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If the Technology Fits: an Evaluation of Mobile Proximity Detection Systems in Underground Coal Mines

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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 present an opportunity to explore and improve the integration of mobile PDSs in underground coal mines. The current research 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 and suggestions for safe technology integration.

Keywords

Occupational safety; Coal mining; Proximity detection; Task-technology fit; Automation

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 powered 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 and See's [3] definition of automation—a mobile PDS actively "selects data, transforms information,

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Compliance with Ethical Standards

Disclaimer The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

Conflict of Interest The authors declare that they have no conflict of interest.

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.

1 Proximity Detection and US 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 2166 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 purchasing 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 [8]. 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 [8]. Data retrieved from the PDS revealed that, prior to the accident, the fatally injured worker's emergency stop override had been activated 87 times [8].

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 [9] and develop recommendations to support safe use [10–12] of PDSs for CMM. The aim of this study was to build on existing research on PDSs by applying the task-technology fit model (TTF) [13, 14] to examine the *fit* between mobile PDS technology and the conditions and job tasks in underground coal mines. More specifically, the aim of the study was to use TTF to systematically investigate recent stakeholder concerns regarding mobile PDSs and provide suggestions to help ensure safe technology integration. The following section includes a review of the TTF model and describes how the framework was adapted for the current study.

2 Task-Technology Fit

Task-technology fit, originally introduced by Dale Goodhue and Ronald Thompson, posits that a technology will aid workers in completing tasks [13, 14]. Further, users' assessments of the system determine the system's usefulness [13]. 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 [13, 14]. 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 [13, 14] 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 [14] original task-technology fit dimensions and the adapted dimensions used for the current study.

3 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 [13, 14] and to reduce perceived resistance [15]. 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 [13, 14]. Conversely, if the mineworker perceives that the new technology makes the task less safe and more difficult, he or she is more likely to evaluate the technology poorly and discontinue or limit use.

Past studies have 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 [16]. Norzaidi and colleagues [15] 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 performance [17].

In regard to an autonomous safety technology such as a 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.

3.1 Study Objectives

The current study had three research 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?

4 Methods

The current exploratory study followed a concurrent triangulation design, which is a mixed-methods approach, as described in this section. This design allows for concurrent collection of qualitative and quantitative data and integration of the results [18]. According to Creswell [18], concurrent triangulation is a valuable traditional model because it "can result in well-validated and substantiated findings" (pp. 213–214). The approach helps to minimize limitations associated with solely using one data collection method [18]. Prior to recruitment and data collection, the study protocol was approved by the NIOSH Institutional Review Board.

4.1 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 bituminous coal mines to participate in the study. Convenience sampling is a non-random selection process that involves recruiting a sample that is easily accessible or available [19]. For this study, the research team identified mines that had previously

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participated in NIOSH research. For final selection, researchers identified mines that were located in distinct geographic regions and that used different PDSs. Table 2 provides an overview of the selected mines.

4.2 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. To capture multiple perspectives, 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.

4.3 Data Collection and Instruments

To ensure the content validity of the data collection instruments (i.e., survey and focus group protocol), the researchers facilitated a 60-min pilot focus group with former coal mine leaders. Content validity is an evaluation of how well the items and overall approach reflect the perspectives of the intended population [21]. According to Brod and colleagues [21], interacting with the population of interest is the most appropriate way to support content validity. Collecting feedback on the instruments and study approach from former leaders helped to achieve this purpose.

Once the instruments were tested and validated, 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 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 [13] dimensions for task-technology fit (see Table 1) [13]. Table 5 provides the list of questions included in the questionnaire. Mine leaders used a five-point Likert scale, which ranged from *strongly agree* to *strongly disagree*, to evaluate the mobile PDS at their mine.

4.4 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% of the participants were classified as favorable. Dimensions rated as *neither agree nor disagree*, *disagree*, or *strongly disagree* by more than 50% were classified as less favorable.

4.5 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 [22]. 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.

5 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 [23].

5.1 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. Figure 2 depicts the dimensions that received favorable evaluations.

5.2 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% 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.

6 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. Figure 4 illustrates and outlines the themes. This section provides a summary of the qualitative results organized by research question. Representative participant quotes are included.[2]

[2]Statements noted as being voiced by one participant often received agreement and support by other group members.

