International Journal of Circular Economy and Waste Management
Volume 1 • Issue 1 • January-June 2021

The Circular Economy, Resilience, and Digital Technology Deployment in the Mining and Mineral Industry

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ABSTRACT

The mining and mineral industry is not easily associated with sustainable development. The one is focused on the exploitation of the planet's limited natural resources, while the other attempts to promote development that meets the needs of the present without compromising the needs of future generations. This article looks at the industry's approach to the core sustainability concepts of the circular economy and resilience and finds that leading companies in this industry have drawn on the concept of resilience in reporting on their sustainability strategies, but that there has been little interest in the concept of the circular economy. The article also assesses the current and potential impact of information and communication technologies in supporting sustainability objectives in the industry. It concludes that technology innovation will be a key enabler in supporting the mining and mineral development industry to more formally address the challenges of sustainable development, and support a transition to a more sustainable future.

KEYWORDS

Circular Economy, Digital Technologies, Information and Communications Technology, Minerals Industry, Mining, Resilience, Sustainable Development

INTRODUCTION

In many ways, the mining and mineral industry appears to be the antithesis of sustainable development. On the one hand, Carvalho (2017), for example, suggested that "mining industries provide most of the materials we rely on to build infrastructures and instruments of daily use, to obtain large amounts of energy, and to supply agriculture with fertilizers that enable most of foods produced. At the same time, mining is the human activity that has been more disturbing to environment and is linked to large social impacts and inequalities." More tellingly, Segura-Salazar and Tavares (2018) suggested that "when compared to other resource industries such as forestry, aquaculture and agriculture, the mining industry is perceived as one of the least committed to sustainable development." On the other hand, sustainable development is typically defined as development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). More specifically some commentators, have argued for an approach to sustainable development which "subordinates economies to the natural environment and society, acknowledging ecological limits to growth" (Roper, 2012). Here, "prioritizing the preservation of nature is pre-eminent" (Hudson, 2005). However, there is growing interest in the relationship between minerals and mining and sustainability and in seeking "a consensus on the

DOI: 10.4018/IJCEWM.2021010102

implications of sustainability in the minerals industry" (Segura-Salazar & Tavares, 2018). In a recent study of Corporate Social Responsibility (CSR) practices in the Portuguese mining industry, Gaspar Alves and Mendes Rodrigues (2017), for example, noted "results suggest that CSR practices are not integrated in the management control system, are not part of a long-term environment strategy, and only reflect compliance with Portuguese legislation." Further, Endl (2017) has observed that "the achievement of sustainable development (SD) in the supply of minerals poses significant challenges for governments and public administrations on all levels."

Around the turn of the millennium, the executive report on the Mining, Minerals and Sustainable Development (MMSD) Project, initiated by nine of the world's leading mining companies, examined "the role of the minerals sector in contributing to sustainable development, and how that contribution could be increased" (International Institute for Environment and Development, 2002). In prescribing an "Agenda for Change", the International Institute for Environment and Development (2002) set out various actions for improving the mineral sector's contribution to sustainable development. A decade later, Buxton (2012a) suggested that "understanding of sustainable development in the mining and minerals sector has markedly improved and there is increased sophistication in talking about how mining should maximise its contribution to sustainable development". However, Buxton (2012b) also suggested "the thinking and language of sustainable development looks a little different" than when the original report was published, that there is "a renewed focus on renewables, resilience and recycling" and that "resource efficiency and closed loop thinking could become business imperatives in the face of increasing pressure on resources" (Buxton, 2012a). At the same time, Dubinski (2013) suggested that "the sustainable development of mining mineral resources is a major challenge for today's global world, addressed to mining companies, people of science associated with mining and many other institutions and organisations." With these thoughts in mind, the objectives of this paper are three fold. Namely, to review the mining and mineral industries' approaches to the concepts of the circular economy and resilience, to assess the current and potential impact of information and communication technologies in supporting sustainable development within these industries and to address some of the challenges the industries face in looking to adopt circular economy and resilience thinking.

SUSTAINABLE DEVELOPMENT CONCEPTS

The modern concept of sustainable development is derived from the landmark report by the World Commission on Environment and Development (1987), and in the last three decades it has become an aspirational principle to guide the meeting of human needs, whilst also ensuring the availability of natural resources for future generations. However, the concept of sustainability, defined by Diesendorf (2000) as "the goal or endpoint of a process called sustainable development", is not new. Du Pisani (2006), for example, demonstrated "how the idea of sustainability evolved through the centuries as a counter to notions of progress" and concluded "fears that present and future generations might not be able to maintain their living standards stimulated a mode of thinking that would inform discourses which prepared the way for the emergence and global adoption of sustainable development." The concept re-appeared in the environmental literature in the 1970s, and since then the term sustainability has become increasingly seen as offering potential solutions to a wide range of challenges and problems, from the global to the local scale, across seemingly almost all walks of life.

