap between the diamond industry and the burgeoning financial markets. Individuals are always confident that the crystals they bought are legitimate and that stolen property can be handed back to the legitimate owner easily. Motivated from these facts, in this article, we surveyed the adoption of BC in the diamond industry, and also present pros and cons of this integration. Then, we discuss issues of the diamond industry operations and based on the literature review, we suggest their probable countermeasures. Then, we analyze various open research issues and challenges associated with integrating the BC in the diamond industry. Finally, we present a case study on frameworks, such as *Everledger* and *Tracr*, which highlights the real-time challenges of integrating BC in the diamond Industry.**

***Index Terms*—Blockchain (BC), diamond industry, security, smart contract.**

I. Introduction

DIAMONDS are one of the most precious and exquisite species of the gems family, which are usually referred to as valuable gemstones used for making precious jewellery items. Natural diamonds takes almost 1–3 billion years to form, but only 20% of them are of gem quality, such facts suffice the high value and importance of high-quality naturally formed diamonds [1]. Diamonds were spotted in Brazil in the initial years of 18th century and later in South Africa in the year 1866 and are now found in other countries, such as Australia and Russia [2], [3]. The worldwide jewellery diamond market value was $82 billion in 2017 [4]. It is also anticipated that the diamond market will be of about $123.83 billion by 2030 [5]. According to a recent study performed by Norta *et al.* [6], 95% of the total demand of diamonds accounts for the consumer demands, while less than 5% of the total demand accounts for the investment demands. According to a report by Frost *et al.* [7] taking the demand–supply shortage that surges every year, they forecasted a demand–supply gap of approximately 41 million carats by 2022 and about 278 million carats by 2050. This will lead to a great volatility in the diamond prices in the coming decades, making diamonds potentially an intriguing investment option.

Even though diamonds are an interesting alternate for the investment asset class, many issues persist in the traditional functioning of the diamond industry, which have restricted their use as an investment asset. It has been witnessed that the rebel groups of Central and Western Africa have utilized “blood diamonds” to fund and plan insurgent activities against the government [8]. Thus, buying diamonds with their origin from these regions is indirectly supporting the insurgent activities carried out by respective rebel groups. Another major reason, which restricts the use of diamonds as an asset instrument is the challenges faced to fix the price of diamonds and policing shrewd behavior in terms of diamond trading [9], [10]. Though, majority factors, such as carat size, color, clarity, and shape determine the price of the diamond. However, there are also some emotional factors associated with it, which drive the price of diamond, making the idea of uniform pricing extraneous [11], [12]. For precious goods having high value, especially something like diamonds, buyers look for its assurance of being of an anticipated quality and the authenticity of their history, that they originate from a genuine source [13]. It is onerous to maintain transparency in the trading process of such high-value precious entities such as diamonds. Thus, trust plays a critical role in trading of diamonds, which makes the idea of open trading of diamonds extremely challenging [14]. The complex processes in the diamond industry at various levels in downstream, midstream, and upstream, which are spread across the globe and the dispersion-rendered contract compliance and high-security management quite strenuous, if not

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impossible [3], [15]. Moreover, there have been many concerns related to the liquidity of diamonds as it is very difficult to redeem diamonds on its original market value, making them a less worthy investment option for the traders [16], [17]. The aforementioned issues are the major reasons, which have restricted the proliferation of diamonds as an investment commodity.

The traditional processes of documenting and authenticating a diamond's journey from mines to the end customer are prone to fraud and chicanery. The diamond industry is plagued by the lack of trust amongst the various contemporaries of the industry [18], highlights the vulnerability of trust in the diamond industry, and also mentions the reasons for the same. The stakeholders of the supply chain in the diamond industry have started demanding a more transparent process. The end customers demanding to know the detailed information of the provenance of the diamonds and they also wish to know whether they have been acquired via an ethical process. To handle such an issue, a tamper-proof tracing mechanism needs to be implemented [19]. Traditionally, the documentation of ownership of the diamond has been recorded on a paper, which can be easily forged and altered [14], [20]. In cases of fraud and theft, it becomes difficult to trace the diamond's footstep in traditional bureaucracies, which lack adequate monitoring and prosecuting institutions [14], [21], [22]. Many banking institutions have also been victimized by fraudulent diamond insurance claims [23]. Owing to such reasons, blockchain (BC) technology's usage in the diamond industry can help in alleviating some of these problems. It provides a reliable method to trace the ownership of the diamonds and can also help in diminishing fraudulent claims by detecting scrupulous activity on the distributed ledger [23], [24]. It enforces a more ethically conscious to trade diamonds and the actors of the supply chain are aware of each and every step of the process, thus enforcing more transparency.

Primarily, BC is a decentralized technology that enables stakeholders to share a common ledger with all the members of the network and the transactions taking place are recorded on it. Moreover, these transactions are encrypted using private-key and public-key cryptography. When a diamond is mined, it is added as a block in the BC and obtains a unique id number, and after the stone is passed on for cutting and grading, the metadata of the stone is added to the ledger and a digital fingerprint of the stone is created. As the diamond is traded in the market, the transaction details are also recorded in the ledger. The end customer can view all the transaction and characteristics of the diamond recorded on the distributed ledger [19], [25].

A. Comparisons With the Existing Surveys

Nowadays, BC is used in various applications ranging from financial sector to healthcare sector. BC owing to its characteristics, such as immutability, tamper proof, traceability, decentralized in nature, transparency, privacy, and security have found numerous applications in fields, such as supply chain management, system facilitating transactions, and SCs. In the recent years, the adoption of BC for the diamond industry has been an area of interest among the researchers. Many researchers have explored applications of BC in the diamond industry, but it lacks concrete and comprehensive work in the domain. Many recent surveys, such as [23], [26], [27], and [28] have analyzed promising applications of BC, such as supply chain traceability, security of BC-based SCs, and applications related to the jewellery industry. Motivated from these facts, in the proposed survey, we have reviewed various SCs, supply chain management, provenance, and transaction frameworks and analyzed their probable extensions to the diamond industry. Table I discusses a relative comparison of the state-of-the-art surveys with the proposed survey.

For example, Williams [29] have explored the probable applications of the BC technology for enhancing the efficacy of various processes such as supply chain management for the diamond industry. However, the real-time applicability of the proposed solution was not included by them. Authors of [6] have proposed a platform based on the BC for enhancing the operations of diamond industry. Cartier *et al.* [19] have presented the advantages of employing BC-based approaches for *traceability* and *tracking* applications in the diamond industry. A similar survey was conducted by Walker and Kemp [23], they have explored various probable applications of the BC for the diamond industry. However, they have not explored all the probable applications associated with the BC for the diamond industry. Juma *et al.* [30] have explored the applications of BC for trade supply chain solutions. However, they have not incorporated the usage of BC for supply chain and trading of diamonds or gem industry. Liu and Liu [27] have analyzed the efficacy of BC-based SCs for security validation. Tonnissen and Teuteberg [28] have analyzed the efficacy of BC-based systems for supply chain and related processes. Gamage *et al.* [26] have presented a systematic review on applications of BC technology and its limitations. But, they have not incorporated other aspects related to the SCs, such as platforms for developing SCs and issues in the implementation of SCs. Li *et al.* [31] have surveyed the feasibility of application of BC for the *supply quality management system* in an open manufacturing model, they have also highlighted the opportunities and challenges that may come along with the adoption of this technique.

B. Problem Statement and Research Contributions

1) Problem Statement: The traditional way of operations of the diamond industry faced a lot of issues, such as supply chain traceability, lack of transparency, and need of trusted third-party for validating the transactions and contracts. Moreover, these issues limit the usage of diamonds as an investment asset and hinder the growth of the diamond industry. After referring to various articles and blogs, it was found that the majority of trading of diamonds presently accounts for the use of diamonds as a jewellery or artifact. However, very less proportion of trading is done for investment purposes. Thus, there was an exigent need to build a solution, which combat the issues persisting in the diamond industry. We are scintillated by the efficacy and significant prowess of BC-based systems for applications, such as *provenance*, *supply chain management*, *transaction*, and SC, which might prove to be highly advantageous for the diamond industry. The BC technology has evolved over a period of time and our findings

TABLE I
COMPARATIVE ANALYSIS OF THE EXISTING SURVEYS WITH THE PROPOSED SURVEY

Related Surveys	Year	Objective	Key contributions	Limitations and Open issues
[29]	2017	Transforming the diamond industry through BC technology.	Discussed shortcoming of the current supply chain system and present the ways, how BC can help to overcome these shortcomings.	Real-time applicability of the proposed solution was included.
[6]	2018	Developing a platform based on BC for transforming traditional operations in the diamond industry.	Highlighted the limiting factors associated with use of diamonds as an investment asset and proposes a platform, which can help to overcome these persistent issues.	They have only explored the theoretical implementation of the system. Thus the efficacy of the proposed system for real-life scenarios is questionable.
[19]	2018	How BC can aid for *Tracking* and *Traceability* applications in the gem industry	Presented the challenges persisting in the current system for *Tracking* and *Traceability*, and present the recent developments based on BC, which can help to overcome these challenges.	The other opportunities (Like security, reliability, etc.) associated with the BC for diamond industry were not incorporated.
[23]	2019	How BC can be helpful for the diamond industry	Highlighted the issues in the traditional functioning of diamond industry and present the ways how BC can help to overcome these issues.	They have not explored all probable applications of BC for diamond industry.
[30]	2019	Comprehensive analysis on employing BC for trade supply chain solutions	Discussed various issues in state-of-art trade supply chain systems and analysed various approaches that have shown promising results to overcome the same.	They have not incorporated usage of BC for supply chain and trading of diamonds or gem industry.
[27]	2019	A systematic analysis security validation of BC-based SCs	Reviewed appropriate literature for the relevance of BC-based SCs for security validation and effectiveness of such validation.	They have not incorporated other aspects related to the SCs such as platforms for developing SCs, issues in implementation of SCs.
[28]	2020	Systematic study of applications of BC technology for operations and supply chain	Discussed the limitations of current operations and supply chain system, and analysed various BC-based approaches, which have shown significant potential to resolve the same.	They have not discussed emerging applications of BC such as diamond supply chain and provenance.
[26]	2020	Comprehensive review on BC-based technology, applications and limitations	Analyzed the application of BC technology for wide variety of applications and identified issues for the same.	They have not carried out an in depth review of various accessible literature for the discussed applications.
[31]	2020	Comprehensive survey of application of BC in industrial scenario and its impact on *Supply Chain Quality Management.*	Discussed detailed technical feasibility of application of BC in *Supply Chain Quality Management* along with ways to adopt this new change in an Open Manufacturing model.	The proposed solution is overly generalized as it is not suitable handle production of virtual products, products that require high customization, and for manufacturers with changing suppliers.
The proposed survey	2020	Study applications of BC in diamond industry	Discussed brief overview about BC technology, reviewed applications of BC, and analysed its probable extensions to the diamond industry.	-

shows that it has a great potential for revolutionizing the diamond industry. In the future, we envision functioning of the diamond industry based on the BC technology, which might lead to burgeoning of the diamond industry and increases the employment opportunities in it.

2) Research Contributions: In the proposed survey, we review the existing literature related to the applications, such as provenance, supply chain management, transaction, and SC based on BC and mainly focusing on its applicability for the diamond industry. Following are the contributions of this article.

1) We present a comprehensive survey on BC for the diamond industry. We highlight the opportunities and challenges for the adoption of BC in the diamond industry.
2) Being a novel topic, this article explores various limitations of the existing diamond industry, such as authenticity, forgery, and ethical sourcing of diamonds and discusses the role of BC in overcoming these shortcomings.
3) We present a solution taxonomy for tasks, such as provenance, supply chain management, transaction, and SC employing BC technology. Moreover, we also present their probable extensions to the diamond industry.
4) Moreover, we also summarize the main findings, emphasizing the research challenges and open issues pertaining to the integration of BC in the diamond industry.

C. Methods and Materials

A systematic analysis and study was carried out as part of the research method for the proposed survey, with an aim to provide a comprehensive analysis on the adoption of BC in the diamond industry. In the proposed survey, we analyze the state-of-the-art techniques for the tangled tasks of supply chain management, provenance, and transactions and explore how if they extended can be beneficial for diamond industry. Also, to highlight the challenges, open issues, and future scopes associated with the same. Our focus is to include the peer-reviewed, high-quality research works in the field from reputed conferences and databases, such as Springer, Science Direct, ACM, Taylor Francis, Wiley, IEEE explore, and Google Scholar. The keywords used for searching the content are: BC, diamond industry, SCs, provenance, and supply chain traceability. We

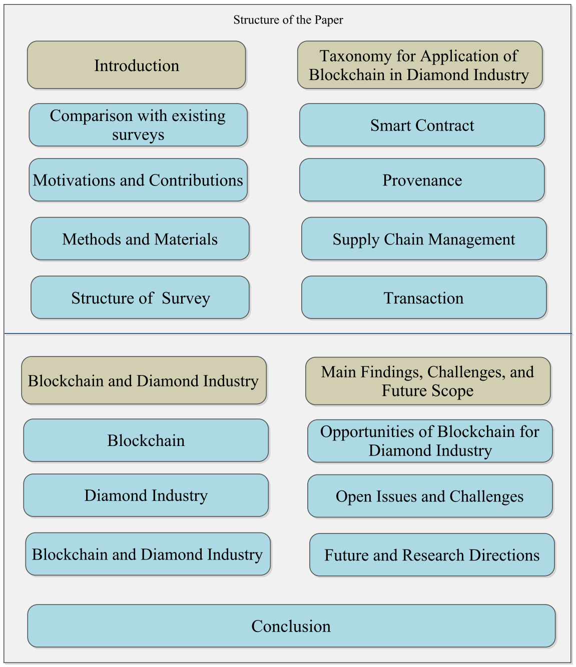

Fig. 1. Structure of the proposed survey.

incorporated a proper methodology to comprehensively review various works in the field and present a systematic survey in the field. We present probable extensions of the discussed work for its applicability in the diamond industry. We analyzed state of the art and discussed their significance in the selected field and included related and recent in the proposed survey.

