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Comparing the Implementation of Two Dust Control Technologies from a Sociotechnical Systems Perspective

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Abstract
A sociotechnical system (STS) creates a framework that allows an examination of how social and technical factors affect organizational outcomes within a specific environmental context. STS has been rigorously studied with a primary research focus addressing worker-technology interactions. Although these interactions are important, the social processes and interactions that occur whenever any technical or environmental change is introduced into the system have been undervalued. If social processes are better understood, mining organizations could efficiently prepare and stabilize for such changes. With this goal in mind, we sought to extend STS theory through applying principles of meta-design to analyze the results of two case study interventions. Specifically, we studied the impact of an unregulated dust control technology (the Helmet-CAM) and a regulated dust control technology (the Continuous Personal Dust Monitor) on factors within an STS including employees' knowledge of, communication about, and use of technology to mitigate respirable dust sources. The results are presented in a way that first, addresses the overarching principles of meta-design STS including organizational participation, flexibility, and communication and second, examines how technology implementation processes differ when the organization is complying with a formal, higher-level requirement. Results show that a prominent focus on the social factors within an STS framework could help reduce unpredictability on the technical side and may improve communication within the system to help reduce adoption time, especially if and when accompanying a new, formal work process.

Keywords Communication · Dust monitoring technology · Organizational interventions · Respirable dust · Socio-technical system

1 Introduction

Safe working conditions are enhanced with the help of compliance measures and formal and informal processes to provide risk control mechanisms for consistent health and safety (H&S) hazards. However, such rules only provide the pretense for safe processes and decisions [1]. Even with the safest possible conditions, where risks are controlled to an appropriate level, there are always changing innovations introduced into the environment that disrupt some part of the overall system. Despite the concept of a sociotechnical system (STS) originating in the British coal mining industry [2, 3], gaps still exist in how (1) technical and social systems are interdependently affected during the implementation of new mine H&S technologies, (2) inter-organizational communication practices (i.e., among workers, managers, and technology) impact H&S determinants at the mine, and (3) environmental factors (i.e., compliance measures, environmental hazards, mine structure) impact the development and eventual implementation of mine technologies.

To study these issues, we examined the impact of an unregulated dust control technology (the Helmet-CAM, described in Cecala and O'Brien [4]) and a regulated dust control technology (the Continuous Personal Dust Monitor (CPDM)) on employees' knowledge of, communication about, and maintenance of dust-reducing work practices within their mine organization. The first case study with the Helmet-CAM occurred with 48 miners and 17 managers from five industrial mineral mines. The second case study with the CPDM occurred with 35 miners and 15 managers from three underground coal mines. Although mining methods are different for these two commodities, the process regarding the integration of new technologies and communication about new information remains relevant for both cases.

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STS research often focuses on different factors to explain *intra*-organizational issues [3, 5]. Alternatively, we focus on the *inter*-organizational issues to better understand communication processes and adherence to H&S practices in response to the implementation of new technologies. For example, any change in a social or technical factor can prompt a change in managerial practices, a shift in how workers can or should identify and assess hazards, and how both groups make decisions in real time using their tools and equipment [6]. However, the level (e.g., organizational, corporate, federal) at which new technologies, rules, and processes are implemented could impact communication and compliance. Using an STS framework to shift analysis from the individual to the overall system can allow for a better understanding of how various interactions influence organizational H&S.

First, an overview of STS is presented, followed by meta-design STS and its five principles. Then, the two case studies are presented, including the current standards that apply to respirable dust exposure for each, the compliance assistance or regulated technology used for each, and data collection procedures. The results are presented in a way that addresses the overarching principles of meta-design STS as well as how these results differ based on the purpose of each technology (compliance assistance versus compliance). Although there are limitations within the present study, such as the small samples, that prevent the results from being generalizable, the study still demonstrates that a prominent focus on the social factors within an STS framework could help reduce unpredictability on the technical side; applying the principles of meta-design STS prior to and during the implementation of technology may improve communication within the system (i.e., mine organization), help reduce individual worker and organizational adoption time of the technology, and improve long-term maintenance of H&S practices on the job. Consequently, the results should be considered by individual mine organizations as a potential learning tool when a new technology or process is introduced on site.

