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ORIGINAL PAPER

Understanding technology in mining and its effect on the work environment

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Abstract
This paper takes its starting point in the fact that many mines have managed to improve its work environment, with regards to, for example, accident occurrence, while at the same time having stopped seeing improvements in these areas even in the wake of technology interventions. Technology projects in the mining industry continue to make claims on further improvements to the work environment, and make wider claims still, but have not addressed underlying causes that lead to underperformance of technology in terms of work environment improvements. This paper suggests that when we look closer at the situation, we find a complex situation in which negative and positive effects on the work environment follow the implementation of new technology. The analysis conducted in the paper further suggests that this has to do with mining environments having reached a level where historically major risks have been addressed; remaining risks, which are still significant, are of such a nature that their singular treatment — attempting to address these risks through isolated action such as new technology — engenders risks elsewhere. At the same time, the mining industry is of such a character that technological sophistications will fail to ultimately address the fundamental underlying causes of technology's underperformance; technology by itself will never be enough. In part, this is due to constraints stemming from the characteristics of the mining industry, resulting in lower and slower technological progress for instance. The paper, thus, proposes a shift in focus with regards to technology, from technology itself to the processes surrounding the development, implementation, and use of technology in the mining industry. The paper, then, outlines some requirements for such a process.

Keywords Mining · Technology · Social sustainability · Health and safety · Sociotechnology

Introduction

This paper investigates the complex relationship that exists between new technology in the mining industry and the effect of this technology on the industry's work environments. The mining industry has a long history of using technology to overcome and solve problems such as work environmental and productivity issues. Indeed, the development and use of new mining technology have increased productivity, and these developments have also coincided with a general improvement of the work environments of the mining industry (Lööw and Nygren 2019; Lööw 2020). The development of new technology in the mining industry continues to address challenges such as these. The advent of digitalisation, for example, promises to help mines to remain competitive while at the same time offering operators comfortable jobs in control rooms (Lööw et al. 2019). However, it would be erroneous to believe that only positive effects follow from new technology, or that these positive effects occur automatically. In fact, a closer examination of the relationship between new technology in the mining industry and its effect on the work environment reveals a complex relationship, one in which unequivocal positive effects rarely surface.

In part, the apparent complexity of the relationship between new technology and work environment effects stems from difficulties in determining the exact effect of new technology in the first place. This difficulty, in turn, partly lies in the fact that only rarely has mining technology developed revolutionarily — that is, brought about significant changes overnight, providing a clear "before-and-after," the base upon of which studies could investigate the outcome of technology implementations. Change has instead

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been evolutionary and incremental, as has been the case with productivity (Bartos 2007; Hartman and Mutmansky 2002); thus, effects have emerged over time.

For work environment improvements, the development and implementation of new technology in the mining industry have a more ambivalent relationship still. While one can discern a positive development in terms of, for example, the occurrence of the number of lost-time injuries in the mining industry, the true status of the work enviroment can seldom be deduced from singular indicators, because work environment improvements are not unequivocal (Blank et al. 1998). For example, previous studies have shown that technology that has offered better protection from rock fall also meant an increase in lone working and the stress associated with such a situation (Eriksson 1991); that new technology may reduce fatal accidents but increase the number of accidents in general (Blank et al. 1996); and that not all benefit equally from new technology (Laflamme and Blank 1996). Furthermore, studies of mining industry technology have found that only a third of technology projects take active consideration of the operator in their design (Horberry and Lynas 2012). With this lack of focus, we can expect only limited positive effects on the work environment.

If one were to go by only a few indicators to determine the relationship between new technology and its effects on the mining industry's work environments, this too presents a problematic picture. For instance, in many countries, the improvement rate of the accident frequency rate has tapered off so that the rate is stable but elevated (compared to other industrial sectors) (Lööw and Nygren 2019; Lööw 2020). Furthermore, while it is clearer that the industry's safety record has improved, it is harder to determine if health effects have been as positive. Indeed, studies suggest that health problems have increased in the mining industry. The European Commission found that in 2007, the mining industry was the economic sector with most work-related health problems in the European Union (European Commission 2010). And that study also showed that the number of work-related health problems in mining had increased — rising more in mining than in other sectors. Yet, safety statistics had simultaneously improved, and improved more in mining than other sectors. Regardless of either development, the mining industry often still is the industry most susceptible to fatal accidents (Lilley et al. 2013), and Elgstrand and Vingård (2013) reported that "Where reliable national statistics exist, mining is generally the sector having the highest, or among 2–3 highest, rates of occupational fatal accidents and … occupational diseases."