6.1 Research Question 1

The first 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 influences the fit of mobile PDSs—*working around mobile machines*.

- *Working around mobile machines*. 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. "The system makes you think. Makes you stay further away—eliminating risk" (*Mine B*). Similarly, another 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.

- *Training*. For the *training* theme, most leaders spoke favorably of the mine's training programs. *Mine A* discussed training approaches that were 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. "Everyone that works with proximity had 10–20 hours of hands-on training. As we have changed the system, we spent time with every individual. We are currently on our fifth zone setup. This is part of why mobile proximity works now" (*Mine B*).

  Mine B also discussed how the dedication of its trainer aided in its success with using a mobile PDS. "[Trainer's name] is a good teacher. He really took it to heart. He spent extra time. It wouldn't have worked with a nonchalant trainer" (*Mine B*). In addition, both mines discussed specific training for their maintenance workers.

- *Culture. 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. "Here we had the right behaviors to begin with. We had a low tolerance to being by equipment. Mineworkers were not allowed to walk beside the equipment. Mineworkers were not allowed in the red zone" (*Mine B*). 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, Leaders at *Mine A* expressed that training and safety equipment were priorities at their mine. Echoing *Mine A's* commitment to safety, leaders from *Mine B* shared that their general manager's decision to adopt the technology was evidence of the mine's values and existing safety culture. "Have to have safety culture…not everyone has a GM [general manager] that says they want to use it" (*Mine B*).

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. "I mean, and unfortunately, I don't think you can police people enough and make them do the right thing. I think in our mine, people probably do the right thing more than any other mine" (*Mine A*).

- *Conditions*. Leaders stated that *conditions* and materials such as thick coal seam and consistent materials throughout the mine helped with mobile PDS implementation. "It is easier at our mine because it is consistent and doesn't change. We can work with that amount of steel because the metal magnifies the zones. We have calibrated the system to that. If we had mesh and no mesh the zones would grow and shrink. This would increase the risk and some miners don't know that it does that" (*Mine B*).

- *Resources*. Mine *resources* such as personnel, maintenance, time, and financial resources aided the mines in implementing their 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% of his time was dedicated to mobile PDS implementation. This individual's efforts and commitment contributed to the mine's success with the 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. "The technician cleans and charges the [MWCs] every day. Everyone checks out and needs to return the [MWC]. They know that they are going to get checked at the end of the day. Better care and reliability because it gets checked by multiple people and they know it will be—this way [MWCs] don't get damaged [as much]" (*Mine B*).

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. "Because we have spare equipment, they don't feel the pressure to fix it, if it breaks on swing shift and we don't have a mechanic on shift" (*Mine B*).

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.

- *Performance*. 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 leader discussed how the system was integrated with the original equipment manufacturer's controls. The interoperability of these technologies helped to eliminate the sudden stops that mobile machine operators had been experiencing. "Our new [manufacturer's name] have some really good technology on them, they are VFD drive haulers. When you get in the warning zone the VFD will back down to 50 kHz, which cuts you more than in half of the speed. When you get in the hazard zone it drops it down to 10 kHz, which you're barely moving and then the brake sets. So it's not an abrupt stop" (*Mine A*).

  Several mine leaders also suggested that, when well-maintained and free from electromagnetic interference issues, the mobile PDS was reliable. "The proximity system is reliable for everyday use. Now that we have worked all the bugs out, it is more reliable" (*Mine B*).

- *Usability and System Features*. 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. "It is easy to see. If you shutdown there is a screen with the locator number that is shutting you down" (*Mine B*). One leader described the simple design of the MWC. "It only has three colors. It beeps. All of that is consistent. One button is easy to use if your vision is good" (*Mine B*).

  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. "When the manufacturer came out to install they said that we needed ten zones and would be good. Now we have 40 zones…a good system has that ability" (*Mine B*). Finally, one leader discussed the usefulness of authorization controls. He used the feature to limit workers' control of the system. "I like minimizing access. It is good to keep control. [It] allows you not to lose control" (*Mine B*).

- *Support*. 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. "Also, the manufacturer representative is five hours away, but comes when called" (*Mine B*).

