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

Part I: Digitalization Processes in the Mining Industry in the Context of Sustainability

Editorial

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(Federal Institute for Geosciences and Natural Resources)
Stilleweg 2
30655 Hannover
Germany

Authors: Prof. Dr. Elisabeth Clausen, Aarti Sörensen, Fabian Uth, Dr. Rudrajit Mitra
RWTH Aachen, Institute for Advanced Mining Technologies

Dr. Felix Lehnen, Berit Schwarze
Brenk Systemplanung

Contact: Dr. Philip Schütte
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
30655 Hannover
mineralische-rohstoffe@bgr.de

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

Part I: Digitalization Processes in the Mining Industry in the Context of Sustainability

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

Aachen, September 2020

Executive Summary

This research study 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). BGR’s efforts intend to push forward the development of evaluation methods and concepts for selected sustainability aspects.

Digitalization in mining, at its core, follows a vision for a digitally connected, autonomous (“smart”) mine in which connected systems are able to reduce the ever-increasing complexity of the site and to improve decision-making in real time. This transformation is largely driven by the need to increase productivity and safety and to reduce operational cost in order to cope with challenges mining operations are facing at this point, such as declining ore grades, more complex, remote or deeper deposits as well as commodity price variations that may include low-price periods.

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. Driven by the overall objective to increase productivity and to improve safety by means of the three main trends – automation, digitalization and electrification – mining as an industry is, at the same time, under an increasing pressure from various stakeholders to change towards more sustainable business practices.

However, a relationship between digitalization and sustainable business practices has not been systematically investigated yet. Furthermore, the impact of the implementation of digitalization technologies on sustainability is largely unknown to date. On first thoughts, digitalization ís expected to produce a significant improvement from a sustainability point of view. However, there can also be negative impacts such as job losses due to implementation of these technologies.

Based on the hypothesis that there is a close link between processes of digitalization on the one hand and various aspects of sustainability on the other, this study systematically examines digitalization trends in mining and their impact on sustainability at a mining process level as well with regard to the global development of the sector.

A second assumption underlying this study is that because digitalization trends are not progressing uniformly worldwide, the impact and benefit of these trends may vary in relation to the geographical region, type of deposit and commodity, mining method or size of the operation. Thus, this study is designed to draw a picture of the differentiated effects of digitalization trends on sustainability that can be observed or expected in the global mining sector. Consequently, the overall objective is to get a comprehensive understanding of the assumed relationship between processes of digitalization and sustainability on both a mining process level as well as on a global scale.

This report constitutes Part I of the overall research study “Assessment of the effects of global digitalization trends on sustainability in mining”. It focusses on introducing core concepts and definitions as well as identifying and defining important digitalization trends, core mining processes and a suitable catalogue of sustainability criteria. The three core chapters of this study are designed to address the three following underlying research questions:

1. What is digitalization in mining?
2. How are digitalization trends affecting mining practices on a process-level?
3. What is the potential impact of digitalization trends on aspects of sustainability from a process-level perspective?

From the current study, it can be seen that digitalization in mining is focused largely on specific set of digitalization technologies. The study identified 15 technologies of high relevance to the industry of which the following take a leading role in shaping the current transformation: automation, integrated platforms, IIoT, simulation and visualization tools, advanced analytics, remote operation centers, connected worker and cybersecurity. With respect to the impact of digitalization technologies on mining at a process level, the study examined eight operational processes as well as the impact in relation to the leadership and management process levels. The analysis shows that cybersecurity has a high impact on the leadership process level since the more digitally integrated operations are, the more vulnerable they become. This issue needs to be addressed across operations and poses a challenge for the leadership of global mining companies. On a management process level, the introduction of integrated platforms, often utilized in combination with visualization and simulation tools and advanced analytics applications, have a particularly high impact, changing the way operations are planned and managed. Operational processes are most significantly impacted by automation to date. Aside from automation, operational processes are particularly impacted by the introduction of IoT devices and the implementation of IIoT as a foundation for creating the connected mine as well as remote operation centers and increasingly connected workers supervised and monitored by wearable devices.

The analysis of the potential impact of these technologies on different dimensions of sustainability is presented in a three-diimensional model of linking digital technologies, mining processes and a set of sustainability criteria. To summarize, the preliminary analysis of this report shows that a high impact of digital technologies on sustainability is to be expected particularly in the areas of improving safety (social pillar), increasing economic efficicency (economic pillar) and the reduction of resource use, including material use, water and energy consumption and the reduction of air and noise emissions (socio-economic pillar and environmental pillar). Consequently, there is an impact to be expected on all three pillars of sustainability, albeit to varying degrees.

These findings indicate that the level of implementation with regards to the technologies that were identified but also with respect to overall digital transformation within the mining industry is still in the early stages.

Part II will expand on the outcome of this part of the study to include an analysis of the level of implementation of digitalization trends and its impact on sustainability from a global perspective. Further, it will take a closer look at the challenges of implementing these digitalization technologies and whether any clusters or patterns may exist along a set number of influencing factors with regard to the level of implementation as well as with respect to the impact on sustainability from a global perspective.

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1. Introduction

Raw materials are the building blocks of societies and indispensable for economic growth and welfare. Despite efforts to reduce material intensity in advanced economies through increased resource efficiency and recycling, primary resource extraction is going to remain central to economic development and growth. In fact, an increasing number of metals play a crucial role not only in high-tech products but also in making the shift to a greener, low-carbon economy possible.

The total world economic output is projected to triple in the period 2010 to 2050 (European Environment Agency 2015). The global primary material use, and thus global primary materials extraction, is projected to more than double from 79 Gigatons (Gt) in 2011 to 167 Gt in 2060. Population growth in conjunction with economic development, a growing global middle class and a gradual convergence of living standards are the drivers behind the rapid increase of global demand for raw materials. Non-metallic minerals, such as sand, gravel and limestone, with their primary use for construction, represent more than half of total global materials use. The use of metals is projected to grow the fastest, from 7 Gt in 2011 to 19 Gt per year until 2060. The rapid increase in the demand for metals is mostly driven by Brazil, Russia, India, Indonesia, China, South Africa (BRIICS), as well as other developing countries. (OECD 2018)

Simultaneously, technological progress, high-tech manufacturing and the transition to low-carbon economies relies on access to a growing number of metals. An increasing range of metals are irreplaceably bound in solar panels, wind turbines, electric vehicles, and energy-efficient lighting, as well as in smartphones and other smart technologies, to name a few. Therefore, leading industrial nations such as Germany – one of the world's largest consumers of raw materials – are highly dependent on a secure supply of many different metals. (European Commission 2020)

There are various efforts and attempts to decouple economic growth from resource consumption (OECD 2018), e.g. by promoting recycling or increasing material and resource efficiency. However, even improved recycling rates may not replace increased mining efforts in the foreseeable future. Consequently, mining, defined as the industry that extracts primary resources from the earth, will remain central to feeding the demand of global growth in the foreseeable future. This is especially true since the growth projections for primary metals are not only accounting for structural changes in the advancing economies but also for improving living standards.

At the same time, mineral production impacts the livelihoods of the communities where it operates in multiple ways. This is especially true since mining as an industry is very diverse ranging from artisanal and small-scale mining (ASM), which is predominantly done through manual or semi-mechanized, labor intensive methods, to highly-automated large-scale operations where several hundred thousand tons of material are moved each day. While these large-scale industrial mining operations employ about 7 million people worldwide and produce the majority of metals and minerals globally, there are more than 40 million (Hobson 2019) people directly engaged in ASM in approximately 80 countries across Africa, Asia, Oceania, and Central and South America. Despite its partly informal nature, ASM sector not only represents an important livelihood and income for the poverty affected local population, it is also responsible for production of various global minerals and metals and therefore plays an important role in the global supply of resources. This includes gold, diamonds, gemstones, the 3T (tantalum, tin, tungsten), cobalt, along with coal and low-value non-metallic raw materials, such as sand, gravel and clay (Carstens 2017). ASM can include men and women working on an individual basis as well as family groups (including children) which poses significant challenges for sustainability with respect to human rights, child labor, as well as health and safety, to name a few.

Industrial mining, on the other hand, faces other challenges with respect to sustainability. For example, materials management, including the extraction, processing and transportation of raw materials is responsible for more than half of all greenhouse gas (GHG) emissions, which is based on scope 1 of GHG inventory guidance. (EPA 2020; OECD 2018) As part of materials management, it is seen that the extraction of primary non-energy resources has a comparably large environmental footprint and a frequently negative public perception regarding its impact on the environment and the communities located near mining operations.

According to the UNDP (UNDP 2016), the mining industry has a unique opportunity to generate significant human, physical, technological and financial resources to advance the Sustainable Development Goals (SDG). These 17 SDGs (Figure 1) were developed by the United Nations (UN) to improve the wellbeing of the present and future generations. The majority of the mining companies has adapted these to deal with sustainable and responsible mining practices. Mining is a global industry, often located in remote, ecologically sensitive and less-developed areas. This may include many indigenous locations. (UNDP 2016)

Figure 1: Mining and the 17 Sustainable Development Goals (SDG) (UNDP 2016)

From a positive aspect, the mining industry can generate a huge impact by creating jobs, spurring innovation and bringing investment and infrastructure at a game-changing scale over long time horizons. (UNDP 2016) Further, according to the ICMM (2020), one of the ways in which a country benefits from mining activities is through the revenues that the government receives in taxes and royalties. However, if managed poorly, mining can lead to environmental degradation, displaced populations, inequality and increased conflict. (UNDP 2016)

Some of the other challenges from a sustainability point of view include social licence to operate and water management. Social License to Operate (SLO) originate from the wider concept of Corporate Social Responsibility (CSR). The concept of earning and maintaining an SLO is now embedded in the mining culture. The majority of the mining companies consider it to be one of the most important tasks of their project, both during establishment and throughout its operational life. In fact, without an SLO some governments will not issue formal permits and licenses required for a project to get started. (Tyson 2018). According to Sánchez and Hartlieb (Sánchez and Hartlieb 2020), the minimal requirements for maintaining the social license to operate is to meet more rigorous environmental regulations and attending to the concerns of local communities.

In mining, water is used within a broad range of activities including mineral processing, dust suppression, slurry transport, and employee requirements. Over the years, the industry has made huge progress in maximizing conservation of water. However, there are operations with significant demands of water from their neighbouring community. (ICMM 2012) Various organisations around the world are looking into water management issues in mining from a sustainability point of view.

News (not only from media) travels the globe in an instant through social media and online news. At the same time, the industrial mining and metals sector is facing increasing demands and rising expectations towards governance issues such as transparency, sustainability and responsibility. These demands arise from across the value chain and stakeholder groups – from shareholders and customers, from governments to communities, and consumers with an increased awareness. Shareholders want to make sure they get a return on investment while increasingly caring about the “triple bottom line” of social, environmental and economic performance – also reflecting the three pillars of sustainability. A new species of “Social Investors” is getting hold in the investment arena looking for socially and environmentally responsible conduct and good Environmental Social and Governance (ESG) Ratings of companies they invest in. Consumer demands for transparency of minerals in end products are also rising, while local communities have increasing demands for communal engagement and long-term benefits to communities. Regulatory pressure comes in the form of carbon taxes or other requirements for environmentally sustainable production. Governments, including Germany’s, are committed to supporting responsible extraction and efficient use of materials as well as improving transparency in raw materials supply chains and decreasing the environmental footprint of mining operations. (BMWi 2020)

In short, today’s internationally operating mining companies are increasingly expected to operate more sustainably while improving productivity at the same time. Therefore, they are challenged in their traditional way of doing business (World Economic Forum 2015). In fact, moving towards more responsible and sustainable business practices is now considered essential for mining businesses to survive in the long term (Ellis 2020).

Excess capital spending during commodity boom cycles has confronted the industry with enormous pressure for cost cutting and productivity[1] improvements. Moreover, while technological advances have improved methods for locating and extracting raw materials, high grade deposit zones in easy to access locations have been largely depleted. The technical possibility of economically mining ores at lower grades increase both the cost and amount of waste rock generated. This in turn affects GHG emissions as well as waste accumulated during production and processing. In addition, remote and deeper deposits drive up developmental and operational costs and may pose additional challenges such as water scarcity or air conditioning

[1] According to a global survey by EY (2017), economists refer to productivity as “multifactor” that measures a range of factors, including labor, capital and material or resource.

needs in underground mines. These additional challenges may also have implications for energy consumption and GHG emissions through long distance transports of material and people as well as air cooling requirements in greater depths.

Consequently, mining companies are being challenged to change, adapt, and innovate in order to remain competitive and economically viable in the future. To date, digitalization and automation have been the key answers to this process of change leading to measurable improvements in productivity and cost management. However, success is not guaranteed by simply introducing new technology. The landscape of digitalization in mining is heterogeneous and success factors are still being evaluated.

In summary, mining operations today are under two kinds of pressure. On the one hand, they have to address challenges that can be considered inherent to the industry, such as changing geology, rising operational costs along with commodity price cycles. In order to meet these challenges the industries needed to grow in size which has been accompanied by a shift towards digitalization and automation, at least for larger operations. On the other hand, mining operations are facing pressure from external stakeholders, which are forcing the industry to take sustainability seriously. Sustainable business practices are no longer a "nice to have", they are increasingly becoming indispensable for long-term productivity, and consequently, economic survival. (Ellis 2020)

However, the discussion on sustainability in mining is still decoupled from discussions on digitalization. While both are considered indispensable for the long-term survival of the industry, potential links between digitalization and sustainability have not been systematically investigated yet. For this reason, this study constitutes a systematic investigation into the potential impact of digitalization on the mining sector and the impact these developments may have on sustainability. Within the scope of this study, all forms of mining, from SMEs to industrial mining, are included in the analysis while the focus is on the production of industrial minerals and metals.

1.1. Structure of the Report

This research study 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). It is intended to support the development of evaluation methods and concepts for selected sustainability aspects.

Based on the hypothesis that there is a close link between sustainability and processes of digitalization, this research study examines current digitalization trends in mining and their impact on sustainability at a mining process level as well as with regard to the global development of the sector. The full study is divided into two parts.

Part I of the study, which is contained in this report, focuses on definitions and conceptual work and on a process-level view on digitalization trends in mining and the impact of digitalization on sustainability issues. This report has three dimensions which are digitalization trends and technologies, mining processes and sustainability criteria. The research questions derived from these three dimensions that are underlying the report are:

1) What is digitalization in mining?
2) How are digitalization trends affecting mining practices on a process-level?
3) What is the potential impact of digitalization trends on aspects of sustainability from a process-level perspective?