D. Structure of This Survey

Fig. 1 depicts the structure of this survey. Section II elicits insights about BC technology and an overview of the diamond industry, and present various opportunities for the integration of BC in the diamond industry. Section III reviews various applications of BC technology and propose their probable extension for the diamond industry. The various applications that have been incorporated are: SCs, transaction, supply chain management, and provenance. The applications discussed have been selected in such a manner that are beneficial for the diamond industry if extended for the same. In Section IV, we discuss various challenges associated with the implementation of BC for the diamond industry with future scope. Finally, Section V concludes the proposed survey. Table II shows the list of abbreviations used throughout this article.

II. BC and Diamond Industry: Background, Definition, and Motivation

This section discusses about the background knowledge of various concepts used in the proposed survey, such as BC and its characteristics, and an overview about the diamond industry. Also, it discusses about the probable use cases and brief of how BC can be integrated in the diamond industry.

TABLE II
List of Abbreviations Used Throughout This Article

Short Form	Abbreviations
BC	Blockchain
DC	Distrbuted Ledger Technology
P2P	peer-to-peer
PoW	Proof of Work
IoT	Internet of Things
ML	Machine Learning
AI	Artificial Intelligence
EVM	Ethereum Virtual Machine
BLE	Blueetooth Low Energy
IR	Intermediate Representation
LLVM	Low Level Virtual Machine
TRU	Traceable Resource Unit
SC	Smart Contract
OPM	Open Provenance Model
EDI	Electronic Data Interchange
RFID	Radio Frequency Identification
POMS	Product Ownership Management system
MM	Manufacturer manager
PM	Product Manager
EPC	Electronic Product Code
HCS	High-value Commodities-as-a-Service
B2B	business-to-business
IBM	International Business Machines
B2C	business-to-consumer
PEST	Political Economical Social Technological
IoV	Internet of Vechiles
RIngCT	Ring Confidential Transaction
ACID	Atomicity, Consistency, Isolation, Durability

A. Blockchain

BC at times also referred to as distributed ledger technology (DLT) that works on a decentralized architecture and on the peer-to-peer (P2P) network protocol [32]. In recent years, there has been a great surge in the interest of researchers in the decentralized systems. It is significant to note that tamper proof, decentralized, immutable, scalable, secure, and accessible by all the peers of the network are the main characteristics of the BC technology [33], [34]. It can be visualized as a sequence of blocks, which can be used for storing and sharing data in a distributed manner. Also, the blocks are immutable, thus the data stored in them cannot be altered [35], [36]. The blocks are linked to each other with the use of pointers, forming a chain-like structure. The linkages between blocks are protected with keys, which are encrypted using metaheuristic cryptographic algorithms. Thus, even if any one of the blocks is tried to be altered by the attackers, then the entire BC gets disrupted. This characteristic of BC makes it tamper proof and enables the users to validate the integrity and veracity of their stored data [37]. BC uses technologies, such as cryptography, digital signature, distributed consensus algorithms, etc., which can enhance its efficacy [38], [39].

BC can be classified as a private or public [40]. To access the public BC no specific permission is required and there are no restrictions as such for who can access the BC. The most popular public BC are Ethereum and Bitcoin [41], [42]. Private BCs are the controlled version of the BCs, where a central entity validates the users part of the BC. Thus, to access the private BC one needs to have special permissions to access it. Moreover, it has extensive applications in revolutionizing the business, such as supply chain and logistics, maintaining

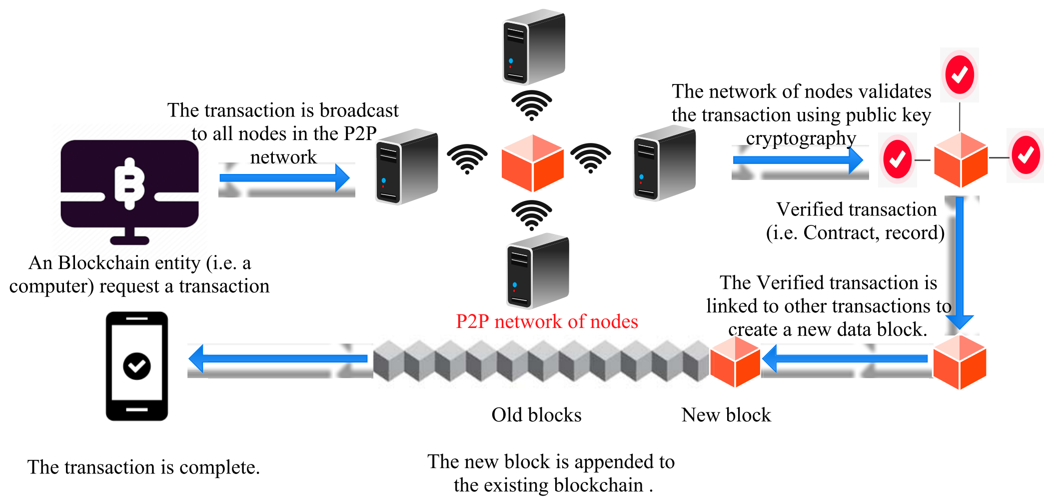

Fig. 2. Operational procedure of BC [45].

transparency in the business process, SCs, smart home, and many others [43], [44]. In the next section, we discuss the main characteristics of BC and its applications in brief.

1) Main Characteristics of BC: BC's decentralized architecture makes it highly robust, tamper proof, and secure technology, though it can be accessed by anyone who is part of the network. Moreover, the BC, unlike centralized systems, is not controlled by a single entity and it has no specific owner. Fig. 2 shows how the operational procedure of BC. Moreover, the subsequent section discusses various terminologies involved in the BC.

1) *Data Block:* BC is a sequence of blocks, forming a chain-like structure. The initial block in the chain is referred to as *genesis block*. With a new block added after a specific time period, the BC expands in size with this new addition of blocks [46]. The block stores information related to: a) the transaction and b) timestamp and is connected with its adjacent neighboring blocks through a hash function. The data block incorporates two main components: a) the transaction records and b) the BC header [47], [48]. The BC header contains the hash value of the block for verification, and the timestamp, which refers to the time at which the block was created, etc. [49].
2) *Distributed Ledger:* It is a sort-of database, in which multiple copies of databases are replicated and shared among the participating nodes in a P2P network. The database shared across the participants can be accessed by all of them who are the members of the network [50]. The distributed ledger stores and maintains the information of the transactions. The timestamp and a unique cryptographic key are associated with the transaction information, which makes the distributed ledger robust, immutable, and secured [51]. Fig. 3 shows the difference between the centralized ledger and distributed ledger.
3) *Consensus Algorithms:* Without the central authority, it becomes obligatory to verify the block authenticity, store the data flow, and assure secure exchange of data in-order to circumvent fraud issues, such as the double spending problem [53]. These issues can be resolved using validation protocols also known as consensus algorithms. In the BC network, a consensus algorithm can be referred to as a process used to reach to a common agreement between multiple untrustworthy nodes on an atomic data block [45], [54]. Bitcoin employs the Proof of Work (PoW) as part of the consensus mechanism [55].
4) *Smart Contracts:* It is a computerized application developed for the BC platform. It is also referred to as a protocol, which makes transaction performance irreversible and traceable in the absence of third party. Post the launch of the Ethereum platform, SCs have been extensively used for various applications [56]. SCs are a self-executable agreement contract developed on the basis of the concept of BC, which are immutable, tamper-proof, and secured against external attacks [27], [57], [58].
5) *Immutability:* It is the primary characteristic of BC-based algorithms that the data stored in a distributed ledger are unalterable over a period of time. It maintains the integrity of the entire system. Each block has a hash key value, connecting it to the previous block and linking it to the next value. To tamper a block successfully, the attacker needs to alter 51% of the ledgers data, stored in the BC network, which is practically not

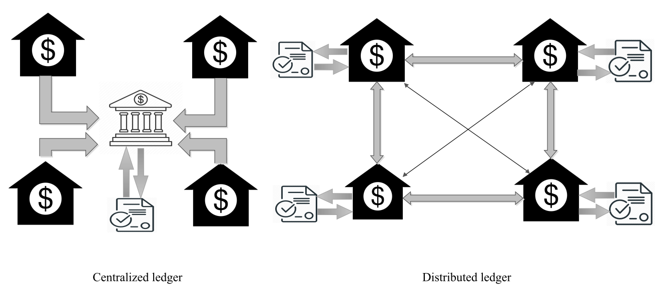

Fig. 3. Centralized ledger versus distributed ledger [52].

possible [59], [60]. These properties of BC enable it to achieve immutability in the system.

6) *Tokenization:* It facilitates the digital representation of goods, services, and rights. It allows the network of different users to exchange values, without involving the central authority [37].
7) *Decentralization:* It implies that the management of transactions does not rely on a central point of control. Instead of rendering transactions between network users contingent on a central authority or third party, BC adopts consensus protocols to verify transactions in a secure and conscientious manner [61]. This prodigious property brings propitious advantages, including eliminating the single-point risk of failure due to central authority disruption, saving operating costs by eliminating the third-party brokerage costs, and also enhancing reliability [62], [63].
8) *Anonymity:* In the BC network, all nodes are unknown to each other, but still the network enables one to transact with unknown nodes reliably and solves the trust issues between the nodes. Thus, BC maintains the privacy of users and also allows them to do transactions with unknown entities ensuring complete trustworthiness [64].
9) *Traceability and Transparency:* It ensures that all the transactions committed in the BC network are organized in a sequential order and the cryptographic hash function binds a block with two neighboring blocks. Thus, each transaction may be traced by analyzing the block details connected by hash keys. Also, the transaction details available on the public BC can be viewed by anyone who is part of the network, which helps to ensure the transparency in the BC network [59], [65].
10) *Validity:* It helps to detect the transactions involving in malicious behavior, which prevents problems, such as double spending, counterfeit transactions, etc. Validity is effectuated by the miners and mining tools. Also, it is to be noted that the validity and consensus algorithms are not the same. For example, a miner is the owner of a particular block, which consists of several transactions. It is possible that the transaction validity has been authenticated, but its not necessary that block would have achieved consensus in the BC.
11) *Security:* BC employs metaheuristic cryptographic algorithms for enabling security in transactions between the participants of the network [66]. There is no apparent mathematical or logical relationship between the private and public keys, which makes it very difficult rather practically impossible to guess the private key of other members from the member's public key. This property of BC safeguards its data against possible attacks and mitigates the concerns related to data leakage [67], [68].

2) Applications of BC (Overview): The concept of linking blocks by cryptographic chains was first suggested by Scott Stornetta and Stuart Haber in 1991. They proposed a system in which transaction or data were stored with the timestamp, which was tamper proof and cannot be altered [74]. The first BC network was designed by Nakamoto and Bitcoin [55].

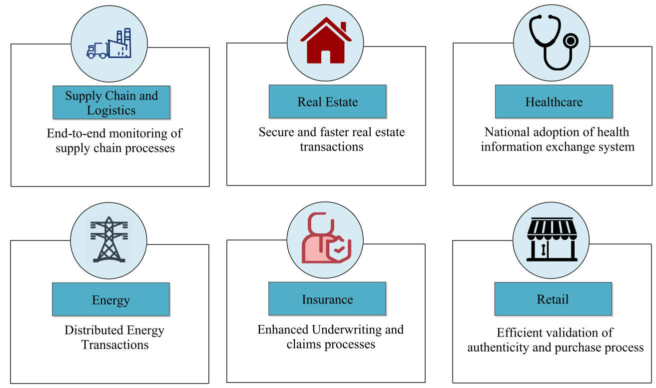

Fig. 4. Applications specific view of BC technology [87].

This network designed by him was for specially implementing cryptocurrency known as Bitcoin [32]. Nakamoto blends the precursory technologies employed for security, such as asymmetric encryption, consensus algorithms [75], Hashcash [76], and the Merklee tree [77] to design the cryptocurrency named as Bitcoin. BC initially used for a cryptocurrency, but today has evolved to such a level that has found numerous applications in almost all the fields, starting from the banking, healthcare [78], and finance sector to the film and art industry for copyright protection [79], [80]. Fig. 4 shows applications of BC in various sectors. From Bitcoin, the concept of BC was extended to other applications in the finance sector such as SCs, they are efficient programs, which are self-executing and irreversible in nature [81]. They ensure trustworthy transactions between two unknown parties. Moreover, they eliminate the involvement of third parties, resulting in reduced operational costs and enhanced efficiency [82], [83]. Also, it has been extensively used for the asset management, such as tracking the history of the asset and storing the details pertaining to the asset efficiently [84], [85]. Also, for processing insurance claims, BC-based application can work as an ideal framework that enables riskless functioning and ease the process of claim settlements [86].

