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Identifying Risks Associated With Human-System Interactions in Remote-Controlled and Autonomous Mining Operations

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Abstract

The objective of the project was to answer the question: What risk assessment techniques deliver the most effective and user accepted means of identifying risks associated with human-system interactions in remote-controlled and autonomous mining operations Four hazard identification methods were assessed across three case studies – human-autonomous surface haulage interactions, autonomous longwall mining and remote control of processing plants: 1. Preliminary Hazard Analysis (PHA/HAZID) (Traditional Method) 2. Failure Mode and Effects Criticality Analysis (FMECA) (Traditional Method) 3. System Theoretic Process Analysis (STPA) (Systems-theory Method) 4. Strategies Analysis for Enhancing Resilience (SAfER) (Systems-theory Method) The methods included a literature review, an analysis of the outcomes of workshops with industry participants, and a survey of participants' feedback. Three one-day workshops were held in a combination of face-to-face and remote modes with 8-9 industry participants in each. Feedback from the participants and analysis of workshop information suggest that no single approach is effective alone across the range of automation case studies. Using multiple methods may well be advantageous. HAZID is easy to use, and perceived as most useful for identifying threats. SAfER was perceived as the most effective for identifying magnitude of impacts and suggesting follow-up actions. SAfER also had the highest overall effectiveness. HAZID is useful for broader scopes and lower required detail, whereas FMECA, STPA and SAfER are naturally narrower in scope but can support a more detailed focus analysis in a particular area: equipment failure, control system design holes and human decision strategies. A combination of different methods could be the best way forward, however it may be that only parts of each method need to be combined with parts of another, rather that perform two or more full analyses.

Introduction:

The mining industry is developing and implementing automation and other new technologies at an increasing rapid rate. Examples include autonomous haul trucks, autonomous drills, automated longwall miners, remotely operated processing plants, autonomous trains and smaller robots and drones. Such technologies are adopted to improve worker health and safety by reducing their exposure to high risk situations, as well as to improve operational efficiencies. However, automation and the adoption of new technologies does not completely remove people from operations. Technology still needs to be cleaned, serviced and maintained by humans. Thus, the introduction of autonomous and automated technologies has the potential to introduce new and different human system interaction risks. Such risks are evident in the following accidents:

The risk assessment process is outlined ISO31000:2018 the International Standard for Risk Management as shown in the green box of Figure 1. When risk assessments are undertaken for mining and related operations, they often done so using traditional hazard identification techniques.

Such techniques are referred to as Hazard Identification techniques (HAZID), Broad Brush Risk Assessments (BBRA), Process or Job Hazard Analysis (PHA or JHA), Failure Mode and Effects Analysis or Failure Modes and Effects Criticality Analysis (FMEA or FMECA) or similar. These techniques were developed decades ago and have not been designed to capture the novel and emergent hazards associated with the introduction of new technology, nor with dysfunctional interactions can occur in software-enabled, socio-technical systems where accidents happen even though no individual component failed (Dekker, Cilliers, & Hofmeyr, 2011). Some research has found that traditional risk identification (HAZID) have been shown not to be effective for software-enabled technologies embedded within socio-technical systems (Leveson, 2012). New socio-technical risk assessment approaches such as System Theoretic Process Analysis (STPA) and Strategies Analysis for Enhancing Resilience (SAfER) have been developed and tested to identify risks associated with the introduction and control of technologies in complex socio-technical system, with promising results. However, such techniques have not been tested on mining applications nor with mining industry practitioners. To address this gap, research was conducted with mining industry personnel, to test and assess the efficacy of different risk assessment techniques in identifying human-system interaction risks associated with monitoring, maintaining and controlling autonomous and semi-autonomous systems in mining contexts.

