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Toward a Systems Framework Coupling Safety Culture, Risk Perception, and Hazard Recognition for the Mining Industry

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ABSTRACT

The United States mining industry has made steady progress to improve worker safety and reduce injuries. Despite these gains, the industry remains largely reactive in its approach to health and safety. There remains a primary focus on lagging indicators, such as the numbers of injuries, hours lost, and hazards found at the worksite. To facilitate a more *proactive* approach, new methods are needed to evaluate hazardous conditions and unsafe behaviors. This work explores the relationships among mine workers' hazard recognition abilities, the individual's perception of risk, and the safety culture of the mining workplace. We have conducted a literature review to identify key factors and analytical models in industries where health and safety are a major consideration, including construction, manufacturing, mining, and transportation. Our analysis considered both process-oriented frameworks, such as Systems Thinking approaches, and statistical methods, including Structural Equation Modeling (SEM). A meta-model was then developed to aggregate and examine key factors and potential causal relationships. We discuss the creation of this meta-model, identifying notable structural characteristics and hypotheses for future confirmatory analysis. Use cases are then outlined, including descriptive, evaluative, and generative applications.

Keywords: Health, Safety, Mining, Systems thinking, Structural equation modeling

INTRODUCTION

Although the mining industry has made significant improvements in worker health and safety, operators still struggle to identify occupational health risks and avoid conditions giving rise to safety hazards, both of which are essential for reducing injuries, chronic health conditions, and deaths. The mining industry is largely oriented toward reactive models of health and safety (H&S) management, both in terms of the metrics used, such as reportable incidents, and methods to improve performance – for instance, the Mine Safety and Health Administration's (MSHA) patterns of violations. Furthermore, the design of H&S software systems and technologies is equally oriented toward reaction, with dashboards and performance graphs prominently displaying "lagging indicators" such as the numbers of injuries, hours lost, and hazards found at each worksite. New statistical models are needed

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to better understand and proactively address hazardous conditions and behaviors, so that improved training and controls hierarchies may be deployed to reduce these risks and address related human factors.

Recent studies have examined the impacts of risk attitude, risk perception, and worker experience on hazard recognition in the mining industry (Eiter et al. 2020; Haas et al. 2019; Orr et al. 2018). However, the holistic relationships among these factors – as well as the impacts of other internal and external factors on hazard recognition performance – have not been well-explored for mining. Notable advancements have been made over the last ten years in systems-level approaches, using modeling methodologies such as Systems Thinking Approaches and Structural Equation Modeling (SEM) to better characterize the complex, multi-factor nature of occupational H&S events, environments, and scenarios. A large body of empirical evidence has also been amassed to validate these models in other industries. In this work, we conducted a literature review and developed a meta-model to aggregate findings as an initial step toward exploring the factors and correlations of safety culture, risk perception, and hazards recognition in a mining industry context. The goal of this article is to outline our literature review and modeling methods. We discuss directions for future improvement of the meta-model and its use to analyze health and safety incidents in the mining industry.

LITERATURE REVIEW

We conducted a literature review to identify (1) the primary modeling methodologies and (2) factors studied in prior works that were determined to affect risk perception and hazard recognition. Forty-four scholarly articles were identified, over 80% of which were published within the last ten years. Inclusion criteria included publication in a peer-reviewed journals focused on the topic areas of incident analysis, applied psychology, human factors, occupational health, risk analysis, and safety, with preference given to articles having at least 40 citations. Exclusion criteria included filtering articles that were less than two years old. Key search terms included the three main topics of this article (e.g., "safety culture", "risk perception", and "hazard recognition") as well as the keywords "analysis", "assessment", "factors", "perception", "risk", "root cause analysis", and "safety". Our literature review aggregated data and operations from ten heavy industries, such as construction, manufacturing, mining, nuclear, oil and gas, and transportation; the names of these industries were also included in our search.