BC is also being used in the fields, such as healthcare, smart city, logistics and supply chain management, Internet of Things (IoT), governance, and other business applications [88], [89]. In healthcare, BC is used to store patients' data securely and monitor the data with the ease of access whilst maintaining the privacy of all the stakeholders involved in it [90]. The supply chain and logistics management can greatly be enhanced by employing the BC-based architecture as it has innate characteristics like transparency and efficacious traceability [91], [92]. They have also been implemented in the retail services sector, attempting to eliminate the intermediaries involved in the trade, thereby reducing the operating costs [93]. BC-based payment transactions can also be done and loyalty schemes based on it are also implemented [37]. In recent years, BC has also been implemented for e-governance systems and in the smart city projects [94]. It has also been used in the real estate field for enhanced speed and security in transactions. Also, it has been used for making the system of copyright and maintaining the intellectual property

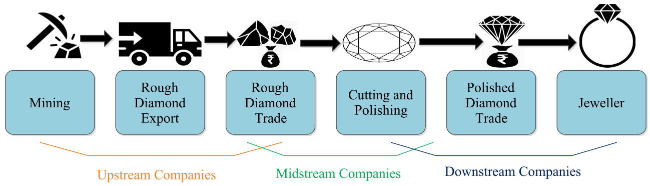

Fig. 5. Overview of the diamond industry [105].

rights more efficacious [95]. Moreover, it has found applications in the energy sector for transactions in the distributed energy network as it aids in lowering the costs of transactions and enhancing the transparency in the process [96], [97]. BC found applications in almost all the fields, integrated with IoT, machine learning (ML), artificial intelligence (AI)-like technologies would lead to a more powerful systems [98], [99]. In a nut shell, BC has revolutionized the operations of various fields and the way data were stored traditionally on our systems. It has led to frugal innovations in the present digital era.

B. Diamond Industry

In this section, we present an overview of the diamond industry and how it is classified on the basis of value chain. Also, we have briefly highlighted the technological advancements that have been brought into the industry.

1) Overview of Diamond Industry: The diamond industry can be classified into three value chains: 1) upstream; 2) midstream; and 3) downstream as it can be visualized in Fig. 5 [100]. The upstream stage in the diamond industry refers to the mining process of the diamonds, which includes how diamonds are sorted and sold in the market to the producers. This stage requires a constant exploration to find the viable locations for mining. The midstream stage is the most intensive stage as it includes a lot of work. In this stage, trading, cutting, and polishing of the rough diamonds takes place. These polished diamonds are distributed to the end users and also the jewellery making takes place in this stage [101]. Finally, the downstream stage involves the marketing and selling of diamonds to the end users, but they want to know whether their diamonds are ethically sourced. This stage is gaining importance as companies are shifting their production models from supply driven to demand driven [102]. The industrial evolution happened from Industry 1.0 to Industry 4.0 has also affected the diamond industry. Earlier, the task of diamond cutting used to be heavily dependent on manual labor, but with the technological advancements, retailers can now perform mass production of diamonds using assembly lines and enhanced cutting and polishing machineries [103]. Cutting machineries are to be chosen in such a way that they maximize the market value of diamonds, which is dependent on the four C's: 1) carat weight; 2) clarity, 3) color; and 4) cut, Nowadays, advanced cutting technologies, such as laser cutting, are being used by the diamond industries. Moreover, advanced diamond planning systems, such as *DiaExpert* by Sarine, are being used by most of the world's leading manufacturers [104]. As the diamond industry evolves, there is a scope for further digitization, which would give more transparency to the process and enforce ethical sourcing of diamonds. These technological advancements would make the stakeholders less apprehensive about the trading of diamonds.

C. Potentials of the BC and Diamond Industry Integration

In the recent years, BC has found extensive applications in high-value businesses such as diamond trading. Reasons for this integration are: enhanced the supply chain, improved the reliability of contracts, for doing secure transactions, validate the authenticity of history associated with the asset, and maintain transparency in the system [106]. In the subsequent sections, we discuss various limitations in the traditional operations of the diamond industry and highlight the probable applications of BC in the diamond industry. Table III describes the key characteristics of a BC and their potentials to the diamond industry.

1) Challenges Faced by the Diamond Industry: In the diamond industry, supply chain is plagued with a lot of shortcomings. Some of them are listed as follows.

1) *Authenticity of Provenance:* One of the major issues with the diamond industry is the lack of trust regarding the authentication of the diamond's origin or the history of their ownership. In the absence of any legitimate technology, the customers have to depend on the experts for the authentication, which may not garner the trust of customers [107].
2) *Ethical Sourcing of Diamonds:* Customers are always keen to know the actual source of the diamonds and they must not be traded conflict or blood diamonds as they are illegal [107]. Despite the established Kimberley process certification scheme, the diamond industry still struggles with the trading of illicit diamonds.
3) *Lack of Trust:* Highlighting, the lack of trust among peers within the diamond industry and also gives the reasoning for it [18].
4) *Forgery and Fraudulent Claims:* The document recording the ownership of the diamond is traditionally on paper and hence is prone to forgery [14]. Many banking institutions have been exploited by fraudulent claims as there is a lack of adequate tracking mechanisms [14], [21]–[23].

2) Opportunities Brought by BC to the Diamond Industry: BC is an emerging technology, which shows promising results for a wide variety of applications. Owing to its characteristics, it has found extensive applications for diamond trading, as given in Table III.

Fig. 6 shows the probable applications of BC in the diamond industry. It completely describes how the information of diamond enters into the BC and how this digital fingerprint can be used for verification and authentication of the diamond. It shows that the value of artifacts like diamonds vary largely based on their historical importance and place of origin. Thus, the authentic provenance for diamond can be maintained by employing BC in it, which will prevent it from frauds, and also verify its history. Moreover, consumers can also validate

TABLE III
MAIN CHARACTERISTICS OF BC AND THEIR POTENTIALS TO DIAMOND INDUSTRY

Characteristic of BC	**Description**	**Potential applications to diamond industry**
Decentralization	Users have complete authority on their data as there is no third party to validate and perform the transactions [45].	Diamond trading involves high value transactions between unknown parties, employing BC removes the need of third party verification for making transactions and eliminates the costs associated with it.
Immutability	The transaction record once written on the block can not be altered or modified and helps to maintain integrity of the BC [69].	The data pertaining to the diamond cannot be manipulated or forged, which provides security against unfair and fraudulent practices.
Provenance	The history associated with entity and its origin is preserved [70].	In artifacts like diamond, the history and origin plays a vital role to determine the price of diamond, BC enables to maintain authentic data related to the diamond.
Traceability	Monitors and tracks the location of entity and maintaining its history [71].	Enhances the supply chain for diamond industry by monitoring the movement of diamonds from mine to till they reach to the market place.
Transparency	It implies all the transactions are visible to anyone on the BC network, which makes the process more auditable and visible [72].	Transparency prevents against counterfeit insurance claims and mitigates the possibilities of insurance fraud in the diamond industry.
Distributed Ledger	It records the transactions securely so that once needed records are replicated at any moment [73].	It scintillates the cross-border transactions in diamond trading, which were traditionally regarded as unsafe and faced issue pertaining to trustworthiness.
Tamper-proof	Implies that no data stored in the BC can be forged or tampered and this aids to preserve the integrity and authenticity of data.	Tamper-proof is one of the key characteristic of SCs, which is beneficial to provide reliability and trustworthiness in the diamond trading.
Security	Blockhain provides security employing encryption protocols and metaheuristic cryptographic algorithms.	It makes the process of storing data of transactions of diamond trading and other information pertaining to the diamonds, highly robust and secure.

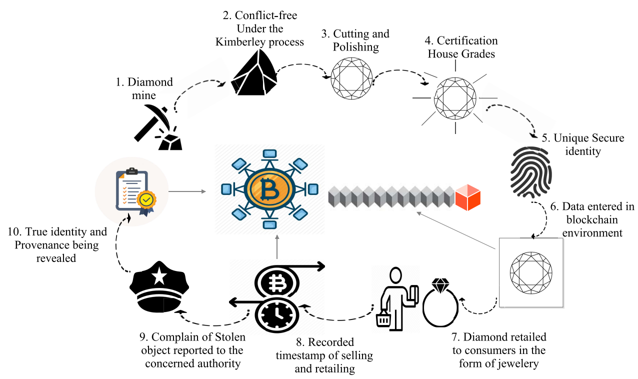

Fig. 6. Flow of execution of transaction in the diamond industry.

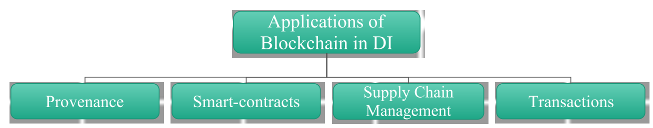

Fig. 7. BC for diamond industry: solution taxonomy.

that the particular diamond is not a "blood diamond." Also, it helps to know about the past owners of the diamond, which provides a protection from the black market and counterfeit transactions. Moreover, properties, such as immutability and tamper resistance of the BC aid in enforcing the idea of SCs. SCs promotes diamond trading at a global level as in diamond trading trust between parties is an important factor. However, with SCs, there is no need of third-party validation, thus giving boost to the diamond trading between unknown parties (without trust). Transparency and traceability help to monitor the movement of diamonds from mines to till they reach to the final market places [108]. Thus, transparency and traceability aid in enhancing the supply chain of raw diamonds as their movement can easily be tracked with BC. Moreover, transparency and traceability protect the theft of diamonds and help insurance companies to identify false claims. It is significant to note that transactions of diamond trading involves a very high value. The BC platform makes the transactions secure and trustworthy, which eliminates the external verification costs for transaction validation [109]. Thus, reducing the operating costs involved in the diamond trading. Overall, BC enhanced the transparency in the diamond markets, preventing transactions of diamonds in black markets, and also make the diamond trading as a safe process, leading to surge in the interest of investors and traders involved in the diamond industry.

III. BC FOR DIAMOND INDUSTRY: SOLUTION TAXONOMY

In this section, we propose a solution taxonomy for the application of BC in the diamond industry. Fig. 7 shows a detailed taxonomy for the same. Then, we have comprehensively analyzed the solutions and architectures proposed by various researchers regarding the adoption of BC in the diamond industry.

A. Smart Contracts

BC technology has been able to support SCs' application, owing to it properties, such as immutability, security, tamper resistance, and privacy. The concept of SCs was coined by Nick Szabo in 1990 [110]. The traditional contract system required involvement of a trusted third party for validation and regulation of the contract, which increases overhead costs and execution time [111]. SCs are self-executing programs, which eliminate the need of third party and are highly secure. They can be build on BC platforms and brought a revolution in the conventional contracts system. Fig. 8 shows the structure of an

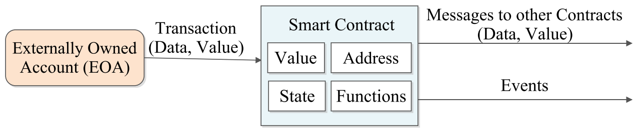

Fig. 8. Structure of an SC to be used in the diamond industry [113].

SC to be used in the diamond industry. It highlights how the external data are input via transactions to the SC and then the SC forms guidelines on how these data are to be treated for further events and control communication with other contracts. It also depicts the key parameters and values, which are part of the SC. In the diamond trading, as a high value is at stake, so the security and trust are key concern between the stakeholders involved in the contract [112]. However, SCs would enable the traders, investors, and other stakeholders to enforce them with security and reliability even if the parties are unknown to each other. Also, the high intermediate party cost involved in the traditional diamond contract system would be mitigated by using SCs. Thus, SCs would enable stakeholders a risk-free service and also mitigate the possibilities of frauds.

The traditional centralized systems have a major flaw, as a single authority captures the control over the entire system, which may lead to corruption, and the misuse of power by the central authority or may result in delay in the approval process. These limitations of the centralized systems were taken care by various researchers. For example, Singla *et al.* [114] proposed a decentralized architecture based on BC technology. They implemented SC for leave management system in Solidity and Ethereum. In their proposed system, the smartphones would work as IoT devices and by it users can access the proposed application [115], [116]. However, due to the resource limitations, the users are not in a position to run the entire BC node on their devices (mobile/laptop). They suggested an alternative classic centralized architecture, which consists of a Web-based interface having node JS server and SQL database with a given number of BC nodes running on it. Users can make transactions using *ethers*, which can be obtained by mining one of the blocks. However, if the user does not run the BC node on his/her system, then the mining needs to be done on the server side. The proposed concept is quite useful, but the mining and scarcity of resources issues need to be addressed. In the midstream diamond industry, tasks, such as cutting, polishing, and shaping of the raw diamonds are carried out. Thus, midstream is a labor-intensive industry and the proposed leave management system may be a boon for the diamond industry as it enables to efficiently monitor the workforce. Also, beneficial for the employees due to ease in accessibility of the system. The SC-based application can also be extended to other similar applications for the diamond industry.