However, Mensah and Casadevall (2019) argued that "sustainable development stands the risk of becoming a cliché like appropriate technology – a fashionable and rhetoric phrase – to which everyone pays homage but nobody seems to define with precision and exactitude." Given these ambiguities, some sustainability discourses have focussed on drilling down to a number of concepts - including the circular economy, resilience, natural capital, sustainable consumption, corporate sustainability and sustainable investment - in an attempt to explore different elements in the transition to a more sustainable future. This paper addresses two of these concepts, namely the circular economy and

resilience, which can be seen as being within the wider and more all embracing concept of sustainable development.

The concept of the circular economy is gaining increasing momentum in political and corporate thinking about the transition to a more sustainable future. Gonzalez et al. (2019), for example, claimed that the fact that the circular economy concept has gained increasing attention in many parts of the world as a tool for optimising resource usage "is due in large part to the awareness of resource scarcity and economic activities' negative impacts on the environment." However, Hartley et al. (2020) suggested "there are relatively few academic studies on policies that may accelerate a transition towards a circular economy", and Morseletto (2020) suggested that to date "no study has investigated circular economy targets in a systematic way." While Murray et al. (2015) suggested that the term circular economy has "been linked with a range of meanings and associations by different authors", they argued that in its most basic form "a circular economy can be loosely defined as one which balances economic development with environmental and resource protection." The Ellen McArthur Foundation, established in 2010 with the aim of accelerating the transition to a circular economy, argued that "a circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times" (Ellen McArthur Foundation, 2017). As such, the concept of the circular economy is often contrasted with the traditional "linear economy" which turns raw materials into waste in the production process and which is seen to lead to environmental pollution and the removal of natural capital from the environment.

Korhonen et al. (2018) suggested that the concept of the circular economy had "almost exclusively been developed and led by practitioners", including policy makers and businesses and that the "scientific research content of circular economy remains largely unexplored." This led the authors to propose a new definition, namely: "Circular economy is an economy constructed from societal production-consumption systems that maximises the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical material flows, renewable energy resources and cascading-type energy flows. Successful circular economy contributes to all three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates." In practice, circular economies are popularly seen to be built around a range of activities, which look to reduce the demand for raw material inputs and natural resources, and to recover, recycle and re-use those inputs and resources as an integral part of the production process. As such, the concept of the circular economy is restorative and regenerative and is contrasted, by its proponents, with the traditional linear economy, which turns raw materials into waste in the production process, and which is seen to lead to environmental pollution and the removal of natural capital from the environment.

Essentially the concept of the circular economy embraces all stages of the product life cycle from product design and production, through marketing and consumption to waste management, recycling and re-use. Consumers have a vital role to play if there is to be a transition to a more circular economy, not least in that they need to be prepared to embrace what they may see as radical new buying behaviours and consumption practices. Within a circular economy, waste management is no longer seen as a problem, but rather as an opportunity to return as much waste as possible back into productive use. The focus is on the prevention, reuse and recycling of waste materials rather than their disposal by landfill. Where waste cannot be prevented, reused or recycled then recovering its energy content is seen to be preferable to landfill and waste to energy solutions are also seen to be integral to the circular economy. A variety of potential environmental gains, energy generating opportunities and business benefits are claimed for a transition to a circular economy. These benefits include substantially reduced carbon dioxide emissions, greater use of renewable sources of energy, reduced pollution levels, the production of energy from waste materials and increased growth and profitability. Within the green economy, products and markets grow as companies pursue market

opportunities in the production and promotion of environmentally sensitive goods and services (Baziana & Tzimitra-Kalogianni, 2016).

