Assessment of the Effects of Global Digitalization Trends on Sustainability in Mining

Part II: Evaluation of Digitalization Trends and their Effects on Sustainability in the Global Mining Sector

Editorial

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Assessment of the Effects of Global Digitalization Trends on Sustainability in Mining

Part II: Evaluation of Digitalization Trends and their Effects on Sustainability in the Global Mining Sector

By Elisabeth Clausen, Aarti Sörensen, Fabian Uth, Rudrajit Mitra, Felix Lehnen, Berit Schwarze

Aachen, December 2020

Executive Summary

The overall objective of the study “Assessment of the effects of global digitalization trends on sustainability in mining”, which was commissioned as part of the in-house research project “Sustainability in mining and in mineral supply chains” at the Federal Institute for Geosciences and Natural Resources (BGR), is to gain a comprehensive understanding of the relationship between processes of digitalization and sustainability.

In existing literature, the discourses on both digital transformation and sustainability often seem to be decoupled from one another. For this reason, the complex relationship between digitalization and sustainability has not yet been considered and investigated in a systematic manner. This study aims to fill this gap.

The study is based on two hypotheses: The first hypothesis claims that there is a close link between processes of digitalization and various aspects of sustainability. The second hypothesis suggests that digitalization trends in the global mining sector are not progressing uniformly worldwide and that, accordingly, the impact and benefit of these trends may vary in relation to the geographical region, commodity, mining method, company size or size of the operation.

On the one hand, the purpose of this study is to investigate the inter-linkages between digitalization and sustainability systematically in order to assess the impact the implementation of digitalization technologies has on sustainability. On the other hand, the purpose of this study is to draw a nuanced picture of the differentiated effects digitalization trends have on sustainability in the global mining sector.

The study is divided into two parts. Part I focused on providing key concepts and definitions to understand digitalization in mining on a process level (Clausen et al. 2020). Based on comprehensive desktop research and a comparative analysis of 150 different literature sources, Part I also identified key trends in digital transformation and provided a detailed analysis of the impact of leading digitalization trends on operational processes as well as on management and leadership processes. Furthermore, Part I included a three-dimensional preliminary analysis of the expected impact of digitalization technologies on processes and defined sustainability criteria.

Part II of the study, which consists of this report, now aims at drawing a comprehensive picture of the current levels of implementation of digitalization initiatives and the impact on sustainability aspects from a global perspective. For this objective the preliminary analysis (Part I) is extended by conducting and evaluating 29 semi-structured interviews with global mining experts. In the interviews the following three research questions were addressed:

1. What are the main characteristics (e.g. drivers, incentives, influencing factors and level of implementation) of the current and anticipated future global landscape of digitalization initiatives in mining?
2. What are the main challenges and opportunities for digitalization in mining from a global perspective?
3. What are the impacts of digitalization technologies on sustainability from a global perspective?

With respect to the first question, the results of the interviews indicate that mining companies have become the drivers of digital transformation, incentivized by the pursuit of improving safety, productivity and cost-efficiency and ensuring long-term competitiveness. In addition, mining companies are driven by the rising expectations exerted by investors, shareholders, communities, regulators, and the (often skeptical) general public with respect to improvements in productivity and cost-efficiency as well as the various dimensions of sustainability.

Regarding the level of implementation of digitalization technologies, the study revealed the following three major findings:

1. On a global scale, mining companies are at various stages along the data value chain with respect to implementing digital initiatives.
2. The level of implementation does not depend on the geographical location of a mining operation. It rather depends on the size of the company and the size of the operation in conjunction with the priorities and decisions set by the respective company leadership.
3. The full potential for digitalization in mining has not been reached yet by far. That confirms digital transformation in mining still being, comparatively speaking, in the early stages.

The results of the cluster analysis of the challenges and opportunities (Question 2) point to an interesting fact: The identified challenges (e.g. talent management, change management and collaboration) are not technical in nature but are generally considered “human factors”. Based on the cluster analysis from the results of the expert interviews, these seem to be considered more relevant, or more pressing, than the technological challenges of digitalization. Further, legal questions (data ownership, liability) and questions of interoperability and standardization do play a role in further advancing the implementation of digital technologies.

Furthermore, the analysis of various influencing factors for the implementation of digitalization initiatives showed that these initiatives, with some exceptions, are more advanced in multi-asset global mining companies with large-scale operations. Digitalization initiatives, albeit a response to increasing stakeholder expectations, are driven by considerations of the business case, expected return on invest and payback period. The business case for digitalization technologies tends to be better for large companies with large operations that can scale the impact of the technologies and have the available capital for the initial investment into new technology.

The identified challenges can also point the way forward and, if addressed successfully, can be transformed into opportunities and success factors for navigating change and improving competitiveness. For example, expanding the IIoT to span the entire operation (e.g. instrumenting all processes, pieces of equipment and people) is considered an immense potential, as it would increase the possible gains from all subsequent steps along the data value chain. In addition, the advancement of data analytics (e.g. for prediction and advancement of interoperability) is expected to move the industry forward in the coming years.

Currently, the industry is in the process of implementing these technologies and there is a small number of companies in the world that have achieved a full or almost full IIoT integration at least at one of their mine sites. Some companies are beginning to transfer successful approaches to other operations. Furthermore, some companies are starting to plan new operations with a high level of automation and digitalization from the onset. However, a full IIoT integration and application of data analytics is still far from being the new normal in the mining industry.

In addition, taking an integrated “value chain approach” and thus considering all processes systematically and holistically is considered one of the prospective key trends in the industry. Integrated value chain approaches are expected to become much more prominent in the coming years due to their immense potential for further optimization across processes and entire operations. Currently, few companies are beginning to realize the potential of taking such an integrated approach to optimization.

With respect to the third question, the interviews indicated that digital technologies have had a positive impact on sustainability criteria such as safety, terms of employment (social pillar) and economic efficiency (economic pillar). Further, the analysis showed that digitalization can provide important tools for improving community engagement and training opportunities for the local workforce, which have been implemented at some of the mine sites that were included in the interviews (socio-economic pillar). In terms of negative impacts on sustainability criteria, the results of the study indicate that the potential for job losses due to automation is considered the largest negative impact of digitalization. However, the interviews also indicate that several mining companies have found ways of addressing this threat and generally do not lay off employees due to automation. In some cases, the full potential of automation might not even be realized in order to keep social stability, which is rated higher than economic efficiency in these cases.

In conclusion, it was possible to verify the results from the preliminary analysis from Part I of the study. The cumulated results of both parts of the study suggest that digitalization initiatives, to date, have had a medium to high impact on the four pillars of sustainability. It was found that the geographical region only has a low influence on the level of implementation of a digital initiative. It is also not possible to discern specific geographical areas that are more advanced than others in terms of the impact that digital technologies have as such. The interviewed experts covered all six continents[1] and represented- as the entire study – only metal-ore producing operations. However, there might be specific regional challenges related to sustainability, such as proximity of the mining operation to communities, the existence of indigenous communities, or the site's remoteness and lack of infrastructure, scarcity of water in high altitudes and dry areas

The results of the report clearly indicate that while the discourses on digitalization and sustainability might be decoupled in literature, in reality these two areas have become inseparable and are closely inter-connected. Digital transformation and sustainability are both no longer optional but important means for ensuring future competitiveness and market positions – not only addressing customers or competitors but also reaching out to other stakeholders such as neighboring communities or employees, i.e. the "social license to operate".

The systematic investigation in this study may provide mining companies and experts across the globe with an increased understanding of the complex inter-relationships between both areas. Further, linking these two transformational processes of digitalization and sustainability more closely can lead to future research as well as contribute to a more nuanced public perception of sustainability in mining and in mineral supply chains.

[1] In Asia, the focus was on China and Indonesia; in Africa the focus was on Southern Africa; in South America the focus was on Chile and Peru; in Europe the focus was on Northern Europe; in North America the focus was on Canada based on the interview partners selected for the study

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List of Abbreviations

AI	Artificial Intelligence
AR	Augmented Reality
ASM	Artisanal and small-scale mining
BGR	German Federal Institute for Geosciences and Natural Re-sources
DPM	Diesel Particulate Matter
ESG	Environmental, Social and Governance
GMG	Global Mining Guidelines Group
GPS	Global Positioning System
IT	Information technology
IoT	Internet of Things
IIoT	Industrial Internet of Things
InSAR	Interferometric Synthetic Aperture Radar
KPI	Key Performance Indicator
LHD	Load Haul Dump
LIDAR	Light detection and ranging
LSM	Large scale mining
ML	Machine Learning
OEM	Original Equipment Manufacturers
OHS	Occupational Health & Safety
ROC	Remote Operation Center
ROI	Return on Investment
UWB	Ultra-Wideband
VOD	Ventilation on demand
VR	Virtual Reality

1. Introduction

Although mining is still in the early stages of digital transformation compared to other industries, the global mining industry has begun the digitalization journey and has been undergoing significant changes over the past decade. Consequently, mining companies have been challenged to change, adapt, and innovate in order to remain competitive and economically viable in the future. Both, digital transformation and sustainability have become central to the discussion on how mining companies can master these challenges.

However, the relationship between digitalization and sustainable business practices has not been investigated systematically yet. The purpose of this research study on the *Assessment of the effects of global digitalization trends on sustainability in mining* is thus to provide a systematic investigation into the correlation between digitalization and sustainability. It shall thus contribute to understanding the current process of change in the global mining sector, especially with regard to the assumed interconnection between processes of digitalization and sustainability on a global scale. Within the scope of this study, while the focus is on metal mining, all forms of mining, from artisanal and SMEs to industrial large-scale mining (LSM), are included in the analysis.

The study, which was commissioned as part of the in-house research project “Sustainability in mining and in mineral supply chains” at the German Federal Institute for Geosciences and Natural Resources (BGR), is divided into two parts.

Part I (Clausen et al. 2020) provides the basic concepts for understanding current digitalization trends in mining on a process level and presents a preliminary analysis of the expected impact of leading digitalization trends on selected sustainability criteria. Based on a desktop-analysis of 150 sources published within the last five years, Part I identifies 15 technologies that are currently shaping the digital transformation in the industry, of which the following eight were found to lead this transformation process: automation, integrated platforms, industrial internet of things (IIoT), simulation and visualization tools, advanced analytics, remote operation centers (ROCs) and connected worker.

With respect to the impact of digitalization technologies on mining at a process level, the study provides insights into the impact these technologies have on the eight operational processes as well as on the leadership and management process levels. In a third step, Part I presents a three-dimensional model linking digital technologies, mining processes and sustainability criteria to analyze the expected impact that leading digitalization technologies have on different aspects of sustainability. This preliminary analysis suggests that digital technologies will have a significant impact on all four pillars of sustainability. A particularly high impact is expected in the areas of improving safety (social pillar), increasing economic efficiency (economic pillar) and in the reduction of resource use, including material use, water and energy consumption as well as the reduction of air and noise emissions (socio-economic pillar and ecological pillar).

In addition, one of the findings from Part I of the study is that the current process of digital transformation, albeit still in its early stages, is taking place predominantly at large-scale highly mechanized and automated mining operations. It was postulated that small-scale mining operations as well as the artisanal mining sector were not playing a major role in the current discussion on digital transformation in the global mining sector. However, since it is conceivable that digitalization technologies could have an impact on all types of mining practices and operations (including smaller operations and artisanal miners) an investigation into these types of mining activities was explicitly included in this report.

Part II of the study, which is contained in this report, is thus designed to build and expand on the findings from Part I. It aims at drawing a comprehensive picture of the current levels of implementation and expected future trends of digitalization initiatives, including the challenges and opportunities mining companies as well as artisanal miners are facing in this context. In addition, the preliminary analysis on the impact of the current transformation on sustainability aspects is validated and expanded to include a more global perspective. For this purpose, this second part of the study is largely based on the analysis and results drawn from 29 semi-structured interviews with global mining experts that were conducted within the scope of this study.

While the two parts of the study differ in terms of their methodological approach, both are based on two main hypotheses: Firstly, it is presumed that processes of digitalization and various aspects of sustainability are closely linked. Thus, the study examines digitalization trends in mining and their impact on sustainability at a mining process level (Part I) as well as with regard to the global development of the sector (Part II). Secondly, it is to be investigated whether the level of implementation as well as the impact and benefit of digitalization trends vary in relation to certain influencing factors i.e. the geographical region, type of commodity, mining method, size of operation or company size.

1.1. Structure of the Report

Part II of the study, which consists of this report, is structured around the following research questions:

- What are the main characteristics (e.g. drivers, incentives, influencing factors and level of implementation) of the current and anticipated future global landscape of digitalization initiatives in mining?
- What are the main challenges and opportunities for digitalization in mining from a global perspective?
- What are the impacts of digitalization technologies on sustainability from a global perspective?

Chapter 2 describes the main characteristics of the global landscape of digitalization initiatives in mining. It discusses the main drivers and incentives of digitalization initiatives and presents the influencing factors based on the cumulated findings from the expert interviews. In addition, Chapter 2 compares the empirical and conceptual findings from Part I to the ground experience, based on the evaluation of the interviews with respect to leading digitalization technologies and expected future trends.

Chapter 3 provides an in-depth analysis of the challenges as well as opportunities in the context of digital transformation based on the results from the expert interviews. Within the framework of this analysis, several clusters of challenges and opportunities were identified and ranked. The specific challenges and opportunities associated with the small-scale mining sector – particularly the artisanal mining sector – are discussed in a separate section. This is because digitalization in the artisanal and small-scale mining (ASM) sectors may be of a different scope and nature than the digital transformation currently taking place in the industrial mining sector.

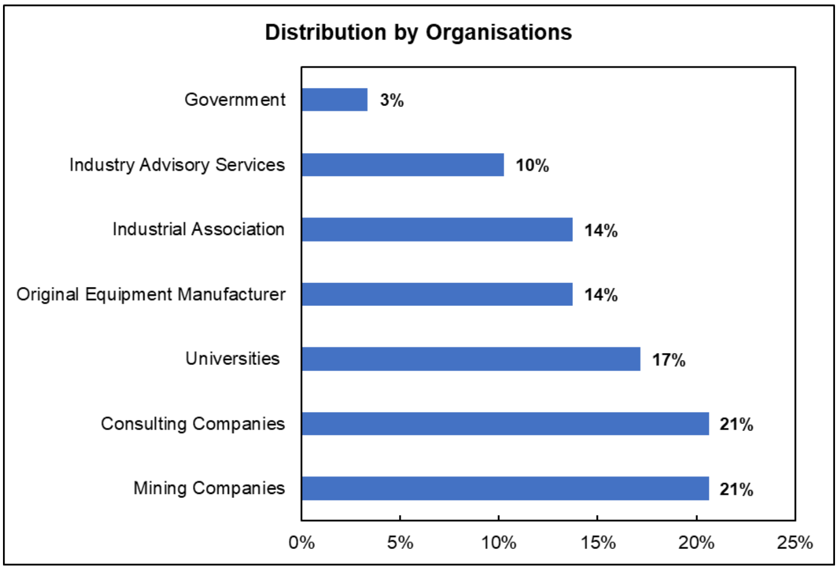
Chapter 4 briefly summarizes the sustainability-related findings from Part I. Then it identifies the impacts of digitalization technologies on the four pillars of sustainability based on the accumulated results of the expert interviews. Concluding remarks on the impact of sustainability from a global perspective answer the third research question of this report.

The concluding Chapter 5 discusses the key findings and insights from Part II in conjunction with the conclusions that were drawn from Part I of the study.

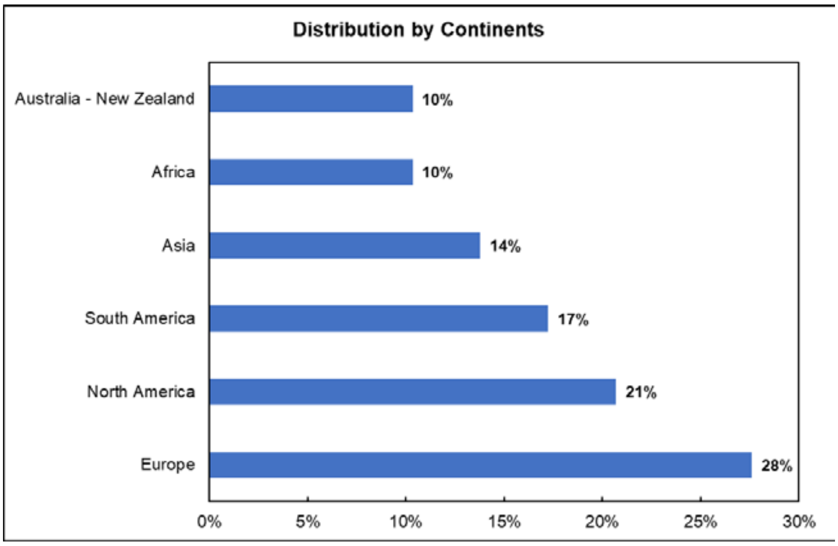
1.2. Methodology

The analyses contained in this report are based on the evaluation of 29 qualitative semi-structured interviews that were conducted with international mining experts for the purpose of this study. The interview partners represented mining companies, original equipment manufacturers (OEMs), consulting houses, industry advisory services (Chambers of Foreign Trade; AHK Competence Centers), universities, industrial associations and governmental organizations from all continents.

Choosing experts from different parts of the industry and from many different countries provided comprehensive insights into digitalization in mining from a global perspective. In order to receive qualified insights into the ASM sector in particular, a number of selected experts on ASM were also interviewed. Figure 1 shows the overall distribution of interview partners by type of organization and geographic region (continents). The responses gathered from the interviews were evaluated entirely anonymously.



(a)



(b)

Figure 1: Distribution of conducted interviews by (a) organization and (b) continent

The methodological approach of this report is based on several different analytical steps in evaluating the interviews. In Chapter 2, the interviews were first analyzed to identify the main drivers and incentives for implementing digitalization technologies in mining operations. Further, the expert interviews were used for validating the current and future digitalization technologies that were identified during the empirical analysis conducted in Part I.

For this purpose, the results of a systematic analysis of technologies mentioned during the expert interviews were collected in a data sheet and, in a further step, were clustered into the categories used during keyword search in Part I of the study. The results of the interviews were then added to the results of Part I to validate the findings on the most prevalent digital technologies. The results were expressed as a percentage of the 29 interviews and the 150 sources from the desktop research.The cumulated findings are depicted in a figure and discussed in this chapter. In a subsequent step, the interviews were analyzed to identify the relevance of the following influencing factors: company size, size of operation, mining method, type of commodity and geographical region. As a result of the analysis, these influencing factors were ranked with respect to their relevance and depicted in a heat map.

In Chapter 3, the various aspects raised during the interviews were again collected in a data sheet. In a subsequent step, these aspects were grouped into various clusters around challenges and opportunities using color codes. A total of ten clusters for the challenges and seven clusters for the opportunities were identified. The clusters were then ranked based on how many times the aspects within each cluster was mentioned during the interviews. The result is depicted in two figures. Since these clusters pertain to highly mechanized industrial mining operations all over the world, the challenges and opportunities pertaining to the ASM sector are discussed separately, based on the cumulated results from the interviews.

In Chapter 4, the respective parts of the interview related to sustainability aspects were analyzed to extract the expert views on the observable impact of digitalization technologies on the various sustainability pillars. These results are then presented in conjunction with a summary of the preliminary findings of Part I to expand on and to validate them. In this way an assessment of the impact of digital initiatives on various sustainability aspects from a global perspective could be provided as a conclusion in this part of the study.

2. Evaluation of Digitalization Trends from a Global Perspective

This chapter evaluates the current and future digitalization trends from a global perspective and thus answers the first research question (Section 1.1) by presenting a picture of the current and anticipated future global landscape of digitalization initiatives in mining. The chapter is divided into three parts: Section 2.1 discusses the main drivers and incentives for implementing digitalization initiatives that emerged from the analysis of the expert interviews. The following sections present the findings of the interviews with respect to digital technologies that are currently at an advanced stage of implementation (Section 2.2) as well as those that are expected to have a high impact on the industry in the near future (Section 2.3). In addition, the results from the interviews are combined with the results from the empirical literature review of Part I of this study. Section 2.4 then presents the findings from the interviews with regards to identifying main characteristics for high levels of implementation of digital technologies from a global perspective. For assessing these characteristics, the findings regarding the influence of geographical regions, type of commodities, mine type and size of operation are presented.

2.1. Drivers and Incentives for Digitalization Initiatives

A detailed analysis of the interviews suggests that the current landscape of medium to large-scale industrial mining operations is characterized by a growing number of stakeholders whose interests need to be carefully considered and managed by the mining companies. Figure 2 depicts the complexity of this landscape between internal and external stakeholders (from a company perspective) and reflects the combined results from the analysis of the expert interviews.

Based on these results, internal stakeholders mainly consist of the board, owner, shareholders, corporate governance and management teams, the employees and, where existent, workers councils. These different groups have a long-term interest in ensuring return on investment (ROI), safe workplaces or occupational health and safety (OHS). In addition, their interest is for the company to be future-oriented, sustainable and to remain competitive. Based on the analysis of the expert interviews, OHS, productivity and cost-efficiency are also the predominant drivers for mining companies to implement digitalization initiatives. Hence, digitalization technologies are considered a key tool to achieve these core objectives in order to remain competitive and address stakeholder needs and concerns.