To answer these questions, Chapter 1 provides an introduction explaining the relevance and context of this study. Chapter 2 focuses on defining key terms and concepts related to digitalization in mining and provides an overview of current digitalization trends and technologies that shape the industry. Through an empirical analysis of existing literature, 15 digital technologies that are driving the current digitalization trends in mining are defined.. Chapter 3 takes a closer look at the various processes related to mining, defining key processes and analyzing the impact digitalization technologies have on those processes. A subsequent section on benchmark projects along with preliminary findings of the two-dimensional analysis – linking mining processes and digitalization technologies – is also included here. Chapter 4 presents a three-dimensional concept for linking digitalization technologies, mining processes and sustainability issues. A catalogue of sustainability issues was compiled for the report, building on existing ones. As a preliminary analysis, the potential impact of digitalization technologies on sustainability issues is discussed on a mining process level. Chapter 5 summarizes the conclusions of this report.

Part II will expand on the outcome of this part of the study to include an analysis of the level of implementation of digitalization trends and its impact on sustainability from a global perspective. Further, it will take a closer look at the challenges of implementing these digitalization technologies in specific mining and commodity markets on a global scale.

1.2. Methodology

The methodological approach of this study can be seen in Figure 2. As a first step, an empirical analysis in form of a keyword search was conducted to identify the current digitalization technologies and trends which are shaping the mining industry. For this, leading industry magazines, websites from mining companies and OEMs as well as reports from leading consulting agencies were systematically analyzed. In total 150 sources were reviewed either in relation to specific projects or in relation to emerging digitalization trends. For each article, the identified trends were stored in a spreadsheet. The source articles were published within the last five years with the majority being published in the years 2018-2020. After the complete data collection, the technologies (i.e. digitalization trends) were summarized into 15 different categories which were clustered based on the analysis of the data.

In a second step, the defined mining processes were analyzed on the basis of benchmark projects, quantitative results of the keyword search as well the expert view of the authors. This was done to determine the relationship between the technologies and the mining process levels they are mostly affecting or being applied at.

The third step of the analysis focuses on how the transformation of mining processes through digitalization technologies impacts specific sustainability issues. A catalogue of sustainability issues underlying the analysis is introduced and is linked with the mining processes. To determine the preliminary complex correlation and impact on the sustainability issues the quantitative results from the keyword search in conjunction with insights from the literature review and expert view of the authors were applied. The impact on the specific sustainability issues is illustrated with application examples. These correlations will be further investigated, validated and clustered through interviews in Part II of the study with its focus on the global implementation.

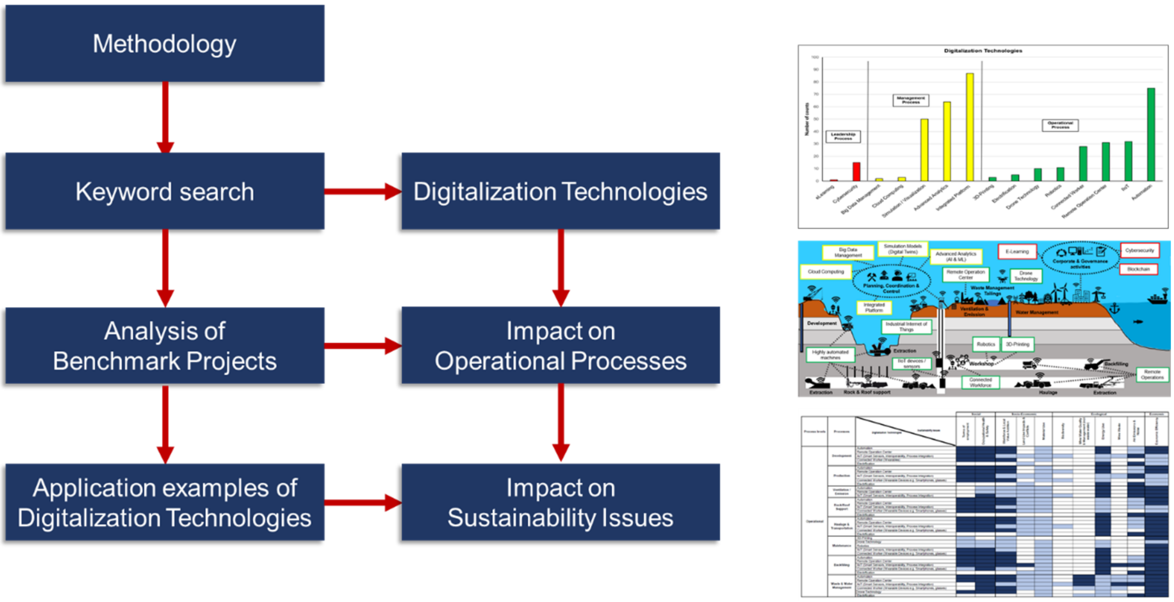

Figure 2: Schematic illustration of methodological research approach. The three figures on the right are provided in details later in the report.

2. Digitalization in Mining

Digitalization in mining is part of the 4th industrial revolution or the transformation towards "Industry 4.0". Characterized by cyber-physical systems, the Internet of Things (IoT) and comprehensive networks intertwining industrial manufacturing with the most advanced information and communication technologies, Industry 4.0 implies the creation of smart, e.g. networked and automated, factories (Figure 3). Hence, digitalization is at the core of this transformation.

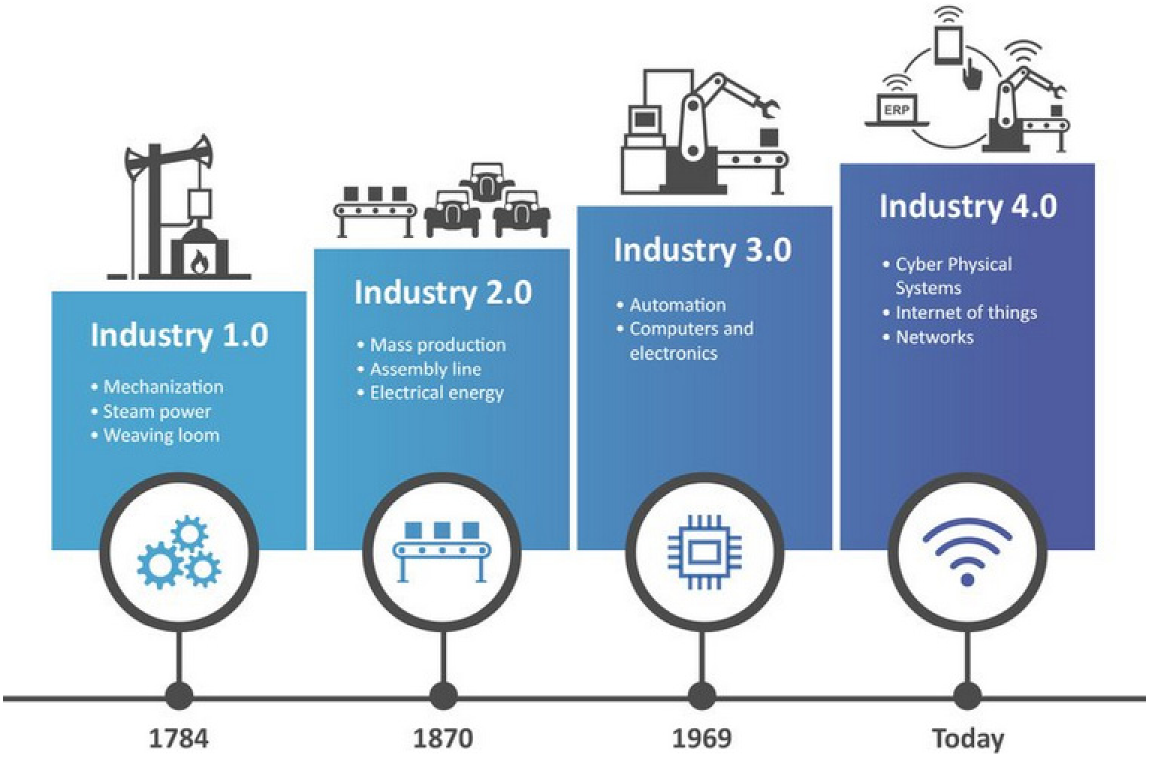

Figure 3: The Four Industrial Revolutions (Amtage 2020)

The transformation towards Industry 4.0 affects virtually all industries, including the mining and minerals sector. Summarized under the term "Mining 4.0" or "Smart Mining", this transformation can be understood as the intelligent connection and integration of mining machines (physical components). It uses information and communication technologies (cyber-systems) to form so-called cyber-physical systems. Here, the exchange and transmission of data and information take place via a platform, the Industrial Internet of Things (IIoT).

A smart mine thus comprises the vision of a digitally connected, autonomous mine in which the connected systems are able to reduce the ever-increasing complexity to such an extent that improved decision-making can be realized in real time. In this context, "real time" is to be understood as "right time", i.e. the information must be available "in time" for the process.

Compared to other industries which have already achieved much higher penetration of digital technologies, changed their business models fundamentally or came up with new business models, the mining industry is still in the earlier stages of the digital journey. Even compared with other heavy-duty industries, mining is still in the early stages of digital maturity, as can be seen in Figure 4.

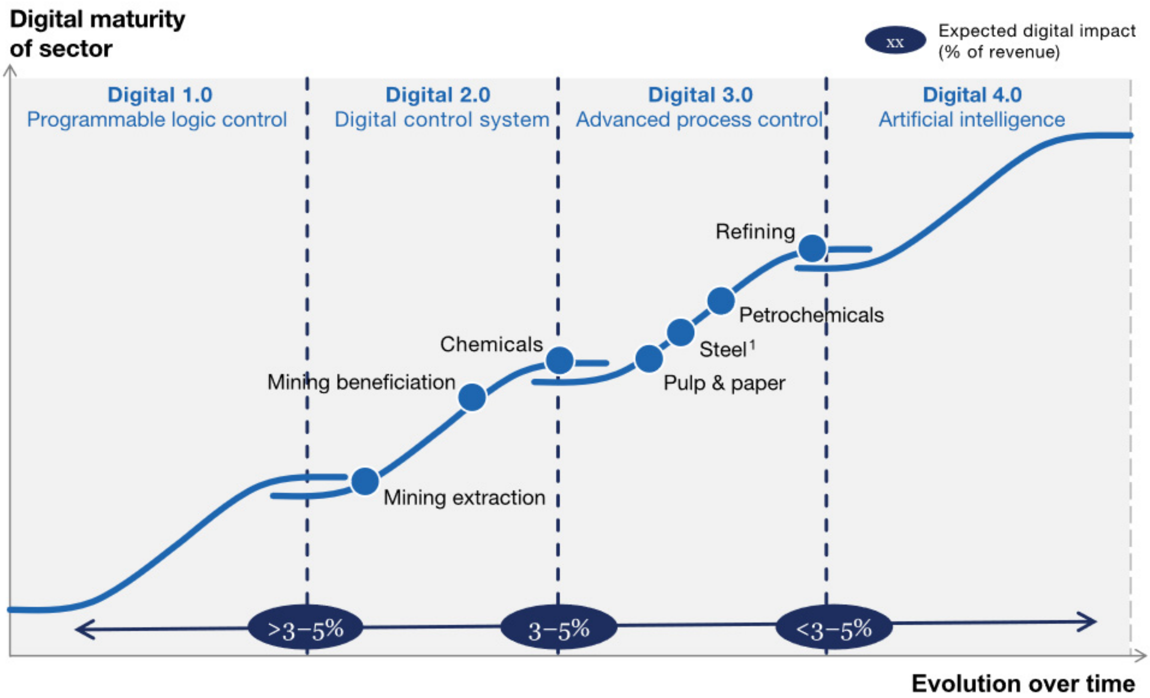

Figure 4: Mapping heavy industry's digital-manufacturing opportunities (Noterdaeme *et al.* 2018)

In mining, digitalization and automation are considered key enablers for cutting certain capital expenditures (CAPEX) and operating expenditures (OPEX) through process optimization and optimized equipment utilization. Even though the potential has not been tapped fully, there are already indications that digitalization and automation have been at least partially responsible for reversing the trend of a steady decline in productivity that has lasted for decades and began to stabilize and reverse only recently (Durrant-Whyte *et al.* 2015; Noterdaeme *et al.* 2018). Nevertheless, it needs to be noted that even though capital expenditures may be cut down due to a better utilization and longer lifetime in the long-term, the capital expenditures of highly automated equipment are generally higher compared to less automated equipment.

However, digitalization in mining is a broad term and sometimes appears nebulous or at least complex and difficult to grasp. Therefore, the next sections of this chapter will provide a deeper insight into digitalization in mining.

The next section (Section 2.1) of the report will provide an overview of relevant concepts, terms and definitions, while Section 2.2 will provide an empirical analysis of current trends in digitalization in mining.

2.1. Terminology & Definitions

The first part of this section will provide an overview of relevant concepts, terms and definitions, while the second part will provide an empirical analysis of current trends in digitalization in mining.

2.1.1. Digitization, Digitalization and Digital Transformation

Digitization, Digitalization and Digital Transformation are three key terms that are sometimes used interchangeably. However, each term has a distinct and different meaning and is therefore defined for the purpose of this study. The definitions were derived by the authors through analyzing and synthesizing definitions from a variety of sources.

- **Digitization** refers to the process of converting analog information to digital format so that computers can store, process and transmit this information with the aim to digitize and automate processes or workflow.
- **Digitalization** refers to the process of moving a business to a digital level through the use of technologies, thereby providing new revenue and opportunities along with creating value.
- **Digital transformation** refers to the customer-driven strategic shift of business that requires cross-cutting organizational change as well as the implementation of digital technologies.
- **Digital business** refers to the creation of new business designs by merging the digital and physical worlds and is an essential step towards digital transformation.

Given these definitions, the current discussion in mining underlying the analysis of trends is focused on processes of **digitalization**.

2.1.2. Mining

According to Hartman and Mutmansky (Hartman and Mutmansky 2002), **mining** is defined as the activity, occupation and industry concerned with the extraction of minerals. It comprises a range of distinct processes, such as exploration, mine development, production, processing, and rehabilitation.