2 A Review of Sociotechnical Systems

Innovative mine technologies, whether or not they are accompanied by or predicated through regulatory action, have become driving forces to help address complex problems in mine H&S. However, technology or even regulation alone cannot function as a way to improve organizational practices and worker performance [7]. Early STS studies argue that, because worker behavior and work practices were so entwined with technical factors, technology could not be understood without understanding workers' social processes [3, 8]. That said, a core insight of STS is the interdependence of the social and technical factors of organizations and the work environment [5].

2.1 Social and Technical Factors

According to Walker and colleagues [9], STS is founded on two primary factors. First, the interaction of social and technical factors facilitates conditions for either a successful or unsuccessful system performance, emphasizing the intersections between social and technical factors [10]. Second, if one of these two factors is adjusted, it is likely that increased unpredictability will occur in the system (i.e., the mine). These factors are defined below.

- Technical: can include machines, tools, technology, or equipment, and are produced and continuously adapted to provide a reliable experience for individual users and serve the needs of the organization [11, 12].
- Social: can include individuals and teams that need to coordinate, control, and continuously evolve to manage emerging risks in the organization [11, 12].

Researchers argue that the "socio" factors do not behave like the 'technical' factors in that people are more unpredictable and non-linear [9]. For example, new employees, new management, or changes to organizational structure may constitute changes to the social factors within an STS. New technologies and equipment can disrupt social factors as well. These two factors can also be impacted by changes in the mine environment whether physical or constructed by those who work at the organization. Specifically, one structural environmental factor that can influence advances in technical factors and changes in social factors is any type of formal or regulated work process that causes changes to the organization.

2.2 Formal or Regulated Processes as Environmental Factors

In general, any H&S regulatory measure or documented process is designed and intended to improve the performance of workers and organizations in ways that reduces hazards. Researchers [13] argue that regulations can serve many functions, including "improving industry's environmental performance, increasing the safety of transportation systems, or reducing workplace risk" (p. 706). It is apparent that mining technology has been enhanced as well as encouraged by regulation [14]. According to Kerr and Newell [15], such policies have the ability to "create constraints and incentives that influence the process of technological change" (p. 317). Within the USA, mining rules and regulations have significantly influenced health, safety, and technological innovations [16] and, as a result, many emerging technologies end up being regulated to some degree to further protect the worker.

To date, there is little empirical evidence about the effects of environmental regulation and other formal work processes on the social factors within an STS [17]. When introducing new technologies, integrating their concepts into organizational and worker processes is difficult [18]. As a result, research has argued that more cultural approaches need to be integrated into aspects of an STS in order to account for changes in the social factors—whether rational or irrational—that occur within the organization [19]. STSs are depicted several ways; one version of the system is illustrated in Fig. 1.

Although an STS may appear to be simple, the processes and interactions that occur within and between these listed factors can be severely disrupted whenever anything new is introduced into the system. In response, an emphasis on the social factors, via a meta-design framework, has been used to help alleviate ambiguity within the organizational system.

2.3 Meta-Design Interventions for STS

There is much support for the argument that, in collaborative systems, one's awareness and understanding occur at a systems level and therefore, collaborative STSs should be analyzed from a systems, rather than an individual, perspective [9, 21]. Instead of looking at the awareness and information processing of one worker or a group of workers within a situation, research has argued for an examination of the interactions or links within an organization [22, 23]. In this sense, one of the most critical challenges of STS is to explain how successful integration of social and technical factors can occur [7]. Research has argued that communication among and within worker activities is the most relevant and impactful component of the STS but is seldom the focus of an empirical study [e.g., 7, 24–26].

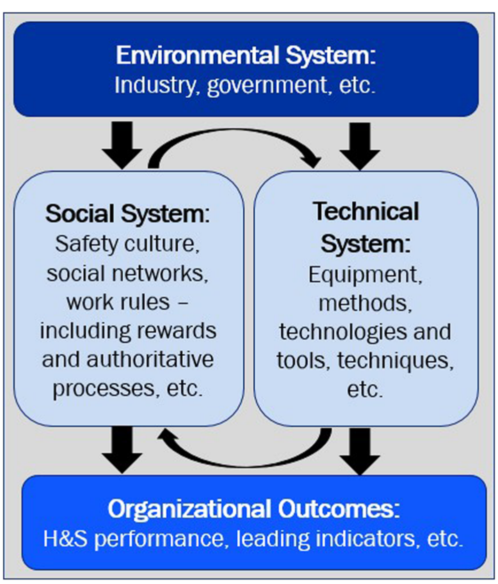

Fig. 1 Factors and relationships within STS including the environmental, social, and technical systems, which feed into organizational outcomes (adapted from Kull and colleagues [20])