As such, while the development and implementation of new mining technology are motivated by their ability to improve the work environments of the mining industry, often technology falls short of these goals. This is especially problematic today as new mining technology makes even wider claims regarding its positive effects: technology will help secure social licences to operate (Price 2019), ensure access to a new and younger workforce (Albanese and McGagh 2011; PwC 2012), and so on. These goals are laudable. But, worryingly, as we have no indication that previous issues with the development, implementation and use of new technology in mining have been addressed, there is a significant risk that these new project will fall short of accomplishing their intended goals.

It is on this foundation that this paper offers an analysis of the relationship between mining technology and the mining industry's work environments, and attempts to explain why mining technology does not continue to improve the work environments of the mining industry, why it fails to reach its intended effects.

On the scope, structure and material of the paper

Whereas previous studies have looked at technology itself (including its use and development) to establish the lack of consideration of, for example, the operator, this paper takes an interest in the other side of the equation: the situation for and in which mining technology is developed and implemented. As such, this paper looks at the current situation of, first, health and safety in the mining industry to explore how technology can fit into the puzzle of further improving this siutation and why, currently, technology remains partly unsuccessful in this regard. The analysis then continues to explore what happens to the work environments of the mining industry in the wake of technology. The analysis then turns to the conditions of the mining industry to outline the constraints imposed on new technology, particularly with regards to the work environment. The final part of the analysis discusses how the situation, and the causes of this situation, could be rectified.

The analysis presented in this paper will have some important constraints. First, the discussion on issues of the work environment presupposes a certain type of work environment; the analysis concerns those work environments that have reached a certain level of "maturity" or "performance," that is, a certain level of mechanisation, for instance, or a relative absence of the most rudamentary risks. This is to say that the analysis is not applicable to all mining activities and is demarcated for artisinal mining activities, for example. Further, the analysis focuses on a few phenomena that will serve to illustrate a larger area of concern. For example, the delving into the health and safety siutation will focus on a few issues that bring the problems of concern in this paper to their edge. This is a significant delineation but one that is necessary to be able to ground a discussion on technology and its relation to these issues; many topics of technology and their relation to health and safety remain under-explored, at least with regards to the role that the conditions of the mining industry, themselves, play in the situation. Here, the argument is that this will *remain* under-explored unless we can establish the significance of these topics for ensuring new mining technology's capacity to address the work environment — establishing this significance, and its implication for the development and implementation of new technology in mining, is the purpose of this paper.

Large parts of the discussion conducted in the paper are based on the author's experience with and involvement in research and development projects on new mining technology. These projects have focused on developing and demonstrating technology such as battery-powered mining machines, semi-autonomous chargers and positioning systems. The author's involvement in these projects have been to investigate effects on the work environment and other closely related areas. Many of the arguments in the paper are an attempt to express some general problems that surfaced in these projects with regards to the technologies' ability to improve upon the work environment.

Finally, the effects described and the mechanisms suggested to be at play in this paper are, by themselves, not necessarily specific to the mining industry. However, as detailed in the later sections of this paper, the particular configuration of these aspects are unique to the industry, and presents it with a particular challenge. That is, the mining industry requires unique interventions even if the problems it experiences are general.

The relation between health, safety, and technology in mining

With regards to the relationship between technology and work environment improvements in the mining industry, this paper identifies the problem to be that of technology failing to accomplish these intended improvements. While technology in the mining industry has managed to improve the work environment — for example, playing an important role in improving the accident frequency trend during the 1900s in Sweden (Lööw and Nygren 2019) and the USA (Hartman and Mutmansky 2002) — the problem identified here is, on the one hand, that some of the potential of technology to improve the work environment remains unrealised and, on the other hand, that technology introduces new risks alongside its improvement upon other risks. In particular, this and later sections will argue that the notion of technological measures as isolated actions to be significant contributing factors to the under-performance of technology with regards to work environmental effects.

On this note, this section takes as its starting point the fact that, as was shown in the introduction, the momentum of improving the accident frequency rates in mining activities of many countries has slowed down, so that the rate is stable but elevated; as its second, that the resultant effects on the work environment are harder to determine as largely positive once more perspectives are taken into consideration. The analysis in this section, then, will attempt to provide an explanation for past improvement and the barriers to further improvements.