Disruptive technologies being implemented by various researchers and are thought as advantageous over the traditional centralized systems. For example, Karamitsos *et al.* [117] proposed a BC-based SC application, which can be used for various applications, but they elaborated its usecase only for the real estate. Their proposed decentralized architecture was developed on the Ethereum platform using Solidity, which would reside on the Ethereum Virtual Machine (EVM) block. The task of implementing traditional contracts for renting the assets in real estate are very tedious as it involves a lot of paper work and also time consuming. Thus, to overcome these limitations and to ease the process of payments, the SC system was proposed. Moreover, the proposed system enables the secure transactions between the parties who might lack of trust. Also, their system eliminates the need of intermediaries, such as Notary, etc., used for validation purpose, as the transaction can be validated by the system itself. Also, the tenants might have to pay for additional services, such as cooling, maintenance, etc. Their system enables the tenant to pay for the extra services directly to the concerned party and the base rent amount directly to the landlord. Thus, their proposed system is highly comprehensive for real estate and strengthens the overall development of smart cities. Diamonds are assets, which are also available on rent and the proposed system can be implemented for diamond rental system. This might be beneficial for the diamond industry as it will enable safe transaction between parties lacking trust. Also, it makes the process of renting of diamonds simple and secure. Their proposed system can be extended for renting of diamond factories, machinery, instruments, etc., used in the diamond industries. A similar decentralized app for renting and sharing of entities was proposed by Bogner *et al.* [118], implementing SC developed on the Ethereum BC. The traditional platforms like Airbnb has tedious registration procedure and also lacks in maintaining privacy of users. Their proposed system enables renting of items without the involvement of third-party verification and without revealing users private information. The proposed app can also be used for the diamond renting system, which strengthens the process of diamond sharing/renting.

The heretic paper certificates are easily forgeable and can also be altered, which decreases the credibility of such certificates. Thus, to combat such prevailing issues of counterfeiting of the certificates, Cheng *et al.* [119] implemented a BC-based SC system for digital certificate. As the BC itself is immutable, tamper proof, and verifiable, it can be used for the digital certificate application. In their proposed system, they generate an electronic file of the paper-based certificate, incorporating other related information into database, and calculate the hashvalue corresponding to the electronic file. Then, this calculated hash value will be stored in the BC system. Then, the system generates a QR code associated with the paper certificate. It will enable the user to validate the veracity of the paper certificate. The system was developed for the education field to verify the marksheet, degree certificates, and transcripts of the student. However, the proposed system can also be used in the diamond industry for the digital certification of the diamonds quality. The value of diamonds largely varies based on their quality, such a digital certificate system would enable to enhance the credibility of the certificates and prevent them from forging to take unfair advantages. Also, the proposed system mitigates the chances of loss of certificates. Thus, the proposed system based on the concept of SC can be extended for digital certification of diamonds, which would bring transparency in the diamond certification process and limit the malpractices in the diamond certification.

Trading of entities involves lots of intermediaries, which increases the cost of it. Also, in trading of entities, such as energy, etc., the calculation of exact price is a tedious task. For example, Han *et al.* [120] proposed an SC framework based on the BC for the trading of energy. It enables the transaction between the buyers and sellers in the energy retail market. Moreover, as the SCs are self executing based on the conditions of the contract, they are highly reliable and secure. Their proposed energy trading mechanism uses a double auction principle to enable trading directly between the buyers and sellers and also restrict their transaction behaviours. Double auction is appropriate for markets, where multiple buyers and sellers are involved. Their proposed system consists of closed bidding, exchange of energy, and the settlement of transactions in an efficient way. Moreover, visual interface is provided for the users so the traders can communicate on the platform that uses Solidity as the coding language. If the buyer has a predilection for renewable energy then it can be included in the proposed system. Thus, their proposed system matches the buyer with seller and also facilitates a secure payment procedure. Their system can be extended for trading of diamonds at global level. However, it is difficult to get the appropriate price of the diamond as many factors influence the pricing of diamonds. Moreover, these systems will enable to connect the interested buyers and sellers of diamonds globally and by enabling trade between mutually disrespectful parties in a reliable and secure way. Also, the amount of money involved in diamond trading is very high and also involves intermediaries. However, their proposed system eliminates the need of third parties and also facilitates a secure payment method. Thus, the proposed system based on the concept of SCs can be extended to enhance the heretic diamond trading methodology, which might suffice to be highly efficacious for the diamond industry.

In industry 4.0, technologies such as IoT is being incorporated with the current production mechanisms. For example, Christidis and Devetsikiotis [56] discussed how BC and SCs can be combined with the IoT environment. They highlighted that supply chains can use BC and SCs in combination with IoT, which confirm timely delivery of a container carrying goods to the destination port. When the container reaches the delivery port, then the SC mentioning the details of the delivery along with the timestamp gets added to the BC. For a complete automated process, they suggested to integrate Bluetooth Low-Energy (BLE) radio and GSM or LTE radios along with the BC client. These radios can communicate with each other as soon as the container arrived and no human intervention is needed. The BLE radio helps to trigger the transaction when the devices are in the proximity. Another way to integrate IoT in the BC network is to use sensors with long range radio called *tap*. They can communicate with each other using SCs and a secure protocol called *Telehash*. Sensors connected to the gateway instead of connecting to each other and also helps in the reduction of deployment cost. A similar technique can be applied in the diamond industry with the onset of industry 4.0, IoT, and SCs can be merged to efficaciously carry out the supply chain process. This technology can be used when dealing with high-priced assets like diamonds, and diamond shipping can be combined with IoT and SCs to ensure that the shipment status is automatically updated without any human intervention.

In traditional power trading systems, the producers and consumers have separate roles, which enables a more real-time and flexible trading of power microgrids and how to enforce safe and secure trading of power between *prosumers* using SCs [121]. The prosumers are considered to be consumers of power and also a small-scale generators of them. To enable instant supply of power between individuals without the intervention of a third-party agency, we need a secure and accountable method for power trading. This can be achieved with SCs that implement the power trading algorithm on the Ethereum BC platform, which is written in Solidity language. In their proposed algorithm, a network topology consisting of light and full nodes is created in which the smart meters of the prosumers act as the light nodes and the power trading platform that offers the computing power acts as the full node. The trading of the power supply takes in the form of auction and the steps of the auctioning algorithm are as follows: initialization, bidding, close, withdraw, and finally, the power supply. In the initialization phase, the SC contains the agreement parameters, such as the amount of supply, time of supply, minimum bidding, auction time, etc. In the auction, the highest bidder at the end of the auctioning time gets the power supply deal. The various functions of the SC are: *Auction*(), which is used to initialize the SC, *Bid*(), which is used to check the constraint of the auction and to begin the bidding process, *Auctionend*(), which is used to choose the buyer and stop the bidding process, and finally, *Withdraw*(), which is used to withdraw the leftover balances. This mechanism is also applicable to diamond industry and the diamond auctioning process can be automated using a similar SC algorithm. This helps to carry out the trading of diamonds via auctioning efficiently and with least human intervention. It is a highly automated process, which eliminates the need for trusting agencies for trading purposes and also eliminates the user intervention.

The lack of trust between the contemporaries is a major issue while making transactions, with the current BC architecture since every transaction is available on the ledger and also visible to all users, which may compromise the privacy of the stakeholders. To handle such a scenario, Kosba *et al.* [122] proposed a decentralized SC system that prevents the transaction from being publicly visible on the BC and thus giving some privacy for the transactions. This system is named as *Hawk*, in which the *Hawk* programmer can code a private SC without implementing cryptography. Here, an efficient cryptography protocol is initiated by the compiler though which the parties can interact on the BC, such as the zero-knowledge proof protocol. Their proposed framework is intended to be extremely intuitive to program and no special programming skills are required for it. Thus, making it extremely user friendly and is divided into two contracts namely: public and private contracts. The public contracts are coded in the Serpent language for the BC platform like Ethereum, whereas the private contracts are written in C language and then passed via the Pinocchio arithmetic circuit compiler. In their proposed framework, they gave a few instances such as the second price auction, where auction and the highest bidder wins the prize, but he/she does not have to pay the highest bid amount, instead the winner has to pay the second-highest bid amount. This type of bidding requires that people are unaware of other people's bidding amount. The private contract portions decides the winner of the sealed auction and decides the amount to be paid by him/her. Also, it makes sure that the participant's data are secured and the amount of money exchanged is also hidden from the others participants. The public contract does not interfere with the private information, such as the exchange amount or the participant's data. Moreover, it protects the auction against defaulters, if a party decides to abort prematurely, then the public contract can be looked after penalizing that person and compensating the rest of the bidders. This type of auction strategy can also be taken against the manager of the auction, thus not giving any unfair advantage to the manager. The diamond industry can also be benefited from this framework as it helps in maintaining the privacy of transactions, and being a high-priced asset industry. The competitors are often demotivated to use BC, owing to its transparent nature. Moreover, it helps the users to be more open toward the adoption of BC architecture for trading.

Employing the SC in industries raises security concern of these SCs so various rehearser explored this issue. For example, Kalra *et al.* [123] predicted that 94.6% of the contracts worth about $0.5 billion are vulnerable to bugs, once they are deployed. Motivated from this issue, they proposed the *ZEUS* framework to prevent SCs from bugs after deployment, and they have also verified the authenticity and exactness of these contracts. They focused on ensuring that the SCs have syntactical correct and are fair in the sense that they uphold high standards of business ethics. In traditional SC code, any syntax error can cause a flawed execution and sometimes also results in an unfair scenario. The ZEUS framework basically employs abstract interpretation and symbolic model checking of SCs that given as input into the framework. It is an automated authentication process for SCs [125]. The SC is given as input, the high-level language of SC and the framework helps to create a correctness and fairness parameters on the extensible access control markup language (XACML) type template. Then, their proposed framework converts the SC and the binding policies into low-level intermediate representation (IR) such as the low-level virtual machine (LLVM) bitcode [126]. This IR document is then analyzed statically and then suggested verification predicates are added to the document. Ultimately, this modified IR document is rendered to the verification engine where the SC's authenticity is judged on the basis of constrained horn clauses [127]–[129]. Over 22 400 SCs were tested for vulnerability and 94.6% of them were vulnerable. ZEUS has provided ground results by rendering in almost zero false negatives and very rare false positives.

Current data sharing practices raise concerns regarding formation of trust between the parties and the level of user involvement. For example, Xuan *et al.* [124] have proposed an incentive-based method for data sharing via BC using SC. Rather than relying on a third party for ensuring mutual trust, they proposed a novel incentive mechanism based on the evolutionary game theory, which can help in dynamically controlling the excitement parameters of the participants and also encouraging them to participate in sharing their data. In their model, there are four conditions of evolutionary game theory that drive the model. At the first stage, there is less participation by the users and condition 4 is used to provide more incentive to the participants so that more amount of data can be shared, after a certain threshold limit, the data sharing can be limited by using a condition 1 to impose a participation cost. Many such stages are iterated until the optimum level of user data sharing is achieved. Later, a detailed unified modeling language (UML) diagram is also described to show how this model can be adopted in SC so that it can be deployed on the BC platform. Such a model can also be beneficial for the diamond industry, as it will help build trust within the stakeholders and enable more transparency of the process. Table IV shows the relative comparisons of SC-based security solutions used for the diamond industry.

B. Provenance

Provenance of an entity is the history associated with the entity incorporating the information of the origin and history of the ownership of the entity. Precious goods and artistic materials, such as jewellery and sculpture are valued based on their historical importance associated with them. Thus, to ensure their origin and validate their history, a efficient provenance mechanism is to be employed. The BC-based system for diamond provenance can prove to be highly efficacious. Diamonds provenance can aid the buyer of the diamond to ensure that purchased one is not a blood diamond. It enables the potential buyers to validate that the diamond was obtained from a legitimate source. Moreover, it also verifies that the diamond is not stolen one and helps to save it from frauds [130]. It also helps in validating the history of diamonds and preventing them from malpractices [131]. It also helps the sellers to get appropriate value for their diamonds. Provenance would also prevent from diamond transactions taking place in the black market. Provenance would enable the traders and investors to transact diamonds reliably and trustfully. It enables the government to validate that there are no illegal or unreported taxes for the artifacts, also protecting them from illegal activities like smuggling. Provenance has been proven to be a critical aspect of the movable assets like diamonds [23]. Increasing manufacturing of synthetically created artificial diamonds, it is of a crucial importance for the buyer to ensure that the diamond is natural and not artificially created [132]. BC owing to its characteristics, such as immutability, open ledger, and transparency can be used for efficient provenance mechanisms [133].