The external stakeholders can be divided into several sectors again: economy, society, media, regulators and politics as well as science. However, those sectors may also have different foci when viewing on mining projects. Thus, the different stakeholder's perception and interests may be associated with different pillars of the sustainability model (Section 4.2).

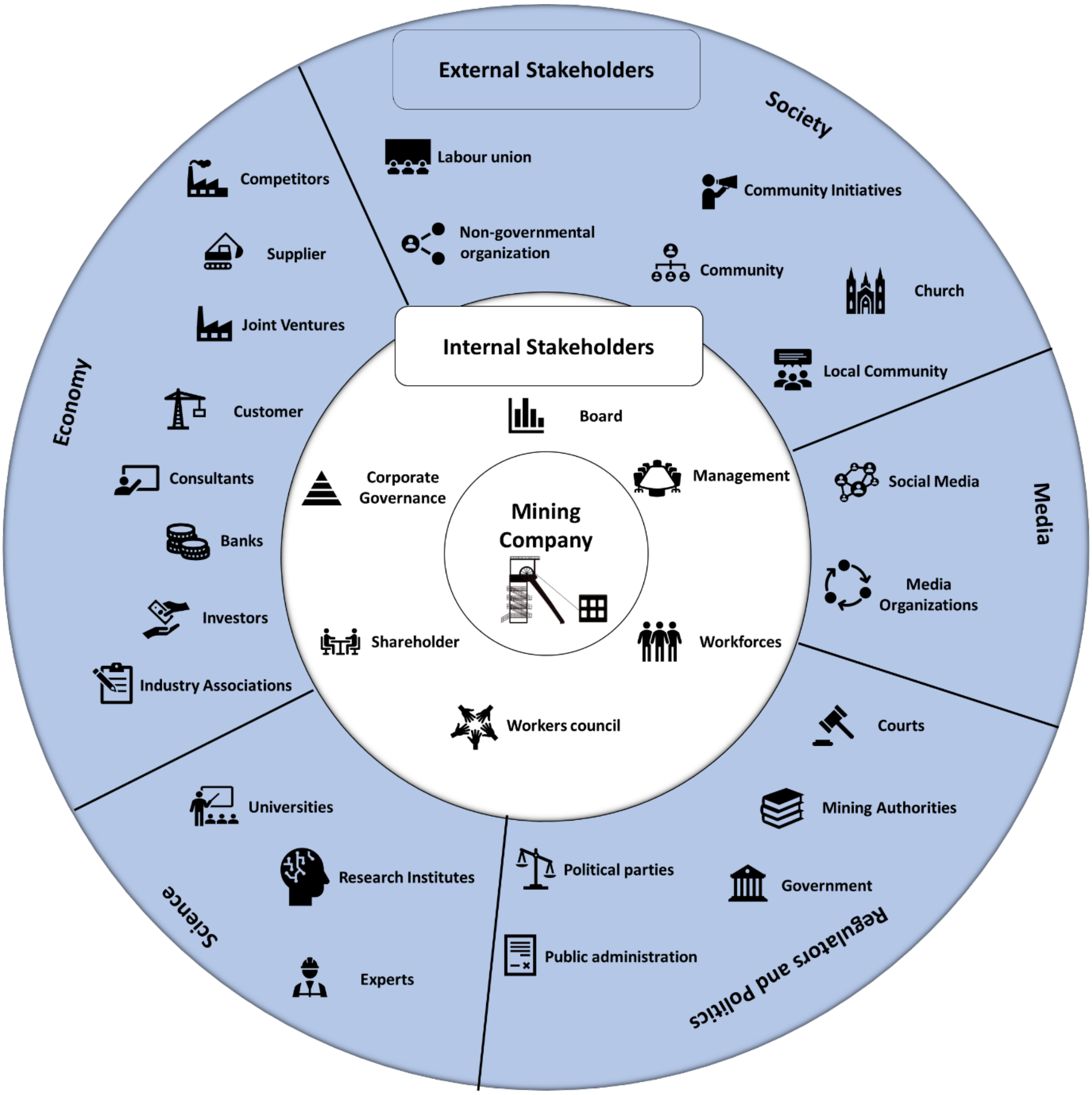


Figure 2: Internal and external stakeholder groups of mining companies or projects

Digital technologies provide opportunities to address all three core objectives (OHS, productivity and cost-efficiency), which provide the leading incentives to implement these technologies. Removing employees from hazardous areas to safer environments (e.g. by remote control) will improve the OHS of the operation. Productivity is increased by improving the quality of the mined material, increasing throughput and optimized processes using digital tools, and by implementing higher levels of automation. Improved cost-efficiency in the operation is achieved through optimizing equipment utilization and predictive maintenance using digital tools as well as by deploying the right kind of operational technology and by replacing older equipment with modern equipment having lower operating costs. Section 2.2 takes a closer look at the specific technologies that are currently or are expected to be deployed in the near future to achieve these objectives.

At the beginning of the digital transformation journey in mining, leading OEMs had to convince the mining companies of the benefit of new digitalization technologies. The combined results of the interviews now indicate a shift in the driving forces in the market: Mining companies are today the main initiators of digitalization and are pushing related innovation initiatives. They are now acting within a complex landscape of stakeholder interests. The incentives for digital technologies have grown stronger.

Nowadays the predominant model seems to be a partnership-based collaboration with OEMs and other suppliers. The interviews also suggest that mining companies, OEMs, and other suppliers collaborate in these kind of partnerships to further develop certain technologies. However, mining companies tend to be much more aware of their requirements and the technologies they wish to deploy than a decade ago and thus are nowadays more pro-actively selecting their providers.

Yet, the interviews also indicate that other stakeholders can incentivize or request certain digital initiatives as well. As an example, mining authorities and regulators can initiate the implementation of digital technologies in mining operations by passing certain new regulations, such as real-time monitoring and the disclosure of water or air quality data. In addition, investors can also put pressure on mining companies to improve their sustainability performance and thus incentivize the implementation of digitalization technologies.

It should also be noted at this point that many interview partners addressed the increasing need for collaboration. The emergence of innovation ecosystems and innovation networks as a key challenge as well as immense opportunity to move the industry forward and to accelerate the current transformation have been addressed (see also Section 3.2.4). These kind of ecosystems, in which mining companies collaborate with suppliers, start-ups, research institutions, and governmental organizations, are emerging across the globe. Some of these networks are initiated by industry and some, e.g. in the case of Chile, are driven by the government in order to move the industry forward through a shared digitalization and innovation roadmap. In some cases, mining companies may also actively support start-ups or the development of start-ups to co-develop new technological solutions, often in conjunction with research institutions and universities.

2.2. Advanced Digitalization Initatives

Part I of this study presented a detailed empirical analysis of current digitalization initiatives to assess the main trends in the implementation of digital technologies. The results from the empirical analysis of 150 articles were visualized to show these main trends in relation to the three process levels (leadership, management, and operational processes; Figure 3).

In order to validate the analysis of Part I, these empirical results have now been combined with the results of the 29 expert interviews. Interview partners were specifically asked to comment on the most relevant technologies that are currently being implemented and that they expect to be implemented in the near future (five to ten years). The results from the interviews, were plotted (blue colour) beside the results of the previous analysis.

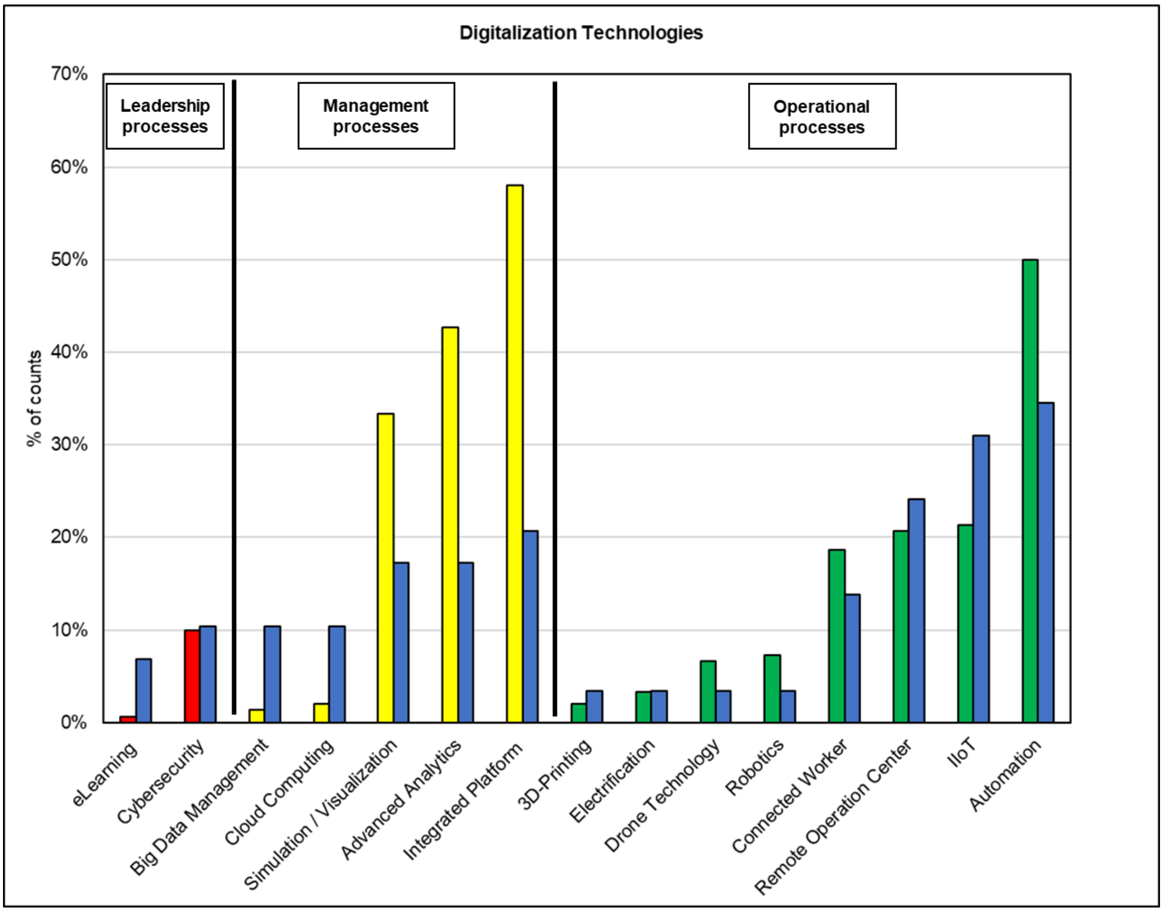


Figure 3: Digitalization technologies and affected mining process levels identified from interviews (blue) and desktop research from 2015 – 2020 (red, yellow, green). These numbers are expressed as % of counts out of 29 interviews (blue) and 150 sources from desktop research (red, yellow, green).

Combining both analyses shows that the findings of Part I could be confirmed and verified by the responses of the interview partners. Both are showing an overall consistent trend in that the technologies with the highest level of implementation according to the desktop analysis were also the ones that were most frequently mentioned by the interview partners (Figure 3). However, during the expert interviews some technologies were mentioned more frequently compared to the desktop research, especially eLearning, Big Data Management and Cloud Computing. The specific definitions of the technologies can be found in Annex A. The challenges and opportunities accompanying the implementation of digitalization technologies will be discussed in Chapter 3.

Building on the insights gained from the expert interviews, the complex correlations between the specific digitalization technologies with the respective operational (green), management (yellow) and leadership (red) processes are illustrated in Figure 4. This illustration is intended to underline the importance, interconnection and dependency of the different digitalization technologies.

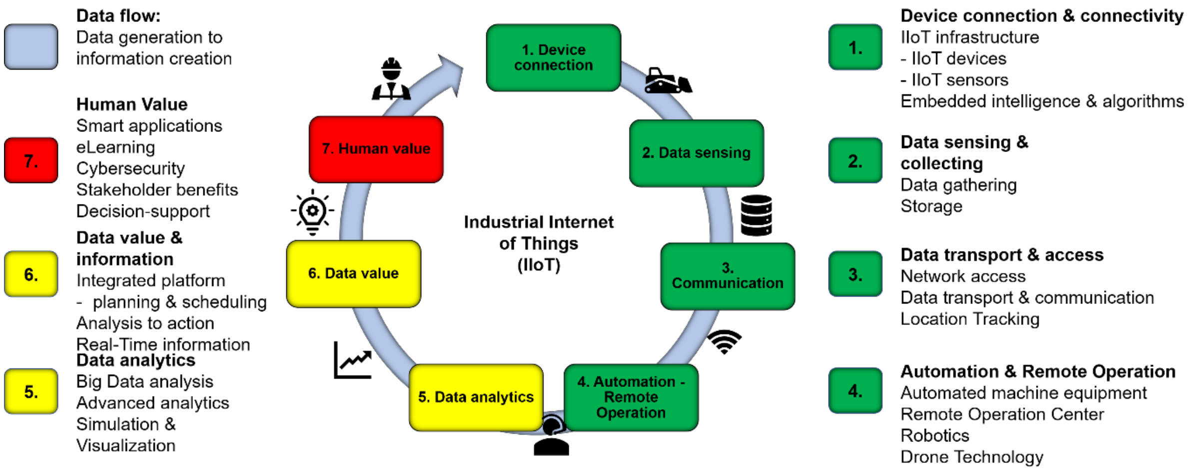


Figure 4: Schematic illustration of data value chain (adapted from i-scoop 2020a). The operational processes are shown in green, management processes are shown in yellow and leadership processes are shown in red.

2.2.1 Operational Processes

The IIoT was one of the most frequently mentioned digitalization technologies during the expert interviews as well as during the desktop research from Part I. As a network infrastructure of physical objects such as IoT devices, sensors and various pieces of equipment, the IIoT represents the fundamental requirement for automation and remote controlled operations, including robotics and drone technology.

The IIoT infrastructure (as illustrated by step 1 in Figure 4) represents the connection of devices and sensors in a single infrastructure and thus constitutes the foundation of connectivity. The IIoT is used for gathering and storing important data (step 2) about the production, machine and equipment conditions, environmental conditions as well as OHS data of the employees such as fatigue monitoring. It was mentioned during the interviews that the industry was far from reaching the full-potential of ubiquitous connectivity and resulting availability of data for further processing and analysis. This has implications for the implementation of the further steps (3) and (4) along the data value chain since the steps (1) to (4) are sequential. Thus, it can be concluded that the full potential is far from being achieved along the entire data value chain.

Step (3) is mainly characterized by the communication and data transmission through the communication network to a central unit such as ROCs. The communication is essential for interoperability and process integration. Besides the core communication and data transmission, technologies such as location tracking are also included in this stage of implementation. Location tracking is a necessary requirement for an optimal implementation of highly automated equipment or remote operations regarding accurate positioning of especially mobile machine equipment, as well as collision awareness systems or the support of mine rescue missions (Lehnen 2016).

The interviews confirmed that the most relevant digitalization technologies affecting operational processes, are the automation of processes and the deployment of highly automated equipment. This was also identified in Part I of the study. ROCs were the third-most frequently named digitalization technology based on the interview results as well as in the desktop research from Part I (see Figure 3). The afore-mentioned technologies relate to step (4). Centralized (surface) control rooms are envisioned for controlling, coordinating, planning and operating automated equipment and conducting other activities of mining companies remotely and for multiple mine sites. All important data is brought together for further processing and analysis in these central control centers and automated and autonomous equipment is managed through tools such as joysticks from these control rooms as well.

Automation and ROCs are both technologies that have had a high impact on improving OHS by reducing occupational accidents.To give an example, Friedman et al. (2019) showed that over the past three decades, the global mining industry has recorded significant declines in accident and injury rates, which is attributed to automation, technological progress in extracting commodities and increased OHS consciousness. Within the years from 2008 to 2017 precipitous declines of 38% in non-coal mines and 46.1% in coal mines for the number of fatalities and permanent disabilities were gathered in the USA (Amoako *et al.* 2020). Another example which can be presented for demonstrating the high impact on increasing the productivity in mining operations is the “hang time reduction”, which increases the effective working time. The hang time is the amount of time in that a full bucket of an excavator is hanging in the air until the ore can be dumped into the truck. By reducing this specific amount of waiting time for one specific excavator at a rate of 18 loads per hour and 20 hours per day, highly automated operations can achieve 500 extra hours of shovel capacity over a period of one year and a resulting productivity increase of more than 2 million tons per year. (Laguna 2020)

The fact that the mining companies have a long-term interest in improving OHS, productivity and efficiency (result of the analysis of the drivers for implementing digital technologies) explains why automation and ROCs (step 4) already have a comparatively high level of implementation globally. These are based on the aforementioned steps (1 to 3) of the data value chain (Figure 4). To give an example, the machine operator in a ROC, who may sit a few hundred kilometers away from the actual mine site, is supported by different sensor technologies such as cameras or light detection and ranging[2] (LIDAR). These IoT sensors are communicating data via the network to the operator to provide him or her with insights about the machine and environmental conditions. In addition, by implementing software applications such as auto-pilots, the underground mining transportation routes can be narrower by design (in accordance with the legal requirements) while the cost incurred by damages or maintenance is reduced. Robotics and drone technologies are increasingly used to support the operators in the ROCs in these kind of processes. Several interview partners also commented that remote control technologies have gained importance during the COVID-19 pandemic as a means to realize social distancing by reducing the number of people working or travelling in underground environments such as the hoisting cage.

Another technology that is related to step (4) and that is dependent on the IIoT & communication infrastructure is the connected worker. The suite of technologies related to the connected worker was frequently mentioned during the interviews and also surfaced during the desktop research. The connected worker is characterized by various wearable devices, such as smartphones, smart glasses, smart watches and also tablets or smart helmets. Through these wearable devices, operators are supported in their respective activities. In the same time they are connected to the ROCs and transmit real-time information to the control center. These data may indicate their position within the mine but may also transmit information on health indicators such as fatigue monitoring etc.. Some of the experts reported that wearable devices were also used for measuring social distancing and trace contact among employees during the COVID-19 pandemic.

2.2.2 Management Processes

Aside from digitalization technologies affecting operational processes, other relevant digitalization technologies affecting the management processes were mentioned during the expert interviews as well, further validating the results of Part I of the study. Among these technologies

[2] According to the Geospatial World, LiDAR, or light detection and ranging, is a popular remote sensing method used for measuring the exact distance of an object on the earth’s surface.

are integrated platforms, advanced analytics, simulation and visualization, cloud computing and big data management (Figure 3).

According to Figure 4, these technologies can be divided into the following steps of the data value chain: Data analytics (5) and Data value (6). Data analytics covers all aspects of big data management, advanced analytics as well as visualization and simulation of process related data. Big data management, more specifically, deals with high volume, high velocity and/or high variety of data in a secure, efficient and cost-effective way (Gartner Glossary 2020).

The data gathered throughout the operations provide the input for advanced analytics technologies including artificial intelligence (AI). AI can be used to detect and recognize patterns in the data to derive selected actions such as predictions of machine component behaviour under specific conditions or create forecasts about the raw material production of the mining company based on existing data. However, the interview partners also mentioned that mining companies are hiring more data analysts to handle the various data streams and derive information that can support decision-making processes. According to the interviews, advanced analytics using AI is still at an early stage of implementation.

Simulation and visualization technologies include virtual reality (VR), augmented reality (AR) and digital twin applications. These applications and technologoies are supporting the perception and representation of processes, which can then be used to identify opportunities for improving OHS (reducing risks), productivity (reducing downtimes), and cost-efficiency (reducing maintenance cost).

The data value step (6) of the data value chain (Figure 4) focuses on gaining valuable real-time information, which are extracted through data analysis (5), and hereby are supporting specific actions and decisions in much shorter intervals. For example, the integrated platforms are representing the central software environment, which is connecting all IoT devices, sensors, equipment and connected workers with each other and is merging all available information within a single platform. Through this centralized availability of real-time information, the task management (organization, planning and scheduling of tasks and activities) can be improved.

Another purpose of such an integrated platform is not only the tracking of equipment and workers, but also of tasks and other activities. This allows an even more advanced analysis of processes and process optimization. As already stated with respect to automation, remote operation and connected workers, the IoT and related devices are prerequisite for achieving the full-potential of such an integrated platform.

Furthermore, such integrated platforms are supporting the specific intersections between departments within the mining companies and improve the exchange of information, for example at shift changes. This improved exchange can be applied along the entire value chain from the development, extraction, rock & roof support to haulage & transportation to the processing plant and even to downstream processes. Furthermore, supporting processes such as water & waste management, ventilation, backfilling and maintenance can be supervised and managed through integrated platforms.

2.2.3 Leadership Processes

Human value (7) represents the last step of the data value chain as depicted in Figure 4. The human value covers eLearning opportunities initiated by mining companies (or mining schools) to provide continuous education and training opportunities for the employees (Figure 3). While eLearning has been an important tool for education and training in mining companies even before the COVID-19 pandemic, it has now become a very important option for education and training opportunities for existing as well as new potential employees.