To conduct such an analysis, we are helped by adopting the view that accidents and ill-health depend on the presence of harmful energies. Haddon (1963) introduced this perspective, arguing that for an accident to occur, an energy must interact with a vulnerable object; when this energy surpasses a certain threshold, damage occurs. The model is also applicable to health issues, as these can still be understood as energies interacting with vulnerable objects: suffocation, for example, is an interference with normal energy exchange (Haddon 1963). In any case, improving health and safety becomes a question of reducing exposure to energies (be those energies in the form of potential energies, and the like, or harmful substances). To this end, Haddon introduced the hierarchy of control, stipulating that accidents can be protected against, most effectively, in the following order (Haddon 1973; Harms-Ringdahl 2013):

1. Eliminate the energy
2. Restrict the magnitude of the energy
3. Safer alternative solutions
4. Prevent the build-up of an extreme magnitude of energy
5. Prevent the release of energy
6. Controlled reduction of energy
7. Separate object and energy:
    a. in space
    b. in time
8. Safety protection on the energy source
9. Personal protective equipment
10. Limit the consequences when an accident occurs

This view, that of accidents and ill-health occurring in interaction between energies and vulnerable objects, offers an explanation of technology's relationship with an improved work environment in the mining industry: the largest improvement to the work environment in the mining industry came in the form of improving upon quite a rudimentary situation; accident and ill-health arose from more or less obvious exposures to harmful energies where technology could offer protection or contribute to decreasing this exposure. As technological development has progressed, however, these "low hanging fruits" have become fewer. Thus, the manner through which technology can continue to improve protection and further decrease exposure is less obvious. The slowing down of the improvements to the accident frequency rate is, in other words, due to the problems that technology can address, most readily and directly, having now been addressed; technology implementations are starting to hit diminishing returns, in that many work environment issues are at such a level that there are no immediately obvious actions, that is, actions that clearly improve upon the current situation without unintended effects elsewhere. (Note that many mining operations still face dire situations in terms of workplace accidents. The argument presented here is not really applicable to such cases, because these have yet to use technology to address the rudimentary risks. Additionally, in many cases productivity in mining has increased due to new machinery having increased their capacities (Hartman and Mutmansky 2002); because productivity in mining relates to volume moved per unit of time, energy intensity has increased.)

Note, also, that in the energy model technological interventions relate directly to the first six interventions; the remaining four imply organisational measures or depend on the individual. Technological measures, measures of the higher-order, still leave behind risks, sometimes called "residual risk" (Nyoni et al. 2019). Such risks need other solutions than technology, such as organisational measures (Lööw and Nygren 2019; Komljenovic et al. 2017). The residual risks could be considered trivial, in a sense, but are still responsible for many of the accidents that occur in the mining industry (Lööw and Nygren 2019). It is hard to justify higher-order measures for these risks. Lööw and Nygren (2019) argued:

> Consider slip, trip and fall accidents: while energy is certainly a part of these accidents (i.e. kinetic energy), technology is not as readily able to offer protection. People trip because of irregularities in the floor, for exemple. Here technology can only protect the operator to the extent that it either separates the operator from irregularities in the floor or results in more regular floor surfaces.

Technology, in other words, stops being a reasonable sole measure at some point. Yet, when technology is suggested as an appropriate measure to improve the work environment of the mining industry, technology is suggested for an environment that, to a large part, is made up of residual risks. When we then have to do with a situation that requires organisational measures, such as fostering safe behaviours, the applicability of the energy model diminishes. With this, we lose the simple relationship between technology and protection against energies; approaching the improvement of the work environments of the mining industry through technology with these assumptions is a likely contribution to the equivocal effects on the work environment.

It is of course debatable whether there ever were such a time during which technology had unequivocal positive effects on the working environment. Likely, the outcome of technology implementations has always been multifaceted, engendering both positive and negative effects. The argument here, however, is that the final, aggregated effect has been positive in the past, whereas presently, we may be more doubtful as to the balance between positive and negative outcomes. One example of this is the period of 1999 and 2007 in the European Union, investigated by the European Commission (European Commission 2010) (mentioned in the introduction). That study found that the mining industry of the European Union experienced a positive trend with regards to its accident frequency rate (though all sectors displayed a positive trend, mining saw one of the largest decrease in accidents) while at the same time experiencing an increase in the rate of work-related health problem. This increase in work-related health problems was greater in mining than in other sectors, and the rate of 2007 was the highest of all economic sectors in the European Union. Such developments point toward the notion that new risks are introduced alongside new technology, that technology implementations have had unintended side-effects.

We can continue the analysis with reference to the hierarchy of control. This analysis, in short, suggests that the effectiveness of measures varies according to the addressed problem. This is important because, one, the situation that technology will have to address is one where several different work environmental problems exist; and two, what may be an effecitve measure for one issue might have little effect on other issues and, in a worst case scenario, increase the risks associated with these other issues. The following example is simplified but illustrates the mechanism. To reduce operators' exposure to dust, water spraying techniques can be used (Kissell 2003). But in turn, this will make surfaces where this technique is used more slippery, which increases the risk of slips and falls (which already causes a significant number of accidents in mines Radomsky et al. 2001). Dust exposure can then, instead, be lessened by decreasing the time operators spend in dusty areas, but that may put more pressure on completing tasks under stricter time frames. This increased stress could increased the likelihood for accidents (Carayon and Smith 2000). Other technical solutions do not navigate this issue either. Using mining equipment with isolated cabins can protect the operator from dust exposure (granted that procedures are in place that prevent dust from entering the cabin through clothing, for example (Kissell 2003; Horberry et al. 2011)), but dust can still decrease visibility and interfere with sensors.