The provenance of jewellery artifacts is very critical and there was an exigent need to develop efficient solution for provenance of valuable artifacts and jewellery. For example, Orenge [134] developed an architecture based on the BC technology for provenance of jewellery items and presented a proof of concept for application in handicraft jewellery by a case study. The system was known as *provJewellery*, which is a decentralized application for the provenance of handcrafted jewellery. The mapping process is carried out and the physical

TABLE IV
RELATIVE COMPARISONS OF SC-BASED SECURITY SOLUTIONS FOR THE DIAMOND INDUSTRY

Author	**Year**	**Proposed Area**	**Key contributions**	**Probable extension to the diamond industry**
Bogner *et al.* [118]	2016	Renting and Sharing Services	The presented decentralized SC-based system enables entities to rent and share assets not requiring involvement of a trusted third party and maintaining privacy of the users.	The system could be extended for leveraging of machinery, human resource, etc. in the diamond industry among various organizations.
Christidis *et al.* [56]	2016	Integrating SCs and Internet of Things.	The shipping containers were equipped with radio and sensors which automatically enabled the authentication and delivery status update as they reached the destination port.	The proposed method can be employed for shipping of diamond and integration with IoT for seamless transitioning to Industry 4.0.
Kosba *et al.* [122]	2016	Enhancing privacy of transactions on the BC.	Their *"Hawk"* framework aims at enabling privacy of transactions using public and private SCs and this helps in maintaining the anonymity of the amount of exchange.	This framework can be applied for promoting the use of BC for auctioning and trading of diamonds, as traders are often reluctant to use BC due to its sheer transparency.
Kalra *et al.* [123]	2018	Enhancing SC's correctness.	Their *"Zeus"* framework helps to increase the correctness and reduces the vulnerability of the SCs after their deployment by adding verification predicates to the SC.	As discussed there are several ways in which SCs can be used in diamond industry and consequently such framework can be adopted to increase the security of SCs and make them less vulnerable.
Karamitsos *et al.* [117]	2018	Real Estate	They proposed a system employing SCs for real estate asset management which eases the process of renting of assets and saves time by reducing the paper work required.	The proposed system could be employed for managing the process of renting of diamonds.
Myung and Lee [121]	2018	Power Trading	They proposed SCs for secure auctioning and trading of power supply in the efficient microgrid power distribution environment.	The proposed system can be used for human interaction free auctioning process of diamonds, it promotes a more secure auctioning process for high priced assets like diamonds.
Cheng *et al.* [119]	2018	Educational Degree- Digital Certification	The proposed system was able to overcome the issues of heretic paper-based certification like forgery, counterfeiting and ensure reliability of certificate.	The architecture could be extended for certification of diamonds in the diamond industry, as ensuring authenticity of information is a big problem for the diamond industry.
Singla *et al.* [114]	2019	Educational Institutes-Leave Management System	The system was proposed to combat the issues in traditional centralised architecture like misuse of authority, unnecessary time lag for approval.	Diamond industry is labour oriented and the proposed system would aid for efficacious human resource management in the organizations.
Han *et al.* [120]	2020	Energy Trading	Suggested framework employing SCs enables to trading of energy take place directly between buyer and seller without involvement of external parties and ensure reliability and security in the process.	Framework proposed could be incorporated for trading of diamonds, it would promote trading of diamonds at global level with ease and high reliability.
Xuan *et al.* [124]	2020	Data sharing incentive model for BC platforms using SC	The proposed model introduces an incentive based model based on evolutionary game model to promote optimum level of data sharing among participants.	The proposed model can be used for diamond industry as it will help to build more trust among the stakeholders and enable a more transparent procedure between them.

jewellery is linked to its corresponding digital record using the QR code technology. The QR code tags are capable of uniquely identifying an item. At the backend, the system maintains the data related to the jewellery in MySQL database and Django is employed as the webserver in their proposed system. It enables to track and trace a single piece of the jewellery from its origin till final delivery to retail stores. The system is build in such a way that scanning the QR code facilitates with a link, which accessed the history of the jewel from its place of origin. Their proposed system is implemented on a public BC network employing the Ethereum platform. This can be used for the provenance of handicraft jewellery and has additional functions, such as transparency and validation, and allows to transact the jewellery by implementing SC. The proposed system can be extended for provenance of diamonds, which act as an authenticate source as it contains history of diamonds. The proposed system enhances the process of trading of diamonds and beneficial for the over all growth of the diamond industry.

The traditional paper-based solutions or maintaining simply a database for the provenance of artifacts is inefficient as the data can easily be forged and manipulated by the attackers. Thus, traditional systems faced a lot of problems and there is need of an efficacious provenance mechanism for jewellery and other artistic works. For example, Ivan [135] proposed a novel BC-based system, employing the Hyperledger Fabric for tracking provenance of handcrafted jewellery. It also uses other related data, such as purchase order details, etc., and integrated with SCs to get more benefits out of the system, such as monitoring the supply chain process, digital certification, etc. The Hyperledger framework was used to authenticate the identity of users, which prevents from malicious users entering into the network. Moreover, Hyperledger is scalable and comprehensively designed, which facilitates to use plugins with it. Also, the system is build in such a way that it monitors the complete process from the order placement till the order is delivered and transfer of ownership and payment is successful. Their proposed system helps artisan workers and can be extended for the provenance of diamonds. For diamonds, the place of their origin and their historical importance are essential factors to decide the price of diamond. Thus, the proposed system if employed for diamonds can act as an authenticate platform to validate the historical data of diamonds. Thus, the proposed system if extended for diamond industry would reduce the overhead and operational cost involved in diamond trading.

The provenance of luxury goods or movable physical assets has been an area for the interest among the researchers in recent years [136], [137]. BC-based solutions have shown significant prowess for the same. For example, Kim and Laskowski [138] suggested a BC-based solution for provenance and supply chain traceability of goods. The ontology-based BC system employed SCs for maintaining the provenance trace and it was build on Ethereum. The TOVE traceability ontology is employed as an integral part of the proposed BC-based solution. The traceable resource unit (TRU) is used as a representation of entity and it is assumed to be traceable owing to the fact that it is neither an abstracted nor an aggregated entity. The Truffle framework was employed to build an interface, which facilitates to interact with SC deployed on the system, and also formulating predicates, inputs, and defining the state of objects. TRU are immutable so they can not be altered. As the proposed SCs are immutable, tamper resistant, and coupled with Web technologies so they serve as great tool for implementing the provenance system. The proposed system can be extended for the provenance of diamond in the supply chain or for the provenance in general. The efficient provenance system can aid in reliable diamond trading even when distrustful parties are involved and it would be a great boon for the trading of diamonds at international levels.

In the food industry, it is important to trace the provenance of the products, and due to more awareness, the consumers are keen to know from where their food is coming and they want a more transparent process. For example, Malik *et al.* [139] proposed a three-tier consortium framework called *ProductChain*, which focuses on reliable tracing of food items from farm to fork. Their system works in synchronization with the key entities of the food supply chain, such as the food testing laboratories and other government institutions. Their framework provides all the essential data to the stakeholders and the consumers, whereas it also promotes maintaining the data privacy from competitors. There is a scalability issue entangled with tracking all the movements of a food product, which can be rectified using *shards*. These which are parallel BCs, and use to do parallel processing instead of sequential, and each shard has its own local ledger to record activities. These shards are organized on the basis of geographical locations. The members of this framework are categorized as: nonparticipating, participating, governance board, and validators and each member has their own level of access rights in the BC. The participants are able to view the transactions made by them only, and if the consumer needs to access the complete transactions, then the global validator keeps a query engine to give full or partial representation of a product's ledger. The three tiers are as follows: 1) Tier 1 consists of participants and non participants, actors of the food supply chain (participants) and the consumers (nonparticipants); 2) Tier 2 consists validators, which maintains all the local ledgers and parallel shards run in this tier; and finally, 3) Tier 3 is the BC query manager where the consumers can look up the product story. This framework can be applied to diamond industry to efficiently handle the scalability issue while tracking the detailed provenance. This would also increase the consumer's trust in the system since this framework incorporates governance authorities too.

Querying a large BC database to trace the provenance of a product is an offline process as this type of querying cannot be accomplished efficiently in an online mode. For example, Ruan *et al.* [70] implemented a novel provenance architecture called *LineageChain*, which can provide information related to provenance at runtime. They have also incorporated a novel skip list index feature in their framework for efficient query processing. With the help of SCs, they are able to provide provenance information at the time of execution. The information is provided to the users with an interface to the SC, and for the secure transactions, they made use of the Merkle Tree hashing system, which provides efficient authentication. To address the challenge of provenance query processing time, they introduced a novel skip list index feature, which allows them to sustain small storage overheads and makes the performance of querying independent of the size of BC. Their proposed architecture was implemented using Hyperledger, and it uses ForkBase [140], which is a BC-optimized storage for its implementation. The results show that their architecture is extremely efficient in query processing and also does not incur a large storage overhead. A similar system can be adopted in the diamond industry, which provide their customers with runtime provenance facility and, also enables SC applications to integrate with provenance tracking.

Ramachandran and Kantarcioglu [141] proposed a system called *SmartProvenance* that used BC to correctly record the provenance data and self verify all the provenance records and also manage them. They made use of SCs and open provenance model (OPM) to record all the immutable BC data footprints. The, the existing systems did not verify the changes to provenance before they were immutably stored in the BC. Their system *SmartProvenance* resolves the aforementioned issue by validating all the changes before they are logged on the system with SCs. The proposed system uses Ethereum BC with the Meteor framework, and them penalizing for the wrong provenance changes. Verification for provenance changes is done via a voting mechanism, in which the initiator suggests the changes to be made to an existing record. These changes are verified and compared to the original document and then a timer automatically starts when the changes are suggested by the initiator. In the voting process, two types of voting procedures are followed: 1) majority voting and 2) randomized voting. If the changes are approved by voters, then the deposit of the initiator is refunded; whereas, if the changes are deemed wrongful by the voters, then the deposit amount of the initiator is distributed among the voters. This promotes the desirable behavior among the initiators and also gives incentive to the voters to take part. The votes are taken into consideration until the timer terminates. The diamond industry can make use of this *SmartProvenance* system to enable secure gathering

TABLE V
RELATIVE COMPARISONS OF PROVENANCE-BASED SOLUTIONS FOR THE DIAMOND INDUSTRY

Author	**Year**	**Proposed Area**	**Key contributions**	**Probable extension to the diamond industry**
Orenge *et al.* [134]	2018	Jwellery-ProvJwellery	Decentralized application for provenance of typically handcrafted jewellery incorporating the QR code technology for maintaining digital record.	The proposed framework could be employed for maintaining credible history pertaining to the origin and source of diamonds.
Kim *et al.* [138]	2018	Provenance and traceability of goods	The proposed architecture is capable of tracing the goods through its entire process of supply chain.	The system could be employed for maintaining authenticate information pertaining to provenance of diamonds.
Malik *et al.* [139]	2018	Scalable provenance in food supply chain	Their framework put forward parallel BC concept called *"shards"*, it helps with scalability issues while tracking provenance.	The framework can be extended to diamond industry to efficiently track provenance and safeguard the trust of consumers.
Kantarcioglu *et al.* [141]	2018	Self verifying BC provenance system	They proposed *"SmartProvenance"*, which enables system to verify suggested changes to the provenance with the help of voting mechanism and promotes trustworthy behavior with system of reward-penalty.	This system can be useful to ensure that only verified changes can be made to provenance details and can help to reduce ownership frauds like insurance claim frauds.
Ivan *et al.* [135]	2019	Artifacts and handicraft jewellery	The proposed system resolves the issue of provenance for handicraft jewellery, also incorporates digital certification, purchase order details in the system.	The system could be extended for maintaining authentic data related to the history associated with the diamond.
Ruan *et al.* [70]	2019	Efficient and Improved data provenance on BC	Proposed *"LineageChain"* architecture for provenance, which enabled efficient querying of data along with incurring minimal storage overhead.	The architecture could be useful for querying provenance efficiently and securely and also useful for implementing provenance with the help of SCs.

of data and verification of the provenance data before it is immutably saved on the BC. This may help to prevent fraudulent insurance claims in the diamond industry, which often arise due to ownership issues.

BC-based various platforms are available for authentication and provenance of diamonds. For example, Choi [142] analyzed various platforms employing BC for the task of provenance of diamonds. Also, analyzed the usability and benefits of BC technology supported platforms against the traditional platforms, which employed traditional databases to store information. Results show that employing the BC-supported platforms for task of authentication and provenance of diamonds had more value and advantages compared to traditional systems. For the trading of diamonds, the consumer wants to make sure about the origin of diamonds, veracity of the information of diamond pertaining to the history of diamond, and the diamonds specification are authenticate. Thus, value proposition for integrating BC supported platforms for tasks of the provenance is very high and would be beneficial for consumers as well as manufacturers. Table V shows the relative comparisons of provenance-based solutions used for the diamond industry.

C. Supply Chain Management

The supply chain management is one of the most critical business processes for any industry. The process of supply chain includes the products and services and encompasses all processes, which transforms raw materials into finished products [143]. It requires effective streamlining of supply side operations of the business to enhance the customer value and gain a competitive edge in the industry [144]. Also, efficacious supply chain process aids organizations to reduce their operational costs and to sustain their position in the global market [145]. However, supply chains are highly tangled and consist of multiechelon, geographically dissevered entities vying to increase their business and gain customers [146]. Globalization, complex government strategies, and diverse cultural and human practices in supply chain make it very challenging to analyze information and the associated control risk in it [147], [148]. Inefficacious transactions, counterfeiting, pilfering, forgery, and inefficient implementation of supply chains, result in the lack of trust and thus, there is a need for the enhanced sharing of information and legitimacy [149]. BC, owing to its characteristics, such as transparency, traceability, and tamper proof, is used in supply chain management process. BC integrated with supply chain leads to renaissance in the business processes of various industries [150]. In the supply chain management, as the BC is immutable, it mitigates the possibility of fraud, due to the efficiency in tracking facility, which results in decrease in costs, and obliterates the need of paperwork. Thus, it reduces the time required and owing to the enhancement in visibility, it leads to the enhancement in trust in the entire process involving multiple stakeholders. Also, BC can facilitate transactions employing cryptocurrencies between the suppliers and buyers, rather than relying on electronic data interchange (EDI).

The supply chain is a critical process for the diamond industry and Fig. 9 represents the processes involved in supply chain for diamonds industry. The first step is to discover probable places where diamonds might be found and mining is to be carried out to extract the diamonds. After the raw diamonds are obtained, they go through various processes, such as cutting, polishing, etc., and multiple parties are involved in the same. Thus, many stakeholders are involved in the supply chain of diamonds and it is important that the authenticity of the data pertaining to the diamond is maintained in the process. It is significant to note that for supply chain involving high value, precious goods like diamonds traceability is of crucial importance. BC, owing to its inherent characteristics,

Fig. 9. Overview of diamond supply chain [152].

such as immutability and transparency, has found applications in the diamond supply chain management process. Also, BC-enabled supply chain management system helps to build robust and traceable supply chain networks involving transaction of entities like diamonds [151].