From the articles in our literature review, 12 notable models were selected for further analysis (Table 1). Models were selected using the following criteria: (1) the model was well-defined in terms of factors and correlations, to a degree that it could be graphed unambiguously; (2) the model was validated by hypothesis testing and empirical data (e.g., via confirmatory factor analysis), as opposed to being a purely conceptual framework; and (3) the model provides a detailed explanation of the potential causal relationships among factors relating to *at least* two of risk perception, hazard recognition, and/or

Table 1. Selected analytical methodologies used to model risk perception and hazard recognition in numerous industries.

Article	Industry	Methodology	Select Factor Labels
Fyhri and Backer-Grøndahl 2012	Transport	Measurement Model	Personality traits
Goh et al. 2010	Waste Disposal	Systems Thinking	Risk management capacity; Revenue stream
Leiter et al. 2009	Printing	SEM	Perception of severity; Worry; Perceived control
Lin et al. 2013	Oil & Gas	Bayesian Belief Network	Commitment; Fitness for work; Task complexity
Ma et al. 2021	Construction	Systems Thinking + SEM	Group norms; Alertness; Supervision
Maiti et al. 2004	Mining	SEM	Personality; Worker injuries; Job involvement
Man et al. 2019	Construction	Measurement Model	Perceived probability; Perceived severity; Stress
Shin et al. 2014	Construction	Systems Thinking	Risk perception; Attitude; Intention
Wang et al. 2016	Construction	SEM	Work characteristics; Safety management; Risk tolerance
Xia et al. 2017	Construction	SEM	Perceived probability; Perceived severity; Perceived negative utility
Xia et al. 2020	Construction	SEM	Supervisor climate; Coworker climate; Safety motivation
You et al. 2013	Transport	SEM	Job risk; Everyday risk; Locus of control

safety culture. Note that Table 1 outlines only a subset of the factors identified in each work. In total, over 70 factor labels were identified during our review, illustrating the diversity and complexity of the design space for these models.

The models considered a wide range of factors, including those that were internal to the worker (i.e., internal factors), influences on workers' communities of practice via culture or environment (i.e., external factors), and processes or actions occurring within the workplace itself (i.e., process-based factors). Furthermore, many labels referenced the same or similar factors via different terminology. For example, the concept of workers exhibiting safe behavior was variously described as "rate of safe behaviors" (Shin et al. 2014), "safety performance" versus "unsafe behaviors" (Wang et al. 2016), "safety participation" (Xia et al 2017), "safety compliance" (Xia et al. 2020), and "safety operation behavior" (You et al. 2013). A goal of this work was to review and aggregate these factor labels using a Model Consolidation process (discussed below), as a foundation for future empirical validation studies.

Our literature review identified two prevalent analytical methodologies:

Systems Thinking Approaches. Systems Thinking approaches explore the dynamics of an activity from a socio-economic viewpoint, characterizing feedback loops and delays between socio-economic factors to identify, explain, and ultimately eliminate problems within the system. A strength of the approach rests in its ability to formalize and characterize behaviors, communications, and economic processes within complex systems, as are often found in industrial workplaces. A detailed treatment of Systems Thinking may be found in Marias et al. (2006).

Structural Equation Modeling. SEM is a statistical methodology which examines the potential causal relationships between factors impacting both the individual and the community. SEM can characterize life experience, cognitive processes, and social and/or environmental pressures more effectively than Systems Thinking Approaches (Maiti et al. 2004). Notably, SEM also provides mechanisms to explore hidden variables that may impact the system and is robust to measurement error. A discussion of SEM may be found in DeVellis and Thorpe (2021).

Although each approach provides distinct advantages, both Systems Thinking and SEM are descriptively powerful methods for characterizing multifactor systems; furthermore, the relationships between factors within these models can be validated through empirical studies.

