Alignment of tertiary curricula and needs of future mines - A case study of the world's top mining engineering schools

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The world is fast moving towards the fourth industrial revolution (4IR) which is characterised by digital and disruptive technologies. Many industries are already at advanced stages of applying 4IR technologies including the mining industry. These technologies require a new set of skills for the industry to thrive in the 4IR. One of the factors to ensure the successful implementation of such technologies in the industry is the preparation of 4IR-ready graduates by mining engineering schools. Therefore, this paper analysed curricula of the top ten mining engineering schools based on the Quacquarelli Symonds (QS) World University Rankings of mineral and mining engineering as a subject. The aim of the study was to analyse whether the schools have evidently responded to the needs of the mines of the future by providing 4IR skills related courses in their mining engineering curricula. It was found that mining engineering schools have started incorporating some 4IR skills related courses in their curricula albeit still very few. It is recommended that schools should speedily revise their curricula to support this transformation of the mining industry.

Keywords: Fourth industrial revolution skills, mining engineering curriculum, mines of the future

INTRODUCTION

The world has advanced through different industrial revolutions in the last three centuries starting with the first revolution in the late 18th century. These revolutions are summarised in Figure 1.

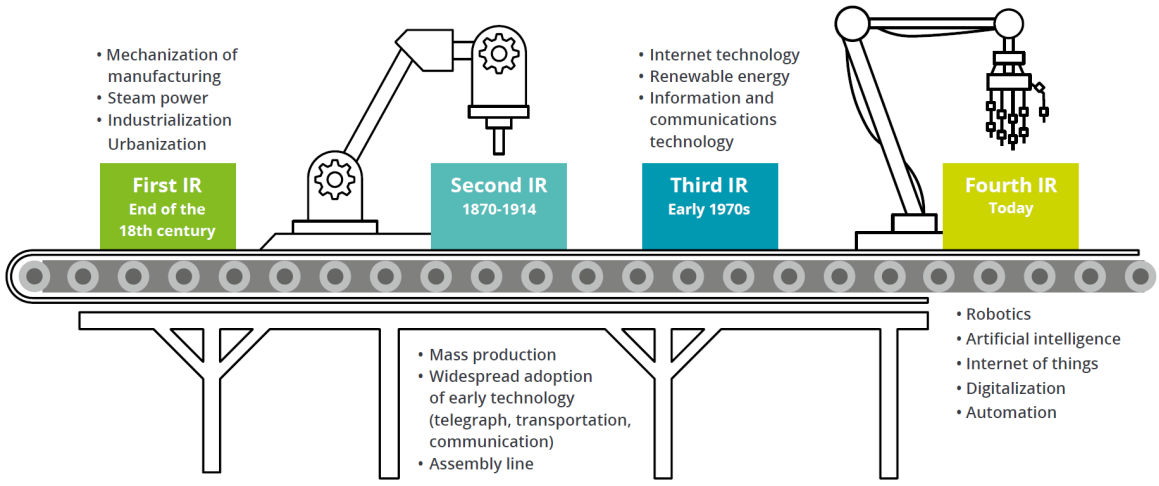

Figure 1. Summary of the four industrial revolutions. (Source: Deloitte, 2018)

The first industrial revolution saw the substitution of animals and humans with fossil fuels and mechanics as primary sources of power (World Economic Forum, 2016a). The revolution began in Britain and later spread to other parts of the world. This was followed by the second industrial revolution which began in the late 19th century and saw the introduction of electricity, gas and oil power; rapid industrialisation and mass production (Manufacturing Data Summit, 2019). The third industrial revolution began in the mid-20th century. The revolution was characterised by the development of electronics, digital systems, and rapid advances in computing power, enabling new and faster ways of communication (World Economic Forum, 2016a; Manufacturing Data Summit, 2019). According to Manufacturing Data Summit (2019), the third industrial revolution era saw an unprecedented increase in the development of electronics that enabled the automation of industrial processes. The 21st century saw the introduction of the fourth industrial revolution (4IR). Even though a proceeding revolution has always improved on a preceding revolution, the 4IR is anticipated to significantly introduce new ways of technology interacting with humans (World Economic Forum, 2016a). The revolution is expected to change every aspect of life, and how humans interact with technology (Deloitte, 2018).