Exploration as well as mineral processing are not considered as part of this study. Since the mining process itself consists of many sub-processes, the focus of this report will be on these sub-processes, which will be analyzed with respect to the potential impact that digitalization technologies will have on mining at a process-level.

In summary, this chapter focuses on analyzing digital trends for the sub-processes related to the extraction of metal ores.

2.1.3. Mining Process Levels

In order to support the analysis of the impact of digitalization technologies on mining processes, it is useful to subsume the various processes (that will be defined in the next section) under three process levels, namely leadership, management and operational. This is helpful to determine the area of impact of the digital technologies as part of the later analysis.

The three process levels (Figure 5) each deals with specific tasks:

- The leadership process level deals with corporate and governance activities involving multiple operations of a mining company as well as the C-Suite level;
- The management process level deals with organizational activities and personnel including planning, coordination, control and adjustments of the production process and allocation of resources including equipment utilization and work plans;
- The operational process level deals with both core mining processes, which will be further defined in the next section.

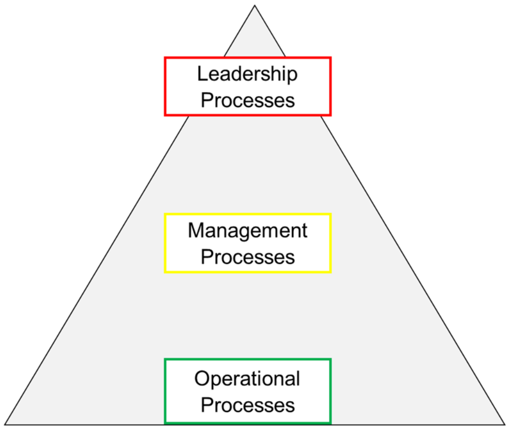

Figure 5: Process map of global mining companies (adapted from Alpar *et al*. 2002; Accenture 2011)

The illustration is meant to allude to the interconnection of the processes but also reflecting the hierarchy of processes within a specific organization. The color coding was added by the authors to distinguish between the process levels and will be applied in graphical depictions throughout the report.

2.1.4. Operational Processes in Mining

Whereas leadership processes are focused on corporate and governance activities and management processes are dealing primarily with organizational activities and personnel including planning, coordination, control, the operational processes need to be further categorized into sub-processes relevant for this report.

The distinction and selection of operational sub-processes was done in order to be able to identify and analyze digitalization trends within core operational processes and as such provide a process-level view on digitalization in mining. The focus is explicitly placed on core processes of production and does not include horizontal processes such as logistics and infrastructure as separate processes due to the complexity of each of the individual sub-processes.

Figure 6 provides an overview of the process levels and operational sub-processes that are defined in the following paragraphs.

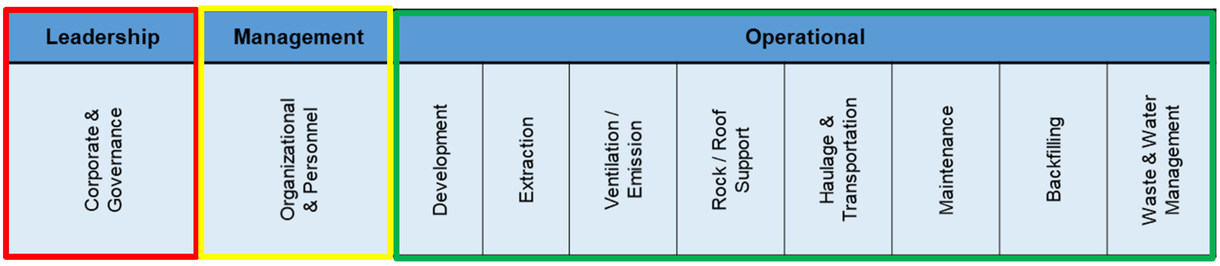

Figure 6: Classification of the mining processes used for the study

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.

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 safety-critical.

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 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 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 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 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 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 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).

2.2. Trends in Digitalization Technologies

In order to identify current digitalization trends in mining, a keyword search was conducted to gather empirical data on the most prevalent trends and technologies currently shaping the mining industry and the shift towards digitalization.

For the keyword search, leading industry magazines, websites from mining companies and OEMs along with reports from leading consulting agencies were systematically analyzed using the keywords "mining digitalization" and/or "mining digitalisation". Accounting for the difference in spelling between British and American English was important as the number of search results differed immensely based on the predominant spelling used in a particular industry magazine, region or publication.

For the keyword search, a total of 150 sources were analyzed systematically either in relation to specific projects or in relation to emerging digitalization trends. For each article, the identified trends were stored in a spreadsheet. The source articles were published within the last five years with the majority being published after 2017.

After the complete data collection, the technologies (i.e. digitalization trends) were summarized into 15 different categories which were derived based on the analysis of the data. In a further step of the analysis, the total count of how many times each of the 15 technologies was mentioned in the dataset was evaluated. In addition, the authors used their expert views to determine the relationship between the technologies and the (mining) process level they are mostly affecting or being applied at (Figure 7).

Again, technologies which are mostly affecting the operational mining processes are illustrated in a green color, using the color code from the process levels introduced above. Technologies mostly impacting management processes are colored yellow and those affecting company leadership are colored in red. The height of the bars indicates the number of counts of the specific digitalization technology in the empirical data set.

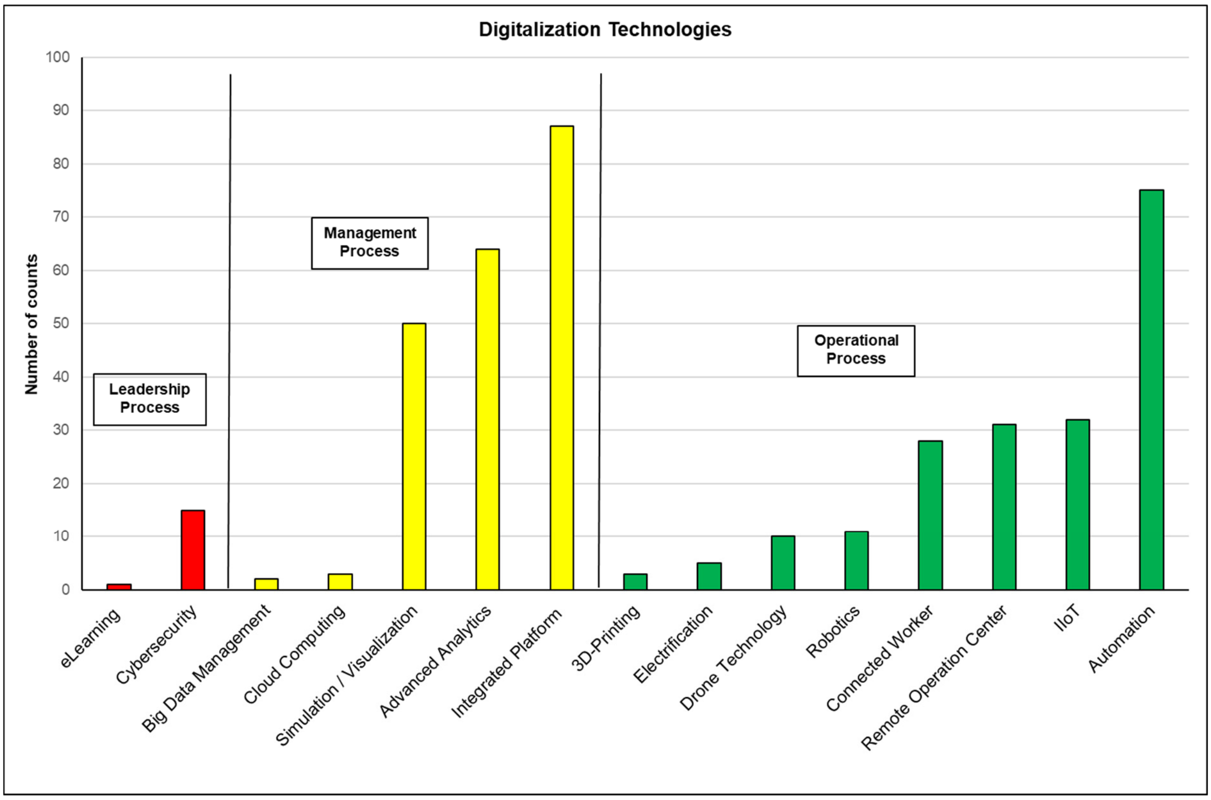

Figure 7: Digitalization technologies and affected mining process levels identified from 2015 – 2020

From the above figure, it is clear that the operation process is highly impacted by technologies designed to improve safety of the workers and remove people from high-risk areas. These include, amongst others, drone technology, connected worker, robotics and remote operation centers. Furthermore, these processes are also affected by technologies intending to improve productivity and reduce operational costs along with availability of data as a prerequisite for process and production optimization. These include automation and remote operation centers for the former and IIoT for the latter.

The analysis further shows that the management process level is the level most affected by digitalization technologies. This is because at the management level all the data generated on the operational level is used to increase transparency of processes and production data and to use this knowledge to adjust processes, production rates, equipment utilization etc. within short timeframes or close to real-time. One of the core technologies leading these processes is advanced analytics, which is required to derive valuable information from the datasets in order to improve decision-making. Technologies used for modelling, simulation and data visualization are closely related and integrated platforms and IoT devices are considered core technologies as well since they are closely related to utilizing advanced analytics and simulation / modeling tools across various processes in particular.

For the leadership processes, blockchain and cybersecurity was found to be the most relevant trends. Blockchain is emerging and being piloted as a technology to improve supply chain transparency as a response to regulatory and consumer led pressure for transparency with respect to the sources of specific metals in consumer products. It is a technology that is not directly related to mining operations or their immediate management but associated with downstream supply chain management and is therefore represented at the leadership level. However, since the focus of the study is on the mining industry and not on the entire value chain, blockchain will not be discussed further in subsequent chapters. However, another trend that the C-Suites of mining companies are concerned with according to the data is cybersecurity. There are examples of hacker attacks on mining operations with significant impact such as production halts. Since digitalization bears certain vulnerability for cyberattacks, this topic needs to be addressed by the industry and is certainly more intensively discussed now than a few years ago.

Before going into a more in-depth discussion of these technologies with regards to their impact on individual mining processes, a definition and short description of each of the 15 technologies is provided in the following paragraphs.

2.2.1. Definition of Digitalization Technologies mainly impacting operational processes

- **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 (ABB 2020a) 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 and as 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 2020a). 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 2020b). 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 Operation 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.

2.2.2. Defining Digitalization Technologies mainly impacting management processes

- **Integrated platform**: IIoT platform or integrated platform enables IoT device and endpoint management[2], connectivity and network management, data management, processing and analysis, application development, security, access control, monitoring, event processing and interfacing/integration (i-scoop 2020c). See also IIoT in Section 2.2.1.

- **Advanced Analytics**: It is a collective term, which includes the forecast of future developments based on action-oriented knowledge that supports management decisions

[2] Endpoint management is the ability to centrally discover, provision, deploy, update, and troubleshoot endpoint devices within an organization (BMC (2020).

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).

2.2.3. Definition of Technologies impacting mainly leadership processes

- **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.

Based on these definitions and preliminary analysis, Chapter 3 will provide a more detailed discussion of these 15 digitalization technologies and their impact on individual mining processes.

3. Digitalization at the Mining Process Level

Chapter 2 provided an overview of mining process levels and individual processes as well as a detailed analysis of relevant digitalization technologies shaping the current digitalization trends in the global mining industry.

As a next step, this chapter provides an in-depth analysis and discussion of the impact of these 15 selected digitalization technologies on individual mining processes. This is followed by an overview of selected global benchmark projects, which will further illustrate some of the key findings. A concluding section will summarize the findings and give some indications for the degree of implementation as well as some of the challenges implied with this transition. These preliminary insights presented in Section 3.3 will be further investigated and validated through expert interviews in Part II of the study, which will focus systematically on the level of implementation from a global perspective.

3.1. Impact of Digitalization Technologies on Mining Processes

As a summary of the analysis in Chapter 2, Figure 8 presents an illustration of the digitalization technologies impacting the various process levels in an operation.

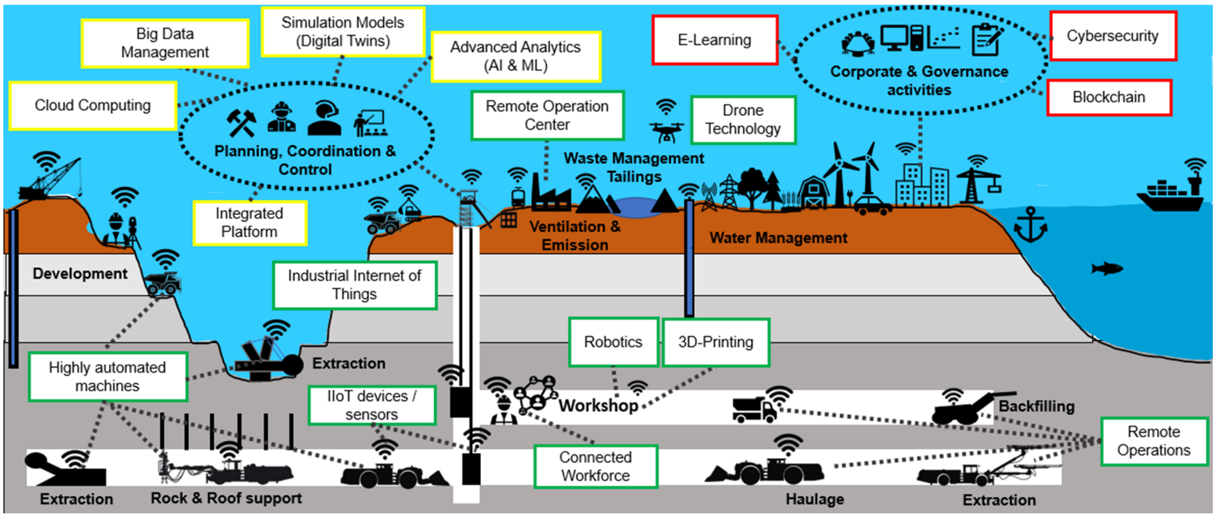

Figure 8: Schematic illustration of mining processes affected by digitalization technologies

For the further analysis conducted in this chapter, the mining processes are again organized into three process levels, namely operational, management and leadership processes. Using the same color code for the mining process levels as in Chapter 2, digitalization technologies mainly affecting the operational processes are marked green, those which are mainly affecting management processes are marked yellow and leadership-related trends are marked red.