A leader from *Mine A* shared similar comments about his representative's responsiveness. "Every time I've called our [manufacturer's name] rep, he has answered the phone…and we've had him out on the property numerous times" (*Mine A*). The leader also shared that a representative was involved in training.

- *Requirements*. 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.

6.2 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.

- *Working around mobile machines*. 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. "[A mobile PDS] makes things harder and less safe. For example, because the most common issue is that the mobile equipment backing up to the continuous mining machine doesn't consistently make it in. Continuous mining machine operators will have to walk to the front or side of the car to walk it in, in order to load [the car]" (*Mine B*).

  Another mine leader shared similar thoughts on the increased risks for CMM operators. "The miner operator…had to come out of there and get away from the miner, which put him in contact, closer contact with the coal hauler…yeah, we protect him from the miner but have we added another hazard?" (*Mine A*).

  In addition to the increased risk, worker frustration was also a major concern for mine leaders. "[We] made zones bigger, so we don't have risk. Now [we] have other risks like increased walking and frustration" (*Mine B*).

- *Operating mobile machines*. 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. "Yeah, once loaded and on any type of grade, it didn't have enough power to pull away" (*Mine A*). As a result, some operators at *Mine B* had to use tow straps to help move the machine, which increased the physical burden on the workers.

- *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. “The machines were not built for these systems…and they just get torn off and all that stuff. So you know they are continuously trying to figure out new ways to protect them” (*Mine A*).

  Additionally, leaders at both mines discussed the complexities involved in troubleshooting for issues with the system and MWCs. “Oh man, you could be troubleshooting an issue that you think you have when in actuality it could be a dead [MWC] halfway across the section. It can cost you a lot of time” (*Mine A*).

- *Setting up the section*. *Setting up the section* was another theme that emerged from the data. *Mine A* ran production 24 h a day, 7 days a week, and did not explicitly discuss section setup or downshift issues. 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. “[The mobile PDS] changes how downshift works. They used to use the cars for a mobile platform, where the miners would ride on the cars. Now, people can still use them as a platform, but are getting up and down. This leads to an increased risk of injury” (*Mine B*).

  Also, leaders reported that attempting to mitigate system interference issues caused workers to change the way they hung cable. “With mobile and mesh, you have to hang the cable at a 45-degree or any angle in order to not magnify or distort the signal” (*Mine B*).

  In addition to increasing workers’ risk for injury, leaders noted that mobile PDSs have also changed mine planning and section setup functions. “We had to change our cut sequence. The roof bolter has to be inby 50 feet as compared to just in. Otherwise we can’t mine and can’t drive by. Also, several changes with ventilation. With the change in depth of cut it changes how we ventilate methane away from the face” (*Mine B*).

- *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. “Proximity inhibits safety inspections. We used to go down and check the face and check the air. We would go around the section. Now we have to stay 50 feet behind. We are not able to observe and talk to people” (*Mine B*). Another mine leader discussed issues related to internal and external visitors.

Mine Characteristics for Research Question 2—Researchers classified all four *mine characteristic* 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. "When you first train miners with the proximity box, they trust that. They want to trust that. But, then do we want to rely on that to be there sole 100% and to keep people safe? No, we don't" (*Mine A*).
- *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. "At that location there wasn't a culture to keep the MWC on. Here culture requires it" (*Mine B*).

  In addition, mine leaders shared their perceptions of how regulations drive technology adoption in the US 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. One mine leader felt that the industry should consider limiting the types of machines that can be equipped with a 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 had low humidity. These conditions introduced challenges with the MWC cases and components. "The orange cases created static…because of the humidity level. It didn't occur [in another geographic region], but it was a problem here" (*Mine B*).

  Mine leaders also discussed the 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 interference for the mobile PDS. The mine addressed the issue by recalibrating the mobile PDS.

  The metal water lines created similar issues. "Our water lines have metal braiding in them. The water lines interfere with the mobile system as the signal travels up the water line and at the feeder" (*Mine B*).

- *Resources*. Resources was also included as a theme for *mine characteristics*. Mine leaders from both mines felt that properly implementing a 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 their production during the early stages of mobile PDS implementation. To address the production decrease, the mine increased maintenance and equipment costs. "But the extra machine increases the maintenance cost, increases the time to perform permissibility checks, and overall increases the manpower required to keep production up" (*Mine B*).