According to Part I, cybersecurity is an important digitalization technology affecting mining companies at a leadership level, which was confirmed by the expert interviews (Figure 3). Cybersecurity also belongs to the human value step (7) of the data value chain. With the progressing implementation of digitalization technologies within mining companies, the security of centralized information such as the ROCs and the entire mine infrastructure including servers and clouds needs to be improved. This improvement includes the change of human behaviour and reflected handling of data and digital technologies and needs a dynamic and multi-faceted approach of education in cybersecurity (Jones et al. 2020). Several interview partners confirmed that cybersecurity is high on the leadership agenda as it requires company-wide precautionary measures but also needs to be addressed industry-wide. Thus dialogue between companies about this issue is becoming more important and more prevalent.

2.3. Expected Future Digitalization Initiatives

Interview partners were specifically asked to comment on the digital technologies which they expect to have the largest impact on the industry over the next five to ten years. The combined results of the interviews are summarized in the following paragraphs based on the process levels presented in the previous section.

2.3.1 Operational Processes

One of the major insights gained from the analysis of the interviews is that the mining industry is far from reaching the full potential of the various digitalization technologies. This applies to all steps of the data value chain (Figure 4). Implementing an IIoT infrastructure spanning the entire mine site (including machine equipment, employees and environment) is capital intensive. The strength of fincancial sources needed to implement an IIoT infrastructure is exemplarily shown by a report completed by a supplier of mobile satellite communication in 2020 (Immarsat 2020)[3].

Since smaller companies do not have the financial resources to spend on IoT based projects, this can be prohibitive for them. Further, the expected ROI is low compared to respective scaling effects at larger mining operations or companies. However, installing an IIoT infrastructure encompassing the entire mine site is a prerequisite to take full advantange of the subsequent steps of the data value chain, such as installing a comprehensive data communication infrastructure.

Consequently, to achieve the full potential from digitalized data-driven operations of an integrated platform within a mining operation, all parts of the operation and all pieces of equipment need to be integrated into the IIoT. Thus, the potential of data gathering and connectivity between different machines, sensors as well as connected worker is **currently being exploited only to a limited extend** but is considered **high regarding future development**. Consequently, it can be expected that the installation of more comprehensive IIoT infrastructure will be a relevant trend within the industry over the coming years.

However, further extending the IIoT infrastructure requires an improved communication infrastructure, which can possibly be achieved by 5G-connection allowing datarates of 10 Gbit/s under ideal conditions (Telekom 2020). Along with the mentioned extension of the IIoT and

[3] The report included 200 respondents from the global mining industry excluding Europe. The respondents stated that over the past three years the amount for IoT based projects, big data analytics, cybersecurity and cloud computing represented about 4% to 6% of the spent IT budget and the amount spent for simulation & visualization technologies (AR, VR) and advanced analytics (machine learning, AI) represented about < 1% to 2% of the IT budget. Further they expected the IT budget for the next three years to be about two times higher than that of the past three years. Also, 39% of the respondents stated that the improved ROI in mining operations is one of the most important drivers for the deployment of an IIoT infrastructure.

communication infrastructure, a high potential for increasing production, OHS and cost-efficiency is based on the implementation of location tracking technologies such as Ultra-Wideband (UWB). In the expert interviews, it was mentioned that UWB and other location tracking technologies are pre-destinated for the application in underground mines due to their ability to achieve highly accurate position information of machines and persons. By this means long-term impacts on the operation such as further automation, collision awareness of highly-automated mobile machines and persons as well as increased awareness and minimized reaction times in case of an emergency or evacuation can be achieved (Section 2.2.1).

With respect to digitalization initiatives expected in the future, one of the interview partners mentioned improved scanning applications, especially in underground areas, for creating improved 3D models of the mines. Furthermore, some interview partners referred to the application of drone technology for the supervision of dangerous areas which cannot be entered safely by human workers, as technologies that are expected to become more prevalent in the near future.

Another example of expected future digitalization initiatives mentioned during the interviews was an increase in highly-automated drilling. Automated drilling operations have proven to be, according to the interview partners, much more precise than those performed by human operators, achieving productivity gains of 20% to 30%. According to the interview results, it is expected that subsequent operational processes like the charging of drilled blast holes with explosives will also be automated in the future. That would increase productivity further. Remote loading was also mentioned in this regard.

With respect to Load Haul and Dump (LHD) operations, one of the interview partners estimated that within the next 7 to 8 years, 85 % of LHDs could be operated remotely. This would offer the potential for further increasing the effective work time of the operators while reducing accidents by moving employees into safer environments. This can result in reduced operational costs and thus increased market competiteveness.

Futhermore, interview partners predicted that the ROC, from where the entire processes are controlled, coordinated and monitored, will be able to operate machine equipment from different OEMs within a unified software environment as interoperability, standardization and process integration advance. While this future development is expected to be implemented in surface and underground environments, the level of implementation is currently higher in surface operations, because requirements like GPS-availability are easier to implement.

However, the interview results suggest that considerable effort is being made in advancing high-precision positioning and localization technologies as a precondition for further automation and the interaction of robotized and automated equipment with humans in underground environments. Over the next decade, further advances in underground automation are to be expected.

Additionally, the electrification of mobile equipment was mentioned during several interviews as a technology that will gain importance over the next few years. That development is further pushed by emerging legal requirements of lower emissions from combustion engines to improve OHS by eliminating diesel particulate matter (DPM) and to reduce CO_2 emissions. This will lead to an increase in the deployment of electrified equipment, which could offer additional benefits such as lower operational costs for energy use compared to diesel-powered machines. A study was conducted where one OEM compared the operational costs (considering industrial cost for diesel and power) over a period of 6 years between a conventional LHD with a LHD including battery as a service model and a LHD with an owned battery. Hereby, the conventional LHD has got the highest operational costs with 2.5 mio. €, followed by the LHD with battery as a service model with about 2.0 mio. €. The LHD with the owned battery has got the lowest operational costs with abot 1.5 mio. € over 6 years. This rough cost estimation shows that the deployment of electrified mobile machine equipment is, from both technological and economic perspective, reasonable for mining companies. (Matthäus 2020) In fact, one of the interview partners mentioned that there was a trend towards mining companies requesting machines that are automated as well as electric; it could be expected that this trend would grow stronger over the next decade – either due to the purchase of new machines or due to combined retrofitting-efforts.

2.3.2 Management Processes

The analysis of the interviews suggests that an increasing impact by the implementation of digitalization technologies on management processes can be expected in the near future. (Big) data analysis is considered to have a high potential to create significant impact over the next few years as data analytics advance and more value can be gained from the available data. In addition, an extended IIoT infrastructure and thus increasing data becoming available from sensors and devices can also provide additional valuable insights about the specific mining operation and thus help realize the full potential of digital connectivity.

This development could be further accelerated by the fact that mining companies, according to several interview partners, are increasingly requesting OEMs to own all process related data from purchased equipment to use these raw data for optimizing specific parts of the operation. While OEMs currently seem to provide a lot of data as a service to mining companies, there may be a discernable trend that mining companies hire their own data analysts, either in-house or through third party contractors, to gain even more insight from the raw data.

While AI in analytics is still at the piloting stage, according to the interview results, especially large companies with the adequate financial means as well as the large-size operations are pushing the advancement of these technologies. They may yield the biggest returns on applying big data analytics and AI.

Digital twins and other simulation and visualization technologies, which can also be applied for analyzing processes for their optimization potential, are also expected to gain relevance and receive higher levels of implementation in the coming years. Further, the analysis of the interviews suggests that this trend will be pushed largely by globally operating mining companies with LSM operations. The incentives here are, again, to increase OHS, productivity and cost-efficiency by using existing data to create forecasts of production and machine conditions in order to derive action- and goal-oriented tasks and optimizations. Again, data-based forecasting is still at the early stages but is expected to become increasingly relevant in the global mining industry.

Integrated platforms which belong to the data value step (6) of the data value chain (Figure 4) will be becoming highly important in the next few years according to the expert interviews. The integrated platforms are representing the central software environment, which is connecting all IoT devices, sensors, equipment and connected worker with each other and is merging all available information within a single platform.

Through this centralized availability of real-time information the task management, organization, planning, scheduling and monitoring of tasks and activities will be improved. According to the expert interviews, larger mining companies will progress on applying integrated platforms to improve the overall view on the production process within the next years. Hereby all gathered data and processed information can be displayed and turned into improved task management. These improvements are again based on the insights of the overall view with high-valuable extracted real-time information of the previous mentioned steps of the data value chain. This allows for optimizing the entire supply chain both locally and globally.

2.3.3 Leadership Processes

According to the expert interviews, the leadership level will be highly affected in the next years by the implementation of digitalization technologies and their respective protection, through the use of cybersecurity.This is caused by the increasing interconnection between the different technologies within the mine infrastructure and the specific requirements for a successful implementation. The specific challenges and opportunities, which need to be considered in leadership processes for a successful implementation of these technologies are discussed in detail in Chapter 3.

During the expert interviews it was mentioned that eLearning will become even more important, for supporting the education and re-training of employees for the new tasks and technologies over all process levels, in the next few years.

Beside cybersecurity and eLearning, the blockchain technology is expected to have the potential to affect leadership processes. The blockchain technology framework could be a future solution, for example, to ensure a safe and secured mining explosives dispatching and transportation process. The blockchain technology possesses the ability to involve different stakeholders from manufacturers to distributors, transporters and individual mines and governmental bodies. These different stakeholders can be engaged seamlessly into the system and can work simultaneously, with transparency and real-time information as it is a highly secured online database that nobody owns yet everybody trusts. (Sengupta and Saha 2020)

2.4. Characteristics of Advanced Digitalization Initiatives

Based on an in-depth analysis of the 29 expert interviews and the 150 publications reviewed in Part I of the study, it was possible to derive findings with regards to the characteristics of advanced digitalization initiatives. The following paragraphs summarize the insights and findings from the analysis with respect to the following influencing factors: company size, size of operation, mining method, type of commodity, and geographical region. The overall outcome allows for the generation of a holistic heat map of these influencing factors which is presented in Section 2.4.6.

2.4.1. Company Size

The mining industry is a global industry, that is dominated by LSM operations with high levels of mechanization and automation. This can be illustrated by the fact that the top 40 global mining companies represents the majority of the revenue of the whole industry (Garside 2020). The majority of these multinational corporations are multi-asset companies that operate across different geographical regions and countries. However, in some countries, there are national mining companies with strong market positions and large operations, such as in China, Peru, Brazil or Canada.

Along these lines, interview partners agreed that small or medium sized mining companies lag far behind in terms of implementing digitalization and automation technologies, independent of geographic region. One exception, that was mentioned during the interviews, however, was Canada, where metal mining companies exist that are actually drivers of innovation and digitalization. These companies operate only one or few mines. However, due to their smaller size, they can take a more agile approach to testing and applying new technologies and they may look for less costly alternatives to some of the approaches large corporations have taken in implementing complex digitalization roadmaps. Similar exceptions exist in Northern Europe, where smaller mining companies have achieved high levels of automation and digitalization.

Thus, in some regions (Canada and Europe were mentioned during the interviews), there are mid-tier mining companies with higher levels of automation and digitalization that are drivers of innovation because of their agility. These companies, based on the interview results, sometimes also find more cost-effective solutions through which they may achieve considerable improvements, for example related to improvement of equipment availability and utilization.

Generally speaking, digitalization initiatives are driven primarily by large companies with large-scale operations that can yield the economic benefits from investing in capital intensive new automated equipment and implement digitalization initiatives on a broader scale. The economic incentive and potential ROI tends to be higher in larger operations because of the high impact of automation and digitally enabled real-time monitoring, predictive maintenance and short-interval control. In addition, with respect to digitalization intiatives, the ROI tends to be better for proven technologies. However, in general, digitalization initiatives are not fundamentally different from other types of investments with respect to expected ROI, according to one of the interviews. Therefore, to conclude, from a global perspective, company size has a **medium to high influence** on implementing digitalization initatives.

2.4.2. Size of Operation

Based on the results from the interviews, companies closely consider the expected ROI, payback periods and the expected overall impact on improving cost-efficiency and reducing OPEX when evaluating the implementation of digital technologies (as discussed in Section 4.1). Thus, while there might be a business case for proven and cost-effective technologies in smaller operations, the overall study results suggest that the individual business case (which includes the expected ROI as it relates to payback periods and expected overall impact) for implementing advanced digital technologies and automation improves with the size of operation, at least for implementing higher levels of digitalization.

Along similar lines, when asked for examples for advanced digitalization, interview partners mostly referred to large-scale operations with high degrees of mechanization and automation. The only exception were the mid-tier companies mentioned above, which also operate comparatively smaller mines.

It follows that the cumulated results of the literature review (Part I) along with the interview analysis suggest that the size of operation especially in conjunction with the company size has a **high influence** on the level of implementation of digital technologies.

However, it should be noted that most of the available literature on digital transformation in mining does not explicitly mention a correlation with the size of operation. One exception, based on an empirical analysis state that “large-scale mining operations appear to select and apply digital technologies suitable to their needs, whereas operations with lower production rates do not implement the currently available digital technologies to the same extent” (Barnewold and Lottermoser 2020). However, the reference to large operations is often implicit, for example in that empirical studies are based on and thus limited to investigations into the world leading companies (Young and Rogers 2019) or that the increasing scale of operations adds pressure to improve productivity in order to remain economically viable and competitive (Gandhi and Santos 2020).

2.4.3. Mining Method

With respect to mining methods, digitalization trends slightly differ between surface and underground operations. This became evident from the literature review and was confirmed by the interview results. Since it is easier to implement autonomous solutions above ground due to the availability of GPS navigation and due to the fact that connectivity and communication systems can be implemented easier on surface, the implementation of automated/autonomous transportation and automated/autonomous drilling is generally more advanced in surface operations than underground.

Based on the literature review in Part I, and according to some of the interview partners, the Pilbara region in Western Australia appears as the most advanced in the world with respect to implementing autonomous solutions at a large-scale, including self-driving haulage trains that operate over several thousand kilometers.

Similarly, ROCs are more advanced for surface operations than underground ones. However, the trend for remote control is also clearly visible in underground operations. There is ongoing research and development work being done in this area across the globe to work towards realizing man-less underground mines that are operated completely or almost completely from surface. With respect to other digitalization technologies, there is no clear distinction that can be derived from the expert interviews concerning the mining method.

Thus, overall, the mining method is deemed to have a **medium influence** on the level of implementation of digital technologies.

2.4.4. Geographic Region

While there are certain regions that are particularly advanced in the implementation of specific technologies, such as autonomous solutions in Western Australia, the overall analysis of the interviews in conjuction with the results from Part I have shown that geography per se is not an influencing factor on the level of implementation of digital initiatives. Thus, it is not possible to rank regions on the globe based on the level of implementation of digital initiatives.

Instead, the implementation of digital initiatives depends on the companies operating in the respective regions. As stated above, company size and size of operation, have a much greater influence on the implementation of digitalization than the location of the mine. However, some regions may have specific hurdles, such as poor connectivity or educational divides that may pose barriers to the introduction of digitalization. Still, the implementation of digitalization initiatives depends on the existence of financially solid (multi)national corporations that can afford to drive technological change – also with respect to necessary investments in regional infrastructure.

Some countries, such as Chile, may support the sector through a national digitalization and innovation roadmap for the mining sector, and others, such as Canada, may have a vivid network of organizations that foster processes of collaboration and open innovation (e.g. so-called junior miners). Yet, the level of implementation depends on the existence of mining companies that have a business case for digital technologies and that are driving the change.

Thus, geographic regions, according to the analysis of this report, have a **low influence** on the level of implementation of digital technologies. This confirms that the mining industry is a globally operating industry that is driven primarily by the incentive to remain competitive and to address and manage complex stakeholder expecations rather than to stop at national borders.

2.4.5. Type of Commodity

This study focuses on metal mines. Thus, interview partners were selected based on their involvement in metal mining operations. With regards to the information collected from the interviews, it can be stated that no significant differentiation is possible among metal mines with regards to the level of implementation of digitalization initiatives. However, it was stated that smaller gold mines may more likely be in a position to afford the CAPEX needed to implement digital technologies, whereas other smaller base or precious metal mines may not be in a position to afford the required upfront investment to implement them.

It was also a consense throughout the the interviews that digitalization initiatives are most advanced in metal mining operations, compared to industrial minerals and quarries. Operations producing industrial minerals are perceived to often not having implemented digitalization technologies at a larger scale and quarries are even less inclined to implement digital solutions.

From the analysis it can be concluded that within the metals sector (base and precious metals), the type of commodity has only **low influence** on the level of implementation of digitalization initiatives.

2.4.6. Influencing Factors for the Level of Implementation of Digitalization Initiatives

Figure 5 summarizes the results of the analysis of influencing factors for the level of implementation of digitalization initatives in a clustered heat map. The green color code indicates a high (dark green) or medium to high (light green) influence, whereas yellow indicates a medium and orange a low influence on the level of implementation of digitalization initiatives. In addition, the overlaps indicate where influences may intersect.

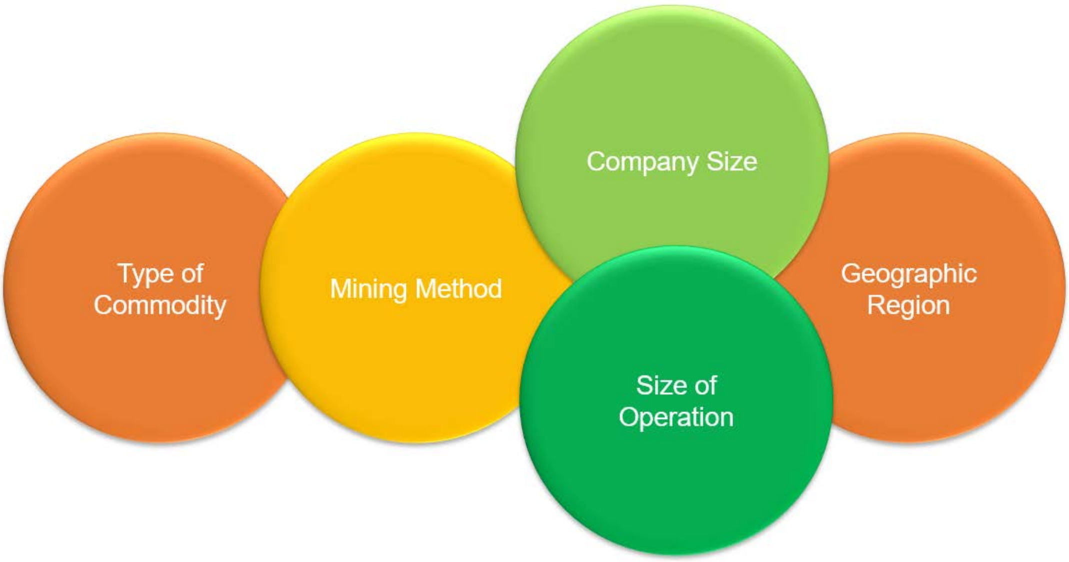


Figure 5: Influencing factors for the level of implementation of digitalization initiatives (green color: high influence; yellow color: medium influence; orange color: low influence)

As a disclaimer, it should be noted that due to the relatively small number of expert interviews this concluding cluster map of influencing factors can only be understood as a preliminary result. To verify these results this analysis would need to be further expanded and supplemented with comparative empirical analysis.

The analysis shows that the highest influencing factors are company size and size of operation, especially when considered in combination. This is notwithstanding the fact that in some regions there are innovative smaller scale mining companies that are actively working towards implementing digital solutions. Yet, from a global perspective, there is a clear trend that digitalization is driven by large corporations that operate large and generally multiple assets across geographic regions: economies of scale and learning effects allow for sustainable investments in innovative technologies.

The mining method has a medium influence on the implementation of digital technologies because of the feasibility of implementing automation, IIoT, communication infrastructures in surface operations and the respective challenges of doing the same in underground environements.

The type of (metal) commodity along with the geographic area are suggested to have the lowest influence on the level of implementation of digital technologies. While there might be unique challenges present in some regions, there is no distinguishable trend globally that would indicate that some regions are generally more advanced than others in implementing digitalization initiatives. This confirms the conclusion from Section 2.1 that digitalization initaitives are primarily driven by mining companies trying to manage their stakeholder expectations.

It also underlines that the mining industry is a truly globalized industry that is highly influenced by large multinational corporations. The incentives for these mutlinational corporations for implementing digital iniatives were also identified and described in Section 2.1. To summarize, global mining corporations are finding themselves under pressure to create safer operations and to remain competitive by successfully increasing productivity and reducing costs through the application of effective digital, operational, automation and electrification technologies.

Some of them may aim to take a leadership position in the application of new technologies while others focus on proven technologies. The future will show if the digital transformation may also imply the increase of a divide between those companies that are successful in adopting and integrating digital technologies and those that are less successful or that may be reluctant to digital transformation. The majority of interview partners did state that they consider those who are lagging behind in adopting digital technologies to be at a disadvantage. In addition, some interview partners pointed out that a potential adverse effect of the digital tranformation could be the increasing divide between those who succeed in this transformation and those who do not.