International business machines (IBMs) with an idea of supply chain management for high-value commodities proposed the use of their signature platform LinuxONE system, for developing architectures for efficient supply chain management [153]. The LinuxONE platform employs the BC framework and facilitates various companies to build and test BC-based frameworks on the cloud platforms for their use. The service is targeted for companies whose supply chain is complex and involves high-value products like diamonds. Thus, the LinuxONE platform might prove to be efficacious for the supply chain management of diamonds. Moreover, the diamond industry is an 150-year-old industry that functions on the basis of trust. Traditional functioning of the diamond industry involving paper-based record maintenance, which is difficult to manage and easy to be manipulated. Thus, the BC-based framework involving the creation of permanent records, which cannot be altered are highly suitable for tracking and maintaining transparency in the supply chain. Thus, their proposed platform could be employed for developing system, which would suffice to be efficacious for the supply chain management for the diamond industry.

In real life, validating the genuineness of the goods has always been challenging task. Technologies like radio-frequency identification (RFID) had been employed over the years for detecting frauds in the supply chain [154]–[156]. But, RFID is not sufficient to maintain authenticity about information of ownership and other related data, as anyone who has access to RFID can manipulate and replicate tags' information. In the present era, BC-based systems have found applications in the field of supply chain and related areas. Toyoda *et al.* [157] proposed an innovative product ownership management system (POMS) based on BC to protect against frauds in the supply chain and post supply chain. The proposed system allows only authenticate manufacturers to claim the first ownership. It enables the buyer to verify that ownership of the product is in the name of the seller only. Their proposed system was developed on the Ethereum platform, employing Solidity as the scripting language. It maintains authentic information pertaining to the ownership record of the product and to achieve it, two types of SCs are implemented, namely, Manufacturer Manager (MM) and Product Manager (PM). MM is implemented to manage information and PM is managed by each manufacturer to manage the information related to the products. In MM, only the administrator can make changes, which is against the idea of decentralization. However, it is implemented for the protection against fraud activities. Various algorithms, such as *enrollManufacturer(), checkAuthorship(), enrollProduct(), checkAuthorship(), shipProduct(),* etc., were implemented to achieve the objective of the system. Their proposed system enables the buyers to decline the purchase request of counterfeits, even with a credible electronic product code (EPC), subject to the condition that the seller does not possess their ownership. The cost is evaluated based on the proof of concept, which turns out to be $1 for upto six transactions of ownership. The proposed system can be extended for maintaining the ownership record of diamonds through the entire diamond supply chain and post it. This system would aid in eradicating malpractices in the diamond industry and prevent from frauds in diamond trading. Also, it maintains transparency in the entire supply chain procedure of diamonds.

In the recent years, supply chain in various industries employed IoT technologies and devices. However, the most state-of-the-art IoT-based traceability and supply chain management systems were developed in a centralised cloud architecture environment, which has issues, such as the lack in transparency and security concerns, such as tampering, data privacy, integrity, and auditability [158], [159]. To combat the aforementioned issues, Caro *et al.* [160] proposed a novel BC-based decentralized architecture named *AgriBlockIoT* for traceability and transparency in the Agri-Food supply chain. The system is implemented either on Ethereum platform or Hyperledger Sawtooth platform, which are publicly accessible. Moreover, it is competent to incorporate and integrate various IoT sensor gadgets. *AgriBlockIoT* ensures consistent and auditable, and traceability of assets. Various functionalities and the business logic were incorporated through the implementation of SCs based on the BC technology. The system is evaluated by deploying it for a typical *from-farm-to-fork* scenario, it implies from the cultivation of crops in the field (farm) to till the consumer consumes it (fork). The results show that the Hyperledger Sawtooth framework is more suitable for the proposed *AgriBlockIoT* system. A similar approach based on RFID and BC technology was proposed by Tian [161] for China Agri-Food supply chain. It uses traceability of trustworthy information in the agri-food supply chain that will efficaciously ensure food protection by gathering, storing, and exchanging the accurate agri-food details in production; Links to process, warehousing, storage and sale. The proposed *AgriBlockIoT* system can be extended for the application in the diamond supply chain to ensure transparency, traceability, and auditability. Also, it maintains the authenticity of information in the complete process and movement of diamonds from their mining to the consumers.

There has been a surge in interest among researchers in the decentralized system in the recent years. Supply chain involving high-value precious commodities, such as diamonds, gems, and artworks are unreliable and lacks trust. To overcome these challenges in trading of luxury goods, Xu *et al.* [162]

presented a novel efficacious supply chain framework based on the BC technology. They proposed a platform namely high-value commodities-as-a-service (HCS) to integrate BC with the high-value goods. HCS is built on the Ethereum platform and used to trace the goods, reliable data security, protection against frauds, and settlement of transactions. The system tracks the goods from their point of origin, i.e., when they are registered on the system. It also facilitates the transaction settlement procedure as the system has its own credit system. SCs are incorporated in the system to assure that all the transactions are equitable and transparent. The history pertaining to goods in the system is authenticate and can be validated. Various functions are incorporated in the system to facilitate a seamless supply chain management system. This system helps to make the supply chain process of diamonds more transparent, trustworthy, and secure. This system could be a boon for the diamond industry as it may attract the attention of investors for the diamond trading and promote transactions of diamonds at global levels.

The traditional textile supply chain system are cumbersome and tangled, owing to the involvement of global suppliers selling their product across the continents. The heretic cross-border supply chain systems not only suffers from the issue of traceability but also fails to maintain transparency in the process. To resolve the persisting issues, ElMessiry and ElMessiry [165] proposed a novel BC-based framework for supply chain management in the textile industry. The textile industry supply chain is prodigious in size involving numerous process, such as weaving, dyeing, etc. Also, their proposed system maintains the quality of goods and not letting it deteriorate at any point during the manufacturing process. The initial step in the supply chain is about the seed and fiber type of material creation, followed by the entire manufacturing process. The transactions in the manufacturing process are recorded in the system and organized in such a way that the previous process of the goods linked with the present status. Fig. 10 represents the workflow of the supply chain industry. The system is automated such that the machine itself validates the reported history from the confirmed owners. After the processing of material, the machine is capable of automatically posting the results to the BC. The consensus protocol is employed, which raises a flag in case there is defect in the material batch. The proposed system can be used for the diamond industry supply chain as the diamond supply chain is also a quite complex process and also involves multiple process.

With the growth of e-commerce trade, it is important to explore systems that will help in managing the e-commerce supply chains. Moreover, with the globalization and growing trade practices, the cross-border trade between business-to-business (B2B) and business-to-consumer (B2C) has also increased. Liu and Li [166] proposed a framework using BC to address the issue of supply chain management for cross border e-commerce. Their objective is to enable BC-based product traceability using novel multichain structure model framework, which facilitates the data management and system design. Their framework used the hierarchical deterministic wallet to enable multi stage management of keys. It also manage keys,

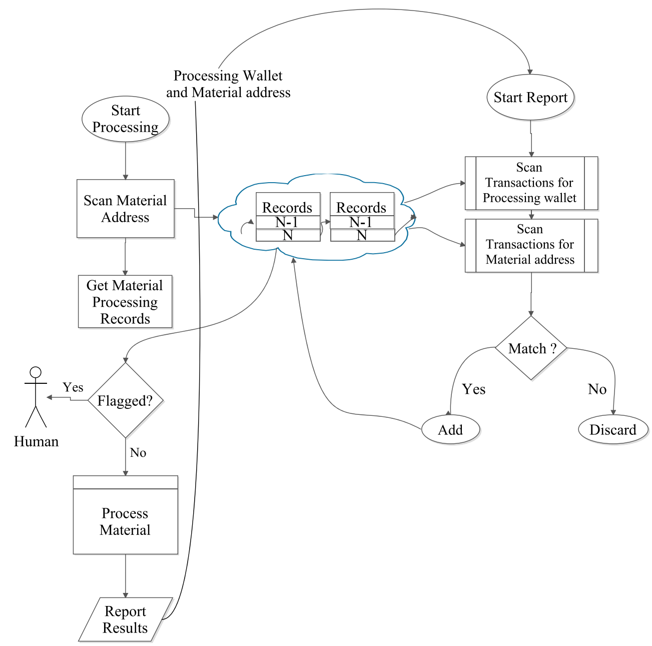

Fig. 10. Workflow of the framework used in supply chain industry [165].

such as function of user's business, authority of administration, and the hierarchy of organization. Various methods proposed by the researchers include the information anchoring method, key distribution method, and information encryption model. These models were evaluated and fortified with the help of several security test cases, such as key recovery, clone attack, counterfeiting tag, and product attack tests. This framework can be helpful for the diamond industry to efficiently manage online trading of diamonds across borders while maintaining the integrity and correctness of the product.

The lack of trust is one of the biggest issues in the existing supply chain systems, and due to the lack of trust between various stakeholders of the supply chain, the flow of trade is limited. For example, Chen *et al.* [164] cited three major challenges regarding the lack of trust in existing supply chain systems: 1) selfish motives of the supply chain members[167]; 2) asymmetric information of the production process [168]; and 3) the cost and restrictions of quality inspection [169]. They proposed a BC supported supply chain quality management framework, which aims to ensure information sharing and quality control. Moreover, their framework was divided into four levels: 1) the bottom most layer, i.e., the first layer is an IoT layer, which consists of GPS, RFID, sensors, and other IoT technologies to assist the logistic process; 2) the second layer is the data layer, which includes the BC and the distributed ledger where information regarding quality data, assets data, transaction data, and logistics data can be recorded; 3) the third layer is the contract layer, which is mainly concerned with maintaining the privacy of data since many enterprises operates on the same BC; and finally, 4) the fourth layer is the business layer, which includes the different business functions to be carried out by enterprises on the BC. The diamond industry can be benefited greatly from this architecture since it can be used to develop quality supply chain

TABLE VI
RELATIVE COMPARISONS OF SUPPLY CHAIN SOLUTIONS FOR THE DIAMOND INDUSTRY

Author	Year	Target Area	Key contributions	Probable extension to the diamond industry
Nash [153]	2016	High value goods supply chain management	IBM have proposed a LinuxONE platform where companies could build and test their BC framework for supply chain management solutions.	The platform could be employed to develop robust supply chain framework which would ensure transparency and traceability throughout the supply chain for diamond industry.
Tian [161]	2016	Agri-Food Supply chain	The system combined RFID and BC technology to ensure traceability of trustworthy information in the agri-food supply chain.	The proposed architecture could employed in the diamond industry, which gives protection against malpractices.
Tse *et al.* [163]	2017	Food supply chain information security	They studied the traditional food supply chains and analyzed them with the help of PEST and demand analysis.	The diamond industry can use this concept to create a more holistic supply chain management and also ensures information security in the supply chain.
Chen *et al.* [164]	2017	Supply chain quality management using BC	They proposed a four layered secure supply chain quality management framework, which addressed the key challenges like lack of trust in the supply chain, etc.	This framework can be used to deal with lack of trust in diamond industry and suggests a secure and high quality solution for supply chain management.
Toyoda *et al.* [157]	2017	Product Ownership Management System (POMS)	The system enables to maintain credible information about the ownership of product throughout the supply chain.	The system could be extended for preserving the history of ownership of diamonds from its mining till it reaches to consumer.
Caro *et al.* [160]	2018	Agri-Food Supply chain	*AgriBlockIoT* ensures consistent and auditable, traceability of assets through the entire supply chain.	The architecture could be employed for ensuring traceability of diamonds through its supply chain.
ElMessiry *et al.* [165]	2018	Textile Industry	Proposed a framework for monitoring the goods as they pass through the various stages in the textile supply chain.	The system could be employed for monitoring the diamonds as they pass through various process such as cutting, polishing, etc.
Xu *et al.* [162]	2019	Luxury Commodities	Proposed HCS platform can trace goods throughout the supply chain and facilitates setllement of transactions.	The framework could aid for making the supply chain of diamonds transparent, trustworthy and secure.
Li *et al.* [166]	2020	Cross-border E-commerce supply chain	They proposed various models and algorithms using a novel multi level distribution framework to enable efficient and secure supply chain management.	The similar architecture can be used in diamond industry to facilitate secured e-commerce supply chain structures across borders.

management using the BC technology. Moreover, it is useful to mitigate the challenges that create a lack of trust among contemporaries of a supply chain.

Ensuring the safety of products and other processes is an important aspect of a food supply chain. Many countries have invested to do research in this emerging area that ensures safety, accountability, and traceability of the systems. For example, Tse *et al.* [163] proposed a BC-based framework for agricultural food supply chain management. They had mainly studied the Chinese market and highlights the reasons why the traditional food supply systems were not sufficient. They used the political economical social technological (PEST) analysis to analyze the application of BC in the food supply chain. First, they studied the traditional food supply chains on the basis of the food security and second, they analyzed the traceability systems platforms of a food supply chain and suggest the upgrades that are needed in the existing traceability systems. Finally, they studied the traditional traceability systems of food supply chain and then amalgamating all the issues of existing technology and building a BC-based supply chain systems for producers, brokers, and consumers. In the BC-based architecture, the customers can request information directly from the food safety agencies, and can obtain a certain level of food safety information online. Applying such a concept to the diamond industry can help in creating more holistic supply chains, which take all the macro environmental factors into consideration.