To adapt to the changes brought by 4IR, industries must be prepared for the anticipated changes. One of the ways to prepare is to develop skills required for the 4IR. Therefore, the aim of this paper was to analyse whether mining engineering schools have adjusted their curriculum to produce graduates who are 4IR-ready. The top ten mining engineering schools in the world based on the 2021 QS World University Rankings by mineral and mining engineering subject were assumed as proxy of the global mineral and mining engineering schools. QS is a university ranking system which was founded by Quacquarelli Symonds Ltd, a London based company (Baccini *et al.*, 2015). It is not the scope of this paper to describe in detail how the QS ranking is done.

Fourth industrial revolution

4IR also known as Industry 4.0. is described by World Economic Forum (2016a) as the "advent of "cyber-physical systems" involving entirely new capabilities for people and machines". It is characterised by technologies such as robotics, automation, internet of things (IoT), artificial intelligence (AI) technologies, quantum computing, digitalisation, digital transformations, personal connected devices, and data analytics (Popular Mechanics, 2020; Manufacturing Data Summit, 2019). Such technologies are developing rapidly which will disrupt the status quo in most economic sectors, while unlocking opportunities for new products and services. Several industries are at different stages of applying 4IR technologies, including the mining industry which is slowly embracing these emerging 4IR technologies to improve its productivity and sustainability. Society of Mining Professors (2019) mentioned that 4IR technologies will have significant implications for the mining industry. They will change the traditional way of extracting minerals which will bring about challenges and opportunities for the industry.

Mines of the future and benefits of 4IR technologies to the mining industry

In the mining industry, 4IR also called Mining 4.0, brings disruptive technologies which will fundamentally change the future of mining operations in terms of operations, safety and economics both negatively and positively. These technologies will transform traditional mines into what are now commonly referred to as mines of the future or digital mines. Society of Mining Professors (2019) defined a mine of the future as a digital mine that embraces digital technologies and IoT to provide monitoring and real-time control systems. Mines of the future will involve mobile computing, cloud data storage, big data analytics, advanced process control and the implementation of autonomous mining equipment (Society of Mining Professors, 2019). Key characteristics of mines of the future's value chain are summarised in Figure 2. These characteristics were supported by Weber-Youngman (2017) cited in Mitra *et al.* (2018).