3. Challenges and Opportunities for the Implementation of Digitalization Initiatives

This chapter addresses the second research question and provides a detailed discussion of the findings from the expert interviews with regard to challenges and opportunities related to the implementation of digital technologies in mining from a global perspective. The conclusions drawn in the different sections in the report are derived from the combined statements of the interviewed experts unless otherwise mentioned.

3.1. Challenges in the Context of Global Digitalization Initiatives

Through the systematic analysis of the expert interviews, it was possible to form clusters that reflect the main challenges that were addressed by the experts in the context of digital transformation in mining. These clusters pertain to highly mechanized industrial mining operations all over the world. In order to include challenges and opportunities pertaining to the ASM sector, these are discussed separately in Section 3.4.

The ten clusters (Figure 6) will be described in more detail in the subsequent sub-sections in the order of their relevance as addressed by the interviewees. The size of the circles correspond with the frequency that certain aspects of the cluster were addressed by the experts and thus indicate the current relevance and importance of the issue for the industry.

Figure 6. Challenges for implementing digitalization initiatives (bubble size corresponding with significance of challenges based on expert interview analysis)

3.1.1 Talent Management

Talent management was by far the most mentioned challenge throughout all the expert interviews. Compared to other challenges, it was mentioned almost three times more often and it was identified by interview partners across different countries and continents as one of the crucial challenges in the context of the digital transformation.

Attracting Suitable Talent

The attraction of suitable talent was the most frequently mentioned aspect across all interviews. What is currently and prospectively concerning the industry is that while traditional skill-sets (of mining engineers and machine operators) are still needed, it is obvious from the interviews that the industry is facing an immense challenge of attracting suitable talent with the skill sets required for managing digitalized and automated operations (e.g. data scientists, IT-specialists etc.). While some skills, such as moving from operating equipment to remotely operating the same equipment from a control room, can be trained on the job, others, especially in areas such as advanced analytics, require the industry to bring in talent from outside the field of traditional mining engineering.

This challenge, according to the interview partners, is amplified by the fact that, especially in industrialized mining countries (here: Australia, Canada, Europe and U.S.), there are large numbers of long-term employees that will retire over the next decade resulting in a shortage of skilled labor. While not all of these positions may be filled again and/or some of these positions may change in terms of their job description once people retire, the looming shortage of skilled labor is an issue that was widely acknowledged by the experts as a key challenge the industry will face.

The Public Image of Mining

The negative public perception of mining as ”dusty, dirty and dangerous” is considered a clear challenge in this context, especially since mining companies are now competing with other industries for specialists, for example data analysts, who seek out or are attracted by other industries that are more digitally advanced or perceived as such. (Abrahamsson and Johansson 2020; Johansson *et al.* 2018; Lööw *et al.* 2019) As one expert from a mining company confirmed, in order to attract the right people, mining companies have to change the way they are perceived by the public and by the generation they wish to attract. Younger generations are attracted to companies with whose purpose and values they identify. Thus, based on the view of this expert and similar thoughts from others, it can be concluded that mining companies may need to re-think their position within society and their values and purpose and align them with the values of the generation they wish to attract.

Bridging Generational Divides

Another related challenge that was mentioned by several interview partners results from the blending of different generations that need to work together and the corresonding differences in expectations regarding work culture. This challenge requires conscious change management and needs to be addressed at the leadership and management level. Traditional hierarchical management structures, for example, can reduce the attractiveness for younger generations who prefer more agile ways of working and flat management structures. In addition, one of the experts pointed out, these traditional and often hierarchical work structures and departmental silos can limit the opportunities for experienced long-standing employees to collaborate with e.g. a younger data scientist to improve a specific area of the operation.

Re-training, Re-skilling, and Continuous Education

A fourth area that is posing challenges in the context of talent management, according to the interview partners, is the need for re-training or re-skilling of staff to enable them to adapt to a changing technological landscape and changing job requirements. In some cases, mining companies provide extensive opportunity for upskilling and continuous education through eLearning modules and on the job training. Where these kind of opportunities are not available or provided by the company, especially if the mine site is located in a developing country, there is the potential for a growing divide between skilled labor that received training elsewhere, even abroad, and the local, often lower skilled workforce that might then be at a disadvantage.

This challenge can be intensified by the fact that there can also be a generational gap: the older and experienced generation of employees might be reluctant to adopt digital ways of working and refuse change, while some workers might not just be reluctant but actually less able to adapt to new ways of working (for example adapting to remote working). They might also be disadvantaged as a consequence.

The gap between digitally able and less digitally able workers may also be widened as a result of differing levels of network connectivity that is available to workers. The COVID-19 pandemic has brought this challenge to the forefront, when remote work (from home) suddenly has or had to become an integral part of working for many employees. In regions such as Africa, where network connectivity is not as widespread as in other parts of the world, workers with low connectivity can potentially be put at a disadvantage.

Adapting Educational Systems

Adapting educational systems to prepare students and engineers in training for the changing landscape of the mining industry, such as including programming skills and analytics into curricula, was another aspect that was raised by several interview partners.

Especially with respect to Africa, the concern was raised that there is a potential for a widening gap between highly skilled employees, which could even be experts that are brought in from outside the country. They could replace local workers, and low skilled workers, who could be at a disadvantage due to the lack of access to education and training. Several interview partners stated that addressing this challenge would require a multi-stakeholder initiative, where mining companies, universities and communities collaborate to ensure access and opportunities for the local population.

3.1.2 Data Management

The second most mentioned area in which the industry is facing challenges in the context of implementing digital technology is the broad field of capturing, transmitting, analysing, storing and managing data.

Connectivity and Communication Infrastructure

In some regions, where network connectivity may not be existent, there is a particular challenge in puting the right backbone of communication infrastructure in place in order to be able to capture and transmit data in real-time or close to real-time. Therefore, as addressed by several interview partners, especially from Africa, reliability of communication systems is also an issue. This may require back-up systems in case of power outages or may require mining companies to install their own infrastructure of communication networks in order to create the foundation for digitalization and digital data capture and transmission.

In addition, several interview partners from various continents commented that in underground environments it is still a challenge to establish reliable communication networks and to ensure data transmission across the mining operation. Especially when the mine expands to new areas, one of the challenges, according to one of the experts, is to implement portable access points to ensure that new areas of the mine can be connected to the data network.

Quality of Data

Aside from these infrastructure related aspects, another challenge that was frequently mentioend was how mining companies can cope with the sheer amount of collected data. The main challenge is to ensure the appropriate quality of data that can provide added value to the decision making process. The aim is to ensure that relevant data is captured and analyzed in a way that it can support decision making processes effectively. One of the experts mentioned that it is important to answer the “what”, “what for”, “how” and “why” questions when collecting data from sensors across the entire operation – before analytics are applied. This is crucial in order to have options like “data lakes” contributing actual added value. However, as several experts stated, a clear understanding how to capture and maximize the value from the available data is still lacking in many cases.

Sharing Data

Yet another challenge that was mentioned in this context is related to sharing data across different functional units within the operation as well as sharing data across companies in order to be able to benchmark best practices and learn from each other. Sharing data within the company bears vast potential to gain insights and to analyse bottlenecks across the entire value chain, as several of the experts pointed out. That helps to optimize not just individual processes but the entire operation. The challenge here is closely related to the persistent culture of departmental silos and functional units that do not “speak to another” (Section 3.1.3).

Similarly, the still widespread hesitancy to share data across companies for benchmarking (Section 3.1.8) to help all parties improve is a limiting factor for moving the industry forward, according to the experts. Organizational bodies, such as innovation networks, that bring different stakeholders and mining companies together to foster innovation, have proven useful to increase the level of sharing and collaboration among mining companies (Section 3.1.4).

3.1.3 Change Management and Culture

Change management and culture were other aspects frequently mentioned – not limited to specific regions or type of interview partners.

Creating Technology Acceptance

As one of the experts pointed out, conscious change management requires constructive, well defined processes that provide orientation and clear targets to management and employees. Change management was mentioned mostly in conjunction with technology adoption and how to engage employees and communities in the process of change in order to increase acceptance rather than resistance. Interview partners all agreed that change is inevitable but also that the management of change is as much a challenge as it is a key for the success of any digitalization initiative.

There was also consensus that change mangagement needs to be an integral part of every project that deals with implementing new technology if the project is to be successful. In addition, it was frequently mentioned that change needs to be communicated early, pro-actively, and continuously. Project managers and management need to be supportive and active advocates of the envisioned change project and technology that is to be adopted if projects are to succeed.

Fluctuations Cause Problems

Another challenge related to change management that was raised by one expert is how to deal with the high turnover of people in positions responsible for managing change and technology implementation. One expert mentioned that implementation processes lack sustainability because of a lack of integration of change initiatives within the company and its overall strategy. This could result in the discontinuation of change iniatives if key persons leave the company.

Changing Company Culture

The discusson of cultural aspects centered around two core themes. On the one hand, the challenge as seen by the experts is related to moving company culture from command and control and hierarchical structures that have traditionally characterized the industry to a culture open to ideas. On the other hand, introducing more horizontal management structures and agile ways of working was mentioned as an important component in allowing the generational gap to be bridged and have younger digital natives interact and work with experienced engineers. One of the experts commented that there were three main cultures that co-existed in mining companies and which usually did not interact well yet: the culture of the operations on site, the corporate culture at the head offices, and the culture of the digital natives and data specialists entering the mining companies. Creating a culture that is encouraging innovation and integrating the different sub-cultures and differing generational views seemed to be an underestimated challenge mining companies are facing.

Breaking up Silos

Cultural change is also required when it comes to de-siloing mining departments in order to successfully identify bottlenecks, several experts stated. In addition, one expert mentioned that de-siloing is necessary to implement a value chain approach towards optimization and bottleneck analysis in order to gain the most benefit from process optimization and process integration. Thus, organizational structures and ways of working need to change in order to allow for sharing data across operational units and, consequently, for a more integrated approach to optimization. According to the experts, this is of high importance if the full potential of process optimization is to be realized.

Clear and Integrated Roadmaps

Change management and cultural change, as several experts pointed out, are closely related and both have to be addressed consciously and actively. In addition, an important factor for moving technology adoption forward and for ensuring its succes, which was mentioned by several experts, is that the company develops a clear roadmap for digitalization with measurable implementation targets that is also integrated with the innovation strategy and the overall corporate strategy. Adopting technology and adopting it sucessfully is considered key for mining companies to remain competitive as late adopters may be at a disadvantage and could even be driven out of the market eventually.

3.1.4 Collaboration and Innovation

The current level of collaboration among mining companies is considered another challenge and limiting factor by several interview partners. This is not limited to sharing data for benchmarking purposes (as mentioned in Section 3.1.2) but includes sharing problems, challenges and solutions to move the industry forward and encourage innovation and innovative approaches. It also includes the issue of looking outside the mining industry for solutions and the challenge of responding to change and the demands for innovation in order to remain competitive.

Collaboration for Innovation

Examples from Canada and Chile that were mentioned during the interviews show that it is possible to create shared digitalization and innovation roadmaps as part of multistakeholder initiatives or innovation networks that have been formed in these regions. In Canada, clear progress can be observed over the past decade in terms of intensifying levels of collaboration. However, it was pointed out by Canadian interview partners that collaboration levels were still low compared to other industries and measured against what was needed to achieve the envisioned innovation targets outlined in the roadmap. It had taken over a decade to develop a shared roadmap. In Chile, a roadmap (Digitalizacion Mineria 2020) that has unified the objectives of the industry was created involving the government as well as all relevant stakeholders.

Learning from Outside the Mining Industry

Another aspect that was mentioned several times was the lack of learning from outside the mining industry. The transformation of the automotive sector was mentioned in this respect as well as the oil & gas industry, both of which are further ahead of mining in terms of collaboration, innovation and adopting new business models or business practices. In addition, as one expert mentioned, automotive and aerospace industry offer great lessons on collaborative systems engineering and design.

Several experts pointed out that the reluctance to learn from other industries seemed at least partly to be rooted in the perception of the mining industry as unique and different from all other industries. In addition, some experts mentioned, because each ore deposit is unique this further contributes to the perception that the potential to learn from others even from within the industry is limited.

Current Business Models

Another challenge for innovation could also result from the predominant business model of the economies of scale, according to one of the experts. Large upfront capital investments and a volatile market, he pointed out, led to cautiousness in taking risks and trying out new technologies. According to the expert, the entire mine planning, approval and operating system, which has become reliant on economies of scale and thus large-scale operations has become inflexible. The challenge then became trying to identify alternatives to economies of scale.

In addition, he stated that learning from other industries and applying new methods was limited by the rigidity of the current incumbment model of planning and operating LSM. Thus, the design process for mines had become highly constrained by regulations meant to protect investors, such as the industry standards NI 43-101 or JORC. These standards forced companies to disclose the design process but through this process the design became fixed and impossible to change because investors did not like to see changes that could imply that the original design was wrong.

Thus, the entire process of designing and approving mines, he stated, was impacted by the need to consider the interests of large investors and as a result was not agile and responsive. As a consequence, immature but major ideas – like a fundamental change of mining method – are ruled out early in the design process, even though the approval process takes so long that the idea may be proven by the time the mine is built. This, according to the interview partner, is a well-known problem of complex system design, which can be compounded by regulators requesting fixed mine designs and thus also contribute to inhibiting more agile approaches.

However, if the company is financially strong and has a track record of managing innovation risk well, then it will be able to explore innovation options that involve a little more risk in the design process. In addition, if the innovation is not complex (e.g. tele-remote operation of machines) then it may not need to be part of the design disclosed to investors, in both cost and risk. It may, however, still be unacceptable to regulators. One could state, he said, that the later in the design process an innovation is introduced, the less complex (and for small companies, the less costly) it must be to survive.

3.1.5 Cybersecurity

Cybersecurity was another challenge that was mentioned by several interview partners. This challenge got even more pressing due to the COVID-19 pandemic as many companies had to shift to remote work “on the fly”. In some cases, experts remarked, this led to workers utilizing their own mobile devices to remain connected and perform remote work, which has increased cyber risks immensely. While firewalls may be installed on company devices, they may not be existent on private devices to the same standards.

Aside from this current situation, cybersecurity is a topic high on the agenda of many company leaderships. This was a result of the analysis of Part I and was confirmed by the interviews. This is not surprising since the more digital devices and IoT applications are installed, the more vulnerable to IT related risks an operation becomes. There have been reported cases of hacks on autonomous trucks in Australia, as one expert mentioned.

3.1.6 Interoperability and Standardization

Another challenge stated in the majority of the interviews and mentioned by mining companies, OEMs and other industry experts alike, was the need for interoperability of components and systems. There was largely consensus among the interview partners that the lack of interoperability is slowing down the digital transformation in mining across the world. It was also stated by most experts that it is a process that will take time and it is expected that the industry will ultimately achieve a shared architecture and framework for digitalization. The Global Mining Guidelines Group (GMG) was mentioned frequently by the interview partners across the globe as one of the most important organizations to push forward the development of such unified architecture for the mining industry.

Compatibility of OEMs and Component Suppliers

In addition, it was stated that mining companies are requesting and driving OEMs to ensure improved compatibility and interoperability of their systems with components from other suppliers. This was confirmed by a representative of a leading OEM, who stated that OEMs need to work with other providers to “please the customer”. Yet, in practice, interoperability still poses challenges and requires frequent “on the go” dealing with errors. One interview partner reported that compatibility meetings are frequently held on site where all parties (suppliers and the mining company) have to sit together to resolve specific issues and problems.

Compatibility between OEMs

Aside from compatibility of OEM machinery with sensors and other components from other suppliers, the compabitility and interoperability of equipment from different OEMs seems to be an even greater issue. Most OEMs offer integrated platforms to go with their suite of machinery and some state that it is compatible with all other components. However, as one expert stated, the level of integration is often not clear and in practice, the integration of equipment and components from different manufacturers still poses challenges and causes problems.

This aspect can also impact decisions around retrofitting and upgrading versus buying new equipment, one of the interview partners pointed out. If a competitor OEM, for example, is offering more advanced solutions, but the current equipment in a mine is configured around solutions provided by a specific OEM, the mining company may decide against switching to a different OEM, even if the capabilities could be improved. That is due to the challenges of having to reconfigure the entire IoT system along with the equipment.

Standardization

With regards to standardization, an interesting comment was made by one interview partner: It was said that full standardization would not be feasible in the mining industry but that it was more about connecting different components, platforms and systems. The challenge then would lie in identifying where standards and a shared framework architechture were required to allow for connecting these different systems, rather than expecting standardization in all areas.

Innovation

Along similar lines, one expert commented that interoperability was also forcing the industry to follow stricter rules that could actually limit innovation. He advocated focusing on deploying mainstream technologies that are centered around the user experience. Using the example of Microsoft and Apple working differently, he commented that technology providers were the ones that had to figure out how to make their solutions work with both providers. In this approach, the most user friendly, practical and best solutions would win, whereas standardization and interoperability frameworks could slow down innovation proceses and technology adoption.

In conclusion, there is largely consensus among the experts that interoperability and, to a lesser extent, standardization are key issues in moving the digital transformation forward and that the lack of interoperability is causing challenges in day to day operations and contributes to slowing down the digital transformation process worldwide. Experts also agreed that it will take time – probably another decade – to achieve a unified framework architecture.

3.1.7 Perceived Job Losses

Another challenge that was mentioned by some interview partners was the mitigation of real or perceived job losses. There was no consensus among the interview partners whether the digital transformation will lead to job losses or just changes of job requirements. However, most experts were of the opinion that, even if job losses occured in the short term (e.g. due to automation), the transformation would not reduce the amount of jobs at mine sites ultimately and/or significantly but would rather lead to a shift in the kinds of jobs available (Section 3.1.1) and where these are located (remote work, remote operations).

However, the fear of job losses creates various levels of resistance to digitalization initiatives on the part of the local workforce, several experts pointed out. It also has the potential for social unrest, an aspect that was mentioned especially with respect to Africa and, to some extent, with respect to South America. Therefore, experts agreed that mitigating perceived job losses and engaging proactively with the local communities and the workforce is crucial. One interviewee representing a mining company even mentioned that they were not implementing automation technology at its full potential because it might result in social unrest. According to one expert, keeping social stability has led to a slower adoption of automated equipment because keeping social stability is considered more valuable for that company than the productivity gains from automated equipment.

Thus, the combined feedback of the interview partners suggests that providing opportunities for upskilling, re-skilling and continuous education appears to be just as important as being transparent, proactively engaging and communicating continously with the local communities about planned digitalization and automation initaitives in order to ensure acceptance of technologies and change projects.

3.1.8 Data Ownership and Liability Issues

The issue of data ownership is also a challenge related to data management that was vividly discussed with the interview partners. The challenge is centered around the distribution of ownership rights between mining companies and OEMs. Based on the feedback from the interview partners there seems to be a trend that mining companies are now requesting to own the data of all the equipment they purchase from OEMs, while OEMs often keep access to the performance related data of the equipment that can suppoprt further optimization of the development of their products.

Mining companies request all data required for continuous process optimization. Frequently, OEMs sell data analysis in the form of reports or dashboards as a service back to the customer (mining company). In some cases, however, mining companies prefer to have access to the raw data and employ their own specialists or hire third party experts to analyze it. Larger mining companies tend to be in a better position for deploying in-house capacity for data analysis, whereas smaller companies may tend to purchase analyzed data from the OEMs. Some companies also deploy external data analysis service providers to analyze the OEM data.

While the issue of data ownership is still a contested one, it seems there is a general consensus growing within the industry about the distribution of ownership rights. It was mentioned, however, that some OEMs are not as willing as others to provide access to the data. Furthermore, mining companies have become much more aware of the importance of owning and analyzing the (raw) data. Obviously, there can be conflicts of interest between mining companies and OEMs, for example, where the life-cycle or replacement rate of components is concerned; it becomes a contested question which data is owned and accessed by whom. One mining company's representative reported that they were able to extend the life-cycle of components significantly after they conducted their own data analysis.

With regards to liability in case of poor decisions made on the part of autonomous machines, the consensus among most interview partners was that to date there have been no reported incidents that would have brought the issue to the top of the agenda. However, it was also generally agreed that this is a grey area that has still not been addressed globally and needs to be included in contracts. One important difference of mining companies operating autonomous machines compared to for example the automobile industry is that autonomous machines in mining operations may operate in isolated areas with no human interaction or no humans in close proximity. Thus, the risk for injuries is minimized drastically. One expert representing an OEM mentioned they had now accumulated three million working hours in over 500 mine sites across the world without a single LTI (Lost Time Injury) reported in conjuction with autonomous equipment. Along the same lines, liability questions related to collisions or breakdowns of autonomous machines were not reported by any interview partner.

3.1.9 Technology Adoption

There are four specific challenges related to technology adoption that were pointed out by some experts.

The first challenge, according to one of the experts, is to agree on KPI's across departments based on the priorities of each department as a starting point for deciding on technologies. This process of prioritization, he stated, is just as important as taking a cross-departmental approach in deciding not just on the KPI's but on the technologies needed to achieve them.

