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Invited Review

Big data management in the mining industry

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Abstract: The mining industry faces a number of challenges that promote the adoption of new technologies. Big data, which is driven by the accelerating progress of information and communication technology, is one of the promising technologies that can reshape the entire mining landscape. Despite numerous attempts to apply big data in the mining industry, fundamental problems of big data, especially big data management (BDM), in the mining industry persist. This paper aims to fill the gap by presenting the basics of BDM. This work provides a brief introduction to big data and BDM, and it discusses the challenges encountered by the mining industry to indicate the necessity of implementing big data. It also summarizes data sources in the mining industry and presents the potential benefits of big data to the mining industry. This work also envisions a future in which a global database project is established and big data is used together with other technologies (i.e., automation), supported by government policies and following international standards. This paper also outlines the precautions for the utilization of BDM in the mining industry.

Keywords: big data; big data management; mining industry

1. Introduction

The advancement of human beings has relied heavily on the mining industry since the beginning of our civilizations [1–7]. Various minerals, including metallic, non-metallic, and energy minerals, have been produced and are essential to many industries. Most of our everyday products cannot be manufactured without the provision of inputs from the mining industry, from smartphones to the cans used for drinks [8]. Over the last several decades, the mining industry has witnessed a commodity supercycle driven by the construction boom, increasing demand from China and other developing countries, and various economic policies [9–10]. Since 2011, the mining industry has met a number of challenges, including declining commodity prices and strict regulations on its social and environmental impacts.

The accelerating progress of technology, especially in the area of information and communication technology (ICT), has led to a large amount of data being generated every day. Dealing with petabytes (10^{15} bytes) of data is a common or even essential requirement for many operating companies. Giant companies like Google and Facebook process large amounts of data every day; about 24 petabytes of data are processed every day by Google, while Facebook received >10 million photos per hour in 2013 [11]. This fast increase of data gives rise to different challenges, such as how to analyze the data, and opportunities, such as what knowledge can be discovered, for governments, organizations, communities, and individuals. The big data era will definitely change the way we live, work, and think [11].

The mining industry is no exception to the pervasive data revolution. Even though the mining industry is at times reluctant to adopt new technologies, embracing big data is almost unavoidable in the modern era. Profit margins decrease dramatically due to the aforementioned challenges encountered by the mining industry. The competitive market leaves few options for the mining industry. Big data is one of the promising technologies that can reshape the entire mining landscape.

In the past decade, the mining industry has made several attempts to embrace big data. Sensors have been embedded across mining operations, generating a vast amount of data in real-time [12]. The generated data include geoscientific data, asset condition data, and operational data, among others. The

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recent advancement in Wi-Fi, 4G, and 5G will provide more potentials in real-time data collection. Real-time data analysis can be performed together with the use of high-speed supercomputers and advances in machine learning [13]. Timely feedback can be provided to mining practitioners and even stakeholders.

Regardless of the progress in the area of big data, the fundamental concepts, opportunities, and precautions of big data management (BDM) are still unclear to the mining industry. As a prerequisite for big data analytics, BDM needs to be treated with extensive attention. No comprehensive studies have been conducted on the crucial aspects of BDM in the mining industry. Bridging this gap will require seamless integration of knowledge from both big data and mining engineering.

The main objective of this paper is to fill the void and present the basics of BDM in the mining industry. A brief introduction to big data is provided in Section 2, followed by an explanation of BDM in Section 3. The challenges encountered by the mining industry are discussed in Section 4 to explain the necessity of embracing big data technology. This paper closes with opportunities in Section 5 and precautions for BDM in the mining industry in Section 6. Although details are not provided in each section, an overall framework is established for future application of BDM in the mining industry. Notably, most of the BDM frameworks proposed in this study are generic in nature and can be easily applied to other industries, such as the construction industry and the energy industry. Moreover, this work is not intended to provide a detailed review of BDM in the mining industry but only a general idea of this topic.