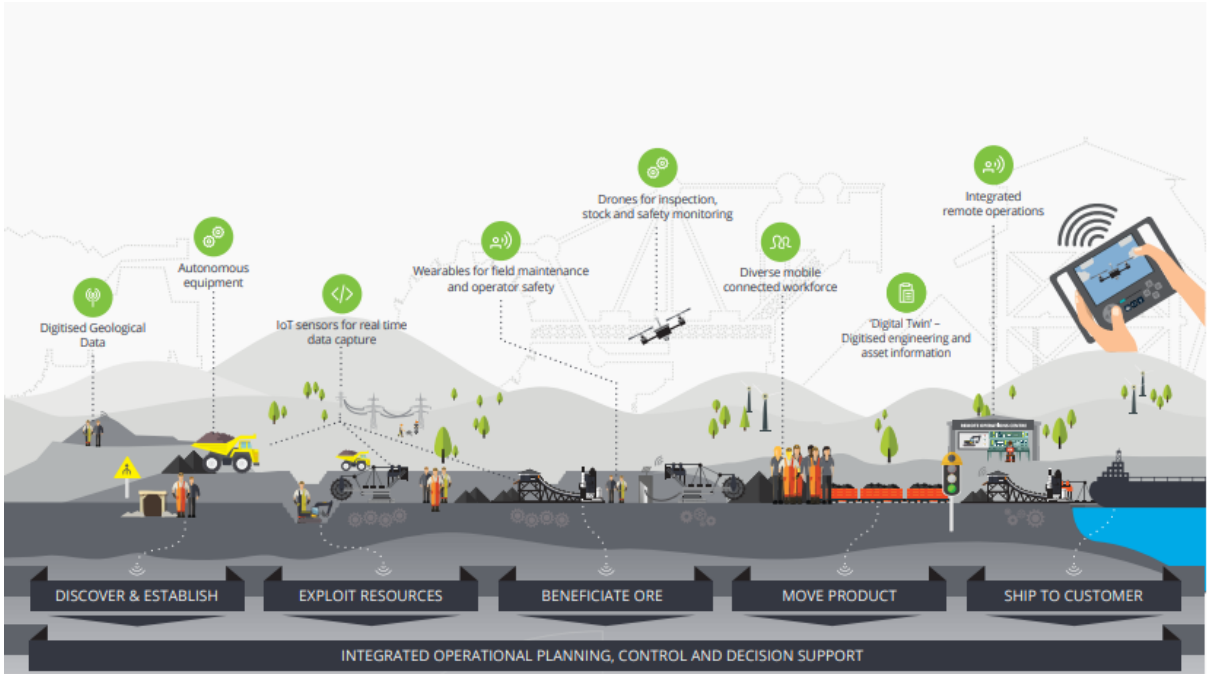

Figure 2. Key features of mines of the future's value chain.
(Source: Deloitte, 2017)

According to Deloitte (2017), 4IR brings an opportunity for industries to use technology to create value. Along the mine value chain, Deloitte (2017) identified opportunities in five operational processes of the digital mine. These are real-time data capture, automation and remote operation, digital twins – digitised geological, engineering and asset data drones and wearables. Big data and real-time analytics will enable mines to collect and analyse a lot of operational performance data in real time. This, combined with AI, will enable better decision making by mine managements thereby improving efficiency in mining operations. Automated mining operations will require fewer operators, but more highly skilled personnel to maintain, analyse and improve operations (Society of Mining Professors, 2019). Mitra *et al.* (2018) indicated that the use of remote controlled and fully autonomous equipment is increasing in the mining industry around the world.

4IR technologies enable mines to go deeper, become safer and more sustainable as robots can operate in places where humans cannot enter safely (Popular Mechanics, 2020). They can operate in extremely harsh environments with less requirement for ventilation. Additionally, 4IR technologies will enable previously uneconomic mineral resources to be extracted profitably because less waste will be mined, resulting in mines being cost efficient compared to traditional mines (Popular Mechanics, 2020).

As mentioned by World Economic Forum (2016a) that "the future is already here", some of these technologies are already being applied in the mining industry especially in mines that employ surface and massive underground mining methods. Examples of technologically advanced mines include Pilbara, Mt Arthur, Ulan West and Northparkes operations, all in Australia; El Teniente Mine in Chile; Kiruna Mine in Sweden (Society of Mining Professors, 2019). Anglo American has introduced what the company calls the FutureSmart Mining programme which involves digitalisation and the application of big data and AI. As mentioned by Anglo American (2021), the programme "brings together step-change innovations in technology and digitalisation to drive targeted safety and sustainability outcomes". This is achieved by employing innovative mining methods to overcome challenges of water availability, lower grades and increasing energy requirements, reducing environmental footprint as well as reducing capital intensity and operating costs (Anglo American, 2021). The programme enables the company's operations to become safer, more water- and energy-efficient and enhances the operations' performance across the entire mining value chain (Anglo American, 2021). Similar benefits of 4IR were mentioned by BHP (2021) who indicated that technology is helping the company to improve

safety, increase productivity, reduce cost, build capability, and accelerate value creation. BHP (2021) also mentioned that the company is leveraging technologies such as cloud computing, cloud storage and smart analytics to enhance decision making and advance mining technologies to automate equipment at some of its operations. Sibanye Stillwater partnered with the University of the Witwatersrand's DigiMine to fasttrack the implementation of 4IR technologies (Sibanye Stillwater, 2021).