Other cases exemplify this phenomena as well. Even in highly automated mines, tasks such as charging still tend to be manual (Abrahamsson and Johansson 2006). These tasks are also among the most susceptible to rock fall. As such, there are efforts to automate these tasks. This certainly has the potential to significantly reduce the risk of rock fall, but the final improvement to the working environment may still not be that clear: first, in some of the mines where this technology is being considered, accidents due to rock falls are rare (Lööw 2020; Lööw et al. 2018); second, operators in these mines have argued that the ability to move and use their bodies during the course of work positively influences their work environment (Lööw 2019) (and this should be considered in the light that risks related to sedentary work in mining are increasing (McPhee 2004)). Thus, automated technology in this case may provide only marginal improvements to safety while removing for these operations tasks that operators find valuable for their work satisfaction, and increasing risk associated with sedentary work tasks.

Moving work to control rooms or isolated cabins is an effective way of reducing exposure, and is one of the long-term goals of mine automation projects (Lööw et al. 2018; Johansson and Johansson 2014). But the asymmetrical automation and mechanisation levels of mining (Abrahamsson and Johansson 2006) — meaning not all operators will not be able to operate machinery or perform their tasks remotely — reduce the efficacy of such solutions; while total exposure may decrease (i.e. fewer people are exposed to high levels of, for instance, noise), operators who operate remotely may be less inclined to, or have a harder time, engaging in practices that limits exposures (e.g. reducing speed). And then, with fewer operators in exposure areas, it may be harder to justify investments into their work environment (cf. Lööw et al. 2019).

At the same time, not all exposure is negative. For ergonomics, there is healthy exposure, for instance. Many ergonomic risks come from strenuous physical activities. But physical activities can be positive if they are of a suitable level. In fact, as mechanisation has removed many physical tasks (McPhee 2004), physical activity might be even more important to combat problems associated with sedentary tasks, which tend to increase as a result of mechanisation. Moreover, which was hinted at above, one technical solution may be better for a certain type of work environment issue than another, even if both have to do with reducing exposure. For example, with exposure to vibrations, remote-control can remove all vibration. However, because remote control is usually implemented in stages — where the first is to operate the machine remotely but still in the direct line-of-sight of the operator — this is a solution that is not optimal for reducing exposure to dust and noise (where isolated cabins are preferable, but instead increase the exposure to vibrations); line-of-sight-based remote operations may then, in fact, increase these exposures.

None of this is to suggest that technical solutions cannot improve upon the situation. Rather, it is to exemplify the mechanisms that introduce negative effects alongside the positive effects. Judging the final effect as positive comes down to whether the positive effect is large enough, that is, introduces more positive effects than it does negative effects. But this is mostly besides the point: the heart of the matter is that the effect will affect different people or groups differently. That is, beyond the trade-off between the effects in and off themselves, trade-offs also have to be managed between different people (cf. Laflamme and Blank 1996). This is before factoring in that, even where there are suitable technical solutions in mining, their design often does not consider the operator (Horberry and Lynas 2012). This leads to technology that is not used as intended, risking the loss of any gains in safety; it is not rare, for example, that operators forego using or wearing personal protection equipment (a type of technology) because of shortcomings in their design (Simpson et al. 2009). Examples of trade-offs not being considered by equipment manufacturers include new machines that reduce the exposure to noise and dust by providing isolated cabins, but that in turn make it harder for operators to see. There are also examples where battery-powered trucks have removed their cabins to improve operator sight. The reasoning goes that because exposure to diesel particulates and noise is now lower, the cabin is no longer needed. The cabin, however, provides crucial protection against rock fall, roll over, and so on (Lööw 2019).

In summary, when the mining industry applies technology to address work environment issues, it does so to a work environment that is characterised by principally different problems. Whereas for noise, vibrations and safety, for example, the hierarchy of control (Haddon 1973) is suitable — the goal is to eliminate the hazard as efficiently as possible — for ergonomics and other areas, where one wants *healthy* exposure, it is no longer a question of striving towards eliminating all exposure. This reperesents a significant trade-off that will have to be dealt with. But there is another trade-off as well. Technology will affect different people differently, depending on in what role and where the person questions work, their age, and so on. In this case, the trade-off is which group should be prioritised. The next section will further explore the aspects of this problem.

