Preprint 19-053

IF THE TECHNOLOGY FITS: AN EVALUATION OF MOBILE PROXIMITY DETECTION SYSTEMS IN UNDERGROUND COAL MINES

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DISCLAIMER

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ABSTRACT

Proximity detection systems (PDSs) for mobile machines have the potential to decrease injuries and fatalities. Early adopters of the technology have identified some challenges, which presents an opportunity to explore and improve the integration of mobile PDSs in underground coal mines. The current study applied the task-technology fit framework to investigate the *fit* between mobile PDS technology and mining relative to health and safety, from the perspective of leaders at two coal mines. Quantitative results from the study show that mine leaders evaluated mobile PDS favorably for training and ease of use, system feedback, user authorization and experience, and less favorably for safety, compatibility, task completion, and reliability. Qualitative results reveal specific task, mine, and system characteristics that may have influenced leaders' evaluations. The study includes considerations for safe technology integration.

INTRODUCTION

Striking, pinning, and crushing accidents related to mobile machines continue to be a major concern in underground coal mining. The National Institute for Occupational Safety and Health (NIOSH) linked 22 of the 75 underground mine fatalities reported between 2011 and 2015 to power haulage [1]. The Mine Safety and Health Administration (MSHA) asserts that proximity detection systems for mobile machines (mobile PDSs) could help to prevent these types of fatal injuries [2].

Mobile PDSs use a collision avoidance technology that allows the mine to establish hazard zones and employ electromagnetic sensors to detect workers equipped with a miner-wearable component (MWC) working near these mining machines. The authors characterize a mobile PDS as an automated technology, because—in line with Lee & See's [3] definition of automation—a mobile PDS actively "selects data, transforms information, makes decisions, or controls processes" (p. 50). When the system detects workers in the established hazard zones, it issues alerts and slows or stops the mobile machine.

Even though a mobile PDS may be a viable and promising safety solution, there are still a number of questions regarding how well this automated technology will fit with mining tasks and conditions. Using a mixed-methods approach, the current study explored factors that influence the fit of mobile PDSs in the underground mining environment.

PDS and U.S. Underground Coal Mining

In 2015, MSHA announced a final rule that required continuous mining machines (CMMs) to be equipped with PDSs [4]. Following the final ruling for PDSs on CMMs, MSHA proposed a rule that would also require mobile PDSs on machines such as scoops and coal haulers [5].

While the proposed rule requiring mine operators to install PDSs on mobile machines has not been enacted, some underground coal mines have implemented this technology. As of 2015, approximately 155 of 2,166 scoops and coal haulage machines had been equipped with PDSs [6].

Since the announcement of MSHA's final and proposed rules, stakeholders have conveyed several concerns related to the technology [7]. In a 2015 hearing on the proposed rule for mobile PDS, stakeholders reported that electromagnetic interference from other mining equipment created system performance issues [7]. Stakeholders also predicted that implementation costs would be a barrier to integrating PDSs into the coal mining industry [7]. Initial costs may include cost to purchase the system and MWCs. These perspectives raise questions regarding the fit between PDS technology and underground coal mining.

Stakeholders have expressed additional questions regarding ways to ensure safe use and acceptance of mobile PDS among mineworkers. Tragically, in June of 2017, a mineworker disabled the PDS on a CMM and was fatally injured [9]. The accident investigation revealed that, prior to this incident; it was a common practice for CMM operators at this mine to engage the system's emergency stop override during production shifts [9]. Data retrieved from the PDS revealed that, prior to the accident, the fatally injured worker's emergency stop override had been activated 87 times [9].

The related safety issues are relevant and critical to consider as PDS technology expands to mobile machines. As the 2017 incident demonstrates, even though PDSs have been employed in coal mines to improve safety, additional research can help to support safe technology implementation and use. Previous NIOSH research has investigated a variety of topics to better understand mineworkers' perspectives [10] and develop recommendations to support safe use [11, 12, 13] of PDSs for CMM. The aim of this study is to build on existing research on PDS by applying the task-technology fit model (TTF) [14, 15] to examine the fit between mobile PDS technology and the conditions and job tasks in underground coal mines.

Task-Technology Fit

Task-technology fit posits that a technology will aid workers in completing tasks [14, 15]. Further, users' assessments of the system determine the system's usefulness [14]. For the current study, the authors conceptualized task-technology fit as the degree to which mobile PDSs aided mineworkers in safely completing mining tasks.