It can be concluded from the discussion in this section that mines of the future will be more efficient, safer, sustainable, smart and operated by highly skilled people. Therefore, advanced technological changes brought by 4IR also require different skills and create new job opportunities. In turn, mining engineering schools should revise their curricula to fit into this new world of the "digital mine" (Society of Mining Professors, 2019).

Skills for mines of the future

Mines have made technological advances over the years, developing from being modern mines to real-time mines and recently to intelligent mines (Society of Mining Professors, 2019). Some of the changes were discussed in the previous section. As mentioned earlier in this paper, to adapt to the change, mining engineering schools must revise their curricula to develop mining engineers of the future (Society of Mining Professors, 2019; Mitra *et al.,* 2018). For example, Mitra *et al.* (2018) mentioned that the University of the Witwatersrand's School of Mining Engineering was reviewing its curriculum to align it with 4IR requirements. The new curriculum will be fully phased in at the end of 2022 (Mitra *et al.*, 2018). It is expected that many other mining engineering schools will follow suit to review their curricula.

Literature is available that characterises skills required for 4IR in general. For example, the World Economic Forum (2016b) listed the following as the top ten skills required:

i. "Complex problem solving.
ii. Critical thinking.
iii. Creativity.
iv. People management.
v. Coordinating with others.
vi. Emotional intelligence.
vii. Judgement and decision making.
viii. Service orientation.
ix. Negotiating.
x. Cognitive flexibility".
xi.

The skills above are mostly interpersonal attributes. Specific to the mining industry, technical skills related to 4IR are required in addition to the above interpersonal attributes.

According to Society of Mining Professors (2019), there is an argument by some people that mines of the future will require less mining engineering skills but more mechanical, mechatronics and computer skills. However, they concluded that rather mining engineering programmes must change to satisfy the needs of the mines of the future. They suggested the following as some of the skills that mining engineering schools can incorporate into their curricula:

i. Advanced statistics to be able to deal with big data associated with 4IR.
ii. Software coding skills.
iii. Competence in a range of important generic data management and analysis of software packages.
iv. Principles of systems engineering and process/systems analysis.
v. Mine robotics and automation.
vi. Data analytics.
vii. Internet of things.

The lists by World Economic Forum (2016b) and Society of Mining Professors (2019) show that the mining industry should adopt emerging technologies from other disciplines.

Methodology

The list of skills for the mines of the future proposed by the Society of Mining Professors (2019) is in alignment with the 4IR technologies as identified by various authors including Deloitte (2017) and Weber-Youngman (2017) cited in Mitra *et al.* (2018). From literature review, common 4IR skills identified are data science, data analytics, computer programming, automation, and robotics, IoT, AI technologies, and digitalisation. Therefore, courses offered by the top ten selected mining engineering schools were mapped against these technical 4IR skills based on the course titles and descriptions as available on the public domain (universities' websites). This was done to analyse the extent to which the skills have been embedded in the schools' curricula. Additionally, the selected schools were contacted via email to make sure that the information collected from the schools' website is correct. However, only two of the ten schools responded. Only undergraduate level mining engineering programmes were considered in the analysis.

Analysis of the curricula in relation to mines of the future needs

The QS World University Rankings is published annually. Figure 3 shows countries which hosted the world's top 50 mineral and mining engineering schools in 2021. The top 50 schools were listed only to provide a broad overview of the top ranked mineral and mining engineering schools. Nonetheless, only the top ten were analysed in detail.