2. Brief introduction to big data

Although the term "big data" has been widely used in many areas, no consensus has been reached with regard to its definition [14]. This lack of an explicit definition is partly due to the rapid development of ICT. Big data was measured in terabytes (10^{12} bytes) a decade ago and is measured in petabytes at present [14]. Despite the vague definition, a clear trend is observed in the emergence of big data. Fig. 1 shows the search interest of webpages (in Google Trends) and the number of publications (in Web of Science) using "big data" as the keyword. Increases in web search started in 2011, and the number of publications increased sharply in 2012.

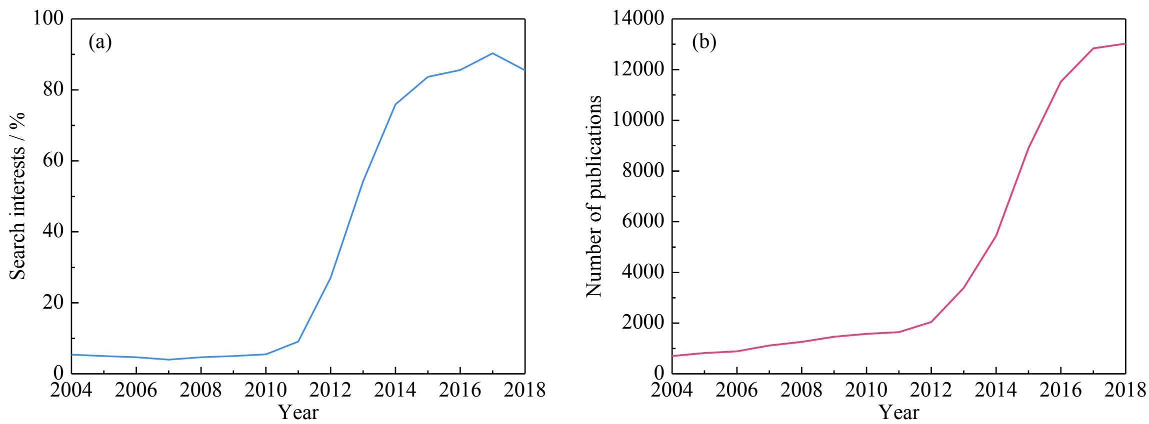

Fig. 1. Emergence of big data from 2004–2018: (a) search interests from Google Trends; (b) the number of publications from Web of Science using "big data" as the keyword.

Driving deeper into the characteristics of big data, different authors have proposed different criteria for the term. Ward and Barker [15] identified three important characteristics of big data to differentiate it from other data we commonly encounter, namely, size, complexity, and technology. Another way to identify big data is by using the attributes of the 5Vs [16–17], which is the abbreviation for volume (large amount of data in petabytes or terabytes), variety (different types of structured, semi-structured, or unstructured data), velocity (continuous streams and analysis of the data in near real-time or virtually real-time), veracity (integrity of data), and value (valuable information behind the data).

The application of big data often consists of three steps: source data collection, data structuring, and knowledge discovery. Fig. 2 illustrates the application procedure of big data. Data structuring is not necessary if structural data are directly collected from mining operations. Various platforms have been developed to facilitate the application of big data, such as horizontal and vertical scaling platforms. Interested readers can refer to Ref. [18] for a detailed discussion about big data platforms.

Unlike BDM, the main focus of big data analytics (BDA)

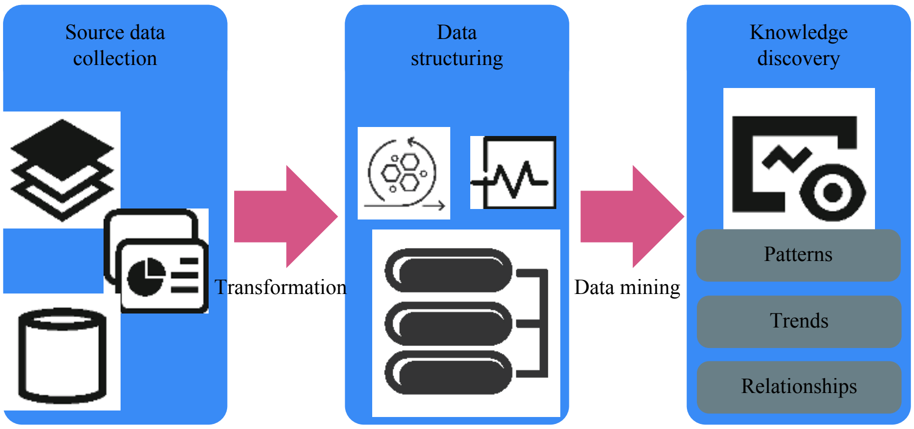

Fig. 2. Application procedure of big data.