As a result of arguments placing communication as a critical piece during any technology integration, an emerging trend in STS has been a focus on the social factors through meta-design [27]. One assumption of meta-design is that future problems cannot always be predicted and that, if users become "co-designers" during development and implementation, then the system's boundaries can be extended to support the needs of workers, workgroups, and the organization [28]. Therefore, the principles of meta-design facilitate action-research that can help improve performance [12, 29]. The primary principles of meta-design frameworks (adapted from Fischer [30]) are discussed below.

2.3.1 Culture of Participation

Participatory design approaches are commonly advocated for in order to allow stakeholders to influence the design of products [31]. In meta-design, a culture of participation is different in that the process solicits participation along with ongoing learning to allow an enhanced version of the product in the end [7]. In a culture of participation, a variety of roles are involved, and these roles constantly change based on those who help develop, implement, or use the technology [32–34]. Organizations that foster such an approach have been successful in integrating a variety of backgrounds, perspectives, and experience to allow space for everyone to contribute their own perspectives [35]. Fischer [35] notes that this process allows users "to act as designers and modify systems, thereby providing them with new levels of personal control" (p. 202).

2.3.2 Empowerment for Adaptation and Evolution

Research has shown that any new technical factor is more effective if it is supported by collaborative work practices [32]. Consequently, the empowerment principle focuses on the adaptability of the STS, primarily through the social factors providing some flexibility. An example may include supportive management who can immediately react and mitigate an identified health hazard. Another way to promote STS adaptability is to allow individual workers to contribute to organizational rules or processes that improve the culture [7]. Therefore, a meta-design framework should provide a variety of opportunities for feedback on tools, methods, processes, or strategies that are amenable to adaptation for the organization's benefit.

2.3.3 Evolutionary Growth

Rather than attempting to build large products or technologies all at once, meta-design encourages small contributions from many people who can contribute to an impactful, sustainable development [7]. This approach requires flexibility because it is unclear how certain aspects will evolve. This principle promotes phases of experimenting or practicing and later alternating with reflection and advancements in development or growth [36] which in turn, allows the ways in which innovations are used to evolve and change for the benefit of individuals and the organization.

2.3.4 Underdesign

Underdesign assumes that technical products are socially constructed throughout design, implementation, and use [26] and therefore, the product should not necessarily be completed during development. Rather, plans detailing how technical factors should be designed, organized, and then implemented should not be decided before the product is finished [7, 37]. Alternatively, underdesign promotes individuals being able to identify problems and contribute improved solutions to the technology [38]. In addition, underdesign does not only refer to hardware or software aspects; it also includes plans that describe how the technology will be used and how collaboration should be coordinated [26].

2.3.5 Structuring of Communication for Designing the In-Between

This principle concerns what kinds of communication can best facilitate adoption of a new organizational process or technology. Meta-design supports communication efforts by developing and promoting interventions that bring people together. Some researchers have proposed something called the sociotechnical walkthrough [39] which goes through a variety of cognitive, team, and structured participatory methods. This process allows leaders to ask prepared questions, gather contributions, and resolve any conflicts, particularly in reference to management support when new products and rules are introduced [29]. This approach supports participation and gives individuals an opportunity to decide how technology can best be used on site.

2.4 Applying Meta-Design Principles to Two Worker-Technology-Organizational Interventions

The principles discussed above reveal three primary themes of meta-design: participation, flexibility and adaptability for continued improvement, and communication. These primary themes underscore the importance of understanding interactions between workers and interactions between workers and their technology or equipment, to best communicate, distribute, and coordinate H&S within the system [40]. However, it has been difficult to empirically observe communication within an organization's STS [41]. A primary challenge to meta-design is motivating people to participate as well as allocating the time for people to participate, which prompts some leaders to use rewards or incentives [7]. Research shows that people tend to participate in personally meaningful issues [38], although other factors may play a role in helping or hindering participation, such as the safety culture, managerial support, efficacy, and workplace rules. But, it can be easy for workers to experience participation overload, especially if they do not have experience in offering constructive feedback [42]. Because of this, a tension between standardization and improvisation has been noted as a meta-design challenge [27].