  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's interference issues. "You've got to figure out all of this electronic interference. And…we don't have those kind of resources" (*Mine A*).

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 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. "I mean several of them do get torn up, but we've hired so many people in the last two years. I mean, I don't know the number but, I would say that…I know I've ordered close to 500" (*Mine A*).
- *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 water-lines, leaky feeder communication cables, radios, steel mesh, cap lights, flashing blue lights, and pulled-up miner cable. "We've incorporated this SOS signal every time it gets interference, it beeps from the time you drop in the mine to the time you get back out of the mine" (*Mine A*).

According to leaders, the electromagnetic interference caused by the CPDM presented major challenges. In some cases, the interference issues were perceived to increase striking, pinning, and crushing risk for the CMM operator. "You're trying to pick up your cable and how many of the miner crushing injuries have been when guys are bending over picking that cable up and trying to hook it on the [CMM] head? That [CPDM] pouch swings around and lays right against that [MWC] and blocks the intended purpose of the [MWC]" (*Mine A*). Mine leaders referenced the NIOSH's recommendation [11] to keep the CPDM 6 in 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 mobile machines compared to CMMs.

Leaders from *Mine B* also shared their thoughts on why the 6 in of separation recommendation has not worked for them. "[CPDM] affects mobile proximity more than the CM [or continuous mining machine]. Six inches [of separation] is not enough. The CM moves slower than mobile and is not noticeable (*Mine B*)." To address the electromagnetic interference issues for the CPDM, the mine established an alternative rule. "We have to have a one-foot rule. The [MWC] has to be greater than one foot away from the CPDM" (*Mine B*).

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 charger that they were manufacturing, I guess the amp hour rating was not correct. The [MWC] would die within hours" (*Mine A*). The system manufacturer helped to resolve the charger issue.

The mine also had issues with some of the components. "Yeah, [manufacturer] outsourced some of their components, especially their cable couplings. Well the company that they purchased couplings from, their mode was incorrect. So plastic or rubber got down in the connection point" (*Mine A*).

- *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. "We have played around with the slowdown in the warning area with [manufacturer's name]'s way of doing that is throwing in a resistor in on the foot switch. And their resistor was too large. The machine wouldn't pull out under a [coal] load" (*Mine A*).
- *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. "Also, this [MWC] and proximity and radio there is not enough room on these guys' belts. So instead of wearing these [MWC] and just hooking it on your belt. They're having to hang it off of it. Now, I wish I could say that it's a perfect world and these guys can put it on the belt and it's

attached there all day. But, they're using rope hanger and everything else so they may walk away and the [MWC] falls off. And they don't even know" (*Mine A*).

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 belts, which included the MWC, to complete strenuous tasks and forget to put them 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. "If you hear a beep all day long around a cable and everything, you're going to tune it out. You get tired of hearing it" (*Mine A*). Another reason is that some workers might not be able to see the visible alerts. "The workforce is aging. I can see the screen, but others can't" (*Mine B*). 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 relative 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. "We don't have the research and development here to manufacture a brand new prox and go through the procedure" (*Mine A*).

Finally, leaders voiced 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 3 weeks.

7 Discussion

The current study evaluated the fit between mobile PDSs and underground mining through the perspectives of mine leaders from two coal mines. Results show that leaders provided favorable evaluations for five of the nine task-technology fit dimensions and less favorable ratings for the remaining four. Results also show how task, mine, and system characteristics influenced these evaluations.

Overall, findings indicate that mobile PDSs have the potential to be a valuable automated safety technology. However, addressing the challenges introduced by mine leaders may improve technology acceptance, fit, and integration efforts. Findings from the study offer three major contributions to occupational health and safety research and mining. The study (1) documents mine leaders' perceptions of mobile PDSs, (2) provides suggestions for mine operators, researchers, and equipment designers, and (3) extends the research on task-technology fit.

In relation to documenting mine leaders' favorable and less favorable perceptions of mobile PDSs, leaders provided positive evaluations for the training and ease of use, quality, locatability, authorization, and user perspective dimensions. Several characteristics influenced these favorable evaluations. For task characteristics, leaders' perceptions that the system reduced human-machine collision risk and improved workers' situational awareness positively influenced evaluations. The characteristics of the mine such as having a thick coal seam, consistent conditions throughout the mine, dedicated resources, effective training, and a strong safety culture also had a positive influence on leaders' evaluations. Additionally, system characteristics that supported leaders' positive evaluations were useful system features, vendor and manufacturer support, and the system's compatibility with mobile machines at their mine.