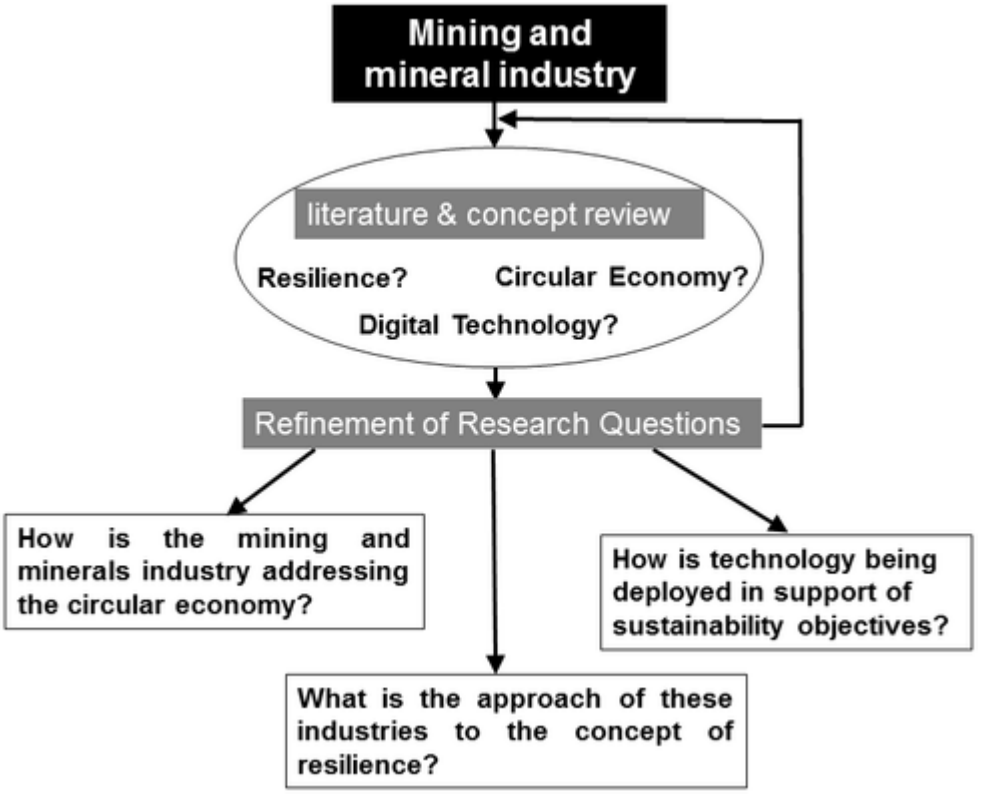
Resilience is an increasingly common element in sustainability and sustainable growth narratives. In everyday language, resilience is seen as the ability to withstand or to bounce back from adversity and disruption. However, in the professional and academic world, a number of meanings can be identified, and while Sharifi and Yamagata (2014) suggested that "despite the abundance of research on resilience there is still no single, universally accepted definition for it", Fabry and Zeghui (2019) argued "there are competing definitions of resilience." Certainly, a number of origins and meanings are claimed for resilience. Hassler and Kohler (2014), for example, claimed that "resilience as a design principle, was an implicit part of construction knowledge before the nineteenth century" and Sharifi and Yamagata (2014) suggested that "the concept of resilience has traditionally been used in physics and psychology." Davoudi et al. (2012) acknowledged that "resilience was first used by physical scientists" and argued that, in the 1960s, "resilience entered the field of ecology." MacKinnon and Derickson (2013) suggested that "the concept of resilience has migrated from the natural and physical sciences to the social sciences and public policy, as the identification of global threats such as economic crisis, climate change and international terrorism has focused attention on the responsive capacities of places and social systems." Adger (2000) defined social resilience as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change." More generally, work across the disciplines is concerned with the ability of systems to withstand and recover from major disruptions.

There is also growing recognition of the importance of resilience within the corporate world. PricewaterhouseCoopers (2017a), for example, emphasised their belief that "enterprise resilience is the most important capability in business today." Here enterprise resilience is defined as "an organisation's capacity to anticipate and react to change, not only to survive, but also to evolve" (PricewaterhouseCoopers, 2017b.) At the same time, there is growing interest in the creation of resilient business strategies. In introducing "resilient business strategies", the BSR (2018) have argued "rather than integrate sustainability into company strategy, we believe companies need to create resilient business strategies." Such strategies are "based on an understanding that rapidly-shifting external context – our changing demographics, disruptive technologies, economic dislocation and natural resource scarcity are not only sustainability issues but also business issues" (BSR, 2018). More generally, Ambler, Beagent and Thurley (2017) stressed the importance of "balancing economic and environmental resilience", and as such emphasised the growing importance of resilience within the corporate world. The nature of relationship between the concepts of resilience and sustainability has been depicted in a number of ways. In some cases, the two terms have been used almost interchangeably, while Weichselgartner and Kelman (2014) suggested that resilience has begun to replace sustainability as a guiding principle in development planning. PricewaterhouseCoopers (2017a) emphasised their belief that "enterprise resilience is the most important capability in business today."

RESEARCH METHOD

The research method was based on a literature review and the authors believe this is an appropriate approach for such an exploratory paper. As such, this article draws its empirical material from corporate sustainability reports published by the leading players in the mining and mineral development industry, from reports published by a number of industry and industry related organisations, from ICT analysts and commentators, and from academic papers. The research has adhered to the approach recommended by Saidani et al. (2017), in that while the inclusion of peer reviewed academic papers "ensures scientific soundness", corporate and industry body reports can be seen to "reflect current industrial reality and needs … and therefore bring meaningful insights". The research methodology was based on an inductive, qualitative approach, focusing on an extensive review of existing academic literature and industry reports.