Through a series of worker-technology-organizational interventions, some of these aforementioned challenges could be overcome including inter-organizational barriers such as how varying roles, processes, and procedures play into worker participation, organizational flexibility and adoption toward technology, and how improvements in communication may positively impact technology implementation and integration. This paper walks through two intervention designs that involved the use of new health technologies, one regulated in its current environment and one that is used for proactive compliance assistance. Within these two case studies, researchers examined mine-site communication during attempts to integrate social and technical factors to ultimately protect workers' long-term health. Using the broad principles of meta-design, this paper informs the ways that new technologies can be introduced and used in the mining industry to help workers maintain their situational awareness while organizations also advance the implementation of these technologies through increased participation, flexibility, and communication.

3 Methods

The roles of dust exposure regulation in mining (environment), dust assessment technologies (technical), and worker awareness and performance along with management implementation and support (social) are not completely clear, nor can a standardized approach exists to ensure that the organizational system remains intact during technology implementation. In addition, specific to respirable dust control in the mining industry, several engineering controls have been identified, developed, and implemented [e.g., see 43, 44], but many engineering solutions can be better integrated with the organization and workers [45]. This paper sought to extend STS in mining through applying principles of meta-design to analyze the results of two case study interventions. For both case studies, a convenience, purposive sampling strategy was used to recruit each mine and the participating workers [46]. All data collection instruments were approved through NIOSH's Institutional Review Board (IRB) and the Office of Management and Budget (OMB) prior to data collection.

3.1 Case Study 1: Helmet-CAM Technology to Reduce Exposure to Respirable Silica Dust

3.1.1 Guidance on Respirable Crystalline Silica Dust Exposure

Because of the serious health outcomes in response to respirable crystalline silica (RCS) exposure, the US Department of Labor's [47] Occupational Safety and Health Administration (OSHA) lowered the permissible exposure limit (PEL) of respirable silica by publicizing the rule "Occupational Exposure to Respirable Crystalline Silica" (81 CFR 16285). Effective June 23, 2016, this regulation reduced the PEL for RCS from 100 $\mu g/m^3$ to 50 $\mu g/m^3$ of air, averaged over an 8-h shift. This obligation had varying enforcement dates by industry over the last 2 years and did *not* include the mining industry. However, it is not unreasonable to assume that MSHA will follow suit and lower the RCS PEL. From a proactive vantage point, it was thought that the mining industry could benefit from quick and economic controls to reduce workers' sources of RCS exposure. To that end, Helmet-CAM technology, described below, was used to examine how the implementation of a non-regulated mining technology could impact communication processes as a means to reduce RCS exposure sources. A description of Helmet-CAM and its accompanying software is below.

3.1.2 Development of Helmet-CAM and EVADE Technology

In response to stakeholder concerns about the physical and practical challenges of assessing and controlling RCS, NIOSH, in cooperation with a large industrial minerals company, developed an assessment technology known as Helmet-CAM with complementary software known as EVADE (Enhanced Video Analysis of Dust Exposure) [4, 48]. The technology includes a lightweight video camera worn on the hardhat or shoulder and an instantaneous dust monitor connected to a 10-mm cyclone also worn on the shoulder. The video recorder and dust monitor are typically placed in a backpack. Miners perform their job tasks as video and dust exposure data are collected, and video footage and dust data are then downloaded to EVADE. The software merges the camera footage and dust data to produce a video that can be played back to identify work areas and tasks that cause elevated RCS exposures [see 4, 48, 49]. The technology is not touted as a compliance tool, but rather a compliance-assistance tool to allow organizations to pinpoint and mitigate trouble spots or processes on their site. Figure 2 shows the components of the Helmet-CAM technology.

During 2011 and 2012, NIOSH researchers performed 12 studies at mining operations to evaluate the effectiveness of this technology [4, 48, 50, 51]. Over 100 miners wore and assessed the technology, with only one worker complaining about wearability issues. EVADE 1.0 software was developed in 2010 and made available to the public in 2012. NIOSH then sought to improve some technical features of the software based on known usability issues, involving stakeholders in the feedback and improvement process. In October 2014, a focus group was conducted with nine members of mine management to understand how management personally used the Helmet-CAM, organizational changes made in response to the technology, and how to improve the EVADE software. Based on these discussions, EVADE was updated to enhance its usability as a compliance-assistance tool and added real-time contaminant assessment tool data for exposures beyond dust, and released to the public in 2015 as EVADE 2.0 (for detailed usability feedback, see Haas et al. [52]). Figure 3 shows the components of EVADE 2.0 output.