Past studies have shown that positive evaluations of fit can promote technology use [15–17] and reduce resistance [15]. In this case, leaders' favorable evaluations for more than half of the dimensions are encouraging. The benefits stated by mine leaders also may help to shape future use and organizational integration strategies. For example, the system's ability to improve workers' situational awareness may make mobile PDSs ideal training solutions. Some manufacturers are currently promoting PDSs in this way.

The study also captured mine leaders' less favorable evaluations, which were reported for the reliability, safety, task completion, and compatibility dimensions. For task characteristics, tasks such as loading, system troubleshooting and maintenance, and safety inspections were described as being more risky, difficult, or frustrating with a mobile PDS. Mine leaders expressed concerns about mobile PDSs introducing unintended safety risks such as greater injury risk for CMM operators during loading tasks, increased risk for musculoskeletal disorders for section workers, and less oversight from mine supervisors.

Mine characteristics such as poor safety culture, low seam heights, variable environmental conditions, and training programs that foster system overreliance or misuse also influenced leaders' less favorable evaluations of fit. While mine characteristics seemed to have a notable influence on leaders' evaluations, three of the five less favorably rated dimensions were directly related to system performance (i.e., reliability, safety, and compatibility).

System characteristics appeared to have the greatest impact on leaders' less favorable evaluations of fit. Factors such as the systems' overall cost, electromagnetic interference issues, false alarms, and lack of compatibility with older mobile equipment were discussed. Additionally, leaders' presented concerns about the design and wearability of the MWCs.

Several of the leaders' concerns and less favorable perceptions about mobile PDSs align with past research findings. For example, leaders' concerns that certain environmental conditions can increase risks align with Peters and colleagues finding that powered haulage fatalities were more prevalent in low seam mines [24]. Another related consideration is that variable mining conditions may make it more challenging for the mining sector to develop standardized mobile PDS integration resources and programs. Integration plans and resources may need to be tailored based on mine characteristics.

Additionally, leaders indicated that mine culture could have a major influence on the fit of mobile PDSs. These perceptions support Russell and Hoag's [25] finding that organizational culture can facilitate or impede technology implementation. To address this concern, mine operators may need to evaluate their organization's safety culture prior to or during mobile PDS implementation.

Leaders' perceptions regarding system performance issues also support previous research findings. Madhavan and colleagues [26] 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 [26]. In line with these findings, system performance concerns and false alarms associated with mobile PDSs negatively influenced evaluations of fit and raised concerns about system misuse and disuse.

While mine leaders expressed a number of important concerns, overall, findings from this study show that mobile PDSs have the potential to be an effective safety technology for US mines. However, to ensure the safe integration of the technology, industry stakeholders should consider critical task-technology fit issues that emerged from this study. Therefore, suggestions for mine operators, researchers, and equipment designers are provided.

7.1 Suggestions for Mine Operators

- Evaluate mine conditions that may pose challenges.
- Identify how a mobile PDS may change specific tasks and mitigate any associated risks.
- Develop training programs for workers including more specialized training for maintenance workers.
- Assess, secure, and dedicate time, personnel, and financial resources for mobile PDS implementation.
- Evaluate the mine's existing safety culture and address any issues.
- Identify ways to manage worker frustration and align organizational practices and policies to deter unsafe behaviors.

7.2 Suggestions for Researchers and Equipment Designers

- Further identify and address the electromagnetic interference issues related to mobile PDSs.
- Provide resources and forums to help share common challenges and best practices.
- Consider ways to improve wearability of the MWC.
- Explore additional system features and functions that will allow mines to meet specific needs through system customization.

Finally, this study contributes to research on task-technology fit by presenting a novel application of the framework in the evaluation of a mine safety technology. As the application of automated technologies and engineering controls continues to grow in occupational health and safety, the adapted TTF model can be further developed and applied by researchers and practitioners to evaluate these emerging technologies and solutions.

8 Limitations

Even though this study offers several contributions to a discussion of task-technology fit in 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 [27]. 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 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 sample size and modifications, the adapted model may require additional testing to ensure its validity and reliability.