Secondly, mining companies face the challenge of selecting and integrating the right technologies from all the available options based on their individual business cases and implementation targets. Integrating technologies into running operations without creating delays or interruptions of the production process is another related challenge.

Thirdly, new technology and new kinds of equipment (automated, with AI capabilities) require distinct approval processes from the respective authorities and reguatory bodies. However, as these approval processes can be slow, this can slow down the adoption process as well.

Last but not least, technology does not just have to be adopted, but has to be integrated into the existing workforce and processes. Consequently, as one mining company representative pointed out, consciously and carefully managing this intersection of people, technology, and processes is the most important factor.

3.1.10 Real-Time Positioning and Localization

Based on the feedback from several interview partners, accurate real-time positioning and localization, especially in underground environments, still poses an immense challenge for mining companies, especially if they operate in remote areas without network connectivity or in underground environments. While remote areas requires installing a respective communication infrastructure from scratch, technologies for the high precision localization and collision awareness in underground environments are still being developed and optimized in collaboration with research.

However, knowing exactly where people and machines are at any given time using high accuracy localization technologies is a key prerequisite for further improving safety as well as for analyzing operations and optimizing processes and equipment utilization, one expert remarked. He also stated that this is an area that still needs technological improvement, especially if one wants to think about the potential interaction of robotized or automated equipment with humans. In addition, several experts mentioned the challenges related to collision avoidance and collision awareness systems. One remarked that due to the lower level of technological maturity, collision avoidance systems have not yet reached their ROI, while others pointed to the challenges related to moving from collision avoidance to collision awareness.

One interesting remark by a mining company's representative was that high accuracy of positioning, especially in relation to the economic zone being mined, is even more important than automating equpiment, since automated equipment put in the wrong place will not improve productivity as much as would be possible when its utilization is optimized first.

3.2 Opportunities Resulting from Digitalization Initiatives

Having assessed the challenges, this chapter looks at opportunities resulting from digitalization initatives using the same methodology for clustering the answers. The seven clusters (Figure 7) will be described in more detail in the subsequent sub-sections in the order of their relevance as addressed by the interviewees. The sizes of the bubbles correspond with the frequency that these opportunities were addressed by the experts.

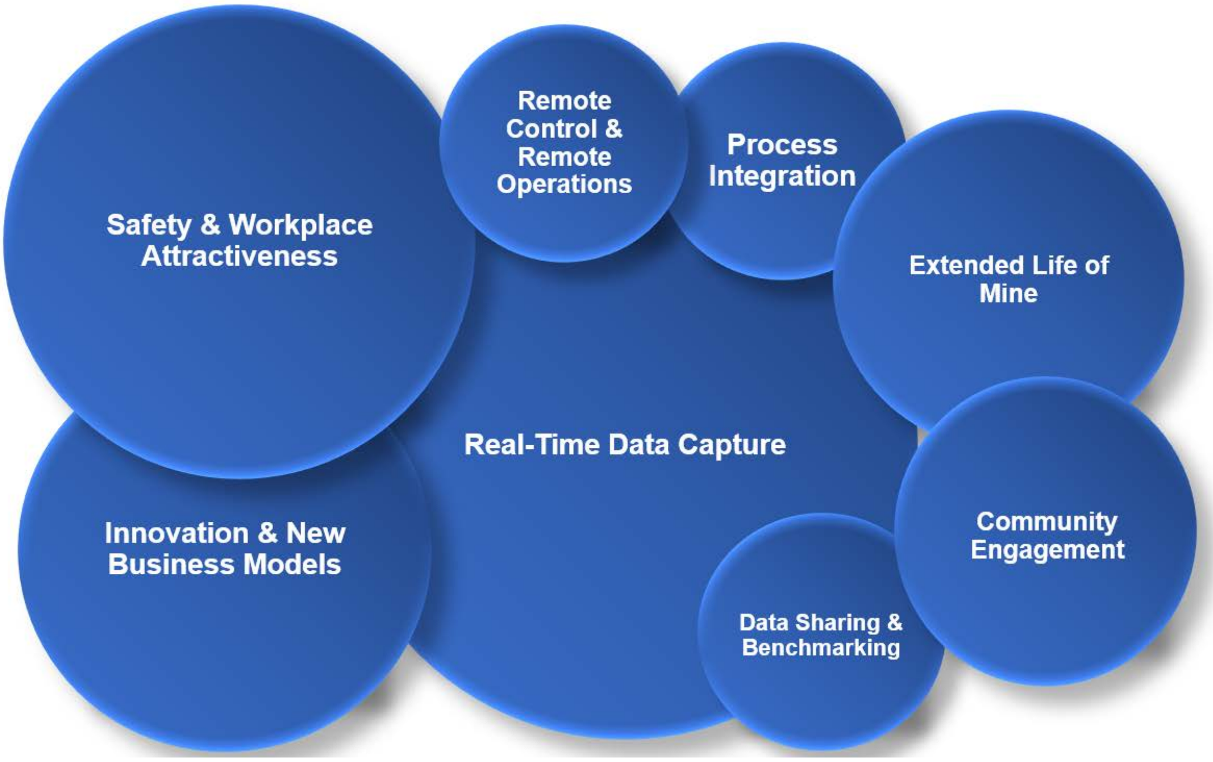


Figure 7. Opportunities from implementation of digitalization initiatives addressed by global experts (bubble size corresponding with number of times the cluster themes were mentioned during expert interviews)

3.2.1 Real-Time Data Capture & Analysis

Despite the challenges associated with data capture, transmission and management, interview partners across the board mentioned the significant benefit arising from real-time data capture (and analysis).

Reduced Variability

The biggest opportunity is considered to come from reducing variability and creating more constant production rates. Reducing the variability of the input to the mining process presents one of the biggest areas for productivity improvements. That is especially beneficial when combined with a value-chain approach which considers not individual processes but looks for optimization potential across the entire production cycle.

Visualization and Simulation

As several interview partners pointed out, visualization and simulation of data on surface through technologies like the digital twin are the foundation for knowing where everything is at any given time. Thus, visualization and simulation are key enablers for real-time decisions, short interval control and for reducing variability in mining operations.

Real-time Decisions & Short Interval Control

In addition, real-time data analysis creates visibility of what is happening in the operation, which allows for faster decision making processes and short interval control. Further, by embedding this in the entire value chain, the managers will be in a position to have transparency of what is happening in the operation at any given time and to make decisions accordingly.

Forecasting

Another opportunity that arises from real-time data analysis is forecasting in production and for equipment with respect to maintenance and anticipation of machine failures. However, this is still at an earlier stage of implementation than the other opportunities mentioned. Significant gains can be made from optimizing equipment availability and utilization of underground mobile equipment, especially if the optimization is integrated across functional units and combined with predictive maintenance, one of the experts illustrated.

3.2.2 Safety and Workplace Attractiveness

The opportunity to improve the OHS and to increase workplace attractiveness was mentioned almost as often as the opportunities related to data capture and analytics.

Remote Operations

The interviewees consider remote operations, which allow for moving the workers from potentially hazardous and rough environments to comfortable and safe control rooms, to have the largest impact on OHS and workplace attractiveness. These control rooms can either be on surface of a mine site or, in case of ROCs, many (hundreds or thousands) kilometers away.

In addition, several interview partners from mining companies reported on how they needed to adapt to the current COVID-19 pandemic and that they have adopted remote work to some extent as a new way of working. Thus, there seems to be a trend, based on the feedback from the mining companies that participated in the interviews, that remote work has advanced much faster than expected. Along similar lines, it was mentioned during the interviews that more people have been moved from underground environments to surface in order to comply with social distancing regulations (i.e. minimizing risks of infection).

Diversity

Some interview partners pointed to the potential of increasing diversity in the workplace resulting from changing ways of work in the industry. If workplaces are moved from remote areas to cities or larger communities and from rough environments dominated by heavy duty equipment to air-conditioned offices with joysticks and dashboards, these workplaces become attractive and accessible to a larger group of potential employees. That includes younger people with advanced digital skills. This was considered by some interview partners a large opportunity for mining companies, especially considering the challenges regarding skills gaps and projected waves of retirees. Thus, the analysis of the interviews suggest that there could be an opportunity for mining to become more inclusive and diverse.

Training

In addition, some interview partners mentioned that digitalization technologies can offer opportunities to enhance safety training and education. Especially simulation and modeling technologies, such as 3-D theatres, utilizing VR technology, are considered useful to improve safety training for employees. In addition, it was mentioned that continuous education modules could potentially be offered utilizing online platforms and thus enhance training and learning for employees.

3.2.3 Extended Life of Mine

The analysis of the interviews suggests that one important opportunity arising from increasing productivity is the ability for optimizing throughput and metal recovery[4]. As some experts mentioned, this could, in turn, reduce the need for greenfield development. In addition, automated and digital technologies could open up opportunities to access deposits that are not accessible nor economically recoverable at this moment. Consequently, more resource efficient and technologically advanced mining operations may therefore compensate, to some extent, for the current comparatively low rates of greenfield exploration and project development, according to some of the interview partners.

3.2.4. Community Engagement

The cumulated results of the interviews suggest that digital technologies can also open up opportunities to engage differently with local communities. Through sharing data related to emissions, water quality etc. with communities, acceptance of mining activities can be improved through increasing transparency. For example, some mining companies are already publishing their emissions and water quality data on their company websites, with some even updating their data in close to real-time. In addition, 3-D modeling and visualization technologies can be utilized to engage communities and support transparent and proactive communication with communities and other stakeholders. Some companies also make monitoring data accessible on their website. Furthermore, virtual mine tours[5] may allow for increased awareness and perception by non-mining stakeholders.

In addition, it was mentioned during the interviews that the digital transformation can offer opportunities for local service or equipment companies to develop around special services and products required by mining companies. This may, however, require multi-stakeholder initiatives and support from national or regional governments as part of regional economic development programs. In Chile, the government is explicitly and directly supporting the development of mining related start-ups related to digitalization in mining as part of its national digitalization and innovation roadmap.

3.2.5 Innovation and New Business Models

Another opportunity that was raised and discussed with some of the interview partners was (open) innovation and collaboration as well as the possiblity for new business models.

Open Innovation

Since low levels of collaboration were considered a challenge for the mining industry by many interview partners, the flip side is increased levels of collaboration and a stronger move towards open innovation. As the cumulated results of the interviews indicate, in some regions, this process towards increasing collaboration and collaborative innovation is facilitated through innovation networks or targeted efforts to create regional innovation ecosystems. Examples from Canada, Chile and Peru showed that these initiatives were able to increase levels of collaboration and the acceptance of open innovation processes over time. Some networks that were described are industry-led, others are initiated and financed by the government. In some areas, large mining companies were also able to foster the creation of regional innovation ecosystems by putting a strong focus on innovation and working with local and regional start-ups and universities or research insistutions.

[4] An actual percentage is highly depending on the type of commodity and deposit and the kind of mining operations.

[5] https://www.bge.de/en/morsleben/info-centre-public-tours/
https://glueckauf.wdr.de/en/

New Business Models

The opportunity was not adressed as often as opportunities for open innovation, however, it was pointed out that there is potential for developping new business models in mining. Facilitated by digitalization and changing stakeholder perceptions and expectations, new business models could evolve around attracting social investors and putting Environmental, Social and Governance (ESG) at the center of the business (Deloitte 2020).

Considering that community conflicts and the Social License to Operate is considered one of the mining sector's top business risk, this could indeed become vital for mining businesses (Mitchell 2019). Negative public perception, the results of the interview analysis suggests, is a key issue for mining companies that not only affects obtaining and maintaining a social license to operate but also negatively affects the recruitment of talent.

Thus, one of the experts pointed out, putting social value creation and benefits for local communities at the core of the business model could become increasingly relevant. Digital technologies, he said, could support the emergence of new and more agile business models that focus on social value creation. These technologies could enable radical transparency and higher standards of accountability of operations, as well as inclusive, iterative and agile mine designs that are developed and adapted together with stakeholders and communities. There is, for example, one start-up company in Canada which is attempting to build a mining company with a different business model focusing on mining-as-a-service and the creation of social value. A closer examination of this new business model can be found in a study by Dunbar et al. (2020).

3.2.6 Remote Control and Remote Operations

The analysis of the interviews suggests that remote control and remote operations hold the potential for implementing the unmanned underground mine by moving all staff to the surface. While this is still a futuristic scenario for underground operations, ROCs that control surface mine sites from hundreds or thousands of kilometers away have already been implemented and are currently most advanced in Australia's Pilbara region, as was mentioned during the interviews. ROCs on surface near the mine site have been implemented at few mine sites in Europe, North America, South America and Africa. The implications for improving OHS and increasing workplace attractiveness have been discussed earlier.

3.2.7 Data Sharing & Benchmarking

Digital technologies also provides opportunities to increase transparency through data sharing and benchmarking, some experts pointed out. Some mentioned that data capture and analysis have already improved transparency of operational processes at many mine sites, while others pointed to the fact that sharing data across the operation has created transparency across the value chain and provided insights for decision making in those cases that mining companies were able to implement the data sharing successfully.

However, there is still a limited number of cases where data sharing across the value chain has been implemented successfully. Other experts mentioned that sharing data across companies can create transparency of best practices and contribute to benchmarking to move the industry forward and, in the best case, foster collaboration rather than competition. Sharing data across companies has been most successful where facilitated by innovation driven organizations[6]. While mining companies are still reluctant to share data across companies, there is a trend towards collaboration within designated organizations and innovation networks that act as a facilitator in this case.

[6] Canadian Mining Innovation Council or Expande in Chile

Putting emission and water quality data on the company website increases transparency for communities and stakeholders (see also Section 3.2.3). Examples that were mentioned during the interviews referred to operations in Africa and Canada. Visualizing data can equally support communication, engagement and communication with stakeholders, from communities to investors. In some cases, increasing transparency is demanded by regulators and mining authorities, in other cases, mining companies are providing company data voluntarily to the public. An example can be seen from a study by Xia (2011) where it was noted that an increasing number of Australian listed mineral mining companies were disclosing environmental information in their annual reports. According to the study, the companies tend to disclose in categories such as “Overall”, “Energy”, “Water”, “Emissions, Effluents and Waste” and “Products and Services” as these are the most common concerns that are raised by the general public. Further, the ICMM has developed various documents in regards to reporting on water quality itself, one of which includes a practical guide to consistent water reporting (IFC 2020).

Another example of transparency can be observed from the Extractive Sector Transparency Measures Act (ESTMA). This act, which was brought into force on June 1, 2015, “delivers on Canada’s international commitments to contribute to global efforts to increase transparency and deter corruption in the extractive sector by requiring extractive entities active in Canada to publicly disclose, on an annual basis, specific payments made to all governments in Canada and abroad.” (NR Canada 2020)

Although the topics of value chain and supply chain transparency are not considered part of this study, since they are out of the technical mining operation’s process, it should be mentioned that the opportunities for increasing transparency through digitalization technologies for the tracking and traceability of minerals and metals were mentioned frequently by the interview partners. Supply chain transparency, e.g. by blockchain efforts, is expected to have a considerable impact moving forward – both up-stream (e.g. in exploration) and down-stream (e.g. in commodity trade) of mining (Section 3.3.2).

3.2.8 Process Integration

An opportunity that was less frequently addressed but should be mentioned because of its potentially large impact is the opportunity for process integration. This opportunity refers to the potential to optimize process integration across the entire value chain, rather than optimizing individual business units or individual processes of the operation. The benefits that can be gained from taking a more integrated and value chain based approach to optimization (from pit to port) are immense, according to the experts who raised this point.

One part of this process can be the creation of “data lakes” to collect, store, and analyze data from across the operation. This kind of integration bears the potential to “mine the white spaces”, as one expert put it, which can be found at the intersections of different units and processes. While individual processes may be transparent and well understood, hand-over points between one process (moving material horizontally underground) and another (moving material vertically to surface) can bear immense potential for optimization, the expert said. He alluded to the fact that these opportunities have not yet been exploited but present future opportunities for mining companies to benefit from data generated by digital tools.

3.3 Challenges and Opportunities for ASM

The clusters for challenges and opportunities discussed in Sections 3.1 and 3.2 are applicable to médium- to large-scale industrial mining operations across the globe. As discussed in Chapter 2, the main characteristics for advanced levels of digitalization are not related to geographical regions or mine types (although the focus for digitalization initiatives differ between open pit and underground operations). However, they are strongly related to the size of the company as well as its operation.

One of the outcomes of Part I of this study was the observation that ASM operations did not appear in the literature and keyword-based analysis of mining journals in the context of digitalization initatives. Thus, one of the open questions for Part II of the study was what kind of opportunities (and challenges) may exist for ASM with regard to utilizing digital technologies. To answer these questions, at least preliminarily, experts from the area of artisanal mining were sought out and a question on opportunities for artisanal miners was included in the questionnaire for all interview partners. The next sub-sections discuss the most important findings from the interviews in relation to the ASM sector.

3.3.1 Challenges for ASM

ASM operations are dealing with different sets of challenges than large-scale industrial operations and thus cannot be compared to their large-scale, often globally operating counterparts. Therefore, rather than a comparison, the starting point has to be that there are large differences in what is an appropriate technology based on the type and scale of mining operation.

While large autonomous machines and integrated platforms may be appropriate for industrial LSM operations, they are hardly suitable for the ASM sector. Consequently, the challenges applicable to the ASM sector are of a completely different nature. For this section, a number of selected experts on the ASM sector were interviewed. In addition, all interview partners were asked to comment on opportunities and challenges for the ASM sector. The discussion below represents the cumulated findings of the interview results.

Access to Capital

Based on the results of the interviews, the greatest challenge for small-scale mining operations (with equipment) is the required capital to invest in technology. Investing in digital technologies is thus simply outside of the scope of possibilities, even though there could be potential benefits. In most regions, small-scale mining operations, therefore, lag far behind in terms of implementing digital initiatives.

One exception that was mentioned during the interviews were small-scale gold producers, who sometimes run operations with enough surplus value to be able to invest in some digital technologies like sensors. Another exception that was raised during the interviews is the mid-tier mining sector in Canada (Section 2.4.1). One single-asset Canadian mining company named Nouveau Monde Graphite, that was mentioned during one of the interviews for example, has undertaken the task to create the first fully-electric open pit mine and is working with a suite of partners to realize this goal (NMG 2020).

Blurred Lines of Illegitimacy

With respect to artisanal miners, one of the greatest challenges, aside from lack of capital, according to one of the ASM experts, is the blurred line between informality and illegitimacy in the sector. Legitimate informal mining activities can benefit from the digital technologies in that they could support the process of formalization, which will be discussed in Section 3.3.2.

However, tracking cell phones or satellite imaging could also be used to track mining activities that are considered illegitimate and thus may be perceived as a “threat” by the artisanal miners. Considering the varying and sometimes inexistent legal frameworks in the over 100 different countries where artisanal mining activity occurs, this can pose a potential threat to the livelihood of artisanal miners who may reject digital technologies, even cell phones, for this reason, one of the ASM experts stated.

3.3.2 Opportunities for ASM

Interestingly, the opportunities, especially in the context of artisanal mining, far outnumber the challenges that were addressed by the interview partners. With respect to small-scale miners (using mechanized equipment) no distinct opportunities were mentioned. Thus, the following paragraphs focus on opportunities arising from digitalization in the context of artisanal mining activities.

Formalization and Governance

Digital technologies could be applied to increase the level of formalization in the ASM sector, according to the interviewed ASM experts. One expert pointed out that since the lack of data and lack of understanding of the sector is one of the major constraints for ASM activity becoming integrated into a formal national economy, digital data collection can contribute to understanding the sector. Consequently, digital data collection can improve not only formalization but also ASM-related initiatives led by international organizations, such as the World Bank. However, another ASM expert remarked, even though information and communication technologies (ICT4D) could be used for mining regulators and local authorities to create or improve outreach strategies, governments often still lack the capacity to interpret and use the available data and thus to take full advantage of this opportunity.

Remote Sensing

In addition, remote sensing can play a role in monitoring informal ASM activity. Technologies to realize remote sensing are still being developed. One example of a current R&D project that was mentioned by an ASM expert was the “ASM Spotter”.[7] This technology, currently being developed by RWTH Aachen University in partnership with a machine learning company, uses satellite imagery as a base data set. With input from geologists and based on the development of a suitable algorithm, the technology has demonstrated to be able to identify surface ASM activities with 80-90 % accuracy. The algorithm analyzes changes in the landscape (forest, presence of equipment, sedimentation, coloration of water bodies etc.). Albeit still in development, this could have far reaching implications for mapping of and data collection on ASM activities.

Connectivity and Social Integration

The largest direct impact on the miners themselves, however, comes from digital connectivity and the use of cell phones or internet connection. This was confirmed not just by the ASM experts but also by other interview partners. One example that was mentioned were internet-coffee shops that were set up in ASM communities which contributed to social integration through the exchange of information between miners and families or within and between communities.

In addition, several interview partners pointed out that common mainstream communication tools like WhatsApp have become more prevalent to exchange messages and information among artisanal miners and now play an important role in the organization of the cooperatives to keep the members informed and to organize meetings. Especially during the COVID-19 pandemic, one ASM expert reported, and even during lockdown, cell-phone based communication technology meant that miners (who were sometimes locked at mine sites) were able to communicate with their families.