Purpose:
The research sought to answer the following research question: What combination of risk assessment techniques delivers the most effective means of identifying risks associated with human-system interactions in remote and autonomous mining operations? This question will be answered by conducting a comparative study, where the following four HAZID methods will be investigated:

The investigations will include a formal literature review as well as collaborative workshops with industry personnel to test and assess the application of these techniques on the following three case studies:

1. Human-system interactions in surface mine automated haulage areas
2. Autonomous longwall mining operations underground
3. Remote control of coal processing plants

Specifically the objectives associated with the industry personnel collaborations are:

- Familiarisation training in the preparation and application of the techniques
- Conducting collaborative workshops to apply the techniques to produce HAZID, FMEA, SAfER and STPA analyses on abovementioned case studies
- Evaluating the outputs of the techniques in terms of the identification of technical, human and human-technical interaction risks associated with the supervision and control of autonomous haulage technology.
- Collecting industry participant feedback on the usability and usefulness of each technique in delivering meaningful insights into human-system interaction risks associated with automated haulage and semi-autonomous operations

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It is important to note that the risk assessments produced were based on a hypothetical and generalised scope. They did not relate to a specific context or technology and therefore should not be considered or used as an actual operations' risk assessment. Operations considering or actually introducing or operating autonomous or semi-autonomous machines must undertake their own risk assessments.
Method:

A tripartite approach was taken to the methodology as shown in Figure 2. The detailed method for each of the three pieces of research is described next.

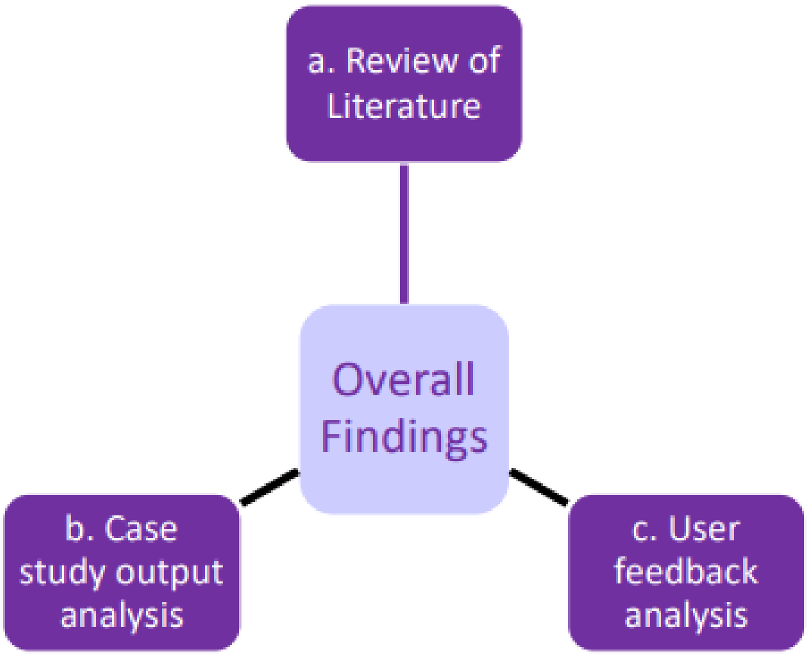

Figure 2: Overall research approach

Literature review

A literature search was conducted by exploring the history and the application of the hazard analysis and risk assessment methodologies used in industries around the world other than in the mining industry. The research body of knowledge in terms of comparing methods for effectiveness is lean and so branching into other industry sectors was necessary. Also included were articles about application and actual practice in industry since the research was lean. The anecdotal practices and how and how often the methods are used was included as that also indicates what methods people prefer. Data bases searched: ScienceDirect Scopus Web of Science Key words used included HAZOP, FTA, What If, FMEA, STPA, STAMP, SAfER, PRA, QRA, hazard, safety, Risk and Risk Assessment. As a result, over 600 papers were screened with only 20 remaining for inclusion.

Case Study Analysis

As mentioned above the case study analysis investigated studied: - Surface mine automated haulage; - Underground longwall automation; and - Remote processing plant operation scenarios. The purpose of performing risk assessments on these case studies was to: - Identify human-system interaction risks associated with the supervision and control of autonomous haulage technology - Use the identified human-system interaction risks to assess the efficacy (in terms of usability and utility) of different risk assessment techniques To perform the risk assessments on each of the case studies, this project undertook the following: 1. Representatives from industry were invited to participate in different case study analyses. 2. In collaboration with industry participants, a scope was developed for the three case study scenarios prior to the workshop which outlined the scenario using diagrams and with a scope table that used the PLEATS framework described.