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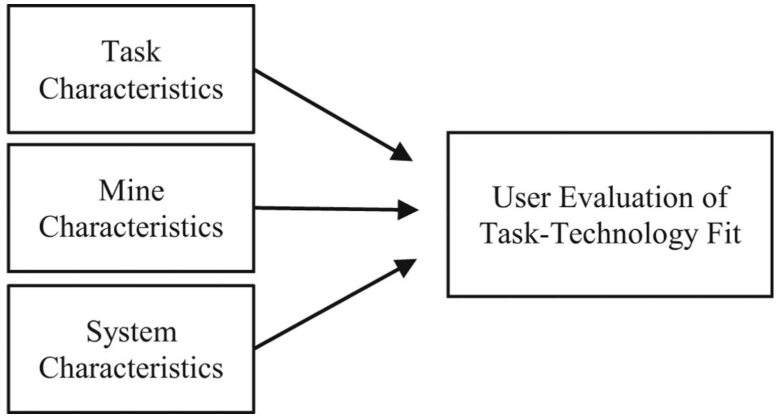

Fig. 1.
Adapted version of Goodhue's [13] task-technology fit model

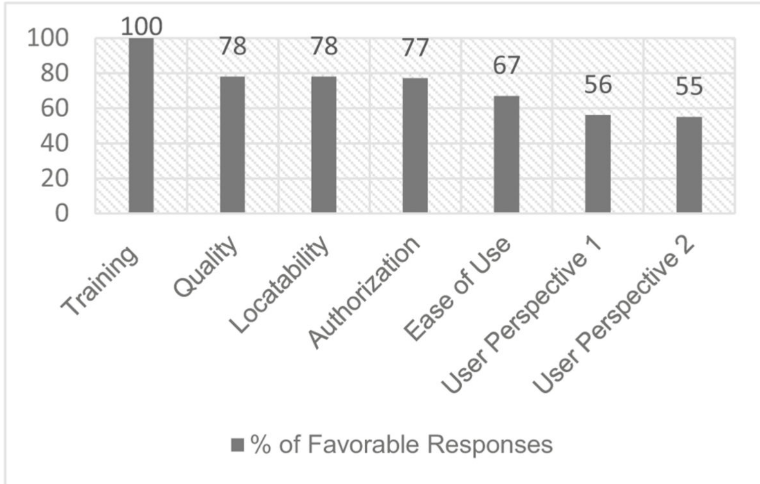

Fig. 2.

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

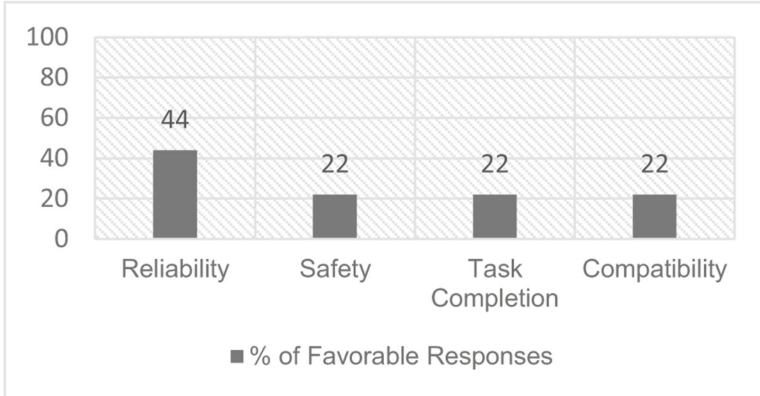

Fig. 3.
Graph illustrating the dimensions characterized as less favorable and showing the percentage of leaders that responded less favorably to the task-technology fit dimension