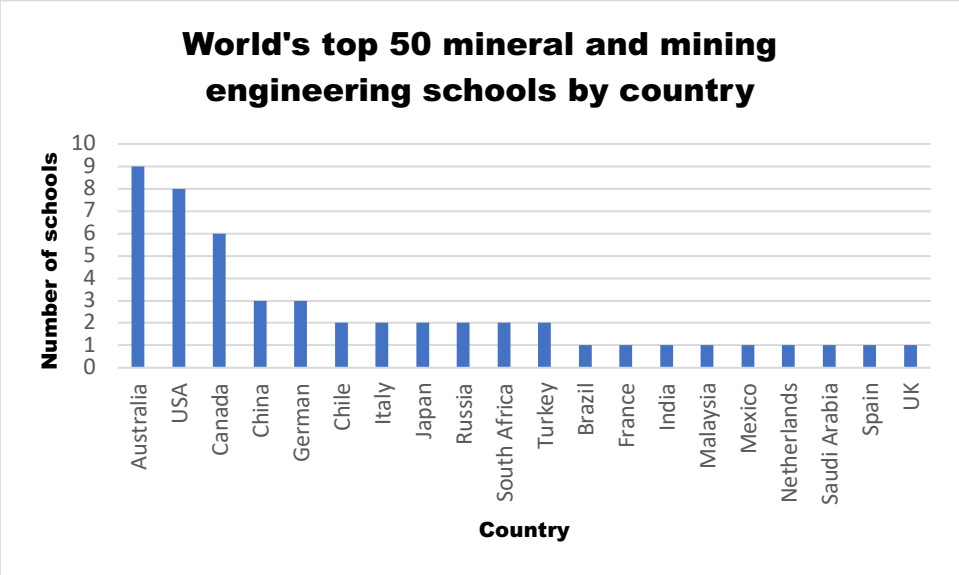

Figure 3. Countries hosting the world's top 50 mineral and mining engineering schools in 2021. (Source: Quacquarelli Symonds Limited, 2021)

Figure 3 shows that Australia hosted the highest number of schools followed by the USA. This high number of schools in Australia and USA is likely because the two countries are the significant mineral producers in the world. In 2018, Australia and USA respectively ranked 2nd and 3rd globally in terms of metallic minerals and coal production value in US dollars according to Statista (2018). This shows that mineral and mining engineering schools play an important role in supporting the mining industry. However, despite China being ranked the top producer in the same year (Statista, 2018), it had relatively fewer top ranked schools as shown in Figure 3. Figure 4 shows continents which hosted the top 50 mining engineering schools in 2021.

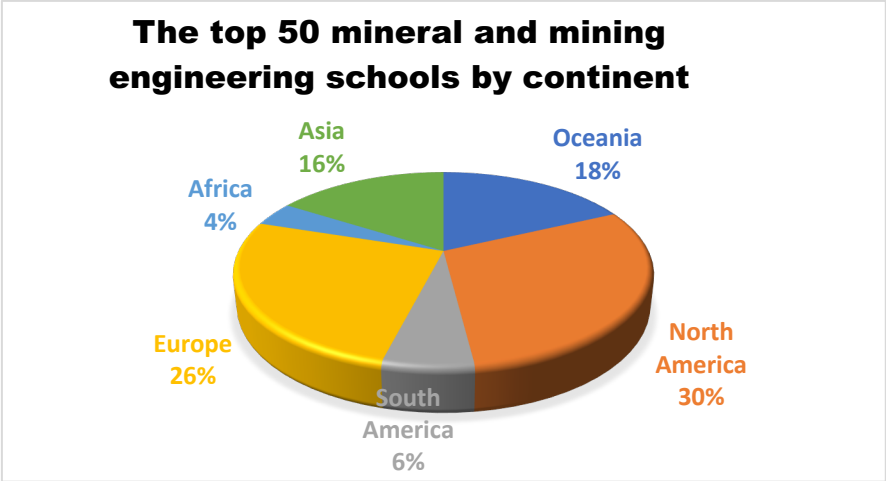

Figure 4. Continents hosting the top 50 mineral and mining engineering schools in 2021.

North America hosted the highest number of schools in the top 50 QS ranking. According to Quacquarelli Symonds Limited (2021), the top ten universities by mineral and mining engineering subjects in 2021 were:

1. Colorado School of Mines.
2. Curtin University.
3. The University of Queensland.
4. McGill University.
5. University of New South Wales.
6. The University of Western Australia.
7. Queen's University.
8. University of Exeter.
9. The University of British Columbia.
10. The Pennsylvania State University.