is data mining, such as state-of-the-art machine learning techniques [19–22]. Given the considerable difference between BDM and BDA, the topics will be covered in different papers. BDM is the first topic to be explained as it is the prerequisite for the subsequent BDA.

3. Challenges in the mining industry

This section summarizes the challenges encountered by the mining industry. Although those challenges are not directly related to big data, their occurrence has increased the need for innovations and new technologies. Harnessing the potential of BDM and BDA will help the mining industry increase its productivity and response more actively to uncertainties. Notably, the implementation of BDM in the mining industry is not the counterpart for the following challenges. BDM should instead promote the elimination of these challenges due to its unique benefits. Moreover, BDM can promote challenge-solving in the long term, such as intelligent infrastructure development.

Declining commodity prices is one of the most profound challenges for the mining industry. Up to 2010, commodity prices have increased continuously because of the pro-growth policies, speculations, and massive infrastructure development of the emerging market, especially China. Commodity prices peaked in 2011 and started to move downward. One primary cause for the declining commodity prices is the slowing economic growth, which is also mainly influenced by China, thus decreasing the demand for metals and minerals. The profit margins of the mining industry have thus decreased. The net profit margin for the top 40 mining companies was 25% in 2010, which decreased to 2% in 2013 [9].

Another challenge is the social and environmental issues associated with mining operations. The industry's high fatality ratio, loss of livelihoods, acid mine drainage, deforestation, noise, dust, and air and water pollution, among other issues, have been the subject of increasing scrutiny. Recycling, closing the production loop, cleaner production, zero waste, and recovery of resources are all terms that are frequently signaled to the mining industry. Nowadays, mining operations need not only a regulatory license to mine but also a social license to operate because companies cannot afford any tensions or disruptions arising from discontented neighbors. How to mitigate the impacts of mining and, at the same time, offset the increased environmental and social costs is the essential question facing the mining industry.

Increased mining depth is another bottleneck for the development of the mining industry. With the depletion of near-surface deposits, the mining operations have to extend to a great depth to ensure a continuous supply of metals and minerals [23–24]. Mineral excavation at a depth of over 1000 m is now quite common in countries with abundant reserves and developed mining technologies, such as South Africa, Canada, the United States, and China [25]. However, deeper deposits mean more difficult and expensive exploration and excavation. In addition, the waste-to-product ratio will be increased, putting more pressure on waste management of the mining industry. Researchers [26] indicated that the electricity cost of copper mining and concentrating would increase by 7% with every 100 m increase in mining depth.

The lack of infrastructure is a further barrier to the mining industry. The rail and transmission line are the main infrastructure for the coal industry, for example. Such infrastructure in undeveloped areas cannot satisfy the need for coal mining [27]. The insufficient infrastructure will not only decrease the confidence of the mining industry but also bring about social issues such as limited opportunities for education [28–29]. Other difficulties faced by the mining industry include but are not limited to lack of funding, declining skilled labor, corruption, low level of exploration, and increasing regulatory pressure.

4. BDM in the mining industry

4.1. What is BDM?

Unlike Fig. 2, which illustrates big data in terms of its application procedure, another way to understand big data is through more detailed processes. Big data processes can be classified into two main classes, namely, BDM and BDA. BDM primarily deals with data collection, pre-processing, storage, and sharing, which are essential for the implementation of BDA [30]. The objective of BDA is mainly interpretation and knowledge discovery. Fig. 3 illustrates the major processes of big data. BDM and BDA focus on different aspects of big data. Moreover, BDM is the prerequisite of BDA, and the successful application of big data in the mining industry relies heavily on BDM. Thus, this study discusses the basics of BDM in the mining industry.