The supply chain management is indeed a critical application of the BC and it seems promising to solve various issues of the diamond industry. Motivated from these issues, Kshetri and Loukoianova [170] discussed various examples and analyzed applications of BC in the supply chain network. The famous examples of organizations employing BC for the supply chain management include Accenture and digital ventures, Toyota, Alibaba, and JD.com. Accenture and digital ventures pioneered procure-to-pay (the process a company uses to acquire raw materials needed to do business) solution for that particular business. The proposed solution focuses to facilitate purchasing processes, payments, and access to finance for supply chain partners. They employed R3's Corda opensource platform to develop their framework. Toyota incorporated BC into their supply chain to track auto parts across the globe, throughout various factories, and suppliers, and provides and share information on a real-time basis among the various entities involved like customers and manufacturers in the supply chain network. The proposed BC-based supply chain solution solves the issue of fake products and boosts consumer safety. Such a supply chain framework could also be extended for the diamond industry, which would aid the diamond industry to monitor the diamonds throughout the process of supply chain and help consumers facilitate with valuable information pertaining to the diamonds. Table VI shows relative comparisons of supply chain solutions used for the diamond industry.

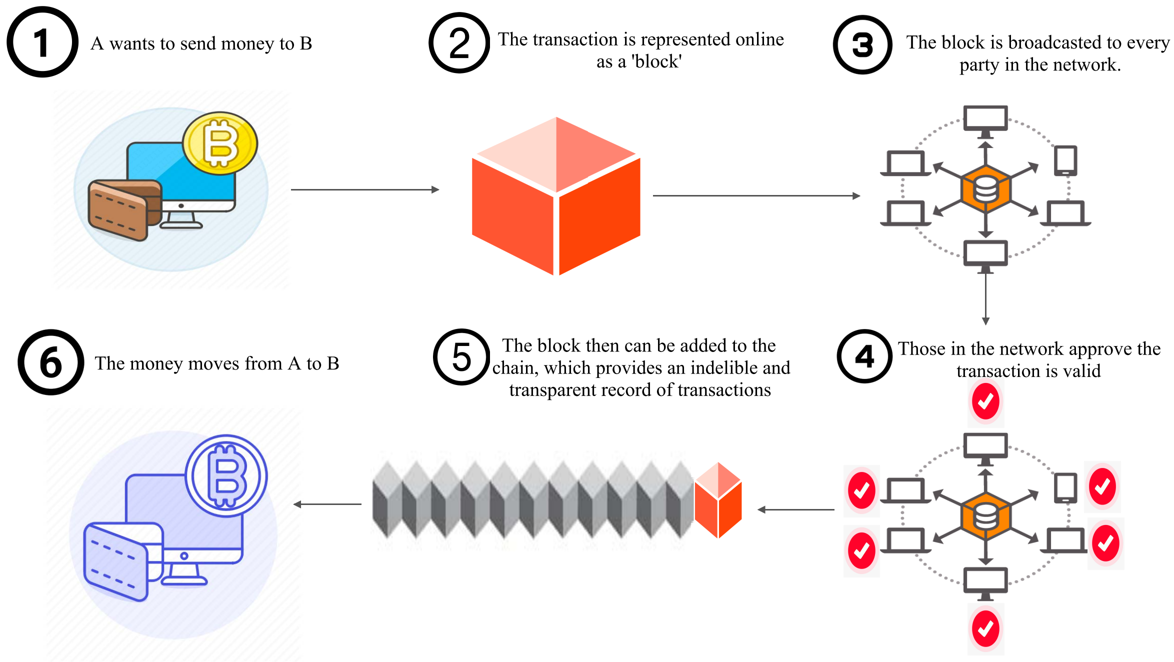

Fig. 11. Flow of transaction on the BC [173].

D. Transaction

Traditional transaction using physical currency are risky as there are chances of theft, possibilities of getting torn, etc., which led to an idea of digitization of currency. The digitized currency, such as E-wallets, etc., had issues, such as the security of transactions, chances of fraud or counterfeit transaction, and dubious acceptance of such currency. This aroused the need of improvements for the existing transactions systems. In recent years, to combat the issues of heretic transaction mechanisms, BC has been emerged as a viable solution. Cryptocurrency known as Bitcoin was the pioneering application working on the principles of BC technology.

In the recent years, BC has been employed for various applications, such as SCs, supply chain management, healthcare, voting, and many other applications [171]. BC is a distributed ledger, which can record and store transactions taking place on the network. Moreover, it possess characteristics, such as immutability, tamper resistant, enhanced security owing to consensus algorithms, etc., which maintain privacy as well as reliability of the transactions committed in the P2P network. Transactions on BC are stored in a chain-like fashion and they can be accessed in a sequential manner. It has the capability to validate the veracity of transactions without a trusted third party or centralized entity being involved [172]. Fig. 11 shows the flow of transactions taking place on BC and the details of these transactions on public BC are visible to everyone who are a part of the network. Thus, the BC-based transactions system maintains transparency in the transaction process.

BC-based transactions have been in trend recently, owing to its features, such as security, reliability and privacy. However, the time taken to process the BC-based transactions is more compared to the digital transactions that take place on the Internet, which lacks to maintain the privacy in the systems. Thus, either users had to choose between privacy and speed. To overcome such issues and primarily focusing on fraud control in BC-based transactions, Davis [174] proposed an efficacious mechanism, which connects BC-based transactions with privately verified profile information. The information of various account holders is stored that incorporates information like account identifier as well as account data, also stores personal account data. The system also embeds features, such as the transaction identifier and merchant identifier to establish linkages between the BC transaction and user profile so that fraud can be restrained for the transactions taking place over the BC. Also, as the transactions are embedded with the privately verified identities, the execution time of transactions is also reduced. In the diamond industry, transactions are of high value, owing to the preciousness of diamonds. Thus, the transaction procedure has to be made highly secure as even small loophole in the system could lead to loss of large amount of monetary value. The proposed system can be extended for transactions in the diamond industry, which prevents fraud and build trust between the transacting parties.

BC had been used extensively to commit transactions, but over a period of time, it has also been used for other applications, such as smart cities, e-governance, etc. For example, Gu *et al.* [175] proposed a novel architecture for transaction of digital resources on the social network. On the social network, the members of the community can upload a digital resource, and if the nonmember wants to access it, then he/she has to pay a price. It facilitates an autonomous hoard transaction mechanism capable of recording and maintaining transaction details over the social network. As BC applications are decentralized, so the voting protocols can be used to evaluate whether a transaction should be executed or needs to be aborted. The system also uses SCs with prefixed clauses to implement the proposed system. The resource request and signing of approval of the request are done based on the voting protocols. Special scripting language instructions are embedded in the framework to provide security against external malicious users, which are not part of the community. The diamonds are costly assets and the user needs to spend a huge amount of money to buy them, which makes them a less interesting option for the small-scale and medium-scale investors. However, extending the proposed system might enable a group (community) to jointly own a diamond and promote intergroup trading of diamonds, which opens doors for the diamond industry. There are prefixed protocols on which buying or selling of the diamond must be decided. Thus, the proposed system if extended, may lead to a great surge among interest of investors for the trading of diamonds.

The BC-based transactions are secured and trustworthy. But, the state-of-the-art techniques restricted a user to alter or abort transaction that has been misaddressed or sent to a wrong person. There is a need to devise a method, which helps to get the users' funds back to them. So, if a transaction once accepted in the BC cannot be stopped even if user wants it, which leads to losses in scenario where the transaction was misaddressed or sent to wrong entity. To overcome this issue, Alruwaili and Kruger [176] proposed a framework, which uses a novel protocol for the preauthorization of transactions. This protocol needs consent of all the members involved in the transaction. BC validates the final agreement. Also, the receiver unknowingly receives payment, which may also indicate chances of bribe. The proposed system gives receivers an authority to accept the transaction and the system promises that it mitigates the chances of fraud and such losses. In the diamond industry, there may be transactions in which multiple parties are involved. These are complex to execute, so the proposed system can be extended to such functionality. Moreover, the receiver consent-based system protects from malpractices and frauds in the diamond trading process.

IoT and BC technologies are very useful when used separately. IoT offers easy automation, whereas BC offers a secured way to exchange assets. For example, Biswas *et al.* [177] combined these two technologies, but this integration is not easy as the rate at which transactions take place in IoT devices is much faster than the transaction processing in BC. Moreover, the integration of BC and IoT is restricted due to scalability of the ledger and the limited resources. The researchers used a local peer network group to connect the BC and IoT devices, which addresses the scalability and transaction speed issues. Their proposed network controls the transactions being added in the BC using a scalable ledger. Their BC-based framework connect all the certified devices to a local peer network, which communicates with an anchor peer network in the universal network. It helps to increase the processed transactions per second in BC and limits the requirements of ledger storage. This technique can be applied to the diamond industry, with the advent of industry 4.0 IoT devices are being integrated in the supply chain. This framework can be combined with BC and IoT technologies that increases the transaction speed.

The integration of IoT applications in BC brings their own set of challenges, Internet of Vehicles (IoV) is one such application of IoT in which various vehicle communicate with each other via public networks. For example, Sharma [178] proposed a distributed clustering technique based on the stochastic model of security derivatives, which help to lower the burden of transactions on the node, and ultimately help to support efficient transaction processing. This mechanism works by selecting most suitable cluster heads. Their experiments show that the proposed system outperformed the traditional BC system, and the transaction load was reduced by 82.06%, the conservation of average energy consumption was about 40.16%. This system can be applied to the diamond industry to reduce the load of transactions. As the supply chain consists of various eclectic components, it is important that there is a sufficient communication between the components without overwhelming the BC architecture.

The confidentiality of the transactions is the most important feature that the stakeholders look into before engaging in BC transactions. Moreover, it is also important to the stakeholders that the sensitive information of the transactions, such as the amount, are concealed from the competitors at the same time. For example, Esgin *et al.* [179] proposed a ring confidential transaction (RingCT) protocol for the BC architecture (MAtRiCT), which preserves the sender's anonymity and also maintains the transaction amount. Moreover, it helps in conducting secure transactions by checking the balance at the sender's and the receiver's side so that double spending or negative amount spending does not occur. This protocol makes the use of stealth addresses to preserve privacy of the sender and receiver. Moreover, their novel RingCT structure leverages major scalability advantages against the traditional linear lattice structure and a significant decrease in transaction size, which also brings down the transaction fees. Their model also provides auditability to prevent fraud transactions. They have also introduced a unique extractions commitment scheme, which helps the stakeholders to retrieve past commitment messages, which helps in the auditing process. Combining the ring structure along with extractable commitment scheme enables a group signature or a ring signature-type feature. This feature gives strength to the diamond industry when the transactions take place between organizations. Here, a representative can authorize the transactions on behalf of the entire organization. Also, this model helps in optimizing the transaction sizes for minimal cost overheads.

While using multiple BC platforms, it becomes difficult to do transactions across these platforms while upholding the atomicity, consistency, isolation, durability (ACID) database properties. Zhao and Li [180] recognized to address the scalability issue several BC platforms can be used to distribute the workload. They proposed two distributed commit protocols to enable scalable cross-platform transactions and also discussed their effectiveness. This article highlighted some features of the existing BC systems, such as they have a centralized broker, they have two party transactions and conventional distributed transactions structure. All these features suggested following limitations that the existing transaction system lacked the atomicity of multi-BC transactions, they

TABLE VII
RELATIVE COMPARISONS OF BC-BASED TRANSACTION SOLUTIONS FOR THE DIAMOND INDUSTRY

Author	Year	Target Area	Key contributions	Probable extension to the diamond industry
Davis *et al.* [174]	2016	Fraud control in transaction	Presented method for connecting BC transactions with privately verified profiles enabling secured and efficient transactions on the BC.	The transactions involving trading of diamonds are of high value, thus such a system can be highly beneficial for protection against fraud.
Biswas *et al.* [177]	2018	Combining IoT and BC for secure transactions.	Proposed a BC-based framework, which combines the IoT and BC. They used a local peer network to communicate with the global peer network to address issues of scalability and transaction speed.	This framework can be applied to diamond industry to support industry 4.0 and create efficient diamond transaction systems using IoT and BC.
Sharma *et al.* [178]	2018	Cost effective transaction processing.	Proposed a distributed clustering mechanism for efficient and cost effective processing of transactions, via selecting the most appropriate cluster heads.	The system can be applied in diamond industry to reduce the transaction and communication cost in the supply chain.
Gu *et al.* [175]	2019	Autonomous Resource Transaction Request	The system facilitates for secured, reliable transactions of digital resources over the social network.	The system could promote group owning of diamonds open a new way for small, medium scale investors to trade in diamonds.
Alruwaili *et al.* [176]	2019	Transaction Enhancement.	The system employs a framework, which needs receiver's consent for the transaction to occur, which might aid in mitigating chances of fraud.	The system could be extended for diamond industry to ease the transactions in which multiple parties are involved.
Esgin *et al.* [179]	2019	Efficient and scalable transaction with group signature.	Proposed *MatRiCT* model, which uses a novel post quantum RingCT protocol that allows efficient and accountable transaction process.	In this framework, the ring signature feature enables efficient transaction practices among the small and medium sized organizations apart from optimising transaction fee overheads.
Zhao *et al.* [180]	2020	Distributed commit protocol for cross-platform BC transactions.	Proposed protocols such as *System Models and Assumptions protocol* and *Synchronous Cross-Blockchain Transactions Protocol (SBP)*, which help in maintaining the ACID properties during cross-platform BC transactions.	Increase the scalability of existing BC systems and thus benefiting the diamond industry.

did not proactively rollback in case of transaction failure. Moreover they also took hours to commit a single cross-BC transaction, which affects the overall performance of the system. They suggested two protocols: 1) *system models and assumptions protocol* and 2) *synchronous cross-BC transactions protocol* (SBP), which address issues, such as the consistency, durability , isolation, and atomicity. These protocols can be of great importance to the diamond industry and also enable the BC to be more scalable with secure and responsible cross-platform transactions. Table VII shows relative comparisons of BC-based transaction solutions used for the diamond industry.