These are referred to as 1, 2, 3 …10 in Table I which maps the identified key 4IR skills against courses within curricula of the selected schools. In the table, a tick represents a 4IR related course identified in the school's curriculum. As mentioned earlier in the methodology section of this paper, most information on courses was only obtained from the respective universities' websites.

Table I. Fourth industrial revolution skills within curricula of the top ten schools

	QS world university rank in 2021									
4IR Skill	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Data science		✓								
Data analytics		✓	✓			✓				
Automation and robotics		✓	✓			✓	✓	✓		
Computer programming		✓		✓	✓	✓	✓			✓
IoT										
AI technologies		✓								
Digitalization		✓								

Colorado School of Mines

The school offers a four-year Bachelor of Science in Mining Engineering degree. However, no 4IR specific course was identified in the school's curriculum published by Colorado School of Mines (2022).

Curtin University
Curtin University offers a four-year Mining Engineering Major (BEng Hons) degree. The university has progressed somewhat in teaching 4IR-related courses. Three courses were identified in the university's curriculum published by Curtin University (2022). These are Introduction to Data Science; Introduction to Mining and Digital Applications; and Mine Automation and New Technologies. According to Curtin University (2022), the Introduction to Data Science course provides a broad introduction to four key aspects of data science which are data retrieval and manipulation; data visualisation; statistical computation and machine learning; and presentation and communication. The course also covers computing and database environments such as R and SQL. The course equips students with basic skills required to convert data into information (Curtin University, 2022).

In addition to introducing students to concepts of the mine value chain and main mining methods currently used in the industry, the Introduction to Mining and Digital Applications course covers data collection approaches and the use of advanced sensor data analytics to inform decision making in the mining context (Curtin University, 2022). Furthermore, the course equips students with knowledge on developments in digital mining systems.

The Mine Automation and New Technologies course provides students with a comprehensive overview of advanced mining systems and methods, including unmanned and remotely operated mining systems, and other digital technologies (Curtin University, 2022). Factors that enable, or hinder, effective automation of mining operations and implementation and utilisation of new technologies along the mine value chain are also covered in the course (Curtin University, 2022).

The University of Queensland
According to The University of Queensland (2022), the university offers the Bachelor of Engineering Honours degree major in mining engineering which can only be undertaken with the Bachelor of Engineering Honours degree specialisation in civil engineering or mechanical engineering or mechatronic engineering. Two courses were identified titled Computational Engineering & Data Analysis and Traffic Flow Theory & Emerging Technologies offered to students majoring in mining engineering under mechanical engineering and civil engineering specialisations, respectively. According to The University of Queensland (2022), the first course focusses on modelling and analysis in mechanical engineering. The course also covers the application of computers to analyse engineering problems through calculation, simulation, and numerical methods. The second course focusses on traffic management strategies. The course also covers emerging and disruptive technologies, such as connected and automated vehicles (The University of Queensland, 2022).

McGill University
The university offers a Bachelor of Engineering degree in Mining Engineering. One course was identified titled Computer Programming for Physical Sciences and Engineering which is offered by the university's School of Computer Science. The course which is compulsory deals with computer programming and introduces students to algorithms development (McGill University, 2022).

University of New South Wales (UNSW Sydney)
The university offers a four-year Bachelor of Engineering (Honours) degree. One core course was identified titled Computing for Engineers which equips students with computing skills for solving problems in engineering. The course is offered by the university's School of Computer Science and Engineering. It covers algorithms, programme structure, data types, arrays, and matrices, reading and writing files, testing, code quality, simulation, animation, visualisation (University of New South Wales, 2022). Two elective courses were identified namely Computer Systems Fundamentals and Software Engineering Fundamentals, both offered by the university's School of Computer Science and Engineering. Both courses cover programming.

The University of Western Australia
The university offers a Bachelor of Engineering majoring in Mining Engineering. According to The University of Western Australia (2022a), one course was identified titled Computer Analysis and

Visualisation which is a core course. In this course, students develop an understanding of scientific computing and modelling, analysis, problem solving and visualisation (The University of Western Australia, 2022a). According to The University of Western Australia (2022a), students learn computational modelling, develop programming skills in data analysis modelling; understand limitations and uncertainty in models; devise and implement computational models; analyse data and hypotheses; are aware of reliability and correctness; and perform simulation and testing.