The work environment in the wake of technology development

To understand why these trade-offs situations arise, we must look at what happens in the wake of technology development. A first part of this analysis is what happens in and between new technological systems. Kern and Schumann (1974) used the concept of "range" to refer to how work tasks integrate into a production system. Technological development creates aggregated systems where an operator acts as a sort of mediator between systems. As technological sophistication increases, so does the range of the system; the operator gradually becomes superfluous. In mining, range is limited, especially in early stages of operations: whereas there is automated drilling there is not automated charging, for instance; and often loading still requires an operator, while transports may be fully automated.

Kern and Schumann studied industrial work in general and found polarising effects of the workforce in the wake of automation and mechanisation (Kern and Schumann 1974). When technology levels increase (e.g. the mechanisation of a manual process, or the automation of a mechanised process), parts of the workforce undertake work that is more qualified such as process control and steering; other parts of the workforce undertake work that is less qualified, such as machine tending, in the role as "mediators." Bright (1958) relates similar conclusions. The automation of secondary and tertiary tasks is often forgotten when new systems are developed and implemented — and these tasks often require manual labour — so that, in effect, even highly automated industries require manual labour.

Technology that hopes to address the work environment must then focus on the parts of work that take place in the mine; because new technology is yet to do away with mediation work or found a way of automating secondary and tertiary tasks, these tasks must take place inside the mine. And it is work inside the mine that presents the worker with risks. Thus, while new technology may *decrease* the total number of workers inside the mine or that are exposed to risks, it does not *remove* the workers from these areas completely. The final effect on the work environment is therefore not guaranteed to be positive. (For example, it might be harder to justify investments into the work environment if fewer workers were to benefit from these investments; or the environment in which mediation work takes place will be one of increased complexity and energy intensity.) This mechanism is one of the reasons why the trade-off issues arise.

In another perspective, McPhee (2004) concluded that because mining work is changing, hazard exposure changes too. Risks now include long working hours, fatigue, mental over- and underload, reduced task variation, increased sedentary work and work in fixed positions, and whole-body vibrations. Hazards, in other words, change with changing environments and technologies. Crucially, however, this does not mean that hazards disappear; new risks emerge, requiring new countermeasures. This too — that is, new risks appearing as a result of the measures deployed to eleminiate other risks — engenders the trade-off situations.

Previous research has noted a general lack of consideration of the user (operators, maintainers and so on) of mining equipment (Horberry et al. 2011). However, this paper suggests that the problem goes beyond this, that the positive effect on the work environment would continue to be limited even if the design of new mining technology would take increased consideration of the users of this technology: gaps between technological agregates would continue to exist, for example, and new risks would still arise. In other words, the problem is more than an information or knowledge problem, or one of lacking attention to appropriate factors.

To exemplify this, we can rely on the notion of familiarity as introduced by Goodman and Garber (1988). They used the concept to refer to:

> … knowledge about the unique characteristics of particular machinery, materials, physical environment, people, and programs that exist in a particular [location] at a particular time. [The] premise is that because of the hazardous and dynamic nature of mining, [familiarity] is critical to effective production and safety practices (Goodman and Garber 1988)

This notion suggests to us that there is a need to distinguish between a *general* configuration of technology and the physical environment throughout the mine, and the *unique* configurations that exist locally (e.g. the state of machinery and physical conditions at the mine face) (Goodman and Garber 1988). Technology bought from a supplier for use in a mine represent a general configuration. That piece of technology itself is (generally) the same regardless of the mine that uses it. But the technology then enters into uniquely configured local contexts and must be able to adapt to it. Here, then, is another reason for trade-off situations arising: the "design gap" between general and unique configurations. There are practical limitations to the extent to which the design of technology can take full consideration of unique configurations. However, technical dimensions form only one aspect of familiarity. In fact, it is the knowledge about the unique characteristics that form familiarity. In other words, there are "social actions" available to bridge this gap.

Further technological aggregation — the continued introduction of automated system in mining, for example — does not necessarily eliminate the distinction between unique and general configurations. One could argue that increasingly sophisticated technology, by sensing and making autonomous decisions regarding the environment in which it operates, at least could handle unique configurations autonomously (that is, without human input). But history has continuously shown this not to be the case. Early, Bainbridge challenged the classic approach to automation design in general, which regards humans as unreliable and inefficient, and thus seeks to minimise their input in the control system (Bainbridge 1983). Yet, "the designer who tries to remove the operator still leaves the operator to do the tasks which the designer cannot think how to automate" (Bainbridge 1983) (cf. Kern and Schumann 1974). Highly automated systems still need humans for supervision, adjustment, maintenance, expansion and improvement; the operator must intervene when the system fails or does not perform as expected, which requires manual control skills and knowledge about the process. Crucially, this is not general knowledge but knowledge regarding a unique context as exemplified in the fact that, when automating a manual task, often the former manual operators become the new operators of the automated system. These operators perform well within the system because, having worked in the unique context in which the system is implemented, they have a fundamental understanding of the technology they control. Subsequent generations of, or simply other, operators do not have same understanding. (This should be viewed in light of, where automated technology do not result in redundancies, workers being assigned new work tasks.)