Metrics applied

A measure of the 'mean' of the distributions for each graph was calculated, for questions 4-7 of the pre-workshop survey and 1-4 of the post-workshop survey. We can consider the y-axis to be a qualitative representation of a continuous variable: either "ease of learning" or "effectiveness". By representing, for example, 'very ineffective' with a value of 1, and 'very effective' with a value of 5, a mean for each methods' distribution can be calculated; for example, see Figure A18. These mean values were used to compare: • Answers to questions 4-7 of pre-workshop survey's for the three different groups of participants, to understand any pre-existing differences between the groups. • Pre-and post-workshop perceptions of participants in each workshop, for each question asked. • Post-workshop answers applicable to each method, to compare the perceptions of participants regarding each method used. The second metric that was applied to the answer distributions is the Shannon Entropy Ratio (SER). The Shannon Entropy is a measure of information related to the distribution. The Shannon Entropy is maximized when the distribution is a uniform distribution, and it is minimized (at a value of 0) when all data points have the same value.

These two extremes represent either 'knowing' nothing about the variable - i.e. if a uniform distribution, the actual value could sit anywhere in the distribution – or being completely sure of the value – i.e. the situation where all data points have the same value. The Shannon Entropy is used as a measure of how much consensus the relevant group of participants had for the particular method they were addressing in each survey question. This is analogous to a measure of the spread of data points around the mean, but it is distinct from the standard deviation. Using the Shannon Entropy measures the spread, but in particular it indicates the amount of information known/unknown about that distribution – thus an indication of consensus. For example, a uniform distribution with the same standard deviation and mean as a gaussian distribution don't have the same information content – there is less certainty about the uniform than the gaussian. This can be directly related to an indication of the consensus of a group of people, and thus the Shannon Entropy was selected as a metric for this analysis. The Shannon Entropy Ratio is simply the ratio of the Shannon Entropy of the distribution divided by the Shannon Entropy of a uniform distribution over the 5 categories of very ineffective/hard -> very effective/easy. This gives a percentage of how close to the uniform distribution the answer distribution is. This is an easy and clear way to compare the level of consensus for each answer distribution. The value of the SER ranges between 0 and 1. The Shannon Entropy is calculated using Equation 1.