IV. MAIN FINDINGS, CHALLENGES, AND FUTURE RESEARCH DIRECTIONS

A. *BC for Diamond Industry*

In this section, we discuss the amalgamation of BC and diamond industry. BC is a distributed ledger framework, in which the transactions are recorded on publicly shared ledgers. It increases the traceability and transparency of the process. The popularity of BC in the cryptocurrency world (popular applications, such as Bitcoin and Ethereum) shows just how efficient, scalable, and accounts for the reliability of BC technology. However, the application of BC technology is not limited to cryptocurrency, it has found application in a wide variety of industries, such as banking, healthcare, agriculture, ride sharing, energy management, power management, and many more. The diamond industry is also no exception, it can unlock a wide variety of benefits from adopting BC technology.

The diamond industry suffers from a lot of problems, such as unethical sourcing of diamonds, forgery of documents, lack of trust between the contemporaries, authentication issues, poor traceability, and secure trading. These issues hinders the growth of the diamond industry. Moreover, the *Provenance* feature helps in tracing the origins of the diamond and helps the customers to figure out whether their diamond was ethically sourced. It also helps the concerned authorities to find out the sources of these trades and helps in further mitigation of unethical sourcing.

SCs are very efficient while dealing with trading of commodities, in this article, we reviewed how SCs were used for the process of auctioning and other integration (BC with the diamond industry). In the diamond industry, SCs can be employed for responsible and secure auctioning and trading of diamonds. Moreover, to ameliorate the lack of trust and to secure sensitive information from public view, these SCs can also be modified to keep the important details of the contract anonymous. They can also be used in the diamond certification process. BC is highly effective in optimizing supply chains and in supply chain management process, due to consistent ledger entries and tracking facilities, it becomes easy to overview the entire supply chain process. As the diamond industry adopts industry 4.0 so SCs can be used for easy integration with IoT devices for enhanced tracking and transparency. Using BC for transactions helps to reduce the transaction overhead and promotes a more cost effective and secure solution.

B. Challenges and Future Research Issues

In this section, we discuss some of the challenges in the integration of BC with the diamond industry. The implementation of BC in the diamond industry seems to be very promising. However, meticulous planing is needed to move forward with the proof of concept and pilot frameworks that have been introduced. Motivated from the aforementioned discussion, we have identified challenges and future research issues faced by the diamond industry during its integration with BC. These challenges and future research directions are as follows.

1) *Privacy:* Since BC has a public ledger, it implies that anyone in the network can view the transaction details. In competitive markets, the stakeholders may view this as a drawback as the competitors can view the confidential information. Encryption mechanisms can be used for controlling the access to the confidential information [181].
2) *Scalability:* There are a lot of transactions taking place in BC; as supply chains move toward integrating IoT devices and other systems to the network, then the load on BC network and the amount of transactions are bound to increase. Initially, the Hyperledger Fabric can process 3000 transactions per second, but with certain architectural optimizations, it can process up to 20 000 transactions per second [182].
3) *Efficiency:* BC systems may suffer from time constraint and latency issues because of consensus cost overhead and the decentralized structure also adds to the transaction processing time. Moreover, the BC structure is resource intensive as there is duplication of data and requirements of network bandwidth are also significant [183].
4) *Memory:* As new blocks are added to the BC, its size keeps increasing. Data apart form the relevant information also take up space and also consume memory resources. Moreover, the immutable nature of the BCs also affects the memory requirements [98].
5) *SC Accuracy:* SCs have immutable characteristics, it is important that their execution is flawless as once they are deployed on the network, they cannot be changed. The order of execution of the SCs is also important for a successful transaction. Hence, developing SCs correctly is a challenging task [98].
6) *Security:* The BC system can face many types of security attacks, such as denial-of-service, endpoint security attacks, code loopholes, Sybil attacks, eclipse attacks, and routing attacks [184]. These types of attacks can disrupt the consensus mechanism and other decision-making mechanisms. Therefore, we need more robust consensus algorithms and security enforcing algorithms.
7) *Infrastructure:* BC-specialized hardware and system infrastructure enhance the effectiveness of many applications based on BCs. These might include network administration, hardware mining, decentralized storage, and protocol communication [185]. Services targeted about the usage of BC are also currently under scrutiny (involving large development firms and financial institutions) [98].
8) *Overcharging:* It is the case, where SC coding is not well configured, including the existence of dead codes, inefficient loop procedures, error handling, etc. So the developers need to be extremely cautious in designing the complex smart contacts, taking all those codes into account, which makes the smart contact cumbersome [186].
9) *Cost:* The current storage costs associated with BC are very high, i.e., \$550 for 1 MB of data [95], [187]. Thus, in the diamond industry, where the competitiveness is increasing day-by-day and the profit margins are becoming thin, to implement BC-based solutions, the cost associated with its storage needs to be optimized.
10) *Regulation:* The application of BC for the diamond industry seems to be promising for enhancing the efficacy of operations. Mutual cooperation, cooperative collaboration, and appropriate consensus mechanisms would be crucial factors for the real-life implementation of BC for the diamond industry [23].
11) *Real-Time Data Integration:* Supply chain management in the diamond industry is becoming a collaborative effort, with manufacturers outsourcing for noncore operations and retaining of the core organization competencies in design and innovation. Thus, such a scenario calls for an exigent need of real-time data flows between various supply chain entities [188].
12) *Supply Chain Risk Management:* Supply chain is mostly cross-functional in nature nowadays, thus risk management is a paramount factor for such supply chains [189]. This can be achieved by exploiting the decentralized nature of BC for the task of traceability and data integration.

V. CASE STUDY: *Everledger* AND *Tracr*

In this section, we explore two major platforms namely, *Everledger* and *Tracr*. These platforms have been able to efficaciously implement BC-based solutions for the purpose of mining and processing of diamonds. In this case study, we will see how these platforms have implemented the BC infrastructure along with their outcomes.

Everledger is a London-based company that employs new technology like BC for tracking and managing the production life-cycle of diamonds from mines to the end customer. Fig. 12 depicts the main highlights of the *Everledger* framework. In 2015, it was the first company to start tracking the life-cycle of high-value assets like diamonds. Their main focus was improving the traceability and provenance tracking for the diamonds. Fig. 13 shows the stakeholders who are a part of the *Everledger* BC network. It shows that *Everledger* is inclusive of various contemporaries and integrates all the necessary actors of diamond industry from mining companies and wholesalers, to the end customers. This makes the BC and

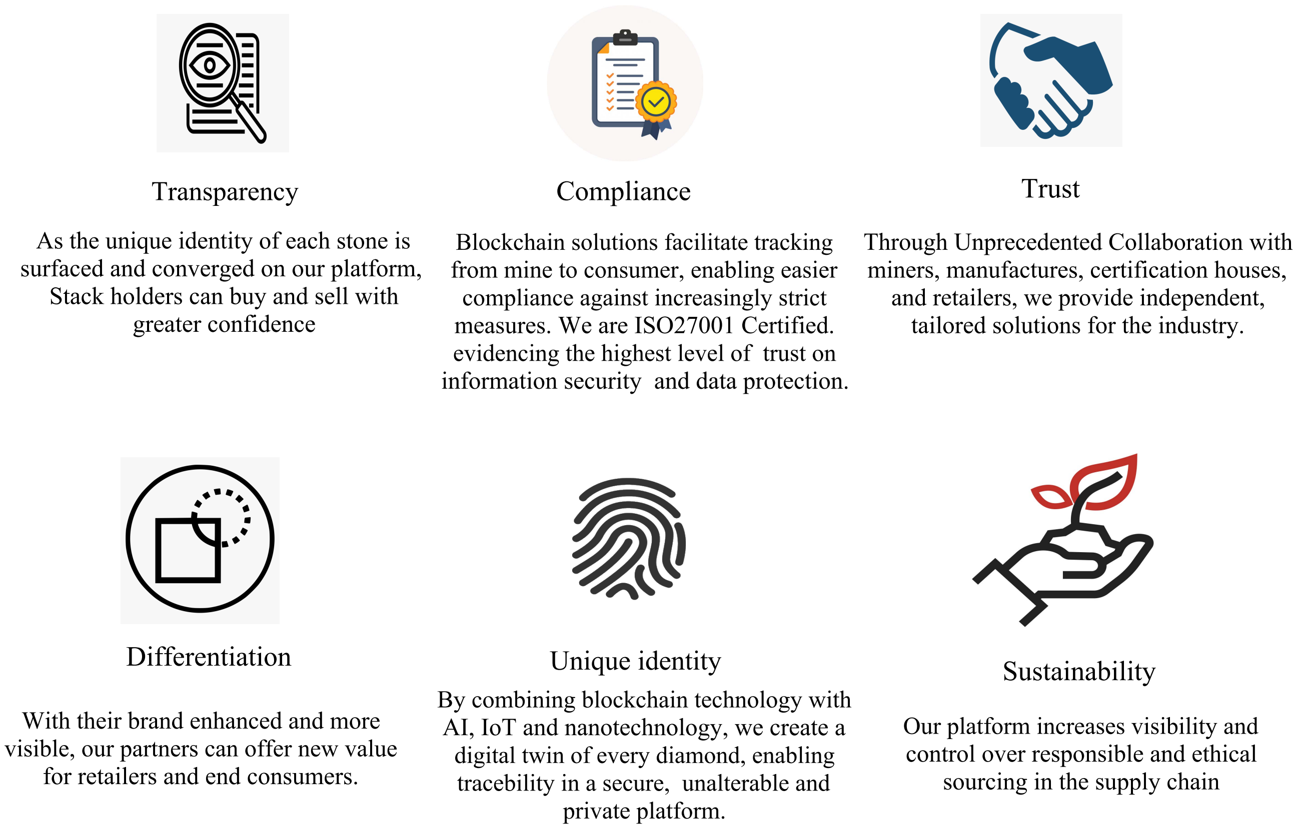

Fig. 12. Key highlights of the *Everledger* framework [190].

diamond industry integration easier and efficient. They collected all data related to diamonds like the previous ownership records, sourcing and mining information, the characteristic of the diamond, and much more. They digitized this information by adding it to the BC network that mitigates frauds and other issues that arise in the paper-based transactions along with an aim to reduce the unethical sourcing of diamond. Their framework helped to battle against the forging of documents, as the forgery was a major catalyst behind failing the Kimberly process. The authenticity of the diamonds relies on the certification process carried out by various certification houses. This process originally was paper based, which is prone to corruption and forgery; therefore, compromising the overall certification of diamonds. *Everledger* records all such details on the BC network, making it a reliable source for customers and other buyers from where they can look up the certification, provenance, and other tracking details. With the help of *Everledger*, the diamond supply chain has become more transparent. Moreover, making compliance easier and in case of any discrepancy, it has fostered trust between the stakeholders. Each diamond stone has its own unique digital identity, hence increasing traceability and their solution is more sustainable compared to the traditional methods [29] [190].

Tracr is a BC platform launched by the DeBeers group [191], they have BC, IoT, AI, and many more current technologies to provide end-to-end solution for diamond supply chains [192]. *Tracr* enables the diamond industry to adopt industry 4.0, the technologies applied by them help to form an efficiently connected industry. The three most important features that this platform leverages to support the digital

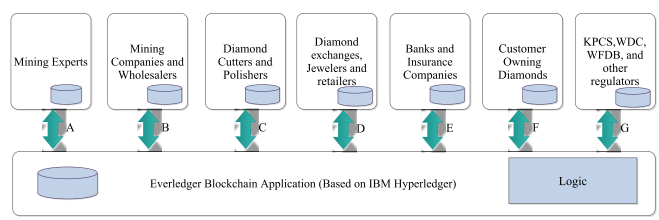

Fig. 13. Key stakeholders of the *Everledger* framework [107].

transformation are: 1) it supports independent industry governance, which makes sure that the technology caters equally and beneficially to all the stakeholders, which, in turn, fosters the trust in customers; 2) their industry data strategy feature that makes sure that the traceability and provenance of the diamond is transparent so that the customers can see the insights regarding their product; and 3) they focus on the Internet of Value, which consists of technologies, such as IoT, AI, and BC along modern privacy and security systems. All of these features work simultaneously to provide a robust and credulous platform for the diamond industry, which the stakeholders can rely and trust.

VI. Conclusion

The evolution of BC over the period of time has led to application of BC in various fields. BC, owing to its specific characteristics, such as *immutability*, *trust*, *transparency*, and *reliability*, seems to be promising in the diamond industry. In this article, we discussed the integration of BC and diamond industry. We presented the challenges and issues persisting in the operations of diamond industry. Then, we presented a solution taxonomy in which we have explored the related literature and proposed their probable extensions for applications in the diamond industry. Then, we presented various research challenges and open issues hampering the real-life implementation of BC for diamond industry. Finally, we presented a brief case study on BC-based frameworks, such as *Everledger* and *Tracr*, which have been implemented for enhancing the operations in the diamond industry. Research on BC to diamond industry is still in its infancy. But, it is obvious that BC will significantly uplift the shape and experience of the future to handle the diamond industry. We believe our timely study will shed a valuable light on the research of the BC-diamond industry integration topics as well as motivate the interested researchers and practitioners to put more research efforts into this promising area. The future of BC in the diamond industry seems promising as it aims to resolve lot of issues with the existing technique and gives the customers and other stakeholders an authentic, trustworthy, and sustainable way to buy and sell diamonds.

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