The original model used three characteristics to inform fit: (1) individual, (2) task, and (3) information system characteristics [14, 15]. Because the current study aimed to explore fit in the underground mining environment, the authors concluded that investigating the influence of mine characteristics was more relevant than individual differences. Therefore, the model was slightly adapted by replacing individual characteristics with mine characteristics. Figure 1 provides an illustration of the adapted version of the model.

User evaluations are another important part of the task-technology fit framework. Goodhue and Thompson [14, 15] identified eight dimensions to assess users' evaluations of task-technology fit. The dimensions were slightly adapted for the current study. Table 1 summarizes the Goodhue and Thompson [15] original task-technology fit dimensions and the adapted dimensions used for the current study.

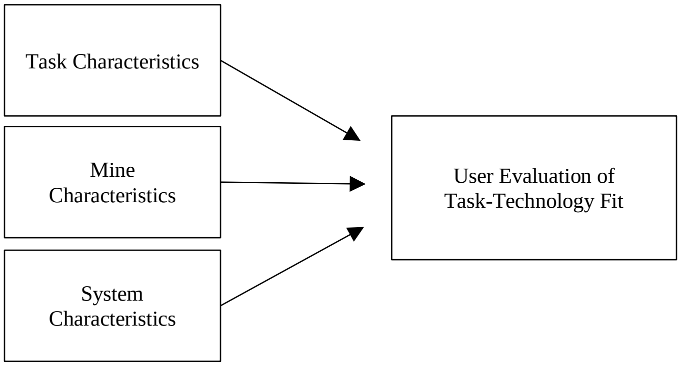

Figure 1. Adapted version of Goodhue's [14] task-technology fit model.

Table 1. Task-Technology Fit Dimensions.

Original TTF Dimension	Current Study TTF Dimension	Description
Compatibility	Compatibility	Ability to work well with other machines, systems, and the conditions of the mine
Production timeliness	Task completion	Ability to support miners in completing tasks
Locatability	Locatability	Ease of identifying system information
System's relationship with users	User perspective	Provides a positive user experience
Training and ease of use	Training and ease of use	Easy to use and obtain effective training
Data quality	Quality	Provides accurate information that keeps workers safe
System reliability	System reliability	Dependability of system and components
Authorization	Authorization	Ease of obtaining authorization to access necessary data
	Safety	Ability to keep workers safe

Why Fit Matters

Fit is important for system designers, mine operators and leaders, and health and safety professionals to consider to safely integrate mobile PDSs into underground coal mines. Past findings on task-technology fit suggest that the workers' favorable evaluations are likely to positively influence system use and performance [14, 15] and to reduce perceived resistance [16]. Consider a scenario where a mineworker uses a new safety technology and finds that it allows him or her to work more safely while loading coal. Based on the main premise of task-technology fit, the worker is likely to evaluate the new technology favorably and, consequently, continue to use the technology [14, 15].

Past studies have also investigated the link between user assessments of fit and outcomes such as technology use, resistance, and performance. Researchers have found task-technology fit to be a significant predictor of internet usage among college students [17]. Norzaidi and colleagues [16] identified a relationship between task-technology fit and organizational intranet use and perceived resistance among mid-level managers. Moreover, the effects of fit may extend beyond simply facilitating individuals to use technology. Previous findings have also shown that fit may facilitate optimal levels of technology use and performance [18].

In regards to an autonomous safety technology such as mobile PDS, use, resistance, and performance are important outcomes to examine. All of these outcomes could potentially influence unsafe behaviors, leading to an increased risk of injury. For example, issues related to system use, resistance, or performance may consequently spur a mineworker to remove the mine-wearable component (MWC) or disable the mobile PDS. If a mineworker removes the MWC, the system cannot detect the worker, thus potentially increasing the risk of injury.

Using the task-technology fit model, researchers and managers can closely examine instances where a mobile PDS impedes task completion. Early identification of these issues may help to ensure safe use and increased acceptance of the safety technology, consequently bolstering implementation efforts. Further, using task-technology fit to identify challenges between job tasks and mobile PDSs offers researchers and practitioners an opportunity to develop recommendations and strategies to improve fit and enhance mine safety.

Study Objectives

The current study had three objectives: (1) to examine users' evaluations of task-technology fit for mobile PDSs, (2) to explore factors that influence the fit between mobile PDSs and underground coal mining, and (3) to offer organizational and system design recommendations that could improve the fit between mobile PDSs and underground mining. Researchers addressed the study objectives through two research questions:

- Research Question 1: What factors positively influence the fit of mobile PDSs in underground coal mines?
- Research Question 2: What factors negatively influence the fit of mobile PDSs in underground coal mines?