The suggestion, then, that the issue of (new) technology in mining with regards to its effects on the work environment not being (i) strictly a knowledge and information problem, and (ii) that it implicates social actions, is to suggest that the issue is one of process rather than a failure of technology of fulfilling specific criteria. Before exploring this notion further, however, we must look towards the constraints of such a process in the mining industry.

The mining industry, its environment and technological constraints

To restate the problem: The situation in the mining industry with regards to its work environments is often such that for solving a problem, there will be trade-offs. The design and implementation of technology will be important in managing and navigating these trade-offs, but will be limited by the nature of the mining industry and its environment. In this section, we will explore these factors to gain deeper understanding for technology's effect on health and safety.

The effects of these limitations on the mining industry can be seen in that the level of technological development is lower in mining compared to other industries (Bellamy and Pravica 2011; Lynas and Horberry 2011). Indeed, some have argued that automation and robotics have yet to significantly change mining processes (Lever 2011). And here, one frequently cited reason is the aspects unique to mining that preclude or complicate the use of (new) technology and high levels of automation:

> … the highly variable and unpredictable mining environment affects the successful execution of each or sequences of unit operations. Thus, automated systems must be able to sense, reason, and adapt to this unpredictable environment in order to function effectively. … [Therefore] many existing automation technologies from other industries are not readily transferred into mining. (Lever 2011)

The latter, the lack of transfer of technology into mining, is often also cited as a technological constraint in the mining industry. And the size of the sector results in similar effects as those cited above: the mining industry is small compared to other industries; competition is not as big and there may be less competitive advantages from technology that addresses aspects (such as safety) that lies beyond technical functionality. Reeves et al. (2009) (on noise control) thus argued that:

> … because of the relatively small market for mining equipment, manufacturers have limited incentives to develop less noisy machinery or more innovative noise controls. Also, the specialized equipment designs imposed by the sometimes-hostile mining environment has limited the transfer of … technologies from other industries.

During technological change, then, technical issues and design challenges may take precedence over other issues. Morton (2017), for example, noted that diesel-powered mining machines have competed with cleaner engines, cleaner fuel and air-conditioned cabins. In switching to battery-power, machines may compete in output, capacity, energy savings etc., instead of work environment improvements.

One could argue that many of the arguments presented above are less applicable to current technological developments in the mining industry: those most readily summarised under the umbrella terms of "digitalisation," "industry/mining 4.0" and similar (Lööw et al. 2019; Johansson et al. 2017). There are two issues with this, however. First, while digitalisation in general promises (as does many other technological projects) to improve work environment and other social aspects (Johansson et al. 2017) — and indeed, these projects often have this *potential* — experience shows that this is seldom the case (European Commission 2021). And this is before factoring in the constraints of the mining industry. Second, where technology does have clear positive effects on the work environment, the rate of technological change is slow in the mining industry, owing to high capital costs, long lifespans and equipment that is expensive to upgrade (Bartos 2007; Randolph 2011). While it is sometimes claimed that that some activities in mining can resemble those used 25–50 years ago (Randolph 2011), the point is that any technological innovation will enter into a environment characterised by legacy technology. Thus, mining operations "can potentially remain captive to technology decisions made many years previously" (Bartos 2007) even if new technology is implemented.

Mining companies, furthermore, are more likely to rely on equipment providers to develop new technology rather than develop these themselves (Hood 2004); mining companies are adaptors rather than innovators (Bartos 2007) and rely on equipment providers for new technology. By itself, this may not be problematic. However, there are mismatches between mining companies and equipment providers in what they consider important and in knowledge of relevant issues (Simpson et al. 2009). Given, furthermore, the timespan that the development of new technology may entail — up to ten years, in some cases (Bartos 2007) — the situation that the technology intended to address may have changed further.

In short, the situation with regard to technology in the mining industry is one in which development is slower owing the unique environmental challenges. Technological innovations from other sectors may not find their way to the mining industry the way they transfer between other sectors. And due to the size of the mining industry, there are less competitive advantages from addressing issues related to health and safety. Individual aspects of this situation are present in other industries than mining. The point is that the particular "configuration" of these aspects puts the mining industry in a unique position; when taken together, the mining industry stands apart from other industries. In discussing the process for the development, implementation and use of technology in mining, this unique position plays an important role.