The correlation of mining processes and digitalization technologies is neither obvious nor explicit. Therefore, it had to be derived from the literature review combined with expert views. In this way, the correlation of processes, process levels and digitalization technologies constitute an original analysis contributing new findings and knowledge while at the same time reflecting the expert views of the researchers.

In the subsequent sections, each of the mining processes is discussed in regards to how they are impacted by the respective digitalization technologies.

The specific impact of the digitalization technologies on each process is differentiated into three levels of impact – high, medium and low/nil.

High impact:	(dark blue)
Medium impact:	(light blue)
Low/nil impact:	(white)

Based on the research results and number of counts for each technology depicted in Figure 7, in conjunction with expert views of the authors to classify the impact, the classifications shown an discussed in the section below were derived.

3.1.1. Digitalization Technologies in Operational Processes

This section discusses the digitalization technologies related to the mining processes from an operational point of view. Table 1 provides a summary of the discussion following below.

Table 1: Overview of operational processes impacted by digitalization technologies

Digitalization Technologies	Operational Processes							
	Development	Extraction	Ventilation / Emission	Roof / Rock Support	Haulage & Transportation	Maintenance	Backfilling	Waste & Water Management
Industrial Internet of Things (IIoT)	High	High	High	High	High	High	High	High
Connected Worker	High	High	High	Medium	Medium	Medium	Low/nil	Low/nil
Remote Operations Centers	High	High	High	High	High	High	High	High
3D Printing	Low/nil	Low/nil	Low/nil	Low/nil	Low/nil	Medium	Low/nil	Low/nil
Drone Technology	Medium	Medium	Medium	Medium	Low/nil	Low/nil	Low/nil	Medium
Robotics	Low/nil	Low/nil	Medium	Medium	Low/nil	Medium	Medium	Medium
Automation	High	High	High	High	High	High	High	High
Electrification	Medium	Medium	High	Medium	High	Low/nil	Low/nil	Low/nil

Development:

Development processes in surface and underground mines are impacted by the deployment of highly **automated** mining equipment for preparing the actual extraction of the ore from the mineral deposit.

Open cut development, which includes stripping off overburden, is characterized by heavy mobile equipment such as automated bucket-wheel excavators (Hein 2020; Mining Technology 2018). Utilizing this highly automated equipment results in increased effective working time and increased availability of the machines. In some operations (e.g. in Western Australia) workers are increasingly removed from autonomously operating haulage equipment.

In addition to automation, surface operations are increasingly transformed by **remote operations.** It should be noted that the **IIoT** is one of the basic requirements for realizing advanced automation and remote operations. It enables a machine operator located in a safe environment (e.g. control room) that can be hundreds or thousands of kilometers away from the mine site to be connected with an operating machine and all necessary sensors and devices). Furthermore, the **connected workforce** is gaining importance in open cut development for tracking the location and selected health indicators of workers.

With regards to underground development, **automation**, **remote operations**, **connected workforce** and the required **IIoT** infrastructure are also applicable and have a similar impact. However, remote operations e.g. for automated drilling, have a higher implementation level at surface mines due to the complexity of installing remote controlled equipment in narrow and GPS-denied underground environments. The same applies for IIoT infrastructure and automation. Yet, underground development is increasingly impacted and penetrated by these technologies in operations developed by major global mining companies.

These four main technologies are projected (and in various cases have already proven) to increase the efficiency, productivity and safety of the development process. Aside from these main technologies the implementation of **electric** or **battery-powered** machine equipment is becoming more important, since specific emissions have to be kept within legally prescribed thresholds. Furthermore, the number of **drone and robotic technologies for** inspection and monitoring tasks in hazardous areas for human workforces is on the rise, especially for underground development.

Extraction:

As with development, the extraction process in surface and underground mining operations is affected by the main digitalization technologies, namely **automation**, **remote operation, connected workforce** and **IIoT**. The main objectives for implementing these technologies in surface mines are achieving higher availabilities of machine equipment, higher effective working times and cost reduction through less deployed but more efficient machines in the extraction processes. Through a digitally enabled **connected workforce** important data and information can be exchanged quickly through the IIoT and workers can be located and tracked in real-time. Furthermore, incidents like collisions between automated or remote operated machine equipment can be reduced or avoided through warning signals sent to machine operators in real-time. **Wearables** allow health monitoring of the workforce and detect e.g. symptoms of fatigue before accidents can occur.

The described digitalization technologies are also implemented in underground extraction processes with the same intentions. In addition to this, **robots** and **drones** are applied to a small degree for inspection or monitoring in hazardous areas which cannot or should rather not be entered by humans.

Ventilation & Emission:

Through the application of sensor-based **IoT** devices in surface operations such as gas sensors, machine data, position information of workforce and equipment and emission values can be monitored on mobile equipment. If necessary, activities can be adapted or measures can be taken to counteract the emissions.

The same applies to underground operations with the possibility to apply ventilation on demand in specific areas of the underground mine using **position information** of workforces and machines. The mine fan is **remote-controlled** and the ventilation can be adapted to the amount of airflow actually needed at any given time in various locations of the mine. The objective is to achieve a safe and efficient work environment by supplying the workforce with enough fresh air to breath, reducing toxic or explosive atmospheric substances through dilution or flushing of undesired gases and creating of tolerable mine climate for the workforce (Reuther, 2010). Since ventilation is a high cost factor in mining operations, ventilation on demand provides enormous opportunities for energy-related cost reductions.

In addition, advanced **IoT devices** can connect directly to an industrial network and conduct the majority of all the air monitoring requirements of a modern mine through a single device. Furthermore, the health condition monitoring data of the workforce, which are collected through **wearable devices**, can be used to improve the management of the ventilation process. **Drones** and **robotic operation** will have an increased potential to take over e.g. gas and temperature monitoring activities in specific areas before the areas are entered by humans.

Rock & Roof Support:

The process of rock & roof support in underground operations is mainly impacted by highly **automated** and **remote operated** equipment. In underground operations, this process has been operated with a high degree of automation to secure the underground working area for workers and machine equipment and protect humans and machines from rock fall. Through the application of **IoT devices,** the rock pressures can systematically be monitored and, through the **IIoT**, communicated in real-time to the **Remote Operation Center** or the control room respectively. However, it should be mentioned, that these operations are in safety sensitive areas and therefore need additional reliability and approval. **Drones** and **robots** are being used for monitoring and inspection tasks such as taking rock samples and thereby prevent humans entering and inspecting high risk areas in underground environments (Zibret and Zebre 2018). In addition, **wearable devices** for workers are allowing a sensor-supported detection of loosened rock on roof or walls. Furthermore, machine equipment for rock & roof support processes is increasingly changed to **electric** (battery-powered) equipment.

Haulage and Transportation:

The haulage process in surface and underground mines is also becoming increasingly **automated** and **remotely operated**. Because of increasing depths and longer distances to the actual operations, the workers need to travel to remote locations, which is an enormous cost factor for mining operations. Therefore, haulage and transportation has been a primary target for high levels of automation to increase productive working hours of the workforce as well as equipment productivity. **IIoT** is the basic requirement for the use of highly automated systems and machines in haulage processes, through which the complete data communication is enabled. Related to other surface and underground mining processes, the hauling equipment is becoming increasingly **electrified** or battery-powered instead of diesel- powered.

Maintenance:

The maintenance process is highly affected by digitalization technologies such as **IoT** devices and sensors, which are gathering data like heat, motion, vibration, pressure or similar parameters. This element of **Big Data Management** is referred to as **Predictive Maintenance** and supports the process of checking and analyzing the operational condition of the machine equipment to reduce or avoid critical machine conditions and resulting failures. The maintenance actions are increasingly affected by **robotics** as well which is supporting the human workforce in replacing, repairing and overhauling the equipment and machines. In addition, the workforce is increasingly equipped with **wearable devices** such as tablets and smart glasses which are supporting the analysis of the machine condition, often also utilizing augmented reality features. In case of failure detections specific components can be automatically replaced by **3D-printed** spare parts.

Backfilling:

Backfilling in surface and underground mines is affected by highly **automated** and **remote-operated** equipment. **IoT devices** are measuring and monitoring the volume and mass of the material which is used to refill quarries or underground excavations. In all types of backfill such as dry sand and rock fill, uncemented hydraulic backfill, cemented hydraulic backfill, cemented rock fill, paste fill, pneumatic and flowable fill, the monitoring is necessary for further automation.

Waste & Water Management:

Water management covers all mining processes and is highly affected by the **IIoT**, which comprise **IoT devices /sensors**, **interoperability** and **process integration**. Based on the information available from the network of sensors, different tasks within the water management such as water supply, water stewardship, impact assessment, monitoring, ground/surface water extraction can be **automated** to a high degree. In addition to the above-mentioned impact of the **IIoT** on the water management processes, information about streamflow / groundwater models and biodiversity can be expanded and specific measures taken according to the mine water management plan. The waste management is also highly affected by the application of **IoT devices** and sensors which are monitoring, for example, the condition of tailing dams to ensure a safe operation. The deployment of **drones and robots**, which are used to support e.g. the monitoring of processes or the sampling of water and waste such as tailings is becoming more important regarding the further automation respective **remote-operation** of processes.

3.1.2. Digitalization Technologies in Management Processes

Management Processes:

On the management process level, all data which is gathered on the operational process level through sensors and IoT devices is **integrated** in **IIoT platforms**. Improved decision making and timely information about deviations from production schedules are the leading incentive driving the transformation towards implementing digital technologies in operational management.

Consequently, the integration of data and relevant information is becoming increasingly important with respect to analyzing processes and machine performance in real-time enabling the optimization of different processes. As can be seen in Table 2, **big data management, cloud computing** and **data analytics** are, in this context, technologies that are utilized to store and analyze the data that is transmitted through the IIoT to the **integrated platform** from all the sensors and IoT devices installed in the operation. The integrated platform gives operations management the opportunity to view all machine data or process data with regards to their status, utilization or work plan at any given time through a single tool. Even historical data can be stored and pulled from the platform, for example data from seismic events or from sensors monitoring gas emissions or rock mechanical parameters.

The data from the integrated platform can then be used for **simulation modelling and visualization** of information about different operational processes or individual pieces of equipment. This means that factors influencing production can be identified more easily and adjustments can be done in shorter intervals, reducing the deviation from production plans. Simulation modelling can also be used for forecasting and planning based on different production scenarios. In many cases, simulation modelling and visualization also utilize technologies such as **digital twins** along with **AR** or **VR**.

The analysis shows that the technologies impacting management processes are highly interconnected. The project-based research showed that often times one of the technologies is highlighted for a particular operation that is part of the digitalization journey. However, none of these technologies can be applied without installing the sensors and data transmission and communication infrastructure in the operations first. In addition to installing the sensors, it is also important to make sure that the data that is gathered is the right kind of data, which can then provide useful information for improvements. Further, the analysis shows that the digitalization technologies, which are highly impacting the management processes are technologies which are generating additional value for the processes. This is in comparison to the technologies, which have a medium impact and are primarily foreseen for data storage and access to the data.

Table 2: Overview of management processes impacted by digitalization technologies

Digitalization Technologies	Management Processes
Simulation Modelling / Visualization	
Cloud Computing	
Advanced Analytics	
Big Data Management	
Integrated Platform	

3.1.3. Digitalization Technologies in Leadership Processes

Leadership Processes

As can be observed from Figure 7, with respect to leadership-related processes, the technology most discussed in the literature is **cybersecurity**. Mining operations that have implemented a higher degree of digital, connected and integrated technologies may become more vulnerable to cyberattacks. In fact, the integration of IoT devices into control systems, and the subsequent connection of once-isolated operational systems with a mine's entire enterprise network, leaves entire operations vulnerable to cyber threats. In short, an increasingly connected operating environment exponentially expands the threat making mining operations also more difficult to protect against attacks (Dohan 2019). The stakes are high for mining companies. A successful attack can put mining operations, equipment, data and employees at risk – and lead to compromised production or even production shut downs in the most severe cases. For example, an attack on Norsk Hydro, one of the largest aluminum producers in the world, forced the company to isolate plants and switch some operations to manual after the entire company's computer network got paralyzed. Cost for the company amounted to 70 million US$ (Dohan 2019).

A second technology that is impacting the leadership process level is **e-learning**. Even though much less discussed in the literature to date, this is an important aspect with regards to retaining, re-skilling or up-skilling the existing workforce. As job profiles and required skills change along with the adoption of digital technologies, companies need to offer opportunities for its workforce to adapt to the changes. E-learning offers opportunities for this kind of on-the-job training. Besides that, e-learning plays an increasing role in the academic training of future mining professionals at universities etc. This trend currently faces another boost due to the Corona crisis (remote teaching). Table 3 provides an overview of the leadership processes that are impacted by the digitalization technologies.

Table 3: Overview of leadership processes impacted by digitalization technologies

Digitalization Technologies	Leadership Processes
eLearning	
Cybersecurity	

3.2. Selected Benchmark Projects

In order to make the analysis of digitalization of distinct mining processes more tangible and to glimpse into the global analysis that will be expanded on in Part II of the study, some selected benchmark projects will be discussed in the following sections.

Anglo American – FutureSmart Mining™ Program

Scale of Operation: Large-scale
Commodities mined: Various metals & coal
Region: Africa

Anglo American is a globally operating diversified metals and coal producer with its origins and a strong presence in Southern Africa. With its so-called FutureSmart Mining™ innovation driven approach to sustainability it has set a global benchmark with respect to the ambitions and goals formulated by the company in regards to sustainability.