METHODS

The current exploratory study followed a concurrent triangulation design, which is a mixed-methods approach, as described in this section. Prior to recruitment and data collection, the NIOSH Institutional Review Board approved the study protocol.

Mine Recruitment

According to MSHA, 12 underground coal mines had installed PDSs on their mobile machines in 2015[1]. Researchers used a convenience sampling approach to invite two of these mines to participate in the study. The two bituminous coal mines were selected because they were located in two distinct geographic regions and used different PDSs.

Table 2. Participating Mines.

	Mine A	*Mine B*
Average Number of Employees[a]	600	300
Annual Coal Production[b]	2,600,000	5,000,000
Annual Hours [b]	700,000	600,000
Mining Method	Longwall	Longwall

[a]Rounded to the nearest hundred.
Annual coal production in tons.
[b]Rounded to the nearest hundred thousand.
Source: MSHA, Mine Data Retrieval System, Annual production for 2017 [19].

Participant Recruitment

Researchers asked mine contacts to identify mine employees who were involved in leading or managing the mobile PDS implementation at their mine site. Researchers recommended including mine operators, supervisors, shift or mine foremen, health and safety professionals, maintenance technicians, and engineers. However, participation was not limited to mine personnel with these titles. Nine mineworkers participated in the study. Because participants were instrumental in the implementation and management of their mine's mobile PDSs, they will be referred to as mine leaders throughout this paper. Tables 3 and 4 summarize the participants' demographic information.

Data Collection and Instruments

Researchers conducted two semi-structured focus groups at the participating mine sites during March and April of 2018. The focus group held at *Mine A* consisted of six mine leaders, and three mine leaders participated at *Mine B*. Before the focus groups, researchers

[1] Shumaker W., MSHA. Personal correspondence, January 12, 2017

asked mine leaders to complete a questionnaire that included demographic questions, with 11 questions assessing the task-technology fit of their mine's mobile PDS. Researchers based the 11 questions on an adaptation of Goodhue's [14] dimensions for task-technology fit (see Table 1) [14]. The questionnaire included items such as *your mine's mobile PDS keeps workers safe*. Mine leaders used a five-point Likert scale, which ranged from *strongly agree* to *strongly disagree*, to evaluate the mobile PDSs at their mine.

Table 3. Participant Experience.

	In Mining	At Current Mine	In Current Position
Years of Experience	**Number of Mine Leaders**		
Less than 1	0	0	2
1-5	0	1	4
6-10	2	2	2
11-15	1	1	0
More than 15	6	5	1
Total	**9**	**9**	**9**

Table 4. Participant Age and Knowledge of Mobile PDSs.

PDS Knowledge	Leaders	Age (years)	
None	0	Range	29-65
Basic	1	Mean	49
Practical	7	*SD*	13
Expert	1		
Total	9		

Quantitative Data Analysis

Researchers entered questionnaire responses in IBM SPSS 19 and analyzed the data using descriptive statistics, which involved computing frequencies and percentages. To gain a better understanding of the successes and barriers related to task-technology fit, researchers characterized the dimensions as either favorable or less favorable based on response percentages. More specifically, dimensions that were rated *strongly agree* or *agree* by more than 50 percent of the participants were classified as favorable. Dimensions rated as *neither agree nor disagree*, *disagree*, or *strongly disagree* by more than 50 percent were classified as less favorable.

Qualitative Data Analysis

Researchers uploaded focus group transcripts to NVivo 11 for data analysis. Using the task-technology fit model as a framework, the authors coded the transcripts through a three-stage process similar to the guidelines established by Campbell and colleagues [20]. First, the authors developed a coding scheme. Second, they individually coded the data and resolved any disagreements. Third, they revised the coding scheme, individually re-coded the transcripts, and resolved any remaining disagreements.

RESULTS

Quantitative Results

User evaluations were measured using nine dimensions of task-technology fit (see Table 1). Quantitative results from the questionnaires are presented in this section and organized by the two research questions presented previously.

Researchers performed a Cronbach's Alpha test for the 11-item survey instrument. Results from Cronbach's Alpha (α = .91) show that the instrument is reliable based on the generally held standard that an alpha of .70 or greater indicates that the construct is reliable [22].