Technology development and implementation as a process

Previous research, as noted above, has suggested that the work environmental problems of the mining industry, in particular with regards to technology, has to do with "poor understanding about the contribution of ergonomics to mining, the range of factors that it includes and how these might be addressed" (McPhee 2004), a lack of consideration of the users of the technology (operators, maintainers and so on) (Horberry and Lynas 2012; Horberry et al. 2011), and that "manufacturers and suppliers are currently falling lamentable short of their duty of care responsibilities" as well as mining companies failing to communicate the importance of these issues (Simpson et al. 2009). This paper does not refute these claims but argues that, even if these problems were rectified, technology would still fail to achieve all of its intended, positive effects on the work environment. The argument so far has suggested this as being due to the nature and characteristics of the mining industry, factors which consistently give rise to situations where technology will bring about negative in addition to positive effects as well as having to be uniquely "configured." Implicit in this is also the suggestion that this situation is unlikely to disappear. Eveland has argued that "the key problem should be less choosing and implementing the 'right' technology than it is developing and putting into place a procedural set for making technology choices intelligently" (Eveland 1986). That is, "A … system that can facilitate change processes rather than sell specific technologies is one that will have long-term success" (Eveland 1986). Eveland presents this argument for technology development and implementation in general, but again, it may be of particular relevance for the mining industry while at the same time being uniquely constrained there.

The typical remedy prescribed to the mining industry, with regards to developing technology that improves the work environment, is the active participation of the workforce in the design of new technology (Horberry et al. 2011, 2018, 2016; Horberry and Burgess-Limerick 2015). Again, this paper does not claim otherwise but wishes to add to this notion. Indeed, the purpose here is not to suggest or specify an alternative method but rather to outline some additional requirements and factors needed for participatory approaches and their facilitation, such that these approaches can address the situation of technology and the work environments of the mining industry described above. This outline will be hinged upon the notions of trade-offs and configurations.

One must realise, in this, the close relationship between trade-offs and local configurations. The need for configurations arises from the mining environment and its characteristics (Goodman and Garber 1988). Trade-offs, too, arise from the nature of the mining environment, in combination with technology's interaction with this environment. Thus trade-offs do not become apparent before technology implementation, which also means they must be managed through configuration.

In outlining our new requirements, we thus, first, need to revisit the notion that designs can be final. That is, that technology can be designed in such a way that it manages to address its users and the work environment wholly, even with the full participation of its users. This "incompletion" of design is not a new idea, though its adaption in industry has varied (Mumford 2006). The idea is the recognition that design never stops, as demands and conditions of the work environment continuously change; as we have seen, this may take on a special importance in the mining industry. While eliminating risks in design (i.e. the development process preceding technology's use) is the most appropriate approach, some risks are impossible to predict and arise only in interaction with other "components" of the system into which the technology is implemented (Carayon et al. 2015). Adjustments, retrofits and add-ons are common with mining technology (Horberry et al. 2011), but their practice should not only be taken as a failure in design. Local configuration, which these practices can be understood as being, is in fact a necessary stage of technology implementation. What is required, then, is a recognition of this need, which implicates how technology is designed and the infrastructure (understood here to include the process and procedures surrounding technology) for its implementation and use.

There are certainly practical limitation to the extent to which physical technology can be configured, that is, modified. An important aspect in this, however, is that technologies "cannot be understood aside from the things they are used to do and the purposes of the individuals and groups that use them" (Eveland 1986); technology extends beyond its physical representation. This means configuration of technology can also happen through its use. Active participation in this sense takes on the meaning of the users of technology actively, and continuously, influencing its use. Of course, users will always, by definition, determine how technology is used, but this needs to be formalised and integrated into organisational processes. Moreover, mining technology does not only exist as physical technology. The increasing "digitalisation" of the mining industry means software increasingly make up the technology of the mining industry (Lööw et al. 2019). Software does not have the same limitation in configuration; it could be argued that software is infinitely modifiable.

The second requirement is related to the thinking of technology as only its physical representation as well: technological intervention must be approached holistically, avoiding isolated action. In one sense, this is an extension of including the use and organisation of technology into the notion of the technology itself; all systems — social, technical and otherwise — must be considered in the development and implementation of technology. In another sense, this means a wider focus of technological interventions, as in a preference for addressing larger parts of the work environment, if not in its entirety, over single issues. Earlier sections gave examples of how singular focus risked missing "the bigger picture," or not acknowledging interdependencies between issues and systems. And "Often when we fail to understand such interdependencies, we suboptimize a system, making one part work a lot better and others work a lot worse" (Eveland 1986), which seems an apt description of the situation.

A third requirement in our outline deals with accessibility of information on which to base decisions on technology. The earlier sections of this paper noted the problem with singular indicators and the general lack of alternative indicators. There is a significant extent to which the complexity of the relationship between technology and the work environment in the mining industry exist because of lacking data for establishing the relationship in the first place; we simply need more ways of measuring and determining the "performance" of the work environment. However, we are faced then with another problem: as the work environment improves — to a level where the argument presented in this paper becomes tenable — quantitative data become unreliable, wherein a few accidents can cause statistics to spike. The idea of alternative, proactive indicators has thus gained traction (ICMM 2012), and the notion of using qualitative data has been suggested (Horberry et al. 2011). This paper cannot give further input on what these indicators should be or which data will be relevant but wishes to make two contributions to the discussion.