Figure 1. Research method and research questions



More specifically, the authors conducted four Internet searches in 2019, using Google as the search engine. First, a search was undertaken on Google using the name of each of the top twenty mining and mineral development companies (Mining.com, 2018) and the term "sustainability report" was used as the key words. The most recent report of these companies was then searched using the terms "resilience" and "circular economy". A second set of searches was then undertaken on Google using the terms "mining and mineral development and resilience" and "mining and mineral development and circular economy", which produced a number of industry organisation and industry related reports. All the corporate and industry reports identified in these two searches are in the public domain, and the authors took the considered view that they did not need to contact the selected companies or organisations to obtain formal permission prior to conducting their research. Third, a search was undertaken on Google Scholar using "the mining and mineral development industry and resilience" and "mining and mineral development industry and circular economy" as the key words and this produced a number of academic research papers. A fourth search focused on "sustainability systems and reporting" in both a general context and with relation to the mining and minerals industry.

In reviewing the available material, certain elements of a bibliometric review (de-Miguel-Molina, de-Miguel-Molina, & Albors, 2015) were adopted, which can be seen as a method broadly used "to draw the big picture in a literature review" (p.1). Börner and Polley (2014) note that this process starts with the formulation of basic questions to be answered in the literature review. In this instance, these questions encompassed the approach and attitude of the mining and minerals industry to sustainability; were there any particular references to the circular economy or resilience issues in the company reports? Were there any models of the circular economy and resilience in the academic literature that could be applied to the mining and minerals industry? How was the industry using

technology to support sustainability reporting? Were the new digital technologies of relevance in progressing sustainability issues? The research attempts to synthesize areas of conceptual knowledge and understanding, and of operational practice, that can contribute to addressing these questions (Mulrow, 1994; Kitchenham, 2004). This provides the basis for a summary of the existing evidence concerning the field of research and identifies debates in the current literature that may promote the development of new lines of enquiry (Figure 1). This initial analysis produced a refinement and repositioning of research aims to address the following questions:

1. How is the mining and minerals industry addressing the circular economy
2. What is the approach of these industries to the concept of resilience?
3. How is technology being deployed in support of sustainability objectives?

FINDINGS AND ANALYSIS

The Circular Economy Within the Mining and Mineral Industry

In posing the question "can mining survive in the circular economy", Resourceful Pathways (2017) claimed "the circular economy can be an opportunity for the mining industry to adapt" and to develop "a more stable business model than the boom and bust swings of mining". However, while Kinnunen and Kaksonen (2020) claimed that "the mining industry is aware of circular economy thinking and also willing to transform towards a circular economy", only one of the top twenty mining companies, namely Glencore, reported on its engagement with the circular economy as part of the sustainability reporting process, and here the focus was on working with industry associations to identify ways in which the company's mining activities could contribute to the circular economy. More specifically, the company reported "investigating the potential of leasing vanadium in battery storage solutions, extracting and reusing the vanadium at the end of the end of the lease term".

Lebre, Corder and Golev (2017) explored the role of the mining industry and suggested that "mines can make significant progress if they apply the circular economy principles at the mine site level". More specifically, their empirical observations at the Mount Morgan mine in Queensland, Australia reveal that the proactive and preventative management of mining waste generates a range of environmental and economic benefits and illustrates how the concept of the circular economy can be applied in a practical manner to mining operations. Zhao et al. (2012) ambitiously claimed that developing a circular economy approach within the mining industry within China has a significant impact on solving mineral resource shortage problems and in reducing waste generation and environmental pollution and in contributing to "the sustainable development of national social economy". Pomykala and Tora (2017) examined the challenges and opportunities associated with the development of a circular economy model in the mining industry within Poland and presented a number of examples of good practice in waste management within the Tauron SA and ZGH Boleslaw SA companies in Poland.

In setting the context for its report on "Mining and Metals in the Circular Economy", the International Council on Mining and Metals (2016) suggested "population growth and the impacts of increased production and consumption, particularly climate change, have become the central drivers for creating more circular economy." In exploring how the mining and mineral industry can contribute to the development of a more circular economy, the International Council on Mining and Metals (2016) claimed "in many senses minerals and metals are ideal technical nutrients for the circular economy." Here a number of activities were identified in contributing to a transition to a more circular economy including mining operations; smelting and refining; products; low carbon energy; and recycling. In focusing on the first of these activities, the report suggested that "there are a variety of circularity aspects that can be pursued within mining operations" (International Council on Mining and Metals, 2016) and reported that a number of guidance programmes had been developed

within various countries to enhance standards and to share best practice across a range of operation and impacts. Further, it is also argued that "circularity is also enhanced at the smelting and refining stage by increasing the recovery of co-products" (International Council on Mining and Metals, 2016) and examples are provided of how copper and nickel producers recover a range of other metals.