MODEL CONSOLIDATION

We observed a substantial degree of similarity in the models considered during our review, suggesting that there are core factors which apply to most industries. To better characterize these common features, an inductive process called Model Consolidation was applied to create an exploratory *Meta-model coupling safety culture, risk perception, and hazards recognition* (C-P-R Meta-model). Model Consolidation is a form of Grounded Theory that originates from the field of human computer interaction (Beyer and Holtzblatt, 2017). During the Model Consolidation process, similar features are identified across a group of data samples (i.e. study models). Each set of similar features is then given a representative label. Features that meet the consensus threshold – in other words, features that occur in the minimum desired percentage of samples – are selected for inclusion into a meta-model describing the dataset. The advantage of the consolidation process is that it amplifies structural features and relationships that have high consistency across models in the sample group, while de-emphasizing features that are unique to specific worksites or occupational domains. The consolidation process has great potential to help us coalesce influencing factors and aggregate the numerous models of safety and risk that have been developed within the occupational H&S community. Consolidation thus increases the robustness of our meta-model and focuses attention on the underlying human factors

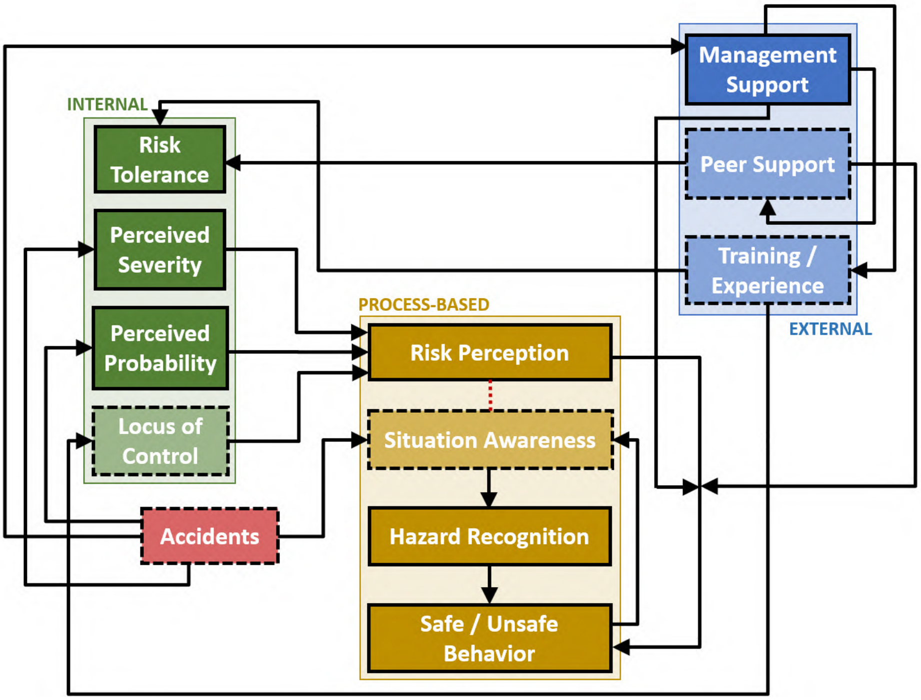

Figure 1: The C-P-R Meta-model: A holistic model coupling safety culture, risk perception, and hazards recognition.

which manifest in many or most sample domains. A detailed discussion of Model Consolidation may be found in Beyer and Holtzblatt (2017).

To apply the consolidation process, 12 study models were chosen that represented multiple industries (Table 1). The selection process was outlined in the prior section. We then performed a manual *n*-way crosswalk of the factors in each model with the factors in all other models, associating common factor labels and identifying the factors which occurred in a majority of the samples, as per the Model Consolidation process outlined above. The aggregated C-P-R Meta-model is given in Figure 1. Boxes identify the consolidated factors, which were based on two consensus thresholds. Solid-line boxes indicate factors with a threshold of 75% consensus; in other words, these factors describe constituent factors that were present in at least 75% of the study models from our literature review. The 75% consensus threshold was chosen as it falls within the minimum desirable levels of consistency for factor loading (DeVellis and Thorpe, 2021). Furthermore, dotted boxes were used to indicate other notable factors that had a threshold of 50% consensus. The likely causal pathways are identified by links (arrows) between the factors; note that the links pointing to the centers of other links suggest a direct mediating relationship.

Links in our meta-model were consolidated using a similar process. For each pair of consolidated factors, a crosswalk was performed to identify common links between the underlying factors in each of the constituent models.