[7] https://www.artisanalminingchallenge.com/semi-finalists/asmspotter

Access to Markets and Supply Chains

Smartphones can also help ASM to become more independent from local buyers that may not pay fair prices due to their logistical and information advantages. as the smart-phone allows them to obtain information about current metal prices and alternative buyers.

This can help with empowering and also with legitimizing artisanal miners and provide new ways for formalizing legitimate ASM by improving transparent supply chains and traceability of the sourced material. This becomes crucial when it comes to so-called conflict minerals where traceability is key. Consequently, formally sourcing from ASM requires some kind of tracking and tracing; this may be supported through digital tools, whether it is through barcode tagging or digital chain of custody monitoring through a database (which may have a blockchain or different database architecture). Ensuring traceability of the upstream supply chain allows ASM operations in conflict-affected and high-risk areas to improve their access to formal markets which may be associated with better prices or less extortion of ilegal taxes.

Mobile Banking

In addition, one ASM expert remarked that making mobile banking accessible for the ASM sector can provide vast opportunities to combat money laundering (by replacing cash with digital money transfer) and to improve traceability by providing a second check on mineral routes. Access to mobile banking, he observed, could also contribute to formalizing the sector by enabling reliable processes for, e.g., pre-financing of projects for collectives or individuals. Even though projects in this area have been on hold due to the COVID-19 pandemic, the expert stated, they are in the pipeline for international consultants and organizations active in the sector.

eLearning

Finally, online training through courses and webinars, often using mainstream technology such as Youtube, have become quite common, according to the ASM experts. This has been further accelerated by the COVID-19 pandemic. Whereas trainings were normally held locally by international organizations and outreach offices, it was observed by the expert that they now switched to online training courses. According to the expert, this had been envisioned since the early 2000s, but through the COVID-19 pandemic eLearning has suddenly become mainstream in the outreach of development organizations for capacity building. However, it should be noted here that internet connectivity is a precondition for implementing eLearning programs and for reaching the local communities.

Even though the acceptance of online learning is not as good as “in-person” trainings, people are eager to learn and do attend online lessons, one of the ASM experts observed. He also observed that a recorded webinar can be more effective than a printed binder with handouts and information, especially given low levels of literacy in some communities. Therefore, he concluded that internet-based video platforms have a significant potential in reaching and educating people with low levels of literacy and could thus have a considerable impact moving forward. Other interview partners confirmed that mainstream technologies, such as Youtube, can make a difference in offering opportunities for artisanal miners and their families and communities. Again, this is dependent on available internet connectivity in the respective communities.

In conclusion, the discussion with the ASM experts and the input from other interview partners showed that the technologies, trends and levels of implementation are vastly different within the ASM sector, depending on the size and budget of the operation. Consequently, the interview results suggest that mainstream technologies (e.g. smartphones, Youtube, Whatsapp) have had and will have an impact on the ASM sector in various areas. In addition, the ASM experts suggested that digital technologies could contribute significantly to formalizing the sector and improve traceability of minerals, especially in conflict-affected and high-risk regions.

Thus, the interview results suggest that digital technologies have the potential to empower artisanal miners but can also pose a risk. The risk for illegitimate artisanal miners particularly lies in the (mis-)use of tracking technologies (satellite, cell phone) on the part of regional authorities. Furthermore, satellite data could be used by international mining exploration companies to track legitimate as well as illegitimate artisanal mining activity and use that information to claim the official surface and mineral rights[8].

The authors would thus like to conclude that digital technology is a means to an end and it can be used to empower or disempower artisanal miners, it can present opportunities or risks to their livelihoods, and it can increase or narrow social divides, depending on how, by whom, and with what kind of intention it is being applied. However, from the discussion with the experts it can be concluded that the opportunities outweigh the risks and challenges at this point in time.

3.4 Concluding Remarks

The analysis of the challenges and opportunities related to implementing digitalization initiatives provides an insight to the characteristics of companies that are more successful than others in leading the digital transformation process: Technology, whether it is digital or operational technology, if applied in the right places and in the right way, can have a significant impact on productivity of mining operations. However, it is people who need to work with the technologies and it is people who decide on the corporate strategy, its priorities and who form the corporate culture. This adds an important aspect to the results presented in Chapter 2 stating that company size (in conjunction with the size of the operation) has the highest influence on the level of implementation of digitalization technologies.

Given the results of Chapter 3, this finding could now be extended to include that it is not merely the size of the company or the operation, but the respective leadership decisions, the composition of the workforce and high levels of employee engagement that play a key role in being able to take advantage of the opportunities and master the challenges at hand.

Recalling the clusters on challenges and opportunities, talent management was considered the greatest challenge for international mining companies, whereas real-time data capture presented the greatest opportunitiy. This again suggests that to take full advantage of the opportunities that are there, assembling the right team and suite of people who are capable and willing to drive innovation and change is a necessary prerequisite. This may also imply that the “cultural” processes are at least equally important to technology.

In addition, the mindset and attitude of the leadership of a mining company has a high impact on the level of implementation of digital initiatives. It was commented by many interview partners that those companies[9] which were able to achieve results in the implementation of digitalization technologies in certain areas that can serve as benchmarks for the industry have had leaders who were strongly committed to driving change in the company and who had a clear vision of where they wanted the company to get to. Such a vision can then also contribute to attracting the right kind of people.

If mining companies can change how they are being perceived by the public through presenting and acting by a vision and mission statement that potential future employees are attracted to

[8] In practice, with or without digital tools, exploration companies often use the presence of artisanal miners as an indicator for prolific ore zones. This may later on cause problems in cases where artisanal miners continue exploiting their traditional mining areas inside formal exploration concessions, and no viable LSM-ASM cohabitation strategies are implemented.

[9] Some of these were mentioned as benchmark projects in Part I of the study.

and can identify with, they can attract future talent that aligns with the company values and vision. Developing new business models that place social value at the core of the company vision and mission could present an interesting opportunity. Digitalization technologies can provide important tools and opportunitiy to achieve both.

Thus, lending parallels to the concluding remarks on the ASM sector, digital technology is a means to an end; its success depends on how it is being applied, how it is embedded into the company and its culture, how change is being managed constructively and actively, and if it is part of an overall vision of corporate development. However, without leaders and managers with the right skillsets and mindsets, and without a motivated and engaged workforce, digital technology will not lead to the desired results.

The biggest risk for digitalization to have a disadvantageous effect for companies, the interview results also suggest, may come from not moving along the path of digital transformation and automation as late adopters may risk their competitivenessand may thus face disadvantages in the future . Thus, the current digital transformation could lead to a widening gap between the leaders and laggers, the early and late adopters, and thus spur a selection process for the future generation of mining companies that remain competitive and operational.

Obviously, in reality there are many factors at play and that intersect to determine the success of a company. Therefore, highlighting some elements is not intended to disregard the complexity of the transformation process and long-term success. The intent of the concluding paragraph was to highlight some observations that may contribute to future discussions.

4 Impacts on Sustainability from a Global Perspective

This chapter builds on further analysis of the expert interviews to validate and expand on the findings of Part I of the study with respect to the impact of digitalization initiatives on each of the four pillars of sustainability: Social, Socio-economic, Ecological and Economic pillar (Section 4.1). Part I focused on a preliminary analysis of the technologies that would be expected to impact the various sustainability aspects based on insights and delineations from the desktop research. Part II allows the authors to expand and validate these preliminary findings and provide some tangible examples of observable impacts based on the insights of the global experts.

In addition, this chapter also provides a summarizing view on the impacts of digitalization on sustainability from a global perspective (Section 4.2). Main findings regarding the impacts on the respective pillars of sustainability are presented and influencing factors are briefly discussed. The classification of sustainability used for the analysis in this chapter and for the interviews is depicted in Table 1.

Table 1: Sustainability criteria used in this study (adapted from Kickler & Franken 2017)

Sustainability Pillars	Sustainability Classifications	
	Issues	**Examples**
Social	Terms of Employment	Working Hours & Rest
	Occupational Health & Safety	OHS Management, Workplace Hazards & Machinery, Personal Protective Equipment (PPE), OHS Training
Socio-Economic	Workforce & Local Value Addition	Local Workforce, Local Procurement, Community Initiatives, Support of nearby ASM,
	Land Use Impacts & Conflicts	Mining Impacts, Conflict with Community
	Material Use	Sustainable Sourcing, Efficient use of Natural Resources & Recycling, Material Stewardship
Ecological	Biodiversity	Legally Protected/ Unprotected Areas, Threatened & Invasive Species, Ecosystem Services
	Mine Water Quality & Management	Water Management, Surface Water Flows, Groundwater Use, Mine Dewatering & Pit Lakes, Efficient Use & Recycling
	Energy Use	Efficient Energy Use
	Mine Waste	Reduction of Emissions, Waste Management
	Air Emissions & Noise	Air Quality Management, Noise, Vibration, Dust & other Emissions
Economic	Economic Efficiency	Productivity, Profitability, CAPEX, OPEX, Fair Rating

4.1 Impacts on Specific Aspects of Sustainability

Each of the following sub-sections presents a brief summary of the results from the preliminary analysis of Part I, followed by a summary of the outcomes from the expert interviews and a concluding paragraph to verify the preliminary assessment regarding an overall low, medium or high impact of digitalization initiatives by merging the overall results from Part I and Part II of the study. This is done for each of the four pillars of sustainability.

4.1.1 Impacts on the Social Pillar

The Social Pillar, as defined by the authors, in this context includes the following sustainability issues (Figure 8):

Social	
Terms of Employment	Occupational Health & Safety

Figure 8: Sustainability issues related to the Social Pillar

The preliminary analysis conducted in Part I of the study suggested a **high expected impact** of digital technologies on the social pillar of sustainability. According to the analysis, the highest impact is to be expected from automated and remotely operated machines due to their impact on the OHS of working conditions and on the terms of employment, especially with regards to increasing productive working time. Other technologies that were identified to have an impact on safety were wearable technologies (the connected worker) and integrated platforms for improved monitoring of human and environmental conditions. Simulation and modeling along with eLearning were also mentioned in Part I as they can present opportunities to improve OHS trainings.

Automation, Remote Control and Remote Operation Centers

The expert interviews confirmed that digitalization technologies, especially automation and remote operations, have a significant and direct impact on the terms of employment and on OHS. According to the results of the interviews, the biggest impact is related to moving people away from hazardous areas to safer operating centers located on the surface or even in ROCs that may be located in metropolitan areas and are thus far less remote than the actual operations.

In addition, surface control rooms and ROCs also have an impact on the terms of employment as it not only makes the workplace safer and more pleasant; it also means, for example, that workers can follow more regular work schedules. With respect to ROCs, this may imply remaining closer to home and families instead of operationg on a fly-in fly-out schedule. With respect to operating automated equipment from a surface control room at the mine site, this also drastically reduces the distances workers have to travel to get to the active mining face. Less time spent traveling to the actual working area means that workers can follow more regular eight hour work schedules if they work in a surface control room or a ROC, because travel time to the actual working area is usually added on to the shift time and means that work shifts are between ten and twelve hours rather than eight hours. While reduced travel distances also have an impact on the economic productivity of the work, it also improves the quality of work and thus positively impacts the terms of employment as defined in this context.

In addition, an advanced application of digitalized or remote-controlled technologies also implies that different skill sets (compared to current needs) are required, which has implications for recruitment, retainment and talent management (Section 3.1.1). Workers need to be retrained and upskilled and new talent needs to be attracted, which further impacts the social pillar of sustainability. This also implies opportunities for closing the gender divide in mining by attracting female talent with the respective skill sets. Increasing diversity in this way is considered an opportunity for addressing the looming skills shortages and waves of retirements expected in the next decade.

Consequently, based on the cluster analysis (Section 3.1), talent management is considered the most important challenge for the global mining industry. At the same time, the results also allude to the fact that safe working environments, potentially in less remote areas, also provide opportunities for better work-life balance and for attracting a more diverse set of people and talents, including women. Thus, the results of the interviews suggest that adjusting terms of employment by means of automation, ROCs, cultural changes and talent management, and further improving OHS through remote and automated operations can help attracting a broader range of skilled labor. Therefore, it can be concluded from the cumulated results of the interviews that digital transformation has already had a significant impact on OHS and terms of employment in those companies that have implemented automation at scale and ROCs and will continue to

Remote Work

In addition, especially during the current COVID-19 pandemic, working remotely (as in working from home) and thus changing ways of doing work could also have a negative impact on the social pillar, especially with regards to the mental health aspect of OHS. While not all work can be re-configured to be done remotely, working from home has become much more prevalent in mining as part of managing the pandemic. However, this change towards working remotely has brought with it its own set of challenges.

One of these challenges that was pointed out by one of the interview partners is that there has been a shift towards outcome-based assessments of work. However, according to the expert, this could imply a greater risk of deterioration of mental health because of the pressures and challenges associated with delivering outcomes at work while working from home (while potentially additionally managing other duties around family and/or children, a situation exasperated by the lock-down associated with the covid pandemic) . For people who live alone, the challenge may arise from less contact with colleagues and the feeling of lonliness or being disconnected from co-workers. However, given that miners still often have the image of having to be or being “rough and tough”, challenges that workers may face in adapting to changing working conditions may sometimes not be communicated to the respective supervisors. Therefore, as one expert said, what they have learned as a mining company through the COVID-19 pandemic is that supporting and ensuring the mental wellness of employees is becoming ever more important.

Another challenge associated with remote work is the onboarding of older generations that may be less familiar with digital technologies and also, as was reported by several interview partners, less willing to adapt to new ways of working. Divides between digitally able and less able workers as well as between digitally connected and disconnected workers can increase and lead to challenges. These challenges may be related to keeping all workers engaged and providing additional resources to address these potential divides between employees. Thus, there are new (social) challenges that arise from the changing ways of work that the industry will likely have to face beyond the COVID-19 pandemic.

Wearable Technologies

Based on statements from interview partners representing mining companies, wearable technologies and video monitoring have also become more prevalent and increasingly relevant due to the COVID-19 pandemic. For example, fitness trackers, such as watches, can not only be used for exposure logging for COVID-19 but also to monitor the health and sleep patterns specially for those that work remotely. Consequently, as one interview partner stated, digital technologies enable a more holistic understanding of people’s mental health and physical well-being. In addition, video monitoring is applied in some cases to monitor social distancing and track the assembly of larger groups as part of a COVID-19 prevention and monitoring system at the mine. However, constraints regarding surveillance may be raised by individual workers or their unions.

Real-time Monitoring and Positioning

Another impact on social sustainability that was addressed by several interview partners refers back to real-time monitoring and positioning systems, especially in underground environments[10], which have been applied in most mines that were interviewed or referred to by the interview partners. These systems have created a safer environment because people can not

[10] https://360.here.com/mining-technology-location-data

only be tracked in emergencies but they can also be contacted directly from the control center if they move into a danger zone. This immediate situational awareness and real-time communication underground has reduced the reaction time drastically, especially in emergencies. Therefore, these technologies have had a direct impact on making mines, especially underground mines, much safer places to work.

VR Applications

The application of VR technology to improve OHS training was also mentioned by the interview partners and is considered to be on the rise. Especially VR glasses for simulation were mentioned along with the opportunity to conduct training remotely and across greater distances.

Impact Assessment

Overall, the discussion from the interviews confirmed the preliminary finding from Part I of the study that there is a **high impact** on the social sustainability to be expected from digital technologies. While these impacts can already be observed in mining operations today, the impact is expected to increase even further in the coming years. Considering that improving OHS is one of the main incentives for implementing digital initiatives, a high impact in this area is directly and consciously prioritized and targeted by mining companies across the globe. While the impact on safety is entirely positive, the impact on terms of employment, while mostly positive, can also have negative aspects, especially with regards to mental health considerations in the context of remote work (from home).

4.1.2 Impacts on the Socio-Economic Pillar

The Socio-Economic Pillar includes the following sustainability issues (Figure 9):

Socio-Economic		
Workforce & Local Value Addition	Land Use, Impacts and Conflicts	Material Use

Figure 9: Sustainability issues related to the Socio-Economic Pillar

The preliminary analysis from Part I of the study led to the expectation of a **high impact** of digitalization technologies on the socio-economic pillar. It was stated in the previous study that local procurement processes may be impacted negatively by the IIoT due to more standardized and globalized procurement procedures. Simulation and modeling technologies were expected to impact community engagement by offering opportunities for integrated land-use planning, for example, and to increase overall transparency and thus improve communication with affected stakeholders and communities. Furthermore, integrated platforms (together with IIoT infrastructure, sensors and analytics) can positively impact the efficient use of natural resources and other materials by supporting optimized resource utilization.

Automation

The most frequently mentioned aspect during the interviews, which also constitutes a challenge for the industry (Chapter 3), is the potential of job losses due to automation and addressing this fear among workforces and related stakeholders. However, the interview results suggest that mining companies are finding different ways of mitigating this impact. For example, one mining company has chosen not to automate as much as possible at this stage to keep the social stability intact. This underlines that the social license to operate and sustainability considerations, in some cases, are actually guiding the decision-making processes around the implementation of digital technologies or automated equipment.

Another mining company stated a commitment to train local people in operating automated equipment from the control center. While experts may still need to be brought in from outside local communities, the company planned for and is committed to engaging, training and hiring as many local people as possible. Another mining company made a commitment not to reduce any jobs due to automation but to offer alternative jobs and respective training to those workers that are being replaced by automated machines. These examples indicate that, based on the interview results, mining companies make conscious efforts to manage the transformation and mitigate real or perceived job losses in the context of automation.

Real-Time Data Monitoring

Another aspect that was addressed by several interview partners was how digital technologies can have an impact on building trust among local communities in order to prevent or mitigate conflicts and strengthen the social license to operate. One way of achieving trust is to create transparency by publishing (real-time) monitoring data of water and air quality around the mine site, for example on the company website[11]. This has also been discussed in Section 3.2.6. Several interview partners mentioned that real transparency that goes beyond "shiny charts and marketing measures" is an important element to build and maintain trust moving forward.

VR Technology

In addition, digital tools such as open communication platforms or VR technology that allows virtual mine tours[12,13] could be used to engage directly with the communities in a participatory way and thus build trust by showing what the company is planning to do and by making a mine, whether in the planning stage or already in operation, tangible and understandable for the local population. Another example of this is the "Mining in a Global Environment" along with various other VR module developed at the Australian Centre for Sustainable Mining Practices at UNSW Sydney (ACSMP 2020).

Simulation and Integrated Platforms

Yet another aspect relates to the possibility of extending the life of mine through digital and automation technologies, as has been discussed in Section 3.2.3. If efficiency is increased significantly through automation and digital technology (especially simulation, digital twin, integrated platforms, data analytics), the life of mine may be extended through enabling competitive production at even lower ore grades. However, there were no cases referred to during the interviews and thus specific data on the impact on the life of mine could not be obtained. If fewer new mines would need to open as a consequence, this could, according to the interviewees, strengthen the license to operate and have a positive impact on material use issue within the socio-economic pillar of sustainability in the future.

Network Connectivity

Another aspect that was mentioned by one mining company representative was the positive impact on local value addition that was achieved by providing free WiFi network connectivity to surrounding local communities up to 20 km from the mine. The network is available for anyone who signs into the network. Network connectivity supports schools as well as micro-enterprises along with improved communication among community members. According to the interview partner this had a direct impact on the development of business activity in rural communities around the mine as it allows enterprise to take place independent of the mine.

[11] https://www.bge.de/de/asse/themenschwerpunkte/themenschwerpunkt-das-wasser-in-der-asse/messwerte/

[12] https://vgcx.com/projects/development/eagle-gold-project/eagle-gold-videos/videos/vr-tour-of-the-eagle-gold-mine/

[13] https://files.dnr.state.mn.us/destinations/state_parks/virtual_tours/lake_vermilion/vt_vermilion.html

In rural areas in developing countries, people may have a low standard of living but more and more of them have a smartphone that allows them to establish micro-enterprise activity. In addition, schools are able to utilize the network connectivity and, consequently, the world wide web for pupils and curriculum development. Although this was a single case mentioned during the interviews, it may provide a blueprint for others to follow with similar initiatives.

Impact Assessment

To conclude, the interviews have confirmed that there is a potentially **high impact** of digital technologies on the socio-economic pillar. While there is a potentially negative impact for the workforce where automation replaces jobs, the interview results suggest that mining companies are treading carefully in this area and some are committed to not lay off people while others provide training or even postpone automation in order to address this impact in a positive way.

With respect to community engagement and conflicts and to reduced material use, the impact is positive. However, especially with regards to community engagement, it depends on the individual company's commitment to the communities how they build trust and foster local value addition. Digital technologies, the analysis shows, can provide additional tools to achieve improvements in this area if companies make this a priority.