According to The University of Western Australia (2022b), the school offers other courses which provide programming skills, additive manufacturing, and automation. The school is also developing an advanced surveying course which may include the use of drones and remotely controlled tools for surveying (The University of Western Australia, 2022b).

Queen's University
Queen's University offers a four-year Bachelor of Applied Science in Engineering (Mining Engineering). Three courses were identified titled Introduction to Computer Programming for Engineers, Mining Systems, Automation, & Robotics and Mine-Mechanical Design Project. According to Queen's University (2022), the first course introduces students to concepts, theory, and practice of computer programming. The second course introduces students to the fundamental tools and techniques of automation and robotics as applied to modern mining practice (Queen's University, 2022). Further, the course introduces the basics of systems control, examples of how methods of automatic control can be applied to mining equipment and associated industrial vehicles, as well as to the fundamentals of sensing and navigation as applied to the design of robotic mobile equipment. The third course involves a design project with emphasis on the mechanical aspects of mine or plant design and operation including automation (Queen's University, 2022).

University of Exeter
According to the University of Exeter (2022a), their undergraduate mining engineering programmes were paused at the time of writing this paper. It was further stated that they have always been responsive to the changing demands of prospective students and the mining industry. It is anticipated that their revised curriculum will address the needs of a future 4IR mine. Courses offered by the school which cover 4IR skills are Safety & Sustainability, Soil Mechanics with Mine Tailings Engineering, Feasibility Study and Mine Automation (University of Exeter, 2022b). However, based on the 4IR skills mentioned in the methodology section of this paper the only course that was considered and mapped is Mine Automation.

The University of British Columbia
The University of British Columbia offers a Bachelor of Applied Science (Engineering). No 4IR related course was identified in the school's curriculum published by The University of British Columbia (2022).

The Pennsylvania State University
Pennsylvania State University offers a Bachelor of Science degree in Mining Engineering. One elective course was identified namely Programming for Engineers with C++. The course equips students with knowledge on the development and implementation of algorithms in a procedure-oriented language, with emphasis on numerical methods for engineering problems (The Pennsylvania State University, 2022).

ANALYSIS OF FINDINGS

In general, mining requires various skills which are sourced from different disciplines including geology, survey, electrical and mechanical engineering among others. Similarly, some of the 4IR skills are incorporated in degrees other than mining engineering. Therefore, successful production of 4IR-ready graduates by mining engineering schools requires collaboration with other disciplines. The findings of this paper show that 4IR courses offered by the analysed schools are derived from non-mining disciplines such as mechanical, mechatronics and computer science, as also indicated by Society of Mining Professors (2019). This multi-disciplinary nature which already exists in mining engineering

helps to quickly meet industry needs while preparing graduates who can work in teams with different expertise. The study also found that Curtin University has more 4IR skills related courses among the analysed schools. Also, computer programming and automation and robotics were found to have been incorporated by most schools analysed. Gravitation towards automation and robotics can be attributed to the need to make mines safer by removing people from the mine face.

CONCLUSIONS

The mining industry is experiencing a significant change led by the accelerating pace of technological innovation introduced by the 4IR. This in turn requires the supporting mining engineering educational institutions to revise their curricula to supply the industry with 4IR-ready graduates. This paper has found that the mining engineering schools have mostly started incorporating 4IR related courses in their curricula *albeit* at a slow pace. Of the analysed schools, two schools were found to have at least three 4IR related courses, and two schools have no 4IR-related courses within their curricula. Among the identified and mapped 4IR skills, no course which incorporates IoT was found in any of the schools analysed. It is suggested that mining schools must revise their curricula to include more 4IR courses to support the mining industry as it transforms to the mines of the future.

DISCLAIMER

The opinions and interpretations expressed in this paper are those of the authors only.

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