Anglo American's role as a global leader is confirmed by the Responsible Mining Index Report 2020, which ranks the company as the top performing mining company across all six thematic areas, which are economic development, environmental responsibility, business conduct, lifecycle management, community wellbeing, and working conditions. The report is produced by the Responsible Mining Foundation (RMF), an independent research organization that encourages continuous improvement in responsible mining across the industry. RMF conducted an evidence-based assessment of 38 large-scale mining companies' policies and practices on economic, environmental, social and governance issues for the report. (AngloAmerican 2020)

Interestingly, even though Anglo American is considered a global leader in sustainability practices, the company's projects have not emerged as part of the keyword search on "mining digitalization" in this study. However, this can be explained by the strong focus the company is placing on sustainability and innovation rather than digitalization per se. Data analytics and other technologies are considered mere enablers for the company to achieve its sustainability goals. That is expressed through the following statement by Tony O'Neill, Anglo American's Technical Director: "With all these technologies coming through – much of them driven by higher levels of data and the ability to interrogate that data – the vision we imagined way out into the future, I think, is a lot more tangible than when we started out four years ago." (Gleeson 2019a)

With respect to digitalization, the main focus is currently on advanced process control, Information Technology and Operational Technology (IT/OT) integration and on building a data analytics platform that is an end-to-end data platform supporting the entire value chain. As such, the company is going beyond current attempts for integrated platforms focused on integrating operational processes into a single platform through IIoT. Aside from using AI to interpret data, the company is also aiming at engaging end-users with next generation apps along the value chain. (O'Neill 2019)

Resolute Mining – Syama Mine, Mali

Scale of Operation: Large-scale
Commodities mined: Gold
Region: Africa

Resolute Mining's Syama Mine has caught the attention of the international mining community because it is considered, with respect to automation, to be the most advanced underground mine in the world. With its extension of the mine at its Mali based operations, the company has commissioned a new part of the mine in 2019. This is operated almost entirely from a surface control room where operators are able to control underground production units over shift-change, blasting and re-entry periods, when there are no personnel in the underground mine. One of the main benefits stated by the company is that automation leads to the ability to maintain production over periods when operations would normally cease in a typical manual mine. (Gleeson 2019b)

An important technological backbone of full automation is fiber optic cables and a mine-wide wireless network which connects the control room with the haulage level at 1055 m depth. The network enables the operation of the automated haulage loop, automated re-handle level, mine digitization and production automation, all of which allow operators to monitor and control mine production in real time. In addition, Syama's haul trucks can rapidly transition from laser-based underground navigation to surface-based GPS navigation seamlessly and therefore set a benchmark in this area. In addition, the company has been able to automate its drilling operations, achieving a 21% increase in drill meters and a 20% increase in accuracy in drilling as well as a decrease in manual intervention due to the accuracy of the drilling. The automated drills are operating 24 hours a day and no evacuation is needed for blasting, which improves safety and productivity significantly. (Dyson 2020)

The underground automation, including the drills, haulage vehicles and the integrated platform and software suite for the control room was provided by Sandvik and in part by Orica. Sandvik is, as the keyword research clearly indicated, leading the automation space in mining at the moment and is also a leader in providing integrated platforms and software tools for remote operations management.

Codelco – El Teniente and Chuquicamata Operations Chile

Scale of Operation: Large-scale
Commodities mined: Copper
Region: South America

Another example for extensive automation efforts and a company that is considered a pioneer in automation is Codelco. Codelco is a state-owned Chilean copper producer and one of the biggest copper producers in the world. Codelco has implemented the Sandvik Suites OptiMine and AutoMine at its El Teniente and Chuquicamata operations. The partnership between Sandvik and Codelco goes back to 2004, when the first-ever AutoMine Loading system was installed at Codelco's El Teniente copper mine.

AutoMine covers various aspects of automation, from remote and autonomous operation of a single piece of equipment to multi-machine control and full-fleet automation using automatic mission and traffic control capabilities. To date, the AutoMine platform has been able to log more than 2.5 million hours with zero lost time injuries. OptiMine, as the other tool, is a suite of digital tools for analyzing and optimizing mining production and processes. It integrates relevant data into one source, delivering both real-time and predictive insights to improve operations. OptiMine is open and scalable to other equipment, systems and networks. (Sandvik 2019)

There is no public data available on the exact productivity improvements derived from implementing automation technologies at the Chilean operations, partly because some of the technologies were implemented in 2019.

BHP Billiton - Western Australian Operations

Scale of Operation: Large-scale
Commodities mined: Iron ore
Region: Australia

Measurable impact, has been reported from BHP's Western Australian operations, where BHP claims to have the largest fleet of autonomous blast hole drills in the world. Its 21 autonomous rigs have drilled more than 850,000 holes, each up to 15 m deep. The drills are operated from BHP's Integrated Remote Operations Centre in Perth, Australia, about 1,600 km south of the iron ore mine sites. Early in the program, analysis showed the autonomous PV271s were 16% faster per hole, had 20 % additional utilization and one third extra drill capacity. (Dyson 2019)

Intelligent sensors attached to drill-bits can reduce mine mapping from months to weeks, which allows the company to locate the highest-quality areas much faster. As part of the autonomous drill, new technology sensors are being sent through the blast, detecting ore location as they travel through, with the data being analyzed in real-time by artificially intelligent software. (Hilton 2019)

In addition, haulage costs at BHP's Jimblebar mine reduced by 20% since equipment was fully automated in 2018. Until 2025, BHP is striving to become a fully integrated, highly automated company. As the largest mining company by market capitalization globally, this shows that the world's leading mining companies have entered a race, or at least a competition, for automation and digital transformation. Comparatively speaking, BHP is in many ways still catching up with its rival company, Rio Tinto, which has started its automation and digitalization journey more than a decade ago. Yet, BHP has achieved benchmark outcomes in the area of autonomous drilling and will continue to transform its operations in the years to come.

Rio Tinto – Western Australian Operations

Scale of Operation: Large-scale
Commodities mined: Iron ore
Region: Australia

Rio Tinto has recently made headlines, for implementing the first heavy-haul railway to operate an autonomous network in the world. In June 2019, Rio Tinto completed the transition to an entirely automated operation of its 1500 km railway in the Pilbara region of Western Australia. AutoHaul, which the company describes as the world's largest robot, is operating up to 50 automated and unmanned trains at any one time. Consisting of 240 wagons and achieving a total length of 2.4 km, two to three locomotives haul 28,000 tons of iron ore from the company's 16 mines to the ports of Dampier and Cape Lambert on an average 800 km journey taking 40 hours. The only manned part of the operation remains the last mile at the ports, with drivers joining the trains at the end of the main line. Loading and unloading of product from the wagons is also completely automated. (Smith 2019) In addition, Rio Tinto has implemented a large fleet of autonomous haul trucks in its open pit operations in Australia.

What is less known is that Rio Tinto has also developed a broad suite of digitalization tools in-house that are being used to optimize processes and production such as RTVis™. This software is a complex 3D Visualization Tool with a 3D gaming engine to help visualize different operations. The software allows flying over a site or diving down to the detailed information needed at any one time. It is possible to hover over an excavator, follow a haul truck, or examine an orebody. The software brings together geology, geotechnics, drill and blast, production and planning, and visualizes surface and sub-surface structures. The software also includes various analytic tools to use Big Data for better decision-making. It has delivered tangible benefits including more accurate drilling and blasting, reduced explosive use, and better waste classification. It follows that trucks carry less waste material and more ore, which in turn boosts productivity and lowers costs. In total, 1,700 people are using the software at almost all of Rio Tinto's operations. (Rio Tinto 2020)

Dundee Precious Metals – Chelopech Mine, Bulgaria

Scale of Operation: Large-scale
Commodities mined: Gold
Region: Europe

Anotherbenchmark project comes from Europe, where Dundee Precious Metals (DPM) has been a forerunner not only in underground automation but also in digitalization. CEO Rick Howes, who was admitted to the mining hall of fame for his achievements, coined the term "taking the lid off" to describe what was achieved at Chelopech: making it possible to look into an underground environment as if the lid was lifted and the mine was no longer a "dark hole". (Mining Magazine 2014)

DPM, which has started with this approach in 2009, has been able to achieve impressive results with their IIoT approach. The company has quadrupled its production from about 0.5 Mt/y to nearly 2 Mt/y.

In addition, DPM has been piloting the concept of short interval control to use real-time production information to update a central monitoring and control room. In this approach activities are planned at least three months in advance and at regular intervals performance and production indicators are being checked against the plan in order to decide if adjustments in the plans are needed.

The newest addition to the operation is a drone system that enters the mine and flies autonomously through an underground environment creating a complete three-dimensional (3-D) map of its environment in a global positioning system (GPS)-denied environment. Using light detection and ranging (LiDAR) sensors, the drones carry out missions in the underground spaces within Chelopech that offer a better understanding of areas of the mine that until recently were completely unknown (Schmidt 2020).

Boliden Group – Scandinavian Operations

Scale of Operation: Medium-scale
Commodities mined: Zinc, copper, lead, nickel, gold, palladium, platinum and silver
Region: Europe

The Swedish mining company, Boliden, also appeared in the research and is well-known within the industry as an early adopter of digital technologies. As a company, it is seen to take a very strategic and, at the same time, agile approach to digitalization. As a medium-sized company, it operates five mines and five smelters in Northern Scandinavia. (Boliden 2020) Currently, the company is implementing a unique automation initiative that takes place as a cross-functional program with employees from various departments together with external partners including Volvo, Ericsson, Epiroc and ABB. The long-term goal of this initiative is to streamline mining so that production can continue 24/7 and all year round. Boliden estimates that with better control of the production flow, productivity could increase by 10 - 20%. Full automation, where autonomous machinery operates even when no humans are present, according to company estimates, could increase that number to anywhere between 40% and 80% in overall productivity improvement. (Boliden 2016) Consequently, Boliden's highest priority projects are autonomous trucks and remote-controlled loaders. However, the company also states that fully autonomous mining robots are probably a long way to go still. Another priority is the implementation of 5G networks, which not only lays the groundwork for further automation but also has implications for safety enhancements by reducing response times and improving conditions for remote-control capabilities. Together with ABB, Boliden is also implementing the electrification of surface mining trucks at its Aitik operations to further improve productivity and reduce emissions. (ABB 2020b) Driverless wheel loaders are being tested at one of their operations and remote-controlled drilling rigs have been implemented in more than one operation already. This brief summary shows that Boliden stands out within the industry as it is trying to adapt to the different trends of digitalization and has positioned itself in the vanguard of automation. (Skelleftea 2020)

3.3. Level of Implementation & Challenges for Digital Technology Adoption

There are several insights that can be drawn from the analysis of the most prevalent digitalization technologies that were discussed in Chapter 2 as well as the subsequent analysis of how individual mining processes are affected by these digitalization technologies. The exemplary benchmark projects discussed above have provided an additional glimpse into the actual implementation and adoption of automation and digitalization technologies in global mining operations from four continents.

The strongest impact of digitalization on leadership processes to date is the issue of cybersecurity moving to the agenda of global mining company executives. With increasing connectivity and the reliance on mine-wide networks, the vulnerability for cyber-attacks has increased substantially with potentially enormous costs for affected companies. Furthermore, the ownership of data needs to be clarified between mining companies and OEMs. The ownership of data has not been regulated by law until today. For example mining companies provide information about their enterprise, which can be used by the OEM to develop new technologies on the basis of this information. Contracts are necessary to avoid these adverse consequences for mining companies (Frenz 2019). Furthermore the responsibilities in some special circumstances need to be clarified such as who is liable in case of failure or if the autonomous machine makes a decision that leads to injuries or fatalities.

The strongest impact of digitalization on the management processes is through the implementation of integrated platforms, visualization/modeling software and the application of data analytics and AI to support data-driven decision-making. These technologies allow for increased transparency of all processes in the mine and therefore more accurate planning, increased control over production processes and the ability to check the actual mine design against the plan and make adjustments in short intervals. Consequently, digitalization is a tool to improve operational performance, safety, and potentially also impact sustainability if this is a clear objective of the company. Accenture for example has developed together with Avanade and Microsoft the Connected Mine solution, which aims to monitor production against plan, real-time notifications of events and overview of the operation as well providing supervisors with advanced analytics of real-time data from in-pit equipment. (Accenture 2015) At the same time, digitalization impacts the skillset of the personnel, which can pose a challenge to mining companies. This leads to retraining of the current job skills along with need for new skillsets. In a study by Consejo de Competencias Mineras as stated in Sánchez and Hartlieb (2020), new structures must be designed in advance to prepare employees for this new arrangement along with investment in proper training. An example can be learning to operate the equipments from the remote operation centers. However, this would not require training of operators as developers.

The attraction and retention of skilled workers from younger generations is another challenge mining companies are facing. The image of the industry is still one of being dusty, dirty and dangerous and not of modern workplaces controlling smart machines by joysticks from a control room in an attractive city through gaming-inspired software tools. Retraining and thereby retaining the existing workforce is a challenge in this respect that can hinder the rate of adoption of new technologies in an existing operation.

The strongest impact on the operational processes comes from automation, which is confirmed by the benchmark project analysis. The benchmark analysis clearly shows that automation is, in many cases, the most advanced technological trend in highly mechanized mining operations. Automated haul trucks as well as automated or semi-autonomous drilling are the most common areas for automation to be applied. However, autonomous systems are not yet implemented in reality in mining operations at the moment.

Most of the technologies described still need a lot of research and development as well as demonstration and testing under real mining conditions in order to unfold their full potential within the industry. Some of the research in this area is being conducted by the mining companies in collaboration with the OEMs and research organisations like the AMT. As discussed in Sánchez and Hartlieb (2020), sometimes mining companies focus on their core business, while relying on suppliers for the development of technological solutions. The companies, therefore, avoid the risks associated with larger investments. Further, as stated in Stubrin (2017), this has also increased the emergence of local knowledge intensive mining suppliers. These suppliers have some specific local knowledge which allows them to provide customized soltuions in specific areas that cannot be covered by standardized products offered by large global suppliers.

In order to effectively utilize digital technologies on the management level (especially integrated platforms and simulation modeling / visualization), the right digital infrastructure needs to be put in place, which includes sensors, data-transmission and communication infrastructure and devices that can be connected to IIoT. One of the challenges companies are facing is the up-front investment (CAPEX) required for setting up such an infrastructure in remote regions and in underground environments. As an example, the total expenditure for investment of autonomous trucks at a surface operation in Western Australia amounted to A$18 million. This included autonomous trucks, operation center, AI- or ML-driven software along with the communication network. This resulted in reduced labour and wearing parts costs (A$3,9 million) and an increased production value (A$22 million). (Barnewold and Lottermoser 2020) Considering that mines are very capital-intensive operations, they tend to be risk averse when it comes to trying new technologies not sufficiently proven elsewhere already. However, as can be observed from the benchmark studies, some companies decided to adopt digitalization technologies for some of their processes. Based on the research, it was found that the main incentive for this was improvement of safety and productivity for the operation. No specific other indications of long-term cost savings were obtained during this study and will be further investigated through the interviews in Part II.