In its "Scoping Paper" - entitled "Mining and Metals in a Sustainable World" - the World Economic Forum (2015) claimed that "customers and suppliers expect mining and mineral companies to align with the circular economy". They suggested that "downstream players find that closing the loop on the supply chain through improved product design, extended asset life, reuse and recycling can deliver tangible commercial and environmental gains." Nevertheless, it was argued that mining and mineral companies will need to address three sets of issues if they are to operate effectively within the circular economy. First, companies will have to develop a workforce with a suitable set of skills and capabilities; second, they will need to be more involved in scrap markets and third, they will need to focus on consumer and customer relationships. In identifying the necessary skills to achieve this, the World Economic Forum (2015) stressed the need to build and manage effective relationships with suppliers, customers and consumers across the value chain in that this "serves to drive product innovation and identify opportunities for improved efficiency." At the same time, the World Economic Forum (2015) suggested that by developing these relationships "mining and mineral companies are able to adapt their production processes to more closely meet customer demands and deploy the higher environmental and social standards that consumers expect."

Resilience Within the Mining and Mineral Industry

Seven of the leading twenty mining companies employed the concept of resilience in outlining their approach to climate change. In addressing climate change as a key element in its approach to sustainability, BHP Billiton, for example, reported on its commitment to "building and managing a resilient portfolio" (BHP Billiton, 2016). The company's approach to climate change is built around looking to reduce greenhouse gas emissions, taking measures to adapt to the impact of climate change and working in partnership with governments, industry and the academic community to enhance the global response to climate change. The company emphasised its belief that industry has a vital role to play in working in partnership with governments, investors, peer companies and non-governmental organisations, for example, in developing a long-term policy framework to deliver a measured transition to a lower carbon economy. Further, the company argued that such a policy framework should include a price on carbon, support for the development of low emissions technology and measures to build resilience.

In emphasising its belief that "our minerals and metals have a role in a low carbon future", Rio Tinto (2018) reported that it was "aiming for a substantial decarbonisation by 2050 and are taking steps to manage energy use, manage risk, build resilience to climate change and develop our role in a low carbon future." Anglo American (2018) reported that "building internal agility and ensuring resilience to climate change" was one of the company's five principles in the company's approach to climate change. More specifically, Anglo American (2018) reported that the key elements in its "approach to climate resilience" were "building climate change scenarios using the best available science, using our operating models to identify vulnerability and exposure" and "integrating critical controls into operational risk management." In addressing "climate change", Glencore (2018) outlined the company's "portfolio resilience" to a number of climate scenarios, while in acknowledging that "climate change is a global challenge." Fortesque Metal Group (2017) reported "we are working to ensure the resilience of our operations, company assets, employees and the communities in which we operate."

In its 2017 "Sustainability Report", Teck (2018) drew attention to the company's publication of a "Climate Action and Resilience Portfolio" report. This report outlined the Teck (2018) "climate action strategy", which included "increasing the resilience of our operations by incorporating climate scenarios into project design and mine closure planning." More specifically, Teck (2018) reported

"we will continue to focus on our cost- and carbon- competiveness to ensure the resilience of our steel making coal business" and "we will continue to track and refine key metrics that influence the strength and resilience of our assets in a low carbon world." Vale (2018) recorded that "resilience to climate change" was one issues the company was addressing in prioritising its commitment to the United Nations Sustainable Development Goals.

The focus on resilience was not solely confined to climate change. Rio Tinto, for example, stressed the importance of resilience in promoting mental health and wellbeing amongst its employees. In highlighting the importance of "healthful minds", Rio Tinto (2018) stressed "the need to be more proactive and to build resilience" and the company's goal is "for all employees to be empowered to build their own health, wellbeing and resilience and for Rio Tinto to influence and build a culture for doing this." In addressing "local community engagement and social commitment compliance", Glencore (2018) argued that "through engaging transparently and constructively with the communities living around our operations, we are working towards building economic resilience and diversity as well as ensuring a lasting contribution from our presence."