Research Question 1. The first research question explored dimensions that may have a positive influence on fit. Five of the nine task-technology fit dimensions received favorable responses (i.e., *strongly agree* or *agree*) from the mine leaders: training and ease of use, quality, locatability, authorization, and user perspective.

Research Question 2: The second research question explored the dimensions that may have a negative influence on fit. Four of the nine task-technology fit dimensions were evaluated less favorably (i.e., *neither agree nor disagree*, *disagree*, or *strongly disagree*). In other words, less than 50 percent of the mine leaders provided a positive rating. These dimensions included reliability, safety, task completion, and compatibility. Figure 3 depicts the dimensions that received less favorable evaluations.

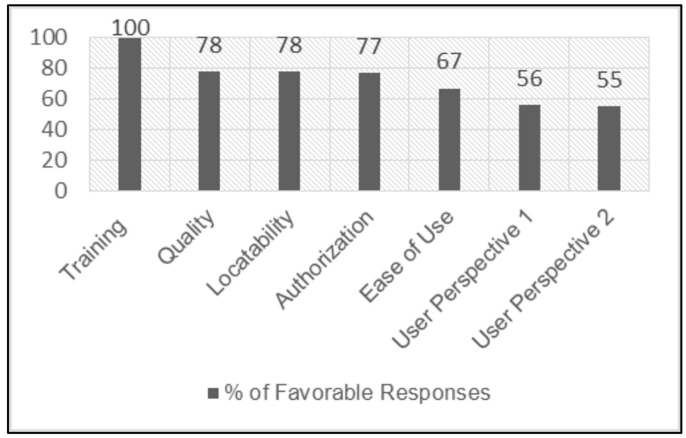

Figure 2. Graph illustrating the dimensions characterized as favorable and showing the percentage of leaders that responded favorably to the task-technology fit dimension.

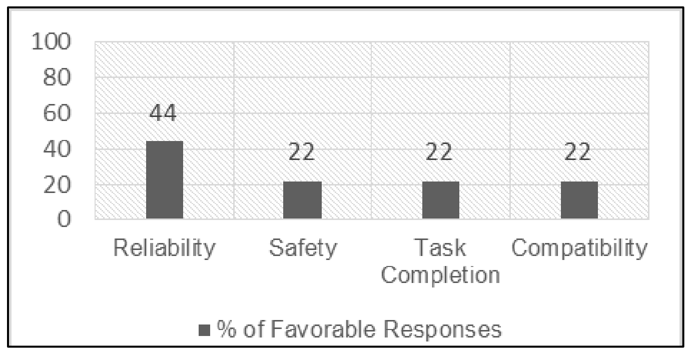

Figure 3. Graph illustrating the dimensions characterized as less favorable and showing the percentage of leaders that responded less favorably to the task-technology fit dimension.

Qualitative Results

Qualitative analysis resulted in 13 themes that researchers classified under the three characteristics from the adapted task-technology fit model. Additionally, researchers classified the 13 themes based on whether they had a negative or positive influence on fit. Several themes were found to have both a positive and negative influence on fit. Themes summarized in Table 5. This section provides a summary of the qualitative results organized by research question.

Table 5. Negative and Positive Themes.

Positive Influence	Negative Influence
Task Characteristics • Working around mobile machines	Task Characteristics • Working around mobile machines • Operating mobile machines • Maintaining mobile machines • Setting up section • Visiting the section
Mine Characteristics • Training • Culture • Conditions • Resources	Mine Characteristics • Training • Culture • Conditions • Resources
System Characteristics • Performance • Usability and system features • Support • Requirements	System Characteristics • Performance • Usability and system features • Support • Requirements

Research Question 1: The research question explored the adapted task-technology fit characteristics that may have a positive influence on the fit of mobile PDSs. Results show that all three characteristics may have a positive influence on fit. The following characteristics and sub themes are described in relation to *Research Question 1*.

Task Characteristics for Research Question 1. Five themes emerged for task characteristics: (1) *working around mobile machines*, (2) *operating mobile machines*, (3) *maintaining mobile machines*, (4) *setting up the section*, and (5) *visiting the section*. Researchers categorized one of the five themes as a factor that positively influence the fit of mobile PDSs—*working around mobile machines*.

<u>*Working around mobile machines*</u>. Researchers based this theme on mine leaders' positive statements about how the mobile PDS has improved workers' situational awareness and motivation to stay further away from mobile machines. Specifically, one mine leader claimed that machine operators were learning the system and doing a better job of positioning themselves further away from machines.