A closer look at BDM reveals that it involves mainly two operations: big data storage and big data processing. At present, big data storage is either performed using distributed file systems (DFS) or the emerging NoSQL database [16]. The DFS is a file system that stores data on a server, allowing client users to easily access and process data in a similar way as when data are stored locally. Hadoop DFS and Tachyon are two commercially available computing DFSs [31]. These two DFSs have pros and cons, which are clearly explained in [16]. The emerging NoSQL database is proposed to overcome the limitations of the DFS, such as scalability, performance, and flexibility [32]. It is currently gaining popularity in myriad data-intensive applications.

As the key to BDM, big data processing focuses on parallel and distributed computations. Recent progress in processing models has greatly improved the efficiency of big data processing. Widely used processing models include MapReduce (MR), MapReduce-like, and General Purpose GPU [33]. MR is a distributed processing model proposed by Google and has two major advantages: hidden details and simplicity. Therefore, MR is widely employed by both industry and academia. The directed acyclic graph (DAG) is a big data processing alternative to MR. Consecutive computation stages can be established in DAG and the execution plan can be optimized. The DAG has been implemented in the Apache Spark engine and is much faster than MR in disk-resident and memory-resident tasks [18].

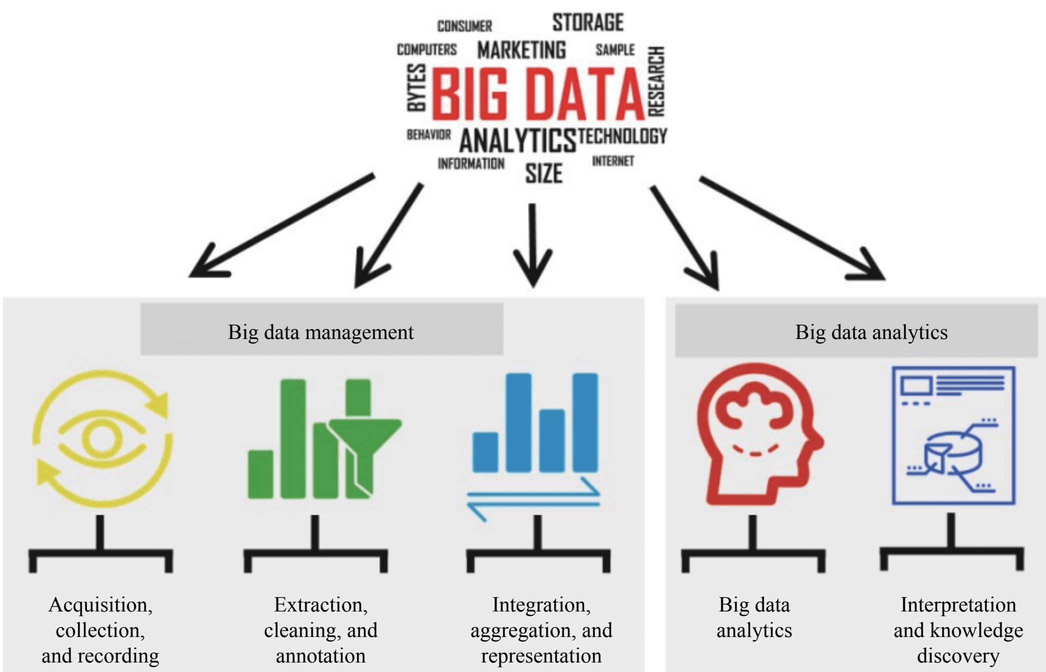

Fig. 3. Major processes of big data.

4.2. Data sources in the mining industry

This section summarizes the data sources in the mining industry. In other words, collecting data from data sources is the first step for the implementation of BDM in the mining industry. As mentioned previously, data can be generated in a structured, semi-structured, or unstructured way. Structured data are often built on a deliberate structure and follow a particular scheme. Thus, they are usually well defined and predictable. Unstructured data have no structure that can be recognized by a computer and are collected in a more natural way. Given that no predefined structure or hierarchy exists in unstructured data, the querying and analysis of unstructured data are slower than those of structured data. Semi-structured data cannot be arranged in a structured way if it contains certain information that can be recognized by a computer. Similar to the data types in other industries, the data type in the mining industry includes text, image, audio, video, spatial, temporal, document, relational data, and domain entities.