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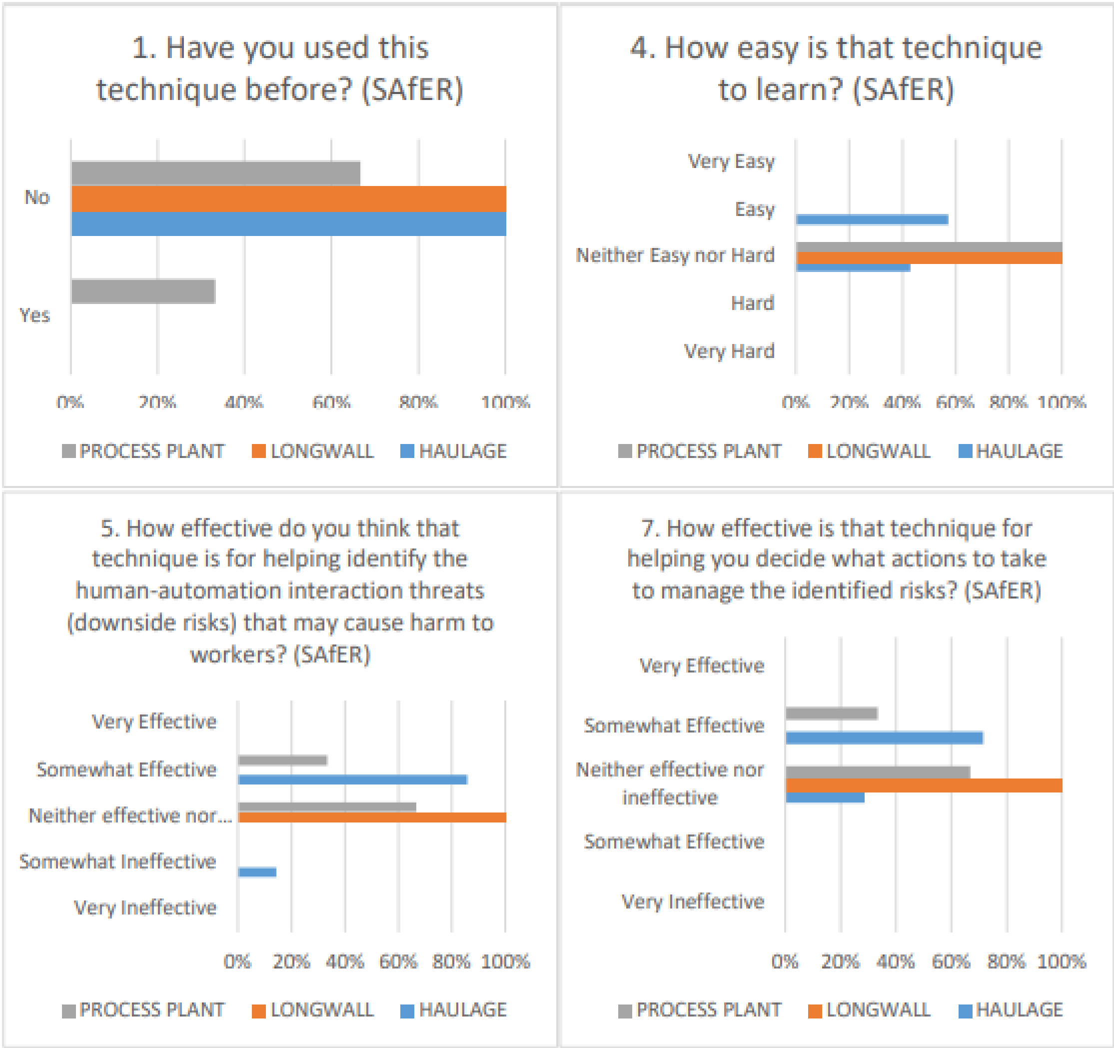

Participants' feedback on SAfER

Results:

The results from each aspect of this research – the literature review, the workshops teaching and applying the different risk assessment techniques and the surveys collecting participant perceptions of each technique are described in the following subsections.

Conclusions

Combining the results of the question analysis with that extract from the free-text comments in Table 5, the following are the key conclusions from this analysis: • Using multiple methods in systems with automation may well be advantageous. For example, note the comments regarding Figure A34. HAZID is easy to use, and perceived as most useful for identifying threats. SAfER was perceived as the most effective for identifying magnitude of impacts and suggesting follow-up actions. SAfER also had the highest overall effectiveness. However, since the SER for STPA was consistently lower than the other methods, it may well be that SAfER's dominance these areas of effectiveness may well not stand up to further experiments, and as more data is gained STPA may indeed be the preferred method. Additionally, from the comments in Table 3, HAZID is useful for broader scopes and lower required detail, whereas FMECA, STPA and SAfER are naturally narrower in scope but can support a more detailed focus analysis in a particular area: equipment failure, control system design holes and human decision strategies. Different methods are useful for different

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purposes, and for systems with automation and the diversity of issues, functions and failures they can experience, using a combination of different methods could be the best way forward. It may turn out that only parts of each method may need to be combined with parts of another, rather that perform two or more full analyses. Exploring this more fully should be a key focus of future work. • The SER score is useful for identifying the most effective method, given a particular survey question. But it is only a clue. Low SER is a clue, not hard evidence, that a method is well understood and has clear consensus for a particular purpose. For example, quite a number of times, STPA had the second highest mean, but lowest SER. Further work should be done on a larger cohort of participants to compare the effectiveness of these different methods, EU report final.docx Page 58 of 109 and to find out the significance of the spread of the data on identifying the best method for a given context.

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