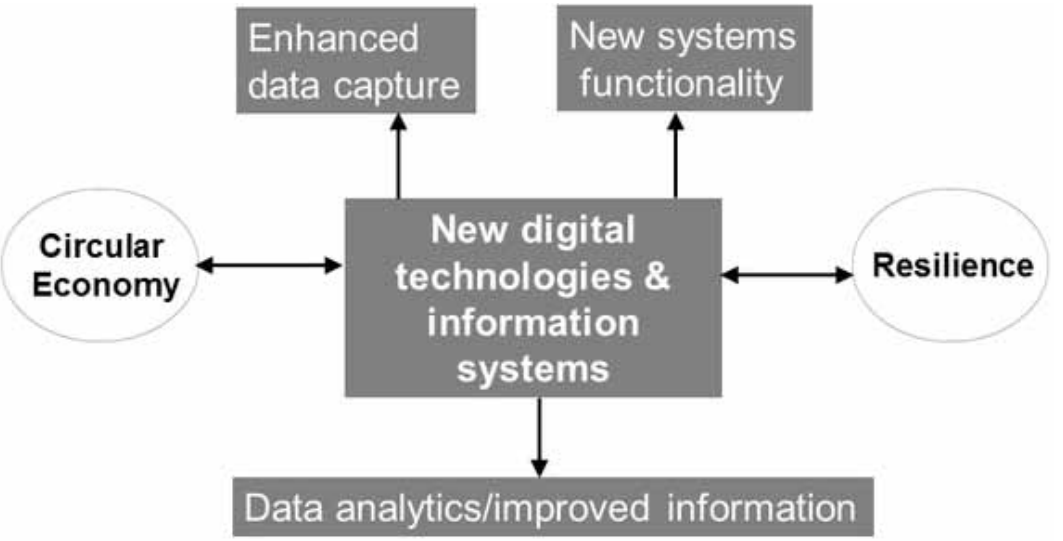
Academic researchers have examined a number of dimensions of resilience within the mining and mineral development industry. Bebbington et al. (2015), for example, looked to explore the relationships between extractive industries, climate change and environmental governance, through the lenses of resilience and risk. More specifically the authors examine the ways in which mining governance and governance for resilience converge and analyse the difficulties in governing extractive industries in a way that manages risk and builds resilience via a case study from El Salvador. Wasylycia-Lewis et al. (2014) explored the social-ecological system associated with large-scale mining operations at Itabira in Brazil through the lens of resilience. The authors' findings reveal the need for local government to have more power in its dealings with the mining corporation and for the development of a dedicated sustainability plan and for all key stakeholders to demonstrate their commitment to co-operating to resolve disturbances even when they fall outside the statutory regulatory approval process. In reflecting on the opportunities for mining companies to contribute to the United Nations Sustainable Development Goals in sub-Saharan Africa, Yakovleva et al. (2017) suggested that the development of renewable energy and climate change resilience capabilities should be amongst the main priorities. Lebre and Corder (2015) argued that "eco-efficiency and resilience (and the resulting increase in a mine's lifetime) are both critical—yet overlooked—characteristics of sustainable mining operations" and put forward a framework to assist in identifying opportunities for improvement and to measure this improvement in terms of its contribution to the sustainability of mining operations.

The Impact of ICTs and Digital Technologies

Digital technologies will play an increasingly important role in helping mining and mineral development companies embrace the sustainability concepts discussed above. This may be viewed as an evolution of existing technologies and their extension to encompass new business processes. This is evidenced in new developments in data capture, data and information processing, and data analysis and information reporting (Figure 2). These developments are distinct from, but interface with, advances in other technologies that are impacting the mining and mineral development industry - for example, cleaner production techniques, environmental control technologies (Rankin, 2011) and froth floatation technologies for processing certain metal sulphide ores (Rajaram & Parameswaran, 2005).

In focusing on data capture, for example, sensor-based technologies can be deployed within the mining and mineral development industry "to monitor the exact usage on heavy machinery in order to increase asset lifecycle and utilization, or to better understand product journeys across the value chain" (Thimmiah, 2018). Information systems design is also evolving to encompass sustainability concepts. Since the turn of the millennium, energy and water management systems have come to the market as specialist "niche" packages. However, as sustainability management is becoming increasingly viewed as a mainstream business function, it is likely that the functionality of the core integrated software packages used by most mining and mineral development companies will be

Figure 2. New digital technologies in support of the circular economy and resilience in the mining and minerals industry



extended to encompass some sustainability management operations such as energy, waste, and water management, and resilience reporting. Indeed, KPMG (2012) reported that "various suppliers of ERP packages offer new add-ons and tools for sustainability reporting", and that "we expect that the trend towards integrated reporting will also be a driver towards integrated solutions." In other words, whilst there are a number of standalone sustainability reporting packages available on the market -see, for example, Quentic (2019) - they will increasingly become part of the mainstream integrated business software packages such as SAP and Oracle.