Data sources in the mining industry can be classified into direct and indirect data sources. Direct data sources, such as Global Positioning System (GPS), conventional geodetic measurement, and commodity price monitoring, represent the data taken from instruments that are specified for data collection. Indirect data sources are data collected as a by-product of mining operations, such as drill and blasting, plant control, and rail track system. Fig. 4 illustrates the major data sources in the mining industry.

With the development of ICT, the data sources in the mining industry will expand. The use of sensors and smart chips to measure system performance in the mining industry has increased sharply, providing indicators for potential failures. Drone systems can be employed to explore new mining areas, monitor landscapes, and measure mine tailing ponds [34]. Promoting the concept of big data is thus significant for the sustainable development of the mining industry.

Given the limited papers about data collection, pre-processing, storage, and sharing of big data in the mining industry and the introduction of these topics in the previous section (Section 4.1), the aforementioned topics will not be covered separately in this study.

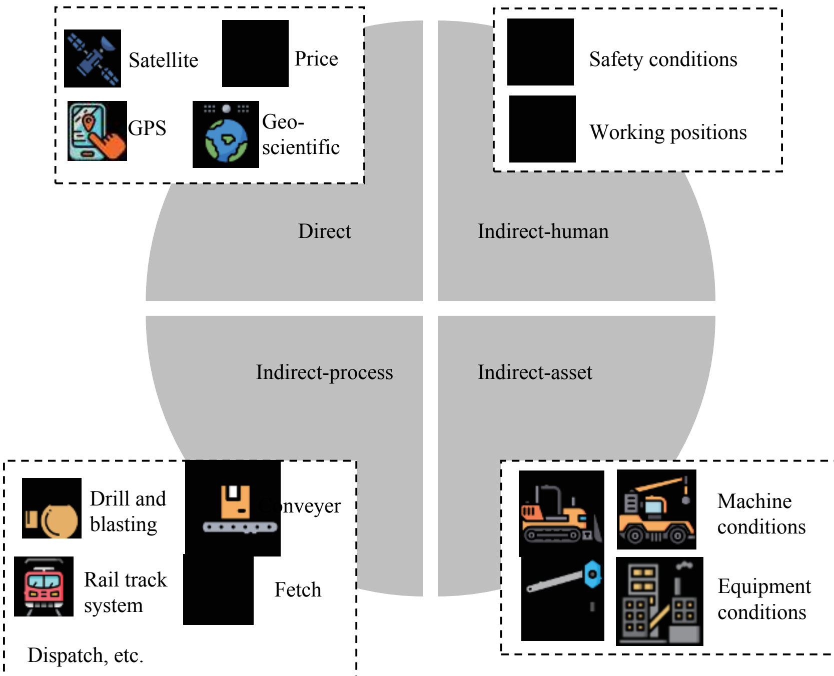

Fig. 4. Major data sources in the mining industry.

4.3. What can big data management bring to the mining industry?

BDM, together with BDA, can contribute to every stage of mining operations. The ultimate objective of big data to the mining industry is to reduce mining interruptions, increase efficiency, reduce costs, and increase profit margins. The following are the specific benefits of embracing big data in the mining industry:

(1) Improve efficiency. Once it has been properly compiled, analyzed, and evaluated, big data can speed up mining operations, such as ore excavation, extraction, and separation, as a result of the power of automation, agile decision-making, and real-time optimization.

(2) Energy management. Big data can help save energy in every mining operation, making the mining process more energy saving and sustainable.

(3) Improve logistics. With automated and optimized transportation, big data can help improve transportation efficiency, reduce operational costs, and identify areas for improvement.

(4) Intelligent business. Through real-time monitoring and analysis of mineral prices, the decision-making process can be improved by big data. Business operation efficiency can improve, and big data can help identify the cost distribution in all mining operations. Moreover, collaborations between various departments and even various companies can be solidified and become smarter with advanced sharing and communication platforms.