Another challenge is the selection of the right suite of technologies and to ensure that they can all be integrated into a single IIoT platform (interoperability). Therefore, implementing digitalization projects in existing mining operations needs to be carefully evaluated beforehand and embedded into the overall strategy for the operation. A key organization, which is focused on multitudes of organizations to achieve multi-vendor multi-platform secure reliable interoperability is the OPC Foundation, which developed the OPC Unified Architecture (UA). The OPC UA is a service-oriented architecture, which is scalable and has timeless durability. Many organizations within industrial automation as well as organizations in mining have rallied around the OPC UA as the strategy for data and information integration and interoperability. (Burke 2016) Further, according to Burke (2016), the ability to automate mining will highly depend on the ability for all aspects of mining, including both the mining companies and vendors, to agree on a common set of terminologies and standardization for mining objects. Through automation and standardization, things like maintenance and reliability of mining equipment will be easy, as information will be available to make intelligent decisions for both condition-based and predictive maintenance scheduling operations.

It should also be mentioned that the standardization process of digitalization approaches in mining is challenging, which results for example from existing infrastructure types such as communication in the different mine sites and the rapid development of digitalization technologies in recent years. The ISO/TC 82 is concerned with specifications of specialized mining machinery and equipment used in opencast (eg. conveyors, high wall miners, rock drill rigs and continuous surface miner) and underground mines (eg. road-header, continuous miner, rock drill rigs, raise boring machines and other equipment). Besides these specific mining machinery specifications, recommended practices and methods are also provided. Industrial-led open platforms such as the Global Mining Guideline Group (GMG) are also providing guidelines for the mining companies, for example, to support creating or replacing mine communication infrastructure, which is the fundamental basis for digitalization technologies.

The other challenge in regards to the move towards digitalization is the option of whether to retrofit older equipments with updated technology or buy new set of equipments. Outdated machinery can have a significant liability for mining companies as it increases the chances of of breakdown and stoppages. The operators should consider retrofitting existing machinery rather than replacing legacy equipment outright at a steep cost, to better meet their needs for the foreseeable future. (SRO Technology 2020). In a report by Moore (2017), Rio Tinto added 76 Komatsu 930E-AT 320 t trucks equipped with the Frontrunner Autonomous Haulage System in its Pilbara iron ore mines adding to their 400-strong truck fleet. These have been estimated to run 15% cheaper than the rest. They are located at the Yandicoogina, Hope Downs 4, Nammuldi and Silvergrass mines in Western Australia. The challenge with the company is now on how to get the autonomy benefits out the rest of the existing fleet. For this, Rio Tinto plans to do retrofits of Komatsu’s AHS system on the older trucks. This may seem to be a much cheaper option than continuing to add brand new autonomous trucks. However the challenge is to make sure the technology allows for mixed fleets of “new AHS” and “retrofit AHS”. (Moore 2017).

An interesting insight from the project-based analysis which is confirmed by the benchmark project evaluation is that operations are often focused on or stand out for one or few particular area(s) in which they have implemented a digitalization initiative. Examples are BHP being the most advanced in semi-autonomous drilling, while Rio Tinto is the most advanced in autonomous railways and trucks. However, to tap the full potential of digitalization a comprehensive implementation of technologies at not just one but all operations of a company is required. Some of the large global mining companies are aiming to achieve this within the next 5 – 10 years. Therefore, it should also be noted here that even though the digital technologies were discussed in conjunction with each other in the previous sections, they have not yet all been implemented together in one single mining operation. Not only are individual operations focused on few digital initiatives, some of the technologies are still in the very early stages of adoption or even at a piloting stage, such as drones, robotics, or 3-D printing. The analysis shows that global mining companies have begun the digital journey but even they have a long way to go to unlock the full potential of the current transformation.

Smaller and/or less highly automated or highly mechanized operations are not considered in the current literature and may face a different set of challenges. Often bigger companies have R&D sections and resources for testing new technologies and systems. These capacities are generally not present in the corporate structure of small mines. (Barnewold and Lottermoser 2020)

Considering the benchmark projects more specifically, it is obvious that mining companies have just started their digital transformation. The opportunities have become obvious to them as well: Attracting younger generations to fill the skill gaps, attracting both shareholders and stakeholders, and, of course, improving productivity and efficiency while cutting cost. However, the upfront CAPEX is significant and not all initiatives generate profit, which is generally not talked about in public. (Matthäus 2020)

Another key insight from the benchmark projects as well as the literature study is that there is a relatively small number of leading OEM's that are driving the digital and automation journeys of the leading global mining companies. For example, behind most of the integrated platforms being implemented globally is Sandvik's OptiMine and AutoMine suite of technologies. It is also the most quoted solution in industry magazines. Some other leading OEM's for automated equipment includes Epiroc, Caterpillar, FLSmith. In addition, these OEM's increasingly work with smaller technology companies and form partnerships to provide additional solutions to the industry. Further, as mentioned earlier, there is evidence of local knowledge intensive mining suppliers (KIMS) such as the Chilean KIMS (Stubrin 2017), which provide customized soltuions in specific areas that cannot be covered by standardized products offered by large global suppliers. However, the general picture seems to suggest that SME's and smaller technology providrs tend to become more dependent on OEMs. However, this cannot be confirmed at this stage from the research and will therefore be more closely investigated in Part II of the study.

However, most definitely collaboration and partnerships have moved to the centerstage of the mining digital transformation. Strategic partnerships are becoming more important and new business models are emerging between OEMs and mining companies, which can also include SMEs or take the form of formalized company consortia or pulic private partnerships as well as less formalized innovation networks. Mining companies have identified the need for innovation and digitalization technologies to increase productivity, efficiency and achieve longer term sustainable growth. Additionally, based on this preliminary analysis, no significant change in mining processes per se will be expected. However, the performance, (resource) efficiency and safety may be increased due to digitalization potentials and technologies by the development and implementation of solutions generated through new business models.

Yet, the research shows that the number of mining companies and projects with an advanced degree of implementation of digital technologies is still limited. In addition, all of the projects that are being discussed in the industry reports, magazines or described on company websites and which show a higher level of implementation are led by major global mining companies. Further, all of those projects undertaking steps towards increased digitalization are highly mechanized and highly automated operations. This means they are located in the top right corner of Figure 9.

Consequently, the fact that only highly mechanized and highly automated operations are being discussed in the accessible literature implies the absence of manual / artisanal and semi-mechanized operations in the current discourse on digitalization in mining. This constitutes a clear gap in the current discussion and poses the question of a potential impact digitalization could have on these sectors of the industry. This is specially important for countries such as Myanmar, where there is no large-scale industrial mining at all in the true sense of the word. Therefore, this will be further elaborated in Part II of the study when also discussing the challenges and opportunities from the current trends and initiatives.

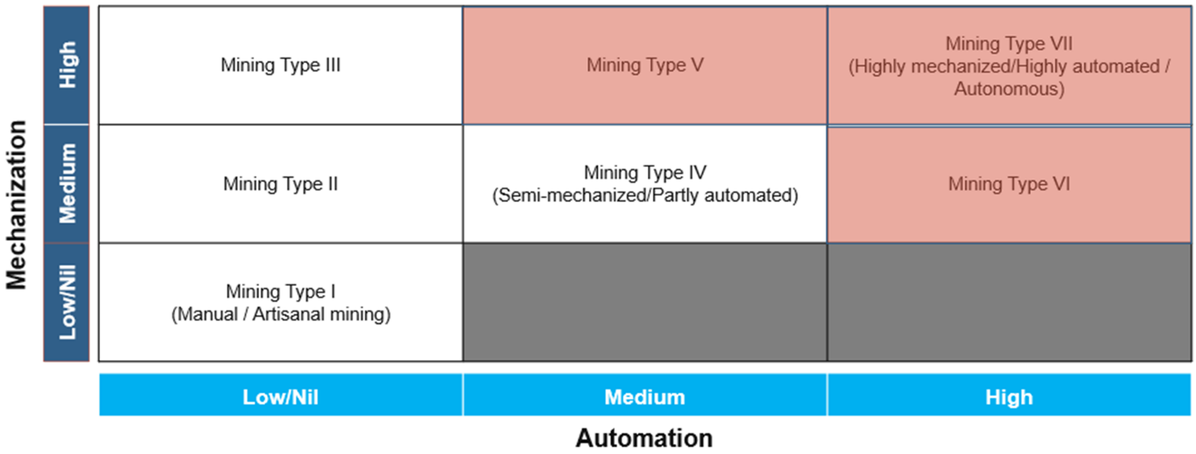

Figure 9: Mining Types by level of automation and mechanization

4. Impacts on Sustainability

This chapter builds on the analyses and insights from previous chapters regarding digitalization trends and mining processes. It now adds a third dimension – sustainability. It thereby addresses the third research question of this report – **What is the potential impact of digitalization in mining processes on various aspects of sustainability?**

The analysis comprises three steps. Firstly, sustainability is defined and the catalogue of sustainability issues underlying the analysis is introduced. Secondly, the sustainability issues are linked with mining processes to indicate which processes are connected to and may impact specific sustainability issues. Thirdly, the digital technologies are included as a third dimension to provide insights into how the transformation of mining processes through digitalization technologies impacts specific sustainability issues.

As stated in the introduction, today's mining companies are increasingly expected to operate more sustainably. This transformation is driven by stakeholders and shareholders, regulators and consumers, communities and policies. Consequently, improving productivity while moving towards more responsible and sustainable business practices is now considered essential for mining businesses – not only to maintain their social license to operate but also to survive as businesses in the long term.

However, the discourse on sustainability in mining is still largely decoupled from the discourse on digitalization. While the former is often focused on the social license to operate and matters of climate change, the latter is often focused on improvements in productivity or OHS. Yet, sustainability has become a matter of business survival and digitalization has become more than a means to realize operational gains. Therefore, this chapter takes a systematic approach at analyzing potential correlations between digital transformation and sustainability issues in terms of if and how digitalization could have an impact on sustainable mine production.

4.1. Terminology & Definitions

The most frequently used definition of sustainable development is from "Our Common Future", also referred to as the Brundtland Report. According to this report, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (IISD 2020) The concept of sustainability is composed of three pillars or dimensions: social, ecological and economic (Figure 10). According to ISO 26000, the three dimensions have been found on the perception of the environment (or ecology, as we mention in this report) being the natural surroundings in which the society and economy function. Both the economy and society are constrained by the ecosystem of the earth. (ISO 26000 2012)

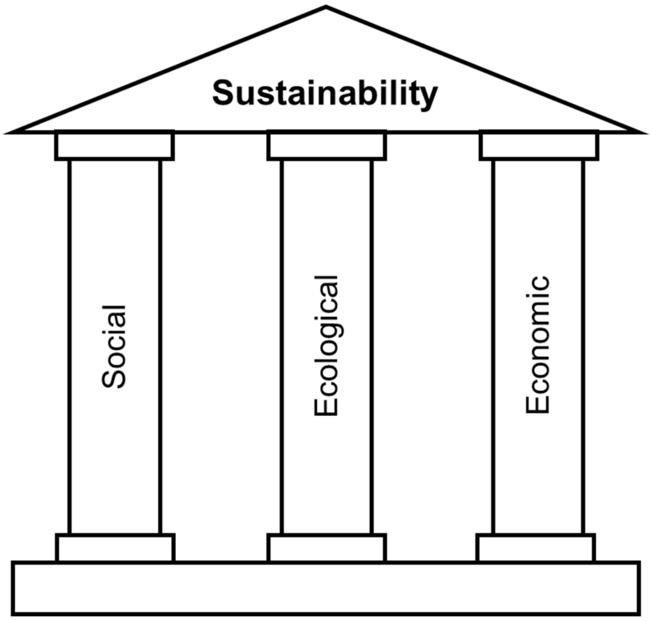

Figure 10: Three pillars of sustainability (adapted from Purvis *et al.* 2019)

Based on definitions from (Beattie 2019), the three pillars can be defined as follows:

Social Pillar: A sustainable business should have the support and approval of its employees, stakeholders and the community it operates in.

Ecological Pillar: Companies approach this pillar with focus on reduction of their carbon footprint, water usage and other issues that will reduce their overall impact on the environment.

Economic Pillar: In order for an organization to be sustainable, it has to be profitable. However, profit at any cost is not aimed for. Instead, criteria as compliance, proper governance or holistic risk management should be considered as well.

While this concept of the three pillars of sustainability (Figure 10) has in fact become ubiquitous, the definition of criteria used to describe sustainability issues in more detail varies. Furthermore, over the last two decades, there has been almost an inflation of standards and initiatives related to sustainability and responsibility in the mining industry. For example, in a 2017 study by the German Ministry of the Environment (Rüttinger and Scholl 2017) on responsible mining, 38 different standards and initiatives in relation to sustainability in mining were compared. While some of these are concerned with responsible practices and transparency in supply chains and finances, many are also addressing different aspects of sustainability.

As mentioned earlier, the mission of the Sustainable Development Goals (SDG) were developed by the United Nations (UN) to improve the wellbeing of the present and future generations. One of these initiatives is the 10 Mining Principles (with Performance Expectations) put forth by the International Council for Mining and Minerals (ICMM 2020b). With the world's leading global mining companies as their member base, ICMM has contributed to shaping the international discussion on sustainable and responsible mining in the last decade. The other initiative that has achieved international attention is the Responsible Mining Index and Framework put forth by the Responsible Mining Foundation, an independent research organization. The RMI Framework focuses on six thematic areas and 43 assessment topics. (RMI 2020) Further, the Extractive Industries Transparency Initiative (EITI) is the global standard that promotes open and accountable management of oil, gas and mineral resources. It ensures transparency and accountability about how a country's natural resources are governed. This ranges from how the rights are issued, to how the resources are monetised, to how they benefit the citizens and the economy. (EITI 2020). Some other examples of initiatives include the Equator Principles and the IFC standards.

In addition to these global initiatives, many attempts for developing sustainability assessment criteria have been put forth in the academic arena also. An example of this can be observed in the PhD study by Pateiro (Pateiro 2008).

However, for the purpose of this report it was decided to use the framework put forth by the BGR (Kickler and Franken 2017) as a starting point. It is a comprehensive framework consisting of issues that provide a suitable context for the analysis intended by this study. These issues are based on the evaluation of 17 sustainability initiatives as developed in the UN SDG. Further, for the scope of the study and the research questions intended to be answered, this provides a suitable framework that is detailed and focused on the three pillars of sustainability rather than the even broader field of responsible mining.