The business intelligence capabilities of software packages are also being developed to include new tools and technologies, providing analytical, predictive and explorative information reporting, often now termed "analytics", which can benefit the mining and minerals extraction industries. The scope of such reporting is also now wider, encompassing information available from the internet and others sources – the so-called "Big Data" - rather than just data generated from within any one company. However, this requires investment in these new technologies. Som (2017) notes that "the mining industry is sitting on a virtual goldmine of very large and complex data sets", but that "the lack of investment in analytical technology prevents the industry from unlocking its true value." These new capabilities can provide information and analysis in support of the circular economy and resilience in the mining and minerals extraction industries through provision of key indicators relating to sustainability monitoring and control. The capture, processing and reporting of information is now facilitated by links based on web-technologies, the so-called "internet of things" (IoT). This means that it is often not necessary to radically change the technology platform to benefit from the technology developments noted above.

Pardo (2018) notes that "the creation, extraction, processing, and sharing of data enabled by digital technologies such as sensors, connected devices and online platforms will lead to a smarter use of resources", and "this enables predictive maintenance and extends the lifetime of a product". Focusing specifically on mining, Som (2017) concludes that "data analytics can be used in every stage of the mining process" and there can be little doubt that digital technologies will play an increasingly important role in supporting a transition to the circular economy and in sustainability management in general. Chakraborti (2018) suggests that big data analytics will "spur the next wave of efficiency gains in ore extraction, analysis, transportation, and processing, by enabling faster and better-informed decisions at all levels". The mining industry can derive several critical business benefits from Big

Data Analytics. These include "ensuring continuous flow of material from ore extraction point to the processing plant; maximizing ores hauled by optimizing bottlenecks in production; reducing non-productive time between unit operations, such as unscheduled maintenance, delays, wastage and waiting time;" (Chakraborti, 2018).

The applications of digital technology in the mining and minerals extraction industries "include building a more comprehensive understanding of the resource base, optimizing material and equipment flow, improving anticipation of failures, increasing mechanization through automation, and monitoring performance in real time" (Durrant-Whyte et al., 2015). Nevertheless, as Pagoropoulos, Pigosso and McAloone (2017) note, "the intersection of circular economy and digital technologies is a small, but fast growing research area that is still in a preparadigmatic stage", as it is still "adopting concepts from other fields and is lacking concrete case studies."

DISCUSSION

A number issues emerge from the above analysis. First, there is some variation in the attention that the concepts of resilience and the circular economy have attracted from a number of the major players within mining and mineral industry. While seven of the top twenty mining companies employed the concept of resilience to help frame their sustainability reports, only one of these companies reported on their engagement with the circular economy as part of their sustainability reporting processes. This suggests that, while some the leading mining and mineral development companies would seem to provide some confirmation of Buxton's (2012a) belief in a renewed focus on resilience, there is little publicly available evidence to support her suggestion that the leading mining and mineral development companies will recognise the business imperative of greater engagement with the concept of the circular economy.

On the one hand this contrast might be seen to reflect the mining and mineral companies' belief that building a more resilient portfolio will not only strike a powerful chord with government policies on reducing carbon emissions and provide new endorsements for the social licence to operate, but will also generate important economic benefits, and possibly a competitive edge, for the companies themselves. On the other hand, there is clearly less public enthusiasm for circular economy approaches within the mining and mineral development industry. This would seem, in part at least, to reflect the mining and mineral industry's history which "over the last 50 years" has been focused on "extracting increasingly more volumes based on a bigger is better paradigm", which was "financially rewarding, as larger equipment with automated control brought economies of scale and low operating costs, often in the form of huge open pit mines and processing plants" (Resourceful Pathways, 2017). Further Resourceful Pathways (2017) argued that "with scale comes more water and energy use, more greenhouse gas emissions and more waste" and "this heads in the very opposite direction to the circular economy." The radical changes, which a substantial transition to a circular economy approach would require, would certainly demand a new business model, which in turn, could be seen as a major challenge to the financially viability and vitality of the industry.

At the same time, academic researchers have published the results of their work on resilience within the mining and mineral development industry and on the contribution circular economy approaches makes to that industry. While research on resilience has embraced a range of themes, including climate change, socio-economic systems and community development, research into the circular economy has been focused largely on waste management. This, in turn, seems to reflect the mining and mineral industry's economic priorities as outlined above. During the last decade, a number of mining and mineral development industry and industry related bodies have published reports, which essentially offer possible policy programmes and prescriptions on how the concepts of resilience and the circular economy might be adopted within the industry. Here the circular economy seems to have attracted more attention than resilience and this may well reflect a growing belief that

at some stage in the not too distant future the mining industry may need to take some of the radical steps required to introduce a more circular approach into its operating practices.