Mine Characteristics for Research Question 1. Researchers identified four themes for *mine characteristics*: (1) *training,* (2) *culture,* (3) *conditions, and* (4) *resources*. Researchers categorized all four themes as positive influences for fit.

<u>*Training*</u>*.* For the *training* theme, most leaders spoke favorably of the mine's training programs. *Mine A* discussed training approaches used to increase workers' understanding of the system's electromagnetic interference issues. *Mine B* expressed how its training was an important part of the implementation process.

Mine B also discussed how the dedication of its trainer aided in its success with using a mobile PDS. In addition, both mines discussed specific training for their maintenance workers.

<u>*Culture.*</u> *Culture* positively influenced mobile PDS implementation and use through organizational policies and practices, management support, and workers' attitudes and values. Prior to adopting mobile PDSs, both mines had policies that restricted miners from going into red zones. Both mines also prohibited the use of mobile machines when the PDS was not operational.

In relation to management support and prioritization of worker safety, *Mine A* expressed that training and safety equipment were priorities at its mine. Echoing *Mine A's* commitment to safety, leaders from *Mine B* shared that its general manager's decision to adopt the technology was evidence of the mine's values and existing safety culture.

Finally, leaders at both mines felt that worker attitudes and values could have a positive influence on mobile PDS implementation. One leader from *Mine A* expressed that injuries are often linked to unsafe behaviors, but workers at his mine were more apt to engage in safe behaviors.

<u>*Conditions.*</u> Leaders stated that *conditions* and materials such as thick coal seam and consistent materials throughout the mine helped with mobile PDS implementation.

<u>*Resources.*</u> Mine *resources* such as personnel, maintenance, time, and financial resources aided the mines in implementing mobile PDS. Leaders from *Mine B* extensively discussed personnel resources. The mine had a designated staff member who led the mobile PDS implementation and training program. Approximately 50 percent of his time was dedicated to mobile PDS. This individual's efforts and commitment contributed to the mine's success with mobile PDS. *Mine B* not only had a designated employee to lead the implementation and training, but also assigned a technician to manage the MWCs.

Additionally, the mine leaders discussed resources that assisted with maintenance and troubleshooting. *Mine B* supplied its maintenance team with laptops. *Mine B* also had spare equipment, which helped to reduce downtime associated with mobile PDS repairs.

Lastly, time and financial resources were necessary to implement mobile PDSs. Leaders at both mines described how the size and funding of their mines offered them advantages such as additional resources and time to become familiar with the system.

System Characteristics for Research Question 1. Researchers identified four themes for *system characteristics*: (1) *performance*, (2) *usability and system features*, (3) *support*, and (4) *requirements*. Researchers categorized all four *system characteristic* themes as positive influences for fit.

<u>*Performance.*</u> The *performance* theme was composed of leaders' perceptions of compatibility and reliability. One mine discussed the system's compatibility with newer mobile machines and potential reliability. More specifically, a mine leader found the system to be compatible with his mine's new coal haulers. The interoperability of these technologies helped to eliminate the sudden stops that mobile machine operators had been experiencing.

Several mine leaders also suggested that, when maintained and free from electromagnetic interference issues, the mobile PDS was reliable.

<u>*Usability and System Features.*</u> In relation to usability, mine leaders shared a variety of system features that positively influenced the fit of mobile PDSs including ease of use, zone setup options, and authorization controls. First, many mine leaders found the locator and MWC to be easy to use. One leader described the simple design of the MWC.

Second, one mine leader favorably mentioned the zone setup feature of the mobile PDS. The mine was able to address some of the interference concerns and performance issues by increasing the number and size of the hazard zones. Finally, one leader discussed the usefulness of authorization controls. He used the feature to limit workers' control of the system.

<u>*Support.*</u> The *support* theme involved vendor, manufacturer, and government agency services, assistance, and resources. Leaders described manufacturer support as a factor that had a positive influence on fit.

At both mines, leaders expressed that their manufacturer representatives had been responsive and helpful. Leaders from *Mine B* stated that the representative assisted with system issues and visited the mine when needed.

A leader from *Mine A* shared similar comments about its manufacturer representative's responsiveness. The leader also shared that a representative was involved in training.

<u>*Requirements.*</u> In relation to *requirements*, system maintenance was noted to have a positive influence on the fit of a mobile PDS in underground coal mines. One of the leaders believed that if the mobile PDS was maintained properly, it would offer protection to a mineworker.