The framework was adapted to include the economic and socio-economic issues of sustainability, which are not included in the original study. Table 4 indicates all the issues and their examples relevant for the purpose of this report based on the three pillars depicted in Figure 10. The detailed definitions of these issues are available in Kickler and Franken (2017) and has been provided in Table 7 – Table 10 in Annex A.

Table 4: 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

4.2. Impact of Digitalization Technologies on Sustainability Issues from a process level view

Based on the sustainability issues introduced in Section 4.1, as a first step of the analysis, the mining processes were mapped with the various sustainability issues to indicate the impact of the individual mining processes on the sustainability issues. According to the researchers, leadership and management processes covers all aspects of sustainability. Keeping this in mind, Table 5 focuses only on the operational processes depicting the results of this analysis.

The analysis is based on the views of the authors in conjunction with insights from the desktop research. Insights from the literature review are based on indirect conclusions as some of the correlations could be derived from the articles, although they were not explicitly mentioned. As stated, the literature review as such did not aim for sustainability issues but for digitalization trends and benchmark projects. It should be mentioned here that this is a preliminary analysis of the complex correlations of sustainability issues and digitalization technologies in mining processes. These correlations which will be further investigated and validated through interviews in Part II of the study with its focus on the global implementation.

To assess the impact of the mining processes on the specific sustainability issues each operational process was analyzed regarding potential impacts based on expert view. The specific impact was differentiated into three levels of impact using the color coding introduced in section 3.1. The impact of each of the 15 digitalization technologies in conjunction with mining processes and process-levels is analyzed regarding their potential impact on any of the defined sustainability issues. The levels of impact were classified for each sustainability issue based on the research results and number of counts for each of the digitalization technology illustrated in Figure 7, along with the expert view of the authors.

Table 6 illustrates the summary of the results of this comprehensive analysis and is a core result of the study. The detailed discussion of the results is described in sections 4.3 – 4.6. Within Table 6 the digitalization technologies are clustered for reasons of clarity into groups for each process level.

Table 11– Table 13 in Annex B includes the detailed list containing each analyzed process level.

Table 5: Correlation between sustainability issues and mining processes (high impact in dark blue)

Sustainability Pillars	Sustainability classifications / Process	Operational							
	Issues	Development	Extraction	Ventilation / Emission	Rock / Roof Support	Haulage & Transporta-tion	Maintenance	Backfilling	Waste & Water Management
Social	Terms of Employment								
	Occupational Health & Safety								
Socio-Economic	Workforce & Local Value Addition								
	Land Use Impacts & Conflicts								
	Material Use								
Ecological	Biodiversity								
	Mine Water Quality & Management (incl. waste water)								
	Energy Use								
	Mine Waste								
	Air Emissions & Noise								
Economic	Economic Efficiency								

Table 6. Impact of digitalization technologies on sustainability issues (high impact in dark blue)

			Social		Socio-Economic			Ecological					Economic
Process Levels	Processes Impacted	Digitalization Technologies / Sustainability Issues	Terms of employment	Operational Health & Safety	Workforce & Local Value Addition	Land Use Impacts & Conflicts	Material Use	Biodiversity	Mine Water Quality & Management	Energy Use	Mine Waste	Air Emissions & Noise	Economic Efficiency
Operational	Dev, Extr, Vent, Rock Sup, Haul, B/fill, Waste/Water Mgmt	Automation											
	Dev, Extr, Vent, Rock Sup, Haul, Main, B/fill, Waste/Water Mgmt	Industrial Internet of Things (IIoT)											
	Dev, Extr, Vent, Rock Sup, Haul, Main, B/fill, Waste/Water Mgmt	Remote Operation Center											
	Dev, Extr, Rock Sup, Haul, Main, B/fill, Waste/Water Mgmt	Connected Worker											
	Main	Robotics											
	Main, Waste/Water Mgmt	Drone Technology											
	Dev, Extr, Rock Sup, Haul, B/fill, Waste/Water Mgmt	Electrification											
	Main	3D-Printing											
Management		Integrated Platforms											
		Advanced Analytics											
		Simulation Modeling / Visualization											
		Cloud Computing											
		Big Data Management											
Leadership		Cybersecurity											
		eLearning											

where, Dev – Development; Extr – Extraction; Vent – Ventilation/Emission; Rock Sup – Rock / Roof Support; Haul – Haulage & Transportation; Main – Maintenance; B/fill – Backfilling; Waste/Water Mgmt – Waste & Water Management

4.3. Impacts of Digitalization Technologies on the Social Pillar

The Social Pillar as defined by the authors in this context includes the following sustainability issues (Figure 11):

Social	
Terms of Employment	Occupational Health & Safety

Figure 11: Sustainability issues related to the Social Pillar

a) Terms of Employment

Level of impact: High

The implementation of digitalization technologies within operational processes is highly affecting the terms of employment of the workforces.

The digitalization technologies that were identified to have the highest impact on the operational processes include highly **automated machines** and equipment or remote-controlled or **remotely operated machines,** connected worker as well as IIoT. As required infrastructure they have a significant impact on the **terms of employment**, in particular on the **productive working time**. This is because higher machine availability through highly automated equipment as well as higher effective working time resulting from remote operations increases the effective working hours for more specific tasks. Especially in mining processes like development, extraction, rock & roof support, haulage & transportation and backfilling, where the distances to the actual working areas is increasing with deeper levels of extraction, the effective working time can be increased using the above-mentioned digitalization technologies.

Through the application of **wearable devices** which includes not only smartphones and tablets, but also smart glasses and watches, the productive working hours can be increased further. That is achieved by supporting employees with (additional) information, evaluation and instructions through digital devices. Wearable devices additionally allow the monitoring of persons regarding the use of machine equipment or localization applications. These applications may have a negative impact on personal rights and privacy of the workforces, which need to be considered.

Additionally, **drone technology** is becoming increasingly important regarding the possibility of gathering specific monitoring data, which can be collected remotely. This saves working time for effective production by eliminating the need for workers manually collecting such data.

b) Occupational Health & Safety

Level of impact: High

The application of the digitalization technologies in the different operational processes is highly affecting the OHS issues within the mines.

Firstly, **OHS management** is supported by the implementation of **integrated platforms** which assist through data management, data processing and analysis as well as monitoring of processes and incidents such as detection of gases, seismic events, accidents as well as the health status of employees.

Secondly, through the relocation of employees away from hazardous areas, especially in underground mining environments, to safer environments such as **Remote Operation Centers** and control rooms on the surface, the number of accidents and injuries can be significantly reduced. Further, more attractive workplaces help to keep workers motivated.

Thirdly, the use of highly **automated** machinery, which is also equipped with sensors for collision avoidance, positioning and navigation, supports the decrease in accidents and injuries and therefore has the potential to reduce **workplace hazards**. Furthermore, automated equipment utilized in particularly hazardous areas, such as rock & roof support works, helps to further minimize workplace hazards. Drone technology used for inspections in unsafe areas is again reducing the exposure to workplace hazards.

Especially in combination with **connected workers**, who are using **wearable devices**, which are becoming increasingly integrated into the **personal protective equipment (PPE)**, the number of accidents and injuries can be further reduced. The advanced PPE, including wearable devices (sensors), is giving warning signals or alerts if highly automated equipment or remote-operated mobile equipment is approaching a worker. That helps avoiding potential collisions between machines and workforces.

Furthermore, the existing **OHS training** methods can be adapted and optimized for the application of **simulation modelling and visualization technologies** such as VR or AR. These technologies offer the possibility of increasing the workers' awareness of specific hazardous incidents or situations potentially occurring in the different operational processes without the risk of physically putting the workers in this situation. Also, regular trainings can be conducted through various **eLearning** tools and platforms to make sure personnel are always up-to-date from an OHS point of view. Health & safety risks may change through newly deployed technologies such as highly automated or remote-operated mobile equipment and training needs to be adapted accordingly. This reduces the risk of mishandling complex machinery, as during maintenance works.

4.4. Impacts of Digitalization Technologies on the Socio-Economic Pillar

The Socio-Economic Pillar includes the following sustainability issues (Figure 12):

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

Figure 12: Sustainability issues related to the Socio-Economic Pillar

a) Workforce & Local Value Addition

Level of impact: High

Within the different operational processes the digitalization technologies have a highly impact on the workforce and local value addition.

The **local workforce** can benefit from digitalization technologies such as wearable devices, which are supporting the activities in the specific operational processes with actual or additional information, evaluation and instructions. The shift towards connected workers requires continuous education and training of the employees. E-Learning is a digitalization technology which has the potential to impact the (local) workforces in all mentioned operational processes. At the same time, the number of (local) employees is reduced by trends towards highly automated or remote-operated machine equipment, which can be controlled and monitored from a Remote Operation Center.

The IIoT is highly affecting the **(local) procurement process**, especially through the development of process integration and interoperability. To give an example, the required materials and products within the operational processes such as machine components, spare parts but also substances and other goods and supplies can be automatically ordered using the respective software applications. Since the expertise for a lot of the very advanced equipment and technologies lies with a smaller number of global OEM's, there is the potential for a negative impact on local procurement through this development. However, local procurement could be strengthened through service contracts in relation to digital or automated equipment if the capabilities are available in the region or can be developed locally – at least by service branches or hubs of globally acting OEMs. This is strongly dependent on the region, where the mine site is located. . Furthermore, the (local) procurement process can be optimized by implementing 3D printing, which has the potential to be substitute conventional supply and ordering processes.

Community Initiatives can potentially benefit from simulation modelling and visualization technologies, which can be used in this context for creating transparency and informing local stakeholder groups about planned activities or operations and the specific impact of the operation. The German Bundesgesellschaft für Endlagerung (BGE), which is the operator of final diposals of radioactive waste in Germany is one example, for involving the community and specific community initiatives in complex topics using such simulation and visualization technologies. In this context the technologies are used for information purposes about actual processes and consultation of local community. But as well many international mining companies are working together with technology companies for embracing such technologies. The company LlamaZOO develops together with mining companies digital twins of the mines for mine planning and community engagement. (AME 2020; BGE 2020; LLama Zoo 2020)

b) Land Use, Impacts and Conflicts

Level of impact: Medium

The implementation of digitalization technologies influences the following examples on a medium level.

Digitalization technologies such as **simulation modelling and visualization** can be used to support integrated approaches for **land-use planning**. Along the same lines, the implementation of **IIoT** implies that sensor data and resulting information about geology, groundwater, biodiversity, emissions and mining damages become available and can be used for the modelling and simulation of different future scenarios. Consequently, with these technologies the land-use planning is becoming more detailed and sophisticated. In addition, the application of **drone technology** is becoming increasingly important for land-use planning and surveying along with monitoring of tailings dams.

With respect to **conflicts with the community**, it is conceivable that simulation and visualization technologies can support the dialogue with stakeholders and local communities (see above: community initiatives) by increasing transparency, information and understanding about the operations and any planned activities as well as their impact on the community. On the other hand, these technologies can be questioned by specific stakeholder groups, regarding contradictory opinions and doubts on the presented technologies.

Further, such modern approaches help to reduce the risk of actual incidents posing hazards such as landslides, tailings dam failures or subsidence.

c) Material Use

Level of impact: High

Integrated platforms with their related technologies (IIoT, sensors, data analytics etc.) can have a high impact on the **efficient use of natural resources (& recycling)**. Based on the information that becomes available from the **IoT devices** such as **sensors** and its analysis and consolidation within the integrated platform, mining companies can control production and planning much more accurately. Through better knowledge about the mineral deposit and the actual production process as well as the composition of the mineral that is being mined, it is possible to increasingly minimize the ratio of waste rock to valuable material. This has a direct impact on the efficient use of natural resources, but also allows mining companies to economically mine lower grade ores. The more selective mineral extraction becomes, the less unnecessary energy is used for the extraction, transportation and processing of waste rock.

4.5. Impacts of Digitalization Technologies on the Ecological Pillar

The Ecological Pillar includes the following sustainability issues (Figure 13):

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

Figure 13: Sustainability issues related to the Ecological Pillar

a) Biodiversity

Level of impact: Medium

Legally protected areas, which are designated by the government for the conservation of biodiversity, can be affected by digitalization technologies on a management process level. According to the Good Practice Guidance for Mining and Biodiversity the Environmental Management System (ISO14001) contains a Biodiversity Action Plan (BAP). The monitoring of changes in biodiversity is a central element of the mentioned BAP, which can be supported by **IoT devices. Sensors** can be used for assessing and monitoring biodiversity in legally protected areas over a specific period of time to analyze changes. For example, the variety of different species within the geographic area can be documented using IoT devices like installed thermal imaging cameras and applied analysis methods, which require transparent and scientifically rigorous procedures as well as the use of external experts. The vegetation can be monitored using GIS databases and specific position information. (ESRI 2020) This process can also be supported by other technologies such as **drones**. Algorithms are known that transform data of drone flights into calculations of bio masses. The information can be integrated in **IIoT platforms** and monitored and analyzed regarding the changes over specific time periods. The same applies for legally unprotected areas. Phenomena such as **threatened & invasive species and ecosystem services** as well as detection of contaminations can potentially be positively affected in a similar way using these technologies.

b) Mine Water Management

Level of impact: High

Water management, which spans all operational processes, can potentially be strongly affected by digitalization technologies. These include **IoT devices** and **sensors**, which can gather data about the water quality, quantity of use etc. These devices are then integrated into **IIoT platforms**, which are supporting water data management, processing and analysis of quality & quantity as well as monitoring of and warnings about critical events such as floodings. The monitoring and prediction of floodings can be implemented by installing or accessing wireless sensors connected with the IIoT and thereby to computational models using advanced analytics to provide real-time data and analyzation of water levels. (Arshad *et al.* 2019) These technologies also have the potential to positively affect surface **water flows, groundwater** use as well as **mine dewatering & pit lakes** in similar ways.

Waste water management processes can also be highly affected by the implementation of digitalization technologies. **IoT devices** can be used for monitoring the quality of water, surface or groundwater bodies related to existing water quality criteria. Furthermore, the identification of acid rock / mine drainage (AMD) is supported by digitalization technologies such as IoT devices and sensors. The use of **simulation modelling and visualization** technologies is supporting measures to avoid, prevent and minimize the occurrence of AMD by improving monitoring and waste handling.