3.2 Helmet-CAM Technology Intervention

This intervention aimed to initiate and enhance mine-site conversations about the risks and potential occurrences of workers' respirable dust exposure as well as provide an impetus for mitigating higher sources of RCS. Data collection occurred in several stages during two separate visits, approximately 6–8 weeks apart at each mine site.

3.2.1 Pre/Post Health and Safety Survey, Interview, and Debrief with Miners

In order to understand potential impacts of the Helmet-CAM technology on miners' performance in relation to reducing exposure to RCS, a 15-min subjective pre- and post-survey was completed with each mineworker [52–56]. The 6-point survey (strongly disagree to strongly agree) was tested for internal consistency using Cronbach's alpha [57]. Cronbach's alpha is a measure for internal consistency that is used to determine how closely related a set of items are as a group [57]. After miners completed the survey, short interviews took place in mine offices. Discussions were 15–35 min, depending on time constraints and the openness of each participant. Using behavioral constructs from theories such as the Health Belief Model [58], workers were prompted to share their personal susceptibility to RCS exposure and potential consequences of their exposure. Additional questions prompted participants to discuss common hazards that they watch for on the job, tasks that expose them to RCS, and behaviors that they engage in to prevent elevated exposures. Participants also discussed various messages that impact their H&S decisions such as how often their supervisors talk with them about RCS and their preferred method of communication.

After completing the pre-survey and interview, individual miners wore the Helmet-CAM setup for approximately 2 h during their work shift. The footage was immediately downloaded into EVADE 2.0 to illustrate potential dust hazards, including the highest exposure peaks throughout the

Fig. 2 Helmet-CAM with video camera lens located on worker's shoulder (left) and helmet (right) and the 10-mm cyclone attached to the backpack shoulder harness

workers' length of wearing the Helmet-CAM. This information was downloaded into EVADE and reviewed with miners and members of management as soon as possible. In most cases, the dust footage was reviewed on the same day—usually on the workers' next break or during lunch—in an effort to initiate discussions about work practices and engineering controls that can reduce exposure to RCS, as well as how managers can support or initiate these controls. Discussions occurred right away so workers would have the benefit of seeing the dust data that was produced while they were wearing Helmet-CAM. During these discussions, workers and managers were able to identify realistic goals to improve upon before the next visit (e.g., changing from cotton gloves to leather gloves, repairing tears in cloth chairs in equipment). Then, on the follow-up visit, approximately 6 weeks later, workers participated in another interview to document changes that had occurred since our last visit, wore the Helmet-CAM again, and then participated in the post-survey assessment to document changes in personal proactivity that had occurred throughout the intervention.

3.2.2 Focus Groups and Helmet-CAM Debriefs with Management

Members of management participated in approximately 1-h interview or focus groups to discuss ways they engage their workforce to be accountable and proactive in protecting their health. For the focus groups, anywhere from four to seven leaders participated, which is typical for this research method [59]. Leaders were asked to share efforts used to ensure