Research Question 2: The second research question explores task-technology fit characteristics that have introduced challenges and barriers for fit. Researchers found that themes from all three task-technology fit characteristics had a negative influence on fit. The following section presents characteristics and themes in relation to *Research Question 2*.

Task Characteristics for Research Question 2. All five of the themes identified for task characteristics negatively influenced the fit of mobile PDS in underground coal mines.

<u>*Working around mobile machines.*</u> Mine leaders often described *working around mobile machines* as a hindrance to working safely and completing tasks. Leaders were mainly concerned with increased risks and worker frustration. One mine leader felt that a mobile PDS increases walking and risks for the CMM operators. Another mine leader shared similar concerns about the increased risks for CMM operators. In addition to the increased risk, worker frustration was also a major concern for mine leaders.

<u>*Operating mobile machines.*</u> In relation to *operating mobile machines*, loading was a major hindrance to safety and efficiency.

Mine leaders from both mines discussed issues with coal haulers getting stuck or not moving after being fully loaded due to the automatic slowdown function that the mobile PDS initiates in warning areas. As a result, some operators at *Mine B* had to use tow straps to help move the machine, which increased these workers' risk for musculoskeletal injuries.

Maintaining mobile machines. Several mine leaders found *maintaining mobile machines* and troubleshooting tasks for the mobile PDS to be challenging. One leader expressed difficulty with installing and maintaining the mobile PDS on existing mobile machines. Additionally, leaders at both mines discussed the complexities involved in troubleshooting for issues with the system and MWCs.

Setting up the section. *Setting up the section* was another theme that emerged from the data. *Mine A* ran production 24 hours a day, seven days a week, and did not report section setup or downshift issues related to mobile PDSs. However, section setup was a key concern for *Mine B*. The mine leaders argued that the mobile PDS had increased the risk and difficulty associated with section setup, mine planning, and downshift work.

Additionally, leaders reported that attempting to mitigate system interference issues caused workers to change the way they hung cable. In addition to increasing workers' risk for injury, leaders noted that mobile PDSs have also changed mine planning and section setup functions.

Visiting the section. In relation to *visiting the section*, two major concerns for leaders from *Mine B* were the impediments that mobile PDSs introduced for conducting safety inspections and hosting section visitors. One mine leader described how mobile PDSs affected safety inspections. Another mine leader discussed issues related to internal and external visitors.

Mine Characteristics for Research Question 2. Researchers classified all four *mine characteristics* themes as having a negative influence on fit. Training. Leaders expressed two key concerns related to mobile PDS training. Some leaders discussed the liability associated with untrained mechanics. Another concern related to training was the potential for workers' overreliance on the mobile PDS.

Culture. Mine leaders described poor safety culture and regulatory drivers for technology adoption as barriers to fit. First, leaders at *Mine B* identified examples and ways that culture could have and has had an adverse effect on mobile PDS implementation at other mines. For example, leaders noted that workers may disable or override the system. One leader described a mine where workers would remove the MWC.

In addition, mine leaders shared their perceptions of how regulations drive technology adoption in the U.S. mining industry. Leaders voiced their thoughts about new regulations influencing mine operators to adopt premature technologies or technologies that have minimal worker acceptance.

Conditions. Leaders' statements about mine *conditions* included concerns regarding the environmental conditions of the mine and static materials that may be present in various mines. Mine leaders identified environmental conditions such as low seam heights, muddy or wet mine floors, and low humidity as factors that can negatively influence fit. Mine leaders expressed their thoughts about equipping scoops with mobile PDSs in mines with low seam heights. Relative to this, one mine leader felt that the industry should consider limiting the types of machines that can be equipped with mobile PDS based on mining conditions.

Leaders also mentioned low humidity as another environmental condition that could cause issues for mobile PDS use. Due to its geographic location, one mine frequently has low humidity. These conditions resulted in static electricity, which affected some of the MWC cases.

Mine leaders also discussed materials used in their mines that presented issues such as steel mesh and braided metal water lines. One mine used steel mesh throughout the mine. The mine found the mesh to be a source of electromagnetic inference for the mobile PDS. The mine addressed the issue by recalibrating the mobile PDS. The metal water lines created similar issues.

Resources. Resources was also included as a theme for *mine characteristics*. Mine leaders from both mines felt that properly implementing mobile PDS was a resource-intensive endeavor. For *Mine B*, a successful implementation required the leaders to increase maintenance and equipment costs. One mine suffered a decline in production during the early stages of mobile PDS implementation. To address the production decrease, the mine increased maintenance and equipment costs.