Combining standardised measurement methodology with prediction models for the estimation of emissions or dispersion helps to also assess the effectiveness of actual or future mitigation efforts. Site-specific data makes these approaches a valuable decision support tool in environmental and water management.

c) Energy Use

Level of impact: High

The energy use of mining companies is highly affected by the implementation of digitalization technologies.

Energy use is a huge cost factor for mines and therefore a lot of focus has been placed on reducing energy consumption, for example in relation to diesel and fuel consumption in haulage processes but also in relation to ventilation cost. Efficient energy use can be increased through the utilization of highly automated or remotely operated machine equipment in all operational processes as well as through the application of ventilation on demand technologies. Improvements in this field allow to sustainably reduce the ecological footprint as well as the OPEX of the mining operation at the same time.

In addition, **IoT devices** and **sensors** can collect data on the energy use of equipment, which can then be analyzed by using **advanced analytics** and **big data management** to determine patterns of energy consumption and search for ways to optimize equipment utilization in order to use energy such as fuel more efficiently. This can be done directly on the machine or as part of the overall analyses done through the integrated platforms.

Furthermore, the shift towards **electrification** of different pieces of equipment, especially those used for material transport and other vehicles in underground mining environments, is affecting energy-use. The shift to electrified or battery-powered equipment leads to a more efficient use of energy.Furthermore, the substitution of vehicles with combustion engine with electric-powered equipment leads to reduced energy regarding ventilation aspects.

d) Mine Waste

Level of impact: Medium

The highest impact on **reducing emissions** is to be expected from the shift towards battery-powered equipment, especially in underground operations. This will also have a huge impact on surface operations which use large fleets of haul trucks, conveyor belts and trains covering long distances. As for all footprint evaluations of battery technologies, the individual performance depends also on the actual energy mix used to charge the batteries at each mine site.

In addition, there is a medium impact of digitalization technologies expected in the support of mine **waste management processes**. The term mine waste refers here to derived 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 implementation of digitalization technologies such as IoT devices such as sensors in mine waste management can support the monitoring of mine waste and emissions into the air, water and land.

Management tools such as **integrated platforms** can be used to monitor and analyze data from the IoT devices and sensors related to mining waste and emissions. Using **data analytics**, the potential impact on the environment can be minimized or, in some cases, potentially even prevented by optimizing haulage logistics (i.e. optimum routing).

The application of **IoT devices** allows furthermore the monitoring of **backfilling** material (such as mine wastes) in specific areas of the mine. Failure of backfill can lead to catastrophic events. Continuous monitoring of the backfilled areas can lead to prevention of such catastrophies. In a same way, the monitoring of **tailing dams** can also be supported using IoT-devices such as **sensors**. Using IoT platforms, advanced analytics and simulation modelling and visualization technologies can support the monitoring of potential events and help evaluate risks and hazards related to tailings dams, such as cracks or dam failure..

e) Air Emissions & Noise

Level of impact: High

Air emissions & noise is potentially highly affected by the implementation of digitalization technologies. The application of **integrated platforms** allows a comprehensive overview, analysis and monitoring of air emissions in several operational processes such as development, extraction, haulage, and ventilation and also during and/or after mine closure. The **IoT devices** installed on the mobile equipment or within the mine infrastructure are measuring the emissions. Using this kind of information on a management process level for planning, coordination and control, measures can be taken to counteract e.g. the emissions of specific machines by substitution or technical adaptations such as filters. **Advanced analytics** and **simulation modelling** and **visualization** can be used for evaluating the most effective ways to optimize processes and equipment use. The same applies to the monitoring of **noise, vibration, dust & other emissions** which occur in all operational processes.

4.6. Impacts of Digitalization Technologies on the Economic Pillar

The Economic Pillar is represented by one sustainability issue and related examples of digitalization technologies (Figure 14):

Figure 14: Sustainability issues related to the Economic Pillar

a) **Economic Efficiency:**

Level of impact: High

The economic pillar is highly affected by the implementation of digitalization technologies in operational as well as management and leadership processes. Technologies such as **advanced analytics** can potentially have a high impact on the management process level since they are used to optimize profitability by analyzing possible optimization of processes, equipment utilization and deployment of resources (including the workforce) and thereby achieve cost reductions in specific operational processes. Advanced Analytics is also applied to analyze the actual and future demands for mineral products. Furthermore, market prices for the mineral products but also for the supply of resources required for production (e.g. electricity) and their potential future price developments can be evaluated using the same technology. Freeport McMoran conducted an analysis on the impact of operational costs and commodity price forecast within a feasibility study cash flow model in a greenfield iron ore mine project. The results show, that refining, energy and transportation costs account major part of the iron ore operating costs. Using this kind of information, project risks such as increase of operational costs by 30% can cause decrease of Net Present Value (NPV) by nearly 50%. (Duru 2020) By the same token, commodity markets may profit from increased transparency as mentionedearlier.

In addition, the implementation of **highly automated or remote operated equipment**, while requiring initial higher CAPEX, leads to higher productivity of the machines and can therefore reduce OPEX, such as for energy-use as well as personnel cost. Studies have shown that automated equipment is working more productively since there are no interruptions in processes due to shift changes and the equipment can work 24/7 leading to higher utilization rates, while also working more effectively thus reducing the consumption of fuel. For example in the Kidd Creek Mine in Ontario Canada, the effective production hours of Load Haul Dump (LHD) equipment was increased by 30% and the specific utilization of each LHD was decreased by 12% through the implementation of highly automated machine equipment. (Jakobs 2020)

Another example is the Syama Project in Mali operated by Resolute Mining. Here 15 million US$ were invested in modern highly automated drilling, LHD and Haulage machine equipment, which leads to an operational cost reduction of 135 US$ per ounce gold. The annual production is 300.000 ounces, which leads to a potential operational cost reduction of approximately 40.5 million US$ per year. (Jakobs 2020) The **electrification** of operational processes can also affect the CAPEX and OPEX of an operation. Diesel-powered machines can be substituted by electrified or battery-powered ones, which improves air quality, especially in underground environments, thereby reducing ventilation costs. This can lead to a reduction in the energy costs which in turn will have an impact on the OPEX. (Matthäus 2020)

5. Conclusions

The main objectives of Part I of this study were to provide a comprehensive understanding of digitalization in mining, including leading trends and technologies dominating the current transformation in the industry, on a process-level of mining and to conduct a preliminary analysis of the impact these trends and technologies could have on various dimensions of sustainability in mining, based on a process-level view of mineral production.

Through an empirical analysis, 15 relevant digital technologies were identified and and three process levels (operational, management and leadership process levels) as well as eight distinct operational processes for mineral production were defined. After analyzing the impact of the technologies on these processes, the potential impact on sustainability was analyzed along the social, socio-economic, environmental and economic pillars of sustainability.

Part I ends with some concluding remarks and an outlook on Part II of the study.

As stated in the introduction, digitalization in mining is largely driven by two factors. The first driving factor is the need to increase productivity and safety. The second driving factor is the need to reduce operational cost in order to cope with challenges mining operations are facing, such as declining ore grades, more complex, remote or deeper deposits as well as volatile commodity prices.

The preliminary results of this study suggest that there is the potential for a close interrelationship between the economic drivers (increasing efficiency and productivity) and improving sustainability performance. This is particularly relevant for the areas of safety (social pillar), process optimization and optimizing equipment utilization (economic pillar). In addition, the reduction of resource use, including material use, water and energy consumption and the reduction of air and noise emissions (socio-economic pillar and environmental pillar) are also relevant aspects in this regard.

This suggests that mining companies could most probably benefit from combining these two objectives and potentially achieve better results in both productivity improvement and sustainability performance by doing so. To this end, the increasing volume of data available today could be used to impact not only productivity but also sustainability KPIs. To meet these objectives, mining companies need to focus on what kind of information needs to be derived out of the increasing ("big") data volumes in order to improve not only productivity but also other sustainability issues.

However, one of the main challenges mining companies yet need to master on a broader scale is finding ways of creating actual added value from the available data to support decision-making processes. While various technologies have evolved over the last decade with respect to increased computing power and capacity, storage capacity, as well as improved sensor and communication technologies, mining is still at the beginning of realizing the vision of a digitally connected, data driven, autonomous and sustainable mine. While digitalization trends often focus on different technologies aiming at autonomous mines and machines, many of these technologies and trends have not yet been implemented by industry, the industry has a way ahead to realize the potential, not only of economic improvement but of improved sustainability performance through digital technologies.

These emerging technologies aiming at autonomous mines and machines are characterized by connected and integrated machinery and processes, environmental perception and self-perception, optimization, M2M-communication, localization and optimization. While many of these concepts are strongly discussed and elaborated on the level of research, the actual level of implementation is still very low, which was also confirmed through the review of selected benchmark projects.

Instead, the analysis of the benchmark projects indicates that, in most cases, the implementation of digitalization at a specific mine site is focused on a particular mining process or area within the operation such as drilling and blasting, fleet automation and production. Thus, the implementation of all the digitalization technologies that emerged through the keyword research at a single mining operation could not be observed. Similarly, at this stage and in the near future, the emergence of new processes or new business models through digitalization technologies cannot yet be observed nor has it been discussed in the literature that was reviewed nor the benchmark projects that were analyzed.

The current focus, as suggested by the empirical analysis of the 15 digitalization technologies, is on automation of processes, predominantly drilling and hauling processes, as well as on the implementation of integrated platforms and related technologies (especially visualization / simulation, advanced analytics, and IoT devices). While the largest impact from automation is on the operational process level, current digitalization initiatives have the largest impact on the management process level. Integrated platforms and related technologies aim and creating real-time knowledge and control of all processes and equipment in order to optimize them. This increased transparency of what is actually happening anywhere in the mine at any given time in conjunction with the ability to adjust and compare plans and actuals, the preliminary analysis in this report suggests, is currently having the strongest impact on global mining operations.

It should be noted, though, that the study focused on digitalization trends from a technology perspective. Nevertheless there are many challenges when it comes to implementation, which are not only technological nature such as standardization, legal issues or interoperability. Some of these challenges will be addressed in part II of the study, which will focus on a more detailed analysis of the level of implementation from a global perspective.

With regard to the level of implementation of digitalization technologies, another important finding of this study is that the analyses of this report show a clear gap in the current discourse on globalization with respect to ASM. While none of these mining types were excluded from the keyword search, it became obvious from the literature review that current discussions of the industry are focused exclusively on highly mechanized and highly automated operations. However, while the current wave of digital transformation, albeit still in its early stages, is taking place predominantly at large-scale highly mechanized and automated mining operations, it is conceivable that digitalization technologies could also have an impact on other types of mining practices and operations. It is also conceivable that smaller operations and companies could benefit from digital initiatives, which is why this particular topic will be further addressed in part II of this study through expert interviews. In addition, it was observed from this study that not only is digital transformation being discussed and implemented at a limited number of large-scale mining operations, the transformation is also largely driven or dominated by a similarly small number of leading OEM's and technology providers. Considering these observations in conjuction with a final observation, which is that digitalization initiatives are most often focused on specific areas of an operation or specific technologies and processes and rarely span the entire operation, it can be stated that the digital transformation in the mining industry overall is indeed still in its early stages.

Part II of the study will expand on the preliminary findings from this study, especially with respect to drawing a more detailed and differentiated picture of the level of implementation on a global scale taking into account different influencing factors such as type of commodity, mining method, geographical region and size of the operation to gain a deeper understanding of the heterogenous transformation towards digitalized mining. In this context, some aspects that were raised in section 3.3. will be expanded upon through insights gained from a series of expert interviews. In addition, part II will also take a closer look at who may benefit most from digitalization initiatives and who may be left behind in the current transformative wave. Thirdly, the impact on sustainability will be analyzed from a global perspective taking into account a possible regional differentiation.

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Annex A

Table 7: 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 8: 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 9: 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 10: 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

Annex B

Table 11: Detailed process level view on digitalization and sustainability for Operational processes in mining

Process levels	Processes	Digitalization Technologies / Sustainability Issues	Social		Socio-Ecomomic			Ecological					Economic
			Terms of employment	Occupational Health & Safety	Workforce & Local Value Addition	Land Use Impacts & Conflicts	Material Use	Biodiversity	Mine Water Quality & Management (incl. waste water)	Energy Use	Mine Waste	Air Emissions & Noise	Economic Efficiency
Operational	Development	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearables)											
		Electrification											
	Extraction	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
		Electrification											
	Ventilation / Emission	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
	Rock/Roof Support	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
		Electrification											
	Haulage & Transportation	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
		Electrification											
	Maintenance	3D-Printing											
		Drone Technology											
		Robotics											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
	Backfilling	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
		Electrification											
	Waste & Water Management	Automation											
		Remote Operation Center											
		IIoT (Smart Sensors, Interoperability, Process Integration)											
		Connected Worker (Wearable Devices e.g. Smartphones, glasses)											
		Drone Technology											
		Electrification											

Table 12: Detailed process level view on digitalization and sustainability for Management processes in mining

			Social		Socio-Ecomomic			Ecological					Economic
Process levels	Processes	Digitalization Technologies / Sustainability Issues	Terms of employment	Occupational Health & Safety	Workforce & Local Value Addition	Land Use Impacts & Conflicts	Material Use	Biodiversity	Mine Water Quality & Management (incl. waste water)	Energy Use	Mine Waste	Air Emissions & Noise	Economic Efficiency
Management		Simulation / Visualization (AR, VR, Digital Twins, SIC, DARQ)											
		Cloud Computing											
		Advanced Analytics (ML, AI)											
		Big Data Management (Predictive Analytics)											
		Integrated Platform											

Table 13: Detailed process level view on digitalization and sustainability for Leadership processes in mining

			Social		Socio-Ecomomic			Ecological					Economic
Process levels	Processes	Digitalization Technologies / Sustainability Issues	Terms of employment	Occupational Health & Safety	Workforce & Local Value Addition	Land Use Impacts & Conflicts	Material Use	Biodiversity	Mine Water Quality & Management (incl. waste water)	Energy Use	Mine Waste	Air Emissions & Noise	Economic Efficiency
Leadership		eLearning											
		Cybersecurity											

Bundesanstalt für
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und Rohstoffe

Bundesanstalt für Geowissenschaften und Rohstoffe
(Federal Institute for Geosciences and Natural Resources)
Stilleweg 2
30655 Hannover

mineralische-rohstoffe@bgr.de
www.bgr.bund.de

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