(5) Safety, security, and reliability. Big data plays a vital role in the safety, security, and reliability of mining operations. The advancement of ICT makes real-time monitoring of practitioners (location, heart rate, temperature, etc.), equipment (posture, operating condition, etc.), and the environment (CO_2, gas concentration, temperature, dust level, etc.) possible. Precursors of mining accidents can be identified based on the above real-time data.

(6) Improved operational management. Big data can help analyze machine reliability and optimize the need for spares. Moreover, smarter procurement of future services can be achieved, which can make prices more negotiable and reduce the overall procurement costs. Predictive maintenance can be achieved with the utilization of big data to reduce interruptions in mining operations.

The aforementioned benefits provide a general idea about implementing BDM in the mining industry. Detailed measurements of the BDM-based profit are beyond the scope of this study. Only a few studies have been conducted on each aforementioned topic. Comprehensive literature reviews will be conducted on each topic for more details about BDM-based profits.

5. Opportunities and future works

Having discussed BDM and the benefits of big data, this section focuses on opportunities and future works to promote the application of big data in the mining industry. Several promising topics will be presented. Note that the following topics are presented as examples, and the concept of big data in the mining industry goes far beyond the following topics. Also, the opportunities associated with BDM and BDA are presented because they are closely related during engineering applications.

5.1. Global database establishment

Database project is the first step for the storage, sharing, and interpretation of big data in the mining industry. An ideal database project should have good extensibility and interoperability with other software. Moreover, it should be multinational, continuously updated, and highly accessible to all mining practitioners around the world. Quality control should be well implemented. The database project can be maintained by several scholars but should be extendable by external users. Several database projects have been initiated by different scholars on different topics, such as the international database for cemented paste backfill initiated by Dr. Chongchong Qi. However, most of the current database projects are merely for dataset sharing, thereby providing limited options for other manipulations of data.

The dataset size in the mining industry could vary significantly for different problems. For some laboratory datasets, they could be small at the beginning to avoid dealing with a large amount of required time and resources immediately. However, these datasets are actually bigger than the experimental data in individual papers. Data mining based on these datasets could reduce the number of laboratory experiments and promote knowledge discovery.

5.2. Big data with intelligent geological survey

At present, a large amount of data are generated by advanced geological surveys. These datasets often present specificity with relation to the geospatial information, leading to the heterogeneity and complexity of geological data. Geological data cover a diverse range of applications and require fast processing, thus requiring special techniques and tools for processing [35]. Past decades have witnessed significant advances in the application of big data in geological surveys, such as in predicting mineral resources in China [36] and discovering near-surface mineralized structures [9]. However, such applications are still in their infancies and far from their peak potentials.

5.3. Big data with automation

The concept of industrial automation has been upgraded with the employment of new technologies. For example, the adoption of radio frequency identification was recognized as the frontier of automation in 2010 [37]. Nowadays, smart sensors and smart devices have generated a growing trend of increasingly big data production. These sensors can not only capture data and information but also communicate or even collaborate on this task. Improved control and effective maintenance can be achieved with prediction and clustering through BDA. The application of big data and automation has been attempted in the mining industry, such as in [38]. However, continued bold development and rapid implementation on this topic are still required.

5.4. Big data with cloud computing, internet of things (IoT), and augmented reality (AR)

The application of big data can be expanded together with cloud computing, IoT, and AR. Cloud computing is an internet computing paradigm that outsources data storage and computation on third-party data centers [37]. It can allow simultaneous access to cloud services by multiple users without individual licenses. IoT represents the connection of devices on the Internet, the application of which often relies on hundreds or even thousands of smart sensors and devices. IoT and big data are closely related in that IoT generates large amounts of data, while big data stores and analyzes the generated data. AR is an emerging technology that can be used to enhance human perception. A mixed world is generated by superimposing computer-generated virtual objects on real scenes. AR provides a promising way to visualize the complexity during the application of big data in the mining industry. Cloud computing, IoT, and AR will accelerate the uptake of big data in the mining industry, which requires new interactive platforms and methodologies for such combinations.