Second, there are issues concerning measurement. While there has been growing interest in measuring progress towards resilience, there has been little or no general agreement on a suitable set of measures, not least because there are different meanings and definitions of resilience. Conzato (2017), however, argued that "producers of resilience data and indicators should be transparent about how and why the data was collected, the indicator methodologies and what they propose to measure, for which part of the system and for whom." Such an approach, Conzato (2017) suggested, "will help to build up a global knowledge base and encourage further discussion amongst different actors to hopefully reach a convergence on resilience principles."

Measuring circularity also presents a major challenge, but in looking to move towards a more circular economy, a number of approaches to measurement have been developed. The Ellen McArthur Foundation, Granta Material Intelligence and Life (2015), for example, have developed a "Circularity Indicators Project" which looks to measure "the circularity of products and businesses." While recognising that "measuring the circularity of a product or service can be a challenge due to the complexity and variety of actions, activities and projects that could be called circular", the US Chamber of Commerce Foundation (2018a) has developed a "Circular Economy Toolbox", which includes a number of metrics to measure impact. The proposed circular economy metrics include the carbon footprint, estimated cost savings when leasing rather than buying, estimated resource and emission offsets and the percentage of a product that can be recycled or repaired at the end of its useful life. At the same time, the US Chamber of Commerce Foundation (2018b) asserted "there is currently no single accepted framework to enable organizations to assess and report on their progress in moving towards circularity" and argued that the lack of such a "framework represents one of the greatest needs, and greatest opportunities, in the circular economy."

Third, notwithstanding the above noted issues regarding measurement, the increasing impact of ICTs and digital technologies can enable a step-change in mining and mineral extraction operations, including radically improved sustainability management and reporting. The World Economic Forum (2017) estimated that digitalisation of the mining and metals industries could bring about a reduction of 610 million tonnes of CO2 emissions, with an estimated value to society and environment of $30 billion by 2025. Aveva (2018) noted that digitalization creates "the opportunity to centralize the monitoring and control functions of all mining processes and operations to a single physical location" and "increases the opportunities to enhance efficiency, responsiveness and profitability across the mining value chain." The challenge for the mining and minerals industry is to harness this technology to achieve the above, but also to support sustainability targets and aspirations.

CONCLUSION

The concepts of resilience and the circular economy have attracted varying degrees of attention within the mining and minerals industry. While a number of the leading mining and mineral development companies have drawn on the concept of resilience in reporting on their sustainability strategies and achievements, there has been little interest in the concept of the circular economy within the industry. Although academic research on resilience within the mining and mineral development industry has embraced a number of themes, work published on the circular economy in the academic journals has been largely in connection with waste management. Amongst industry organisations, the circular economy has attracted more attention than resilience, and this may well reflect a growing recognition of what may become a need for the mining and mineral development industry to more formally address the challenges of sustainable development and of a transition to a more sustainable future.

Looking to the future, the paper provides a mirror against which companies within the mining and minerals industry can review their own approaches to the circular economy and resilience. At a time when all sectors of the economy are under growing pressure to demonstrate their sustainability

credentials, the mining and mineral development companies may well want to continue to incorporate circular economy operations and resilience into their sustainable development strategies, particularly in the face of the pressing need to address climate change. Here, Nelson and Schuchard's (2016) plea that "the mining industry should take a proactive approach to climate change" clearly resonates. Given this is essentially an exploratory paper, and the complex challenges the mining and mineral industry faces in a variety of environments in which they operate, and the complex challenges they face, the authors do not think it appropriate for them to make any detailed managerial and practical recommendations. In summary, an increasing emphasis on, and commitment to, resilience and the circular economy would seem to pose major challenges for the mining and mineral development industry. In theory, the concept of the circular economy, for example, demands major reductions in the extraction of mineral resources and as such provides a daunting challenge to mining and mineral development companies and if the major players within industry look to address the circular economy then their initial focus seems likely to be confined to waste management.

If the mining and minerals industry embraces resilience and the circular economy more fully as an integral part of its commitment to sustainable development, it is inevitable that what Pradip et al. (2019) have called "the transformative potential of integrated digital platforms" will have an important role to play in enabling and supporting such initiatives, and their independent assessment. At the same time, academic researchers may also look to draw up appropriate operational frameworks to guide future work on the concepts of resilience and the circular economy, and the role of digital technologies within the industry, and to integrate these concepts within wider conceptual and theoretical thinking on sustainability. Academic research might look to investigate strategic thinking about the circular economy and resilience within large mining and mineral development companies. Such investigation might include specific detailed case studies of individual companies as well as more comparative investigations across the two industries. Negotiating access to key decision makers may prove to be a thorny issue, in part because sustainable consumption is a sensitive issue, and in part because of the more general issue of commercial confidentiality.

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