4.1.3 Impacts on the Ecological Pillar

The Ecological Pillar includes the following sustainability issues (Figure 10):

Ecological				
Biodiversity	Mine Water Quality & Management	Energy Use	Mine Waste	Air Emissions & Noise

Figure 10: Sustainability issues related to the Ecological Pillar

Based on the preliminary analysis conducted in Part I, a **medium to high impact** on the ecological pillar of sustainability was expected. The expected impact varied among the associated issues. The highest impact was expected for water management, energy use as well as air emissions & noise. The main impact in these areas was expected to come from sensors installed for improving overall monitoring of environmental data feeding suitable performance indicators. In addition, the integration of such sensors in the IIoT and integrated platforms was expected to contribute to reducing waste production, energy use and airborne emissions. Furthermore, drone technology was expected to have an impact on biodiversity monitoring tasks while electrification was suggested to have a potentially significant impact on energy usage as well as on emission reduction.

Sensors & Real-Time Monitoring

The interview partners confirmed that the highest impact on the ecological pillar, especially with respect to mine water quality and emissions, is coming from sensors used for the digital monitoring of water quality, tailings dams, airborne emissions and other environmental indicators. Furthermore, obtaining real-time or frequently updated data on various indicators implies the ability to react much faster in case of deviations. Real-time monitoring, as pointed out by an interview partner, also allows for longer-term studies on certain indicators, such as on changes in biodiversity, while enabling shorter-term decisions.

In addition, information can be validated quickly and actions can be taken instantaneously. Consequently, real-time monitoring, in some cases supported by drones, can improve forecasting and thus contribute to prevent incidents like tailings dam failures that continue to also impact the social license and the public perception of mining companies negatively. Newmont, in addition to real-time monitoring of tailings storage facilities and the use of aerial drones, is currently expanding the use of drone surveys and InSAR technology to monitor tailings dams (Moore 2020). In the future, advanced analytics are considered an interesting aspect for monitoring technologies, especially with respect to the potential for predictions and forecasts.

Robotics

In addition, robotic solutions for taking water samples were mentioned during the interviews as a technology that is already being implemented. This allows to automate sampling activities and to access remote areas. Drones were also mentioned as a technology able to access remote areas or that may be utilized for surveying surface areas.

Electrification

With respect to energy usage, the largest impact was confirmed to come from the shift towards battery electric vehicles, in conjunction with ventilation on demand (VOD). While fuel consumption can be reduced through optimized equipment utilization, the larger impact comes from eliminating diesel equipment altogether. Reducing CO_2 emissions can be a strong driver especially in regions that have implemented carbon tax regimes. However, in underground environments the reduction of emissions leads to a reduced need for ventilation which in turn decreases energy consumption and thus increases the impact. Some interview partners confirmed that OEMs are increasingly expected to combine automation and electrification in their machines.

Impact Assessment

In summary, the aspects that were addressed by the interview partners in addition to the findings from Part I suggest that overall there is a **medium impact** on the ecological pillar of sustainability. The overall impact is considered positive, there was no mention of negative impacts related to the ecological pillar.

Since energy costs have a significant share of OPEX, there are clear incentives on reducing energy consumption. However, the biggest impact is expected to come from electrification, which is, albeit an important trend, not a digital technology. Thus, the impact of digital technologies on energy use is focused on VOD technologies.

Similarly, there are other technologies that mining companies are focusing on in order to address the ecological pillar of sustainability, especially in the area of reducing mine waste, such as dry stacking (avoiding wet tailings), bio-leaching, or new solutions in processing (related to particle sizing or reduced chemical agents for processing). While some of these technologies may have a considerable impact on lessening the environmental footprint, these are not digital technologies. Thus, with respect to the ecological pillar in particular, there are non-digital technological developments which are considered to have a greater impact on lessening the environmental impact than can be expected from digital technologies.

4.1.4 Impacts on the Economic Pillar

The Economic Pillar is represented by the sustainability issue of economic efficiency (Figure 11):

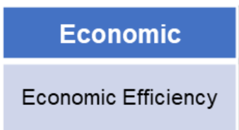


Figure 11: Sustainability issue related to the Economic Pillar

The preliminary findings from Part I suggested a **high impact** on the economic pillar of sustainability, particularly through automated and remotely operated equipment as well as through data analytics and related technologies around simulation and modeling (e.g. digital twin, integrated platforms). The analysis of the interviews confirms these findings.

Automation and ROCs

The cumulated results from the interviews confirm that automation and ROCs constitute impactful technologies for increasing economic efficiency. However, these technologies require not only significant capital investment (in both new and retrofitted equipment), but also require having a reliable communication and data transmission network in place (such as WiFi or 5G; Chapter 2.2). One of the experts stated that companies which installed the communication backbone in underground mines to boost safety now see all the additional benefits that come with it. These companies articulated clearly that they reached their payback faster than expected. Based on the interview results, payback periods that seem most acceptable to mining companies usually range from six months to one year and, in fewer cases, more than one year, depending on the type of equipment.

Simulation and Modeling

In addition, the results from the interviews suggest that digital technologies such as digital twin and simulation and visualization technologies can contribute to significant increases in economic efficiency by creating a more reliable output of the production process. This refers to decreasing variability in the production process through data-based analysis of the entire production process as well as automation. Consequently, as one expert put it, digital technologies can enable mine operators to know the daily input and output of their plant and the daily cost of operation for any particular day. Additionally, it was also pointed out that significant cost efficiencies gains could be realised from knowing where every piece of equipment is at any given time and by ensuring that all equipment is operated at the highest possible level of availability and utilization.

Telemetry

Telemetry[14] is another technology that was mentioned as a technology that has a large impact on economic efficiency while being low on operating costs. According to one interview partner representing a leading OEM, a drop in maintenance cost of up to 40% could be realized using telemetry systems by alerting equipment failures or irregularities at an early stage. In addition, telemetry can be utilized to decrease cost per ton and thus lead to higher profitability and significant paybacks.

Digital Signatures

Another impact on economic efficiency that was mentioned by some of the interview partners referred to the digitalization of administrative processes, such as the introduction of digital signatures. Albeit taking place in the background, digitalizing back office processes, such as introducing digital signatures to make approval processes more efficient, has brought significant cost-savings for mining companies.

Impact Assessment

To summarize the results regarding economic efficiency, automation and ROCs along with advanced data analytics, simulation and modeling and integrated plaforms all have a significant impact on economic efficiency and confirm a **high impact** of digital technologies on this

[14] Telemetry is defined as the measurement of data at a remote source and transmission of the data (typically by radio) to a monitoring station (Dictionary (2020).

pillar of sustainability. Since economic efficiency is being increased through these technologies, the impact is considered positive.

The interview results suggest that investing in the appropriate suite of technologies based on the requirements of the respective operation can help and has helped mining companies to improve productivity and economic efficiency significantly. However, it was also mentioned in the interviews that not all technologies have provided the desired results or ROI. One example that was mentioned were collision avoidance systems, which proved to be costly as they required a lot of costly iterations.

In addition, the cumulated feedback of the interview partners suggests that (proven) technologies that are low in OPEX are favored even if they have a higher initial CAPEX compared to technologies that are high in OPEX because they present lower risks and thus a safer return on invest: Low OPEX may assure an increased resilience against potentially falling metal prices. Furthermore, investments in technologies with a payback period of one to two years are more likely to find approval as results are expected to become tangible within short time frames.

4.2 Concluding Remarks on Sustainability from a Global Perspective

Based on the interview results, the research team drew several conclusions with respect to the impact of digitalization initiatives on the various sustainability pillars from a global perspective.

Firstly, the preliminary results of Part I of the study on the expected impact of digital technologies on the various pillars of sustainability were validated by the expert interviews conducted for Part II. Thus, the combined results of the study suggest that there is indeed a high impact of digital technologies on the social and socio-economic pillar, as well as a high impact on the economic pillar and a medium impact on the ecological pillar of sustainability as depicted in Figure 12 (green shaded bubbles, darker shades correspond with higher impact). With respect to the ecological pillar, the combined results of the interviews suggest that that non-digital technologies have a larger impact than digital ones.

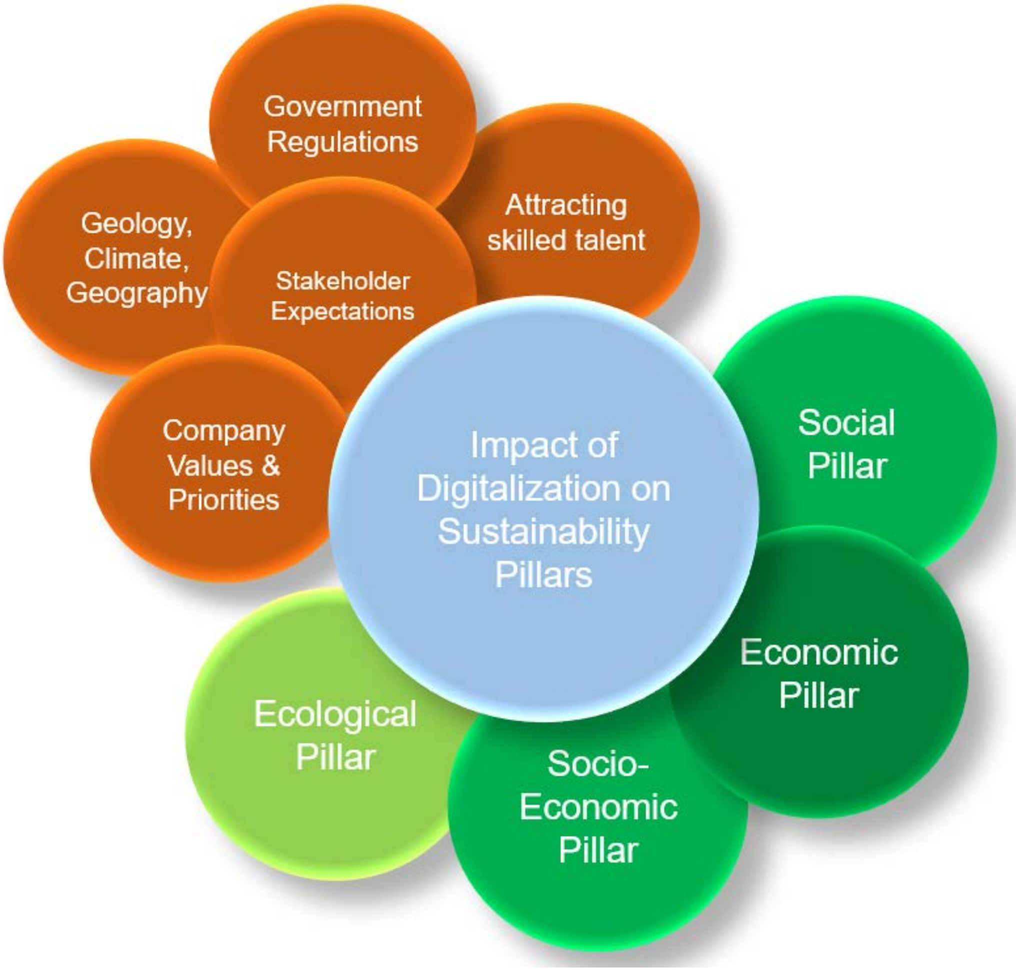


Figure 12: Main drivers (orange) and impact (light green for lower impact, dark green for higher impact of digitalization technologies on sustainability pillars

Secondly, since OHS and economic efficiency are among the main drivers for digital transformation based on the analysis in Chapter 2, a high impact on the social and economic pillars of sustainability is to be expected. However, the overall impact on the socio-economic pillar was more emphasized in the interviews compared to the preliminary analysis of Part I of the study. Considering that the attraction of suitable talent, the impacts on educational needs and training, the mitigation of perceived job losses, and maintaining social stability constitute some of the pressing challenges mining companies face at this time. They are directly related to the digital transformation; it becomes more obvious why the socio-economic dimension is affected more than the initial analysis suggested. Additionally, the impact on the socio-economic pillar increases even further when including considerations around the ASM sector regarding the potential impact of digital technologies on social integration, communication, outreach programs, and potential empowerment of artisanal miners, which was not considered in Part I of the study.

Thirdly, the main drivers and incentives for digital transformation that were discussed in Section 2.1 also impact on the results regarding the impacts on sustainability from a global perspective. That is why Figure 12 also includes a depiction of selected main drivers (orange) of digitalization technologies on sustainability pillars. There may be specific regional challenges that impact how certain aspects of sustainability are prioritized and addressed (such as lack of network connectivity, low levels of education in local communities etc.) or particular challenges related to the geographic location of an operation (e.g. extreme climate conditions) that could lead to particular incentives to improve sustainability certain areas. However, the cumulated results of the interviews suggest that the values, priorities and actions of mining companies and their leadership have the largest influence on taking advantage of the positive impacts on sustainability and responsibly mitigating potentially negative ones. In addition, the analysis suggests that these values, priorities, and actions are required to align more closely today with the expectations of the various stakeholders, from communities and the larger public to stakeholders, shareholders and investors, from regional governments to non-governmental organizations. Yet, how strongly a company focuses on certain aspects of sustainability, especially with regards to the socio-economic and ecological pillars, depends on the values and priorities of the individual mining company.

Lastly, to summarize the results of Part I and Part II of the study, the findings suggest that because mining companies are driving the digital transformation to make their operations safer and to increase economic efficiency and productivity in order to remain competitive, they are directly addressing and impacting the social and economic pilars of sustainability. In addition, they are also driven by increasing stakeholder expectations, which leads them to more explicitly address the socio-economic and ecological pillars of sustainability. While digital technologies play a role and do have an impact in these areas, the cumulated results suggest that there are also other technologies, innovations and activities that may more explicitly target the ecological and socio-economic pillars of sustainability. However, considering rising stakeholder expectations, remaining competitive today implies much more than implementing the newest digital technologies. While late adopters of technology may face some disadvantages, maintaining a social license to operate has actually become a matter of survival for mining companies. Thus, maintaining a social license to operate, improving sustainability performance, changing the public perception of mining to attract new talent, and creating working conditions that make mining more inclusive and allow for greater diversity have become central to ensuring longer term competitiveness for mining companies. Technologies, especially digital technologies, can be strong enablers to achieve these goals if the transformation is managed consciously, priorities are set carefully, and if companies act with integrity on the values and goals they set for themselves. The mining companies that were interviewed for this study are acutely aware of this transformation.

To conclude, while digital transformation and sustainability are often still discussed separately in articles and papers, the interviews suggest that in reality they have already become inseparable and closely inter-related. Sustainability has become a matter of ensuring long-term survival for the mining industry while the digital transformation provides important tools to support the achievement of ambitious goals set by mining companies and stakeholders alike.

5 Conclusions

The main objective of Part II of this study is to expand on the analysis of Part I by drawing a detailed and differentiated picture of the current landscape of the levels of implementation of the digital transformation in the global mining industry. This includes an analysis of the main drivers and incentives, relevant challenges and opportunities as well as of the impact on various sustainability aspects from a global perspective. In addition, Part II intends to validate some of the core findings from Part I and expands on some specific issues that remained open from Part I. Within the scope of Part II, 29 semi-structured expert interviews were conducted in order to validate the results of the systematic literature review conducted in Part I.

The first section of the concluding remarks compares the key findings from Part I to the findings from Part II and provides concluding comments on the open questions from Part I. The second section shows the main findings from Part II with respect to the characteristics of the current landscape of digital transformation in the global mining industry in the context of sustainability.

5.1 Concluding Remarks on Findings and Open Questions from Part I

Four main findings resulted from Part I of the study that will be briefly discussed in the context of the additional findings that resulted from the expert interviews conducted in Part II.

One key finding of Part I was that at the current level of implementation of digital initiatives, mining companies seem to prioritize and focus on optimizing certain areas of the operation (such as automated haulage & transportation, automated drilling, or real-time positioning and navigation, for example) and, consequently, not all available technologies get implemented in a single operation. In addition, based on the analysis conducted in Part I, it was also concluded that finding ways of actually creating added value from the available data to support decision-making processes is one of the main challenges mining companies need to master on a broader scale. Part II confirmed these findings in two ways. On the one hand, the foundational IIoT infrastructure has not been implemented on a broad scale yet. However, as the IIoT infrastructure is required to take full advantage of all subsequent steps along the data value chain (as discussed in Section 2.2), mining companies can only take full advantage of the available technologies as long as all parts of the operation or equipment are integrated into the IIoT infrastructure. On the other hand, mining companies are starting to realize the value and immense potential of integrated optimization approaches that consider the entire value chain of the production cycle “from pit to port”. In addition, mining companies seem to become more aware of the potential of “mining the white spaces” by investigating the significant existing optimization potential that exists specifically at the intersection of different production steps and processes. The cumulated results of the interviews thus indicate that this integrated “value-chain approach” is considered one of the prospective key trends with considerably greater potentials for productivity and efficiency gains that go well beyond those gained from optimizing only specific areas of the operation. The immense potential of this value-chain based approach is also starting to be discussed in recent publications (Görner *et al.* 2020*b*).

A second finding from Part I was that there are implementation challenges which are not technological in nature, such as interoperability and standardization as well as legal issues (data ownership, liability issues, cyber security). These challenges were considered more closely in Part II. The interviews confirmed that these issues are highly relevant for the industry these days. Legal issues pose significant challenges for the implementation of digitalization initiatives (Chapter 3). However, in addition, the interviews brought to light that there are a number of other non-technical challenges that seem to pose even greater challenges for the global mining industry. According to the conducted cluster analysis (Section 3.1) the most pressing challenge is talent management, followed by challenges related to data management and change management, as well as innovation and collaboration. Thus, Part II of the study revealed the important insight that the key challenges of today’s global mining industry in the context of digital transformation are actually not of a technological nature but are associated with managing talent and managing change. How important it is, indeed, to prioritize people, especially in but not limited to times of crisis, such as during the current pandemic, is also confirmed in a recent interview with the CEO of the world's largest mining company, BHP (Görner 2020).

A third finding from Part I of the study was that OEMs have a strong driving role in the current transformation and that the market of digital technologies is quite concentrated on a small number of globally leading OEMs. The conclusions drawn from the expert interviews in Part II confirm this finding only partially. Especially with regard to who is driving the digital transformation, it became evident that the mining companies have superseded the OEMs. While OEMs had originally pushed the market, now the mining companies are pulling the market and driving transformation. Today, mining companies are more aware of the available technologies and their specific requirements, technical needs, and expected winnings. Both mining companies and technology suppliers foster a corresponding ecosystem of innovation and change. Accordingly, partnerships, especially with respect to interoperability, appear and build lighthouse projects – capable to address the challenges and opportunities of the upcoming years.

Lastly, a fourth key finding was that the current discussions on the digital transformation in mining mainly revolves around highly mechanized LSM operations while small/medium-scale operations and the ASM sector are not part of it. Part II addressed this gap by including questions about small/medium-scale operations and the ASM sector into the questionnaire for the semi-structured expert interviews and by interviewing ASM experts among the group of experts. In this context, the analysis of the expert interviews revealed two main insights: Firstly, digitalization in the ASM sectors is of a different scope and nature than the digital transformation the industrial mining sector is currently undergoing; it also follows very different objectives. However, this does not imply that there are no opportunities and challenges arising from digital technologies in the ASM sector. Secondly, the opportunities that the experts mentioned in regard to artisanal mining seem to outweigh the challenges and risks. Thus, the use of (mainstream) digital technologies may hold a high potential for improvements, especially for artisanal miners.

5.2 Conclusions on the Current Landscape of Digital Transformation and Sustainability

In Part I it was concluded that the overall level of implementation of digital technologies in the global mining sector is still comparatively low. This finding could be confirmed from the expert interviews.

Regarding the characterization of the current landscape of digital transformation in the global mining sector, the most relevant finding was that the size of the operation in conjunction with the size of the company has the highest influence on the level of implementation of digital initiatives (Figure 5). In contrast, geographical region and commodity type (only metal producers were considered) were found to have the lowest influence. This confirms the globalized character of the mining industry and that it is mainly globally operating corporations that are driving digital transformation.

However, although mainly globally operating corporations were found to drive the digital transformation, it should be noted, that there are a number of smaller but highly mechanized and technologically advanced mining companies that drive digital transformation, especially in Europe and in Canada. These mid-tier companies are able to test and deploy technologies in a more agile way and sometimes are pioneers in certain areas of technology adoption or find more cost-effective ways to implement certain optimizations compared to large-scale global corporations.

In addition, while the cumulated results from Part I and Part II suggest that there may be regional clusters where certain digital technologies have already been implemented to a higher degree, such as the Pilbara region in Australia. However, what was mentioned even more frequently during the interviews, was how individual companies have achieved measurable and benchmark results through implementing digital technologies successfully. This has been possible due to the strong leadership and commitment from the company management.

This finding is further confirmed from the analysis which kind of digital technologies impact or are expected to impact specific aspects of sustainability. The results of this analysis revealed that the implementation of digital technologies seem to be driven by company priorities intended to address the various stakeholder interests. Therefore, it was concluded that the advancement of sustainability, just as the implementation of digital initiatives, is closely interrelated with the respective company priorities in conjunction with company specific decisions on how to address specific aspects of digitalization and sustainability.

As it was found that the geographical region only has a low influence on the level of implementation of a digital initiative, it is also not possible to discern specific geographical areas that are more advanced than others in terms of the impact that digital technologies have as such. However, there might be specific regional challenges related to sustainability, such as proximity to communities, the existence of indigenous communities, or remoteness and lack of infrastructure, scarcity of water in high altitudes and dry areas. Further, the individual perception or weighing of certain sustainability criteria might differ from one region to the other.