5.5. Big data with integrated system

Even though the use of big data has been attempted in several mining operations, the literature review reveals that these operations are often considered individually. The optimization of operational parameters would be difficult before these mining operations can be integrated into a single system. One possible reason for this difficulty is that these operational parameters are highly correlated, thus influencing each other [39]. The establishment of an integrated system, though elusive at present if all mining operations are considered, would be possible after a better understanding between the operational performance and its operational parameters is obtained. Analysis and prediction based on big data are essential for the integrated system and thus the optimization of operational parameters.

5.6. Government policies and international standards

Policy-making is one of the key factors for the development of big data in the mining industry. The government, as a regulator and promoter, should make efforts to address the information and data policies in the mining industry. These policies should cover all aspects of big data, such as management, usage, and accessibility. At present, the regulations about big data in the mining industry are not clear, which affects the intention of mining companies to implement it.

Metadata standards should be well established as a prerequisite for the long term development of big data in the mining industry. As discussed in Section 5.1, the data in the mining industry are collected in different formats depending on the operations and the type of information. Metadata standards are thus important to ensure the cross-client and cross-platform compatibility of big data services. To date, various metadata standards have been proposed, such as the international standard for geospatial metadata (ISO19115) and the metadata for images in extensible markup language (MIX-Z39.87) [40]. International metadata standards in the mining industry are urgently needed to promote big data collaborations and reuse.

6. Precautions for BDM in the mining industry

Despite the possible opportunities and benefits achieved by implementing big data in the mining industry, some precautions need to be seriously considered. These precautions are challenges for the implementation of BDM in the mining industry and need to be addressed carefully. Data privacy, security, and archiving are prominent issues because big data in the mining industry involves major issues such as personally identifiable information and security of companies' data and information. Security measures, including access control and intrusion prevention, should be adopted in BDM in the mining industry. Data quality, authorship, and governance are also important issues for BDM in the mining industry. Big data with poor quality and are either not certified/verified or collected using dubious methods could lead to incorrect findings.

Cost estimation for adopting BDM in the mining industry is one of the key concerns. Data centers, software licenses, and training of skilled practitioners all entail potential costs that mining companies need to consider before implementation. Instant data communication between project sites (i.e., stopes, tailing dams, and plants) is desired for real-time monitoring and analysis. Although mining sites often suffer from inadequate networking infrastructure, the advancement of Wi-Fi and wireless sensor networks has provided an alternative to cope with data communication issues. Other issues such as proper international research collaborations also need to be considered before big data reaches its full potential in the mining industry.

7. Summary

The advances in ICT have led to the generation of large amounts of data every day. Dealing with petabytes (10^{15} bytes) of data is a common or even essential requirement for many operating companies nowadays. The mining industry is no exception to the pervasive data revolution. Challenges encountered by the mining industry (i.e., decreasing commodity prices and ore grade) causes profit margins to decrease dramatically. The competitive market leaves few options for the mining industry, and big data is one of the most promising technologies to address this problem.

The past decade has witnessed a clear trend for the emergence of big data, which is characterized by the 5Vs: volume, variety, velocity, veracity, and value. The application of big data often consists of source data collection, data structuring, and knowledge discovery. The handling of big data can be classified into BDM and BDA on the basis of application procedures.

The mining industry needs to deal with both direct and indirect data sources. Direct data sources represent the data taken from instruments that are specified for data collection, including GPS and geodetic measurement. Indirect data sources are those data that are collected as a by-product of mining operations, such as drill and blasting. BDM, together with BDA, can bring benefits such as improved efficiency, energy saving, and increased safety, to the mining industry.

The future application of big data can be accelerated through a global database project, the combination of big data with intelligent geological surveys, automation, cloud computing, IoT, AR, integrated systems, support from government policies, and international standards. Precautionary measures need to be implemented seriously during the application of BDM in the mining industry. Related problems include but are not limited to data privacy, security, archiving, quality, authorship, and governance. Cost estimation for adopting BDM in the mining industry should be performed, and instant data communication should be improved. International research collaborations are also needed to ensure that big data reaches its full potential in the mining industry.

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