Leaders from *Mine A* also expressed their concerns regarding the resources necessary to get the mobile PDS functioning properly. The mine leaders found it burdensome to allocate resources and time to understand and address the system interference issues.

System Characteristics for Research Question 2. Researchers categorized all four of the themes for *system characteristics* as having a negative influence on the fit of mobile PDSs.

Requirements. Mine operators have to ensure that a number of system PDS requirements have been met to get mobile PDSs to perform optimally. One requirement discussed by mine leaders was the financial investment. The leaders discussed not only system costs, but also the upfront and ongoing investment required to supply each worker with a MWC.

Performance. Leaders often discussed system performance as a hindrance to fit. More specifically, mine leaders discussed electromagnetic interference issues, technology readiness, and reliability. Across the two focus groups, mine leaders identified a number of interference sources including the continuous personal dust monitor (CPDM), variable-frequency drives (VFDs), computers in mobile machines, surveyor lasers, steel-braided waterlines, leaky feeder communication cables, radios, steel mesh, cap lights, flashing blue lights, and pulled up miner cable.

According to mine leaders, the electromagnetic interference caused by the CPDM presented major challenge for both mines. In some cases, the interference issues were perceived to increase striking, pinning, and crushing risk for the CMM operator. Mine leaders referenced the NIOSH recommendation [22] to keep the CPDM six inches away from the [MWC]. However, they still felt that interference from CPDMs was still an issue due to the way the MWC is worn and speed of the mobile machines compared to the CMM.

Leaders from *Mine B* also shared their thoughts on why the six inches of separation recommendation has not worked for them. To address the electromagnetic interference issues for the CPDM, the mine established an alternative rule.

Due to issues such as electromagnetic interference, many of the mine leaders felt that the technology was not mature enough for consumer use. Leaders at *Mine A* also expressed optimism about the system's potential, but were concerned about the system's existing performance issues.

Some mine leaders felt that some of the system components were unreliable. One leader shared his perceptions on one of the original MWC battery chargers. The mine also had issues with defective components, which were manufactured by an outsourced vendor.

Compatibility. Compatibility also influenced mine leaders' perceptions of system performance. Similar to interference, compatibility affected how the system worked with other equipment and machines. Both mines had installed mobile PDSs on coal haulers. As previously stated, the yellow zone configurations can cause issues when some of the coal haulers are fully loaded with coal.

Usability and system features. *Usability and system features* was also a theme under *system characteristics* that included MWC wearability and system feedback. Some leaders encouraged manufacturers to consider redesigning the MWCs to be smaller or incorporating it into other equipment that the miner is required to wear. At one mine, leaders reported that workers did not have room on their belts to place the MWC. As a result, workers developed alternatives that introduced additional risk.

Leaders also discussed risk associated with wearing and not wearing the MWC. Leaders felt that continuing to add weight on miners' belts would increase the likelihood of workers developing musculoskeletal issues such as knee and back problems. Not wearing the MWC posed risk as well. Some workers would remove their belt, which included the MWC, to complete a strenuous task and forget to put it back on.

In relation to system feedback, some leaders expressed concern about workers responding to the visible and audible alerts. Mine leaders shared three main reasons for these issues. One reason is that mineworkers were tuning out the alarms. Several of these alerts were reported to be false alarms resulting from interference. Another reason is that some workers might not be able to see the visible alerts. Finally, the noise level on the working section might make it difficult to hear the alerts.

Support. The *support* theme included vendor, manufacturer, or government agency service and assistance. Two main concerns were discussed related to the fit of mobile PDS in underground mining: research and development and service from vendor. Leaders from both mines expressed a desire for additional resources and support from vendors, manufacturers, or government agencies to help them to better address the interference issues.

Finally, leaders felt that it took a long time to receive the systems from the manufacturer. Leaders from *Mine A* felt that the ordering process kept them from being able to use their new mobile machines for three weeks.

DISCUSSION

Using a mixed-methods approach and the task-technology fit model, the current study explored factors that influence the fit between mobile PDSs and underground coal mines. This section summarizes key findings from the study.

Five key findings from this study show that mobile PDSs can be a good fit for underground coal mining. First, quantitative results show that five of the nine dimensions (i.e., *training and ease of use*, *quality*, *locatability*, *authorization*, and *user perspective)* have had a positive influence on mine leaders' perspectives of the task-technology fit of mobile PDSs. Past studies have shown that task-technology fit can have a significant influence on technology use [16, 17, 18] and resistance [16]. Leaders' positive assessments for more than half of the dimensions are encouraging for those interested in integrating mobile PDS into mining environments.