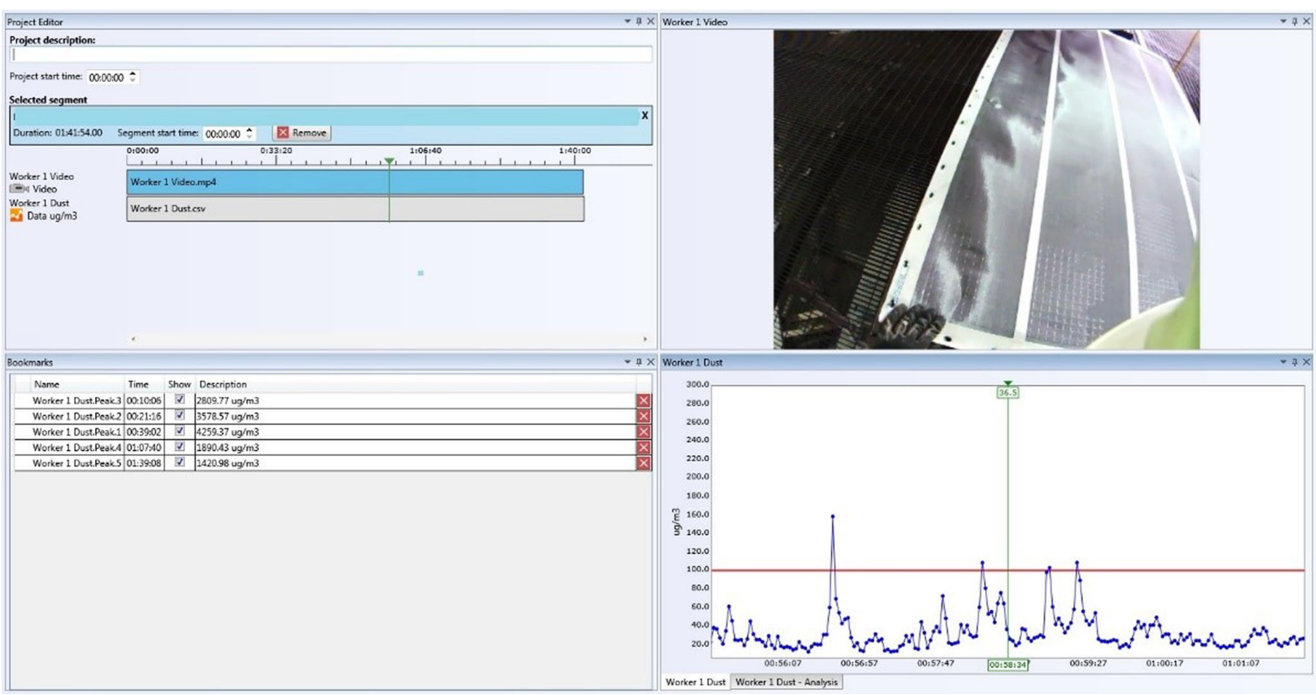

Fig. 3 EVADE 2.0 screenshot showing the software project editor window (top left) the job task being completed by the worker (top right), the worker's five highest exposure peaks while wearing the video exposure monitoring device (bottom left), and a line graph representing the worker's exposure while completing the task (bottom right)

consistent site-wide communication based on previously identified practices [60]. The data allowed researchers to glean more insight into the organizational culture, which was helpful when reviewing the Helmet-CAM data. In addition, feedback was provided to these managers via e-mail, phone, and/or in person throughout the duration of the intervention. NIOSH researchers relayed information about elevated exposure areas, issues associated with elevated exposures, and considerations to possibly reduce exposures. Between NIOSH visits, site-level management could explore new engineering controls and communicate practices that may reduce exposure, which were re-assessed at the follow-up visit.

3.2.3 Participants

This case study involved 48 workers from five mine sites (four industrial mineral/aggregate sites and one metal site) who agreed to participate between April 2015 and September 2016. The first site had 11 participants, the second had 9, then 9, 12, and 7, respectively. Of the 48 participants, 9% were 18–24 years old; 27% were 25–34; 23% were 35–44; 23% were 45–54; and 18% were 55–64. Managers were asked to select job tasks that they felt were more susceptible to RCS exposure in order to provide the organization with relevant information. Participants held job positions such as loader operator, rail loader, lab technician, dry maintenance, clean-up, mine operator, assay lab technician, blaster, load truck operator, electrician, and utility/process operator.

3.3 Case Study 2: CPDM Technology to Reduce Exposure to Respirable Coal Dust

3.3.1 Guidance on Respirable Coal Dust Exposure

On May 1, 2014, MSHA enacted a regulation, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors" (30 CFR Parts 70, 71, 72, 75, and 90), that contained several progressive phases [61]. The most recent phase was that the dust level may not exceed 1.5 mg/m^3 (previously 2 mg/m^3 for any work shift). Another phase of the regulation required mine operators to start using a continuous personal dust monitor (CPDM) by February 1, 2016, for designated occupations (DO) and other designated occupations (ODOs) to monitor and comply with regulatory exposures. As defined in the rule (30 CFR Part 70.208), the DO is the occupation on a mechanized mining unit (MMU) that has been determined by results of respirable dust samples to have the greatest respirable dust concentration [61]. The ODO is another occupation on an MMU that is also designated for sampling. Consequently, underground coal mines are required to use the CPDM to collect 15 valid sampling shifts each for the DO and ODO per quarter per MMU, while complying with the lower standard. The DO and ODO cannot be sampled concurrently, so a minimum of 30 