Links were then propagated to the meta-model if the consensus threshold was achieved. As a greater level of variability was observed among the links between factors, we chose a consensus threshold of 50%. The higher variability among these causal relationships may be due to differences of focus among the studies selected during our literature review (e.g., study authors approached the problem from differing fields of expertise and with differing areas of focus, such as by emphasizing cognitive factors, process controls, economic pressures, or other factors), greater sensitivity to individual industries and workplaces, and/or the presence of other hidden factors.

DISCUSSION

The purpose of this article was to develop a consensus meta-model that can be used to explore the underlying factors and correlations among safety culture, risk perception, and hazards recognition in a mining industry context. From our literature review, we developed the C-P-R Meta-model, which serves as a foundation for three types of analysis: Descriptive, evaluative, and generative. The purpose of these analyses is to (1) understand the overall structure of this system (descriptive analysis); (2) identify key factors and interesting correlations for further derivation and validation (evaluative analysis); and (3) establish a future computational framework to identify the likelihood of potential incidents using data collected through operators' H&S management systems, such as worker safety interactions, job task analyses, training outcomes, and other types of data (generative analysis). In this section, we explore next steps and future directions for each type of analysis.

Descriptive Analysis. Our meta-model (Figure 1) suggests that 12 high-level factors embody the relationships among safety culture, risk perception, and hazard recognition. This system includes internal factors, such as risk tolerance and locus of control, external factors, such as management support and training, and process-related factors that exist downstream, including situational awareness and realized behavior. Seven of these factors exhibited 75% agreement across the constituent models in our review. Through the literature review, it is presumed that causal relationships exist between the internal factors of risk probability, severity, and individual risk tolerance and realized risk perception; these factors are mediated by a variety of external factors, such as management support for safety and peer support for safety, as well as prior occurrences of incidents. Although training was identified as a key influence on realized risk perception, this factor was present in only a minority of the models reviewed. Furthermore, a causal link between risk perception and hazard recognition (represented by a red dotted line in Figure 1) was curiously absent from most of the models in our sample.

Evaluative Analysis. The causal pathways described in our meta-model provide a basis for two types of hypothesis testing. First, confirmatory factor analysis (CFA) will be used to validate and enhance the meta-model, by adding or removing links based on empirical evidence from the mining industry. Two medium-sized operators, with a total of nine active worksites in North America, are participating in our validation study; the CFA process will use survey instruments and data mining methods as outlined in Leiter et al. (2009) and Wang et al. (2016). Second, the meta-model presented in this article is an initial model that will likely be refined through CFA analysis, so that it can be used to explore new types of interventions and their impacts on the system. The mediating relationships identified in our model provide excellent targets due to their hypothesized impact on health and safety performance. For instance, new training programs or controls hierarchies may be implemented that improve worker risk perception or peer support for safety, with outcomes measured by both survey instruments (e.g., attitudinal change) and site incident reports (e.g., lagging indicators), respectively. Specific interventions will be identified in future work.

Generative Analysis. The meta-model also provides a framework for future resiliency testing, as it allows us to create generative models and explore hypothetical outcomes for a given set of assumptions. For example, consider a scenario where a short survey instrument is used to regularly query worker competencies and attitudes toward key H&S hazards; these data may be used to precondition the generative model and explore possible outcomes, such as an increased probability for unsafe behaviors based on workers' survey responses, as well as potential interventions, such as additional training or changes to operating procedures. A robust generative model may be developed by using our validated SEM to create a Systems Thinking model, as per the approach of Ma et al. (2021). Furthermore, data from mine operators participating in our evaluative studies may be used to seed the generative model. A detailed discussion of Systems Thinking for generative analysis may be found in Shin et al. (2014).

CONCLUSION

We have created a meta-model using an inductive process called Model Consolidation to explore fundamental relationships among safety culture, risk perception, and hazards recognition. Our proposed C-P-R Meta-model considers how these factors may be impacted by other influences and mediators within a complex industrial environment. We are now working with mine operators to confirm our model and refine it for use by the mining industry. Future work will focus on using the meta-model to evaluate new training protocols and controls hierarchies. In particular, a process-oriented Systems Thinking model will be developed to examine how changes in internal and external factors may potentially impact operators' health and safety trajectories.

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