One, it is often argued that workers have best knowledge of their work environments and that one should use this knowledge to design good interventions. This should not be taken to mean that workers do not benefit from having access to more data themselves, especially if we are serious about late-stage configuration of technology (which if not undertaken by the users of technology, must be done according to their demands). In other words, current and new data as well as their resultant indicators must be available to workers so that they too can make informed decisions. In this, there is also a question of how these indicators are expressed, or rather how the problems which the indicators are to shine a light upon, are described. Without participation in formulating the work environment problems, they might be defined as careless workers causing accidents — and the object becoming the worker and the goal to control them (Frick et al. 2000), with indicators adapted accordingly. If instead the aim becomes "to satisfy workers' desires for safe and sound work, the workers become actors, who are able to influence the integrated management of [the work environment]" (Frick et al. 2000); influencing the work environment means having an informed understanding of it.

Two, input from workers and others without decision-making power must always have bearing (Lööw 2020), not only when convenient or actively sought. This means a way for workers to voice their concerns, opinions and suggestions regarding technology, work environment and other issues, and that these actually influence decision-making. Input from workers and others are often sought in evaluation of technology, but this should not be the sole instance of seeking their input. Furthermore, reception of this feedback should be unconditional. For example, claiming that a consultation process did not take place, when in fact it did, is usually telling of the surrounding organisational processes. This makes economic sense as well; one may otherwise wonder why managers of successful organisations spend so much of their time doing spontaneous walk-arounds in their organisations (Peters and Waterman 1983; Larsson and Vinberg 2010).

The addition of suitable indicators increases opportunities for evaluating technology projects. This should be done actively, from a multitude of perspectives. That is, beyond factors relating to productivity and economics, the effect on the work environment must be included. This depends on the presence of appropriate indicators but implementations must also be planned so that they can be evaluated. And beyond the technology, the process itself must be evaluated; as neither technology nor the environments it intends to address remains static, the process must adapt to these changed circumstances.

Conclusions

This paper took its starting point in the fact that many mines have managed to significantly improve on issues such as accident occurrence while at the same time having stopped seeing improvements in these areas even in the wake of technology interventions. It suggested, and showed, that when we look closer at the situation, we find a complex situation in which negative and positive effects follow the implementation of new technology. Technology, in this sense, does not live up to its expectations of improving the work environments in the mining industry, which was suggested to be particularly problematic because new technology makes the same and even wider claim without addressing fundamental, underlying causes for technology's under-performance. The analysis then suggested that these causes has to do with mining environments having reached a level where historically major risks have been addressed; remaining risks, which are still significant, are of such a nature that their singular treatment engenders risks elsewhere. At the same time, the mining industry is of such a character that technological sophistications will fail to ultimately address the fundamental underlying causes of technology's underperformance. Attempts to rectify the situation, it was argued, are hindered by constraints stemming from the characteristics of the mining industry, resulting in lower and slower technological progress among other things. Finally, the paper suggested that focus must shift to the process of technological development and implementation, and outlined some requirements for such a process.

In conclusion, this paper suggests that the mining industry will move in a positive direction — that is, in the direction of improved work environment through technological interventions — if it addresses the following, which one could say is the management of trade-offs and the need for configuration:

- Technology requires constant vigilance to ensure its continued suitability for the problems it intends to address and functionality in the environment that it operates; design is never finished, and technology must be adapted in an iterative manner.
- The systems surrounding particular technology must allow for adaptions; adaption includes changes to the systems into which the technology is implemented.
- Technology must be conceived as including its surrounding systems.
- Technological interventions must prefer wider and larger interventions — interventions that consider a multitude of issues — over singular issues, isolated actions, to avoid sub-optimisation.
- More data on the work environments of the mining industry is needed. This data, due to practical if no other reasons, must include qualitative or "soft" data. Indicators that make use of this data must be developed.
- Indicators and other measurements must be made available to the users of technology. The development of these indicators too must involve all its users.
- There must be systems that actively can gather concerns, opinions and suggestions from workers. These must influence decision-making.
- Technology must be actively evaluated, from a multitude of perspectives. The process of technology development and implementation must also be evaluated.

The situation of the mining industry is complex. Currently, it is more complex than it needs to be. Left unaddressed, technology will add to complexity and to its problem rather than the opposite. Change is possible, and needed, but we need to give technology all the attention it deserves, from all relevant perspectives.

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