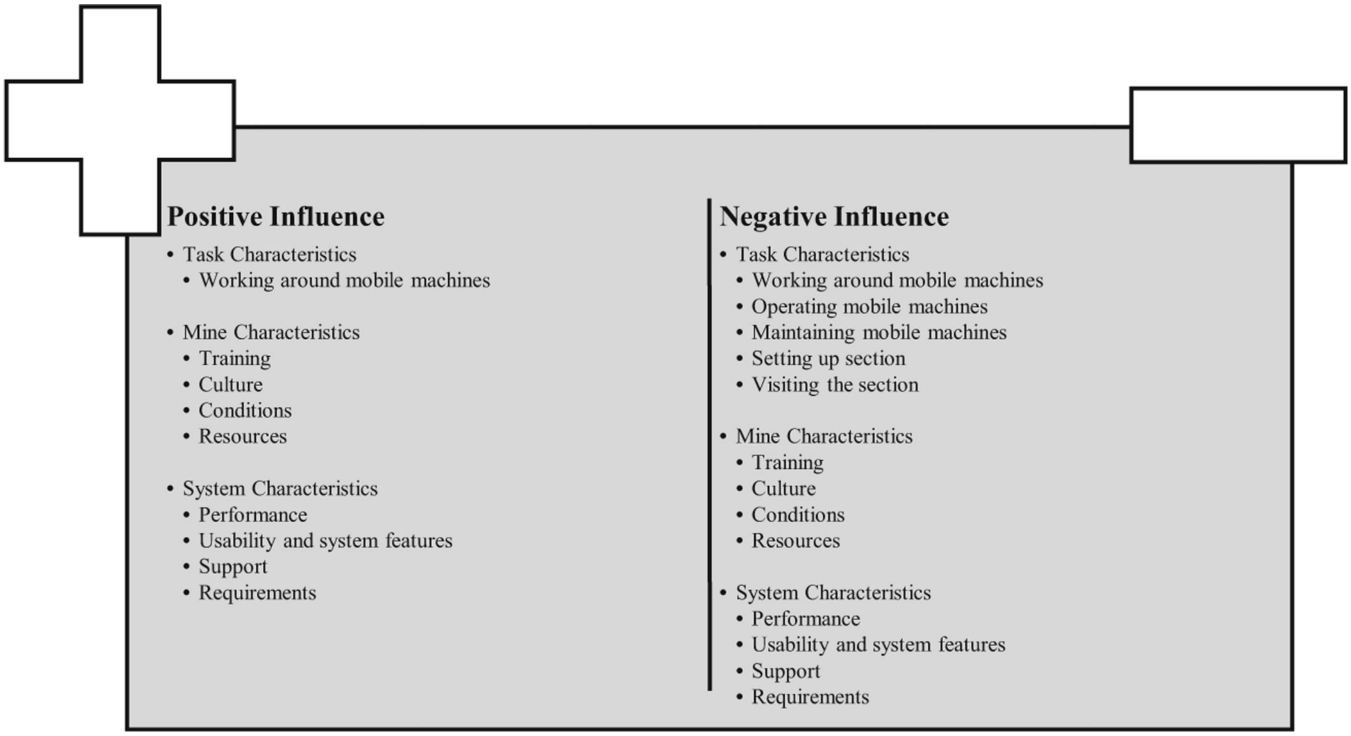

Fig. 4.

Chart depicting 13 themes identified for the three overarching task-technology fit characteristics. Themes that had a positive influence are shown on the left and those that had a negative influence are on the right. Some themes had both a negative and positive influence

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

Original dimensions based on work developed by Goodhue and Thompson [13, 14]

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

Annual coal production in tons.

[a]Rounded to the nearest hundred.

[b]Rounded to the nearest hundred thousand. Source: MSHA, Mine Data Retrieval System, Annual production for 2017 [20]

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		

Table 5

Questionnaire items

Question	Associated TTF dimension
1. Your mine's mobile proximity system keeps workers safe.	Safety
2. Your mine's mobile proximity system works well with other machines, systems and the conditions in your mine.	Compatibility
3. Your mine's mobile proximity system does not interfere with miners' job duties.	Task completion
4. The feedback from your mine's mobile proximity system is easily heard and seen.	Locatability
5. Your workers have received enough training to understand how the mobile proximity system works.	Ease of use and training
6. Your mobile proximity system performs as expected.	User perspective
7. Your mine's mobile proximity system is easy to use.	Ease of use and training
8. Your mine's mobile proximity system responds accurately to miners' locations.	Quality
9. Your workers can rely on machines with mobile proximity to be operational.	Reliability
10. The system information and components of your mine's mobile proximity system are easily accessible to the right people.	Authorization
11. Mobile proximity has had a positive impact on your mine.	User perspective