In the scope of this study, the close links between digitalization and sustainability were investigated systematically and comprehensively for the first time. In Part I it was observed that the discussion on sustainability in mining is still largely decoupled from discussions on digitalization. However, the results of Part II clearly show that, in reality, digitalization and sustainability are already intrinsically linked: The analysis of the drivers and incentives for digital transformation (Chapter 2) clearly shows that economic profits, OHS and sustainability are linked to another and the digitalization technologies as such. Therefore, it can be concluded, that sustainable business practices are no longer a “nice to have”, but are increasingly becoming state of the art and have become indispensable for long-term productivity, and consequently, economic survival of mining companies.

The systematic investigation in this study may provide mining companies and experts across the globe with an increased understanding of the complex inter-relationships between both areas. Further, linking these two transformational processes of digitalization and sustainability more closely can lead to future research as well as contribute to a more nuanced public perception of sustainability in mining and in mineral supply chains.

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Annex A – Definition of Technologies

Table 2: Definitions of technologies affecting the operational process level

Technology	Definition
Automation	A simple definition for automation, according to the Merriam-Webster dictionary, is "the technique of making an apparatus, a process, or a system operate automatically." Along the same lines, the GMG Group report (GMG 2019b) defines automation as the "technique, method, or system of operating and controlling a process or machine by automatic means with minimal human intervention." ABB (2020) provides a useful distinction of four levels of automation as it progresses towards increasing levels of autonomy: **Low / Nil automation:** On this level of automation, the system is entirely manual and the operator completes all tasks or the system provides operational assistance by decision support or remote assistance. **Medium automation**: The system edges into occasional autonomy in certain situations. The automation system takes control in specific circumstances when andas requested by a human operator, for limited periods of time. People are still heavily involved, monitoring the state of operation and specifying the targets for limited control situations. **High automation**: On this level, the automated system takes control in certain situations. This can also be called semi-autonomous. The operator confirms proposed solutions or acting as fallbacks. A pre-requisite is a complete and automated monitoring of the environment. In such a setup, the (remote) operator can still be alerted in exceptional situations and can take over or confirm a suggested resolution strategy. **Autonomous:** This term describes the highest level of automation. On this level, autonomous processes or machines accomplish task(s) without human intervention or direct control in all situations. No user interaction is required for accomplishing the tasks and human operators may be completely absent. The system is further capable to act independently, learn and solve complex tasks and can react to unpredictable events during operations. Crucial elements for further development and use of autonomous systems are flexible IT-infrastructure, artificial intelligence and cyber security. (GMG 2019b)
Industrial Internet of Things (IIoT)	IIoT is a network of physical objects (e.g. IoT devices/sensors) that contain embedded technology to communicate and sense or interact with their internal states and external environment (i-scoop 2020b). That means that (mobile) machines and other sensors and wearables are connected with each other and/or with a digital platform or cloud. The latter collects and stores the data produced by all the sensors and devices in an operation. In the analysis of digitalization trends, the following additional technologies that were also mentioned in the literature were summarized under the umbrella of IIoT technologies: **IoT devices / sensors**: Devices / sensors that detect, measure or indicate any specific quantity such as light, heat, motion, moisture, pressure or similar entities, by converting them into any other form, which is mostly, electrical pulses (i-scoop 2020c). Sensors are the foundation for automation and digitalization as they generate the data that is the basis for increased information about the operation and, consequently, all subsequent optimization processes. **Interoperability**: It is the ability of a system to work with or use the parts or equipment of another system (Merriam Webster 2020). This is highly relevant for mining operations that often use devices from many different supplier companies that often use proprietary technology solutions not compatible with other systems in the operation. However, to realize an IIoT landscape, it is necessary that the machines and systems can all be integrated into a single platform or network. **Process integration**: It is the sharing of events, transactions and data between business processes, typically in real-time. Process integration is often used to implement complex processes that span multiple departments in an organization. Alternatively, it is used to extend processes beyond an organization to customers or partners (Spacey 2017). With respect to mining operations, process integration can also imply that processes which were originally managed as separate processes are integrated into one process through digital technologies. For example, the transition of haulage vehicles from underground to above ground usually meant a change in systems which were not integrated into one system. Through process integration they could be merged into one process from a digital perspective.
Remote Operations Centers	Remote Operation Centers (ROCs) are control rooms, which are foreseen to coordinate multiple areas within a mining operation and even multiple mine sites. Here people with different roles can work together in the same environment (control room consolidation). As all information from local mine sites is available, this facilitates collaboration in production planning, resource planning, specialist support, inventories and spare parts, allowing resources to be optimized across multiple mine sites. That allows precise, holistic and optimized management of mining operations from the rock face to the end customer, and across multiple

	mine sites. This collaboration between systems, equipment and people enables information to be shared and empowers operators to perform optimal control actions and take sound business decisions (Gallestey *et al.* 2015). Especially mines in remote areas benefit from this technology – also from the perspective of challenges related to bringing (and motivating) professionals working far from home or more attractive cities.
Connected Worker	Connected worker refers to workers who work on-site or in remote locations and are equipped with wearable devices e.g. smartphone, data glasses or sensors. They are digitally connected to the industrial company, which assists them in their work with relevant, timely and rich information (Accenture 2020). **Wearables**: Wearables are computer technologies, which workers wear on the body or head. They are a concretization of ubiquitous computing, the omnipresence of data processing, and part of the IoT. One also speaks of wearable technology and wearable computers. Their purpose is usually to support an activity in the real world, for example by providing (additional) information, perspectives, evaluations and instructions (Bendel 2019a).
Robotics	Currently mining robots refer to machines with high-level capabilities to sense and reason about their environment. Such machines in mining are purpose-built robots for foreseen tasks which require successful automation in highly variable and unpredictable mining environments (Corke *et al.* 2008).
Drone Technology	A drone is an aircraft that does not have a pilot but is controlled by someone on the ground, used especially for surveillance and monitoring operations (Cambridge Dictionary 2020).
3D Printing	Three-dimensional (3D) printing is an additive manufacturing process that creates a physical object from a digital design. The process works by laying down thin layers of material in the form of liquid or powdered plastic, metal or cement, and then fusing the layers together (Kenton 2020). This is especially relevant for mining operations with respect to maintenance processes for spare-part creation on site.
Electrification	The conversion of a machine or system to the use of electrical power (Oxford Dictionary 2020). This is generally describing the trend within the industry to move to electric vehicles, which is particularly relevant for underground mines that try to cut emissions, which also has an impact on ventilation costs. The electrification of mines as such is neither a new trend nor is it one of the digitalization trends. However, as it is one of today's most important trends and is often mentioned in connection with digitalization, this trend is listed here. Furthermore, electrification in combination with digitalization may also lead to new digitally enabled business models. For example, the development to substitute combustion engines in machine equipment with electrical powered equipment leads to a business change of the supplier companies, which could offer new services for this specific equipment, like battery.

Table 3: Definitions of technologies affecting the management process level

Technology	Definition
Integrated platform	IIoT platform or integrated platform enables IoT device and endpoint management, connectivity and network management, data management, processing and analysis, application development, security, access control, monitoring, event processing and interfacing/integration (i-scoop 2020d).
Advanced Analytics	It is a collective term, which includes the forecast of future developments based on action-oriented knowledge that supports management decisions to control a company (Lackes and Siepermann 2018). In this study, the following technologies are also included in the term advanced analytics: **Artificial intelligence (AI)**: A branch of computer science dealing with the simulation of intelligent behaviour in computers (Merriam Webster 2020). **Machine learning (ML)**: Different forms of self-learning in the discipline of artificial intelligence and robotic systems. For example, these systems are able to recognize rules and laws in the data and derive conclusions and actions from them. (Bendel 2019b)
Simulation modelling & Visualization	In the context of this study, the term simulation modelling/visualization was chosen as an umbrella term to include the following technologies and processes, which are supporting the perception and representation of processes: **Virtual reality (VR):** It is a computer-generated reality with image (3D) and in many cases also sound. The data is transmitted via large screens, in special rooms (Cave-Automatic Virtual Environment) or via head-mounted display (video or VR glasses). (Bendel 2018) **Augmented reality (AR)**: It refers to a computer-aided perception or representation that adds virtual aspects to the real-world using AR-glasses for display and perception (Markgraf 2018). **Digital twins**: Refers to a data-rich 3D model of a machine or mine site. It represents, reacts to, and can cause changes to the physical twin, the actual machine (BIM Dictionary 2019). **Short interval control**: A structured process in which data are reviewed in short intervals throughout a shift to make improvements and address deviations in real-time (GMG 2019a). **DARQ**: Refers to a group of emerging technologies (distributed ledger technology, artificial intelligence, extended reality (AR, VR), quantum computing) which are considered essential in driving the next wave of innovation and growth (Nazi and Poloni 2019).
Cloud computing	According to the ENISA (European Network and Information Agency), cloud computing is a model that allows convenient access to a shared pool of configurable computing resources (e.g. networks, servers, storage systems, applications and services) via a network anytime, anywhere, that can be made available quickly and with minimal management effort or service provider interaction. (BSI 2020)
Big data management	The process of collecting, keeping and using high-volume, high velocity and / or high variety of data securely, efficient and cost effectively (Gartner Glossary 2020). Big data management supports people, organizations and connected devices to optimize the use of data within the bounds of policy and regulations. This allows in making decisions and taking actions in order to maximize the benefit of organizations (Oracle Deutschland 2020). In this context the following technologies are also included in the category of big data management for the purpose of this study: **Predictive maintenance**: If one or more indicators show that a machine (or assembly of the machine) is likely to be on the verge of failure or that the performance of the equipment is deteriorating, a maintenance effort is triggered. Therefore, a condition-based maintenance action is designed to replace, repair or overhaul that assembly at an appropriate time before actually it fails during operation (Nagel and Riedel 2020).

Table 4: Definitions of technologies affecting the leadership process level

Technology	Definition
Cybersecurity	Refers to the body of technologies, processes, and practices designed to protect networks, devices, programs, and data from attack, damage, or unauthorized access. Cyber security may also be referred to as information technology security (deGroot 2020). With increasing levels of digitalization, mining operations also have become vulnerable to cyberattacks and some have fallen victims to hackers that have halted or interrupted production processes.
eLearning	Also referred to as online learning or electronic learning, eLearning is the acquisition of knowledge which takes place through electronic resources. This is relevant for addressing re-skilling and up-skilling needs of the workforce to adapt to new ways of working, regulations, etc. brought about by digitalization technologies. eLearning methods furthermore include different learning approaches such as blended learning, which combines conventional learning methods with effectivity and flexibility of electronic formats. In addition, equivalent methods and technologies may be applied for day-to-day communication. This increases efficiency by saving travel costs or to address unforeseen challenges such as the Corona pandemic.

Annex B – Definition of Processes

Table 5: Defintion of operational processes

Process	Definition
Development	**The Development Process** can be defined as open cut or underground work carried out for the purpose of opening up a mineral deposit and making the actual mineral extraction possible. Open cut development work includes stripping off overburden until sufficient mineral is exposed to allow viable extraction. Underground work includes shaft sinking along with various other activities leading to access to the deposit.
Extraction	**The Extraction Process** describes the actual process of mining and removal of ore from a mine. Extraction can be done through drilling and blasting or through cutting the rock using rock cutting machines. It is considered one of the processes in mining that still puts workers at risk due to the potential of rock fall after blasting as well as cutting and is therefore safetycritical.
Ventilation	**The Ventilation Process** includes the provision of a directed flow of fresh air and the return of used air and other emissions along all underground openings. Ventilation also includes the installation and maintenance of fans, shafts, permanent airways and cooling stations. Ventilation is safety-critical, energy-intensive and costly for many underground operations and costs keep increasing steadily with increasing depths. There are projects in which ventilation exceeds 25% of total project CAPEX and ventilation and cooling power utilization exceeds 50% of life-of-mine energy costs. (Bluhm *et al.* 2003)
Rock / Roof support	**Rock/Roof Support** describes the process through which openings in rock are supported with various materials such as timber, roof bolts, concrete, tubing, steel, spray-on liners, etc. Similar to the ventilation process, this is an important process considering the safety and integrity of the mine. Rock/roof support is conducted as part of development/extraction process.
Haulage & transportation	**Haulage & Transportation** describes the process of conveying ore, waste rock, and also includes supplies such as materials and components as well as personnel to and from the mine site. This can be done using continuous or discontinuous transportation systems.
Maintenance	**Maintenance** is the process of keeping mining equipment in operational condition by checking it regularly and repairing if necessary (Cambridge Dictionary 2020). It is important to make sure that the equipment in the mine is in working condition and maintained on time to avoid any unplanned downtime, which is a high cost factor for mines.
Backfilling	**Backfilling** is related to any material, including waste rock, used to refill a quarry, underground excavation, or used to provide wall, pillar or back support or provide a working platform after removal or ore from a stope, bench or sub-level. The backfilling process is used in specific mining methods such as cut & fill to maintain stability of the mined out areas and hence it has been defined separately from the rock/roof support process.
Water management	**Water management** deals with all tasks which are related to removing or supplying water to mining operations. This includes mainly ground/surface water extraction, integrated water resource management and water supply. Beside the mentioned tasks the water management also focuses on monitoring, groundwater analysis, establishment of streamflow / groundwater models as well as stakeholder engagement and related tasks (Kickler and Franken 2017).
Waste management	**Waste Management** is mainly related to the handling of mine waste, which refers to material from the extraction, which has no economic value at the time of the production and includes e.g. rock waste, tailings, slag, mine water and gaseous waste. The mine waste management covers the identification, monitoring, proper disposal, but also avoidance and reduction of significant mine waste materials in the operational processes to air, water and land. Furthermore, the mine waste management engages the recovering, re-use and recycling of waste materials (Kickler and Franken 2017).

Annex C – Definition of Sustainability Criteria

Table 6: Definition of sustainability criteria used for the Social pillar of Sustainability (adapted from Kickler and Franken 2017)

Issues	Examples	Definition
Terms of Employment	Working Hours & Rest	Regular working hours including breaks; overtime hours. **Will also include:** Wages & Employee records; Leave entitlement; Social insurance; Vacation.
Occupational Health & Safety	OHS Management	Management systems; legal compliance; policies; qualified staff; performance targets; planning & implementation; prevention measures; risk monitoring; incident investigation; review & improvement plan: employee engagement reporting. **Will also include:** H&S Committee which will provide a mechanism for employees to raise and discuss H&S issues with management.
	Workplace Hazards & Machinery	Safe and healthy workplace, processes & machinery; inspections; elimination of workplace fatalities, injuries and diseases; risk identification; protective measures; warning signals; hazards related to the mining method; fitness. **Will also include:** Electrical hazards; external review for high-risk locations; modification, substitution or elimination of hazardous substances in use.
	Personal Protective Equipment (PPE)	Correct and careful use; training on use; disciplinary process; maintenance.
	OHS Training	Education and training on risk prevention; role-related health and safety risks and hazards; fire safety; emergency procedures & preparedness; first-aid; understandable employee and supplier information about H&S risks in the mine; safety training plan for the security staff.

Table 7: Definition of sustainability criteria used for the Socio-Economic pillar of Sustainability (adapted from Kickler and Franken 2017)

Issues	Examples	Definition
Workforce & Local Value Addition	Local Workforce	Promote local employment & hire local staff; provide training to access created jobs.
	Local Procurement	Local supply chain; purchase of local materials and products of daily use; support local small and medium-sized local enterprises to supply goods and services.
	Community Initiatives	Initiatives for benefitting community including investment for infrastructure investment.
	Support of nearby ASM	Engage with artisanal and small-scale miners (ASM) operating on or around a mining operation; actively promote responsible ASM practices in the mining area; participate in initiatives that enable the professionalization and formalization.
Land Use Impacts & Conflicts	Mining impacts	Ensure sufficient scientific knowledge of potential impacts of the mining activities and that controls can be implemented to mitigate adverse impacts. **Will also include:** impacts due to alluvial mining and offshore mining.
	Conflict with community	This will specifically include conflict between the mining organisation and surrounding agricultural sector, ASM and the community including the indigenous people; resettlements.
Material Use	Sustainable Sourcing	Sourcing policy covering environmental, social and governance aspects; sustainable sourcing for e. g. bought-in gold
	Efficient use of Natural Resources & Recycling	Practices for sustainable and efficient use of natural resources; impact assessment of natural resources usage; local stakeholders access to and use of the resources; cumulative impacts on natural resources in the area; measures for improving material use efficiency; re-use & recycling of material; principles of cleaner production; product design and production processes; benchmarking data for relative level of efficiency
	Material Stewardship	Initiatives; Environmental Life Cycle Assessment (LCA) of own products; public access to LCA information; contribute to development of Life Cycle Inventory (LCI) datasets in the region of operation; external business initiatives; engage with value chain and external stakeholders

Table 8: Definition of sustainability criteria used for the Ecological pillar of Sustainability (adapted from Kickler and Franken 2017)

Issues	Examples	Definition
Biodiversity	Legally Protected/ Unprotected Areas	Areas designated by governments (national & international) as protected/unprotected areas for the conservation of biodiversity; identification procedure; activities in or adjacent areas.
	Threatened & Invasive Species	No net reduction on the global, national or regional population of any critically endangered or endangered species over a reasonable period of time; intentional/accidental introduction of non-native species; strict prohibition of high-risk invasive species; risk assessment.
	Ecosystem Services	Risks & impacts identification process; review on priority ecosystem services; engagement of affected communities; mitigation hierarchy. Will also include: integrated approaches to land-use planning, environmental impact assessments (EIA), biodiversity, conservation & mining.
Mine Water Quality & Management (incl. waste water)	Water Management	Alternative water supplies/projects; stakeholder engagement; impact assessment; mine water management plan; groundwater monitoring, model & analysis; proper disposal of waste water; baseline quality of surface or groundwater bodies; quality criteria for water discharges; quality monitoring. Will also include: Acid mine drainage; Efficient use of water and recycling management; Legal water regimes
	Groundwater Use	Impacts on off-site groundwater uses; groundwater use in arid regions; effects on surface water; water conservation activities; EIA. Will also include: Surface water pass-by flow standards; flow gauging station
	Mine Dewatering & Pit Lakes	Impacts of mine dewatering and mitigation measures; use as production water; provision to other water users; quality and quantity requirements; pit lake shape; pit lake overflow; evaporation losses in arid regions; long-term usage of the pit lake water.
Energy Use	Efficient Energy Use	Improving energy usage efficiency; reduce energy consumption to a minimum; set targets; core business activities; substitution of old machinery consuming high energy with low energy consumption; energy efficient equipment; principles of cleaner production; product design and production processes; benchmarking data; relative level of efficiency. Will also include: Adoption of renewable or low carbon energy usage.
Mine Waste	Reduction of emissions	Identify wastes and emissions to air, water and land; professional disposal; avoid and minimize pollutants/impacts; national requirements; good international industry practice; performance levels (e. g. EHS Guidelines from IFC); local conditions; alternative project location.
	Waste Management	Identify significant wastes to air, water and land; proper disposal; principles to avoid, reduce, recover, re-use and recycle; control of emissions and residues resulting from the handling; national requirements; good international industry practice; regular removal of waste from workplace; environmental impact considerations alongside cost considerations; monitoring. Will also include: hazardous & chemical waste disposal, overburden, tailings & effluents; EIA.
Air Emissions & Noise	Air Quality Management	Develop and implement air quality management plan; reviews; monitoring by professionals; air dispersion modelling consistent with leading methodologies; compliance with air quality criteria; publication of air quality management plan and compliance information.
	Noise, Vibrations, Dust & other Emissions	Prevent and control sources; operating procedures to minimize fugitive emissions; quantify direct and indirect emissions; national standards, internationally recognized methodologies and good practice; allowable levels and time frames; types of noise; blast noise and vibration; level for air blast overpressure, mitigation plan; wildlife or human receptors; mitigation of noise-related complaints; integrate control into operating procedures; dust deposition criteria; dust deposit gauges; air emission plan; ozone-depleting substances, NOx, SOx; EIA; disclosure of material GHG emissions and energy use and emissions reduction targets; reduction plan; material sources of direct and indirect missions; feasible and cost-effective options.

Table 9: Definition of sustainability criteria used for the Economic pillar of Sustainability (adapted from Kickler and Franken 2017)

Issues	Examples	Definition
Economic Efficiency	Productivity	An expression of labour productivity based either upon the ratio of grams/tonnes of ore mined to the total number of employees or the area mined in square metres to the total number of employees.
	Profitability	Degree to which the mine will yield profit or financial gain. Also, the state of yielding profit or financial gain; shareholder return.
	CAPEX	CAPEX: Total capital expenditure (incl. investments into R&D) on mining assets to create, maintain and expand operations (Does not include daily operating costs).
	OPEX	OPEX: Cash cost including production costs, royalties, marketing and re-fining charges, together with all administration expenses plus deprecia-tion and amortisation.
	Fair markets	Pricing; Extortion; Compliance; Liability and Accounting; Provisions and Compensations

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