Second, mobile PDSs can improve mineworkers' situational awareness. Qualitative results suggest that mobile PDSs make workers more cognizant of mobile machines and red zones. They also present an opportunity for mine leaders to use mobile PDSs to help train mineworkers on safe practices for operating and working near mobile machines. Some manufacturers are currently promoting PDSs as training tools.

Third, system features that allow for ease of use, customization, and control have a positive influence on task-technology fit. Mine leaders favorably evaluated and described these features. For example, some mobile PDS models allow users to establish customized zones and assign varying levels of access to workers.

Fourth, mobile PDSs align best in mines with strong safety cultures, and that can dedicate time and resources to implementation, training, and maintenance. Current study results that show the influence of mine culture on the fit of mobile PDSs support past findings, which suggest that organizational culture can facilitate or impede technology implementation [25].

Fifth, mobile PDSs fit best with mines that have or plan to acquire mobile machines that are compatible with the system's technology. Implementing mobile PDSs may require mine operators to assess existing equipment to ensure compatibility.

Finally, vendors and manufacturers can contribute to fit. Stakeholders' responsiveness and support can help mines successfully implement mobile PDSs.

While study findings reveal that mine leaders favorably evaluated more than half of the task-technology fit dimensions and that several factors have a positive impact on mobile PDS implementation, this study shows some factors that may present barriers to fit.

First, quantitative results show that mine leaders evaluated the reliability, safety, task completion, and compatibility dimensions less favorably. Some of these dimensions (i.e., reliability, safety and compatibility) are directly associated with system performance.

In this study, mine leaders reported electromagnetic interference and false alarms as major concerns. In a past study, Madhaven and colleagues [23] found that poor system performance and false alarms had an adverse effect on user trust and reliance. Consequently, workers with low trust and reliance in a system tend to overestimate their own abilities and attempt tasks without the system [23]. For mobile PDSs, poor system performance and false alarms seem to be negatively influencing the fit of the system, which could lead to system misuse or disuse.

Second, qualitative results show that tasks such as working around, operating, and maintaining mobile machines, and setting up and visiting the section may be more difficult or hazardous due to mobile PDSs. Mine leaders presented three key safety concerns: injury to CMM operators during loading tasks, musculoskeletal disorders to workers, and fewer inspections and less oversight from mine supervisors.

Third, leaders felt that worker overreliance on or misuse of mobile PDSs may introduce new risks. Training programs may need to be adapted to help establish appropriate reliance on mobile PDSs.

Fourth, leaders expressed that specific mine characteristics such as poor safety culture, unique mining conditions, and limited resources may create misalignment between mobile PDSs and the mine. Underground coal mine conditions can vary greatly, putting workers at greater risk for injury. For example, Peters and colleagues [24] reported that fatalities involving powered haulage were more prevalent in mines with low seams. Mine variations, such as seam height, make it difficult to develop standardized programs to support mobile PDS integration. However, this may present an opportunity for stakeholders to identify and address additional mine characteristics that make PDS use challenging or hazardous prior to full integration or use.

Finally, results show system characteristics such as electromagnetic interference, MWC wearability, and upfront and ongoing investment costs. Additionally, study results present opportunities for further research and development to help support future technology integration efforts. Several of these findings support perspectives previously expressed by stakeholders [7].

Limitations

Even though this study offers several contributions on the fit of PDS in coal mines, three key limitations need to be considered. First, the results from this study were based on a small sample of mines, which were recruited using a convenience sampling approach. Consequently, user perspectives and evaluations may not be reflective of all underground coal mines. In addition, sample size recommendations for Cronbach's Alpha vary [26]. Therefore, the small sample size may have had an effect on the robustness of the Cronbach's Alpha Test. Second, researchers collected data for this study during the enactment of the final rule for PDSs for CMMs (i.e., March of 2018). Even though the study focused on mobile PDSs, the new regulation for CMMs may have shaped mine leaders' perspectives and evaluations of mobile PDSs. Finally, the study used an adapted version of the task-technology fit model. Cronbach's alpha shows that the instrument was reliable. However, considering the small sample and modifications, the adapted model may require additional testing to ensure its validity and reliability.

ACKNOWLEDGMENTS

The authors would like to thank the mine leaders that participated in this study for their time and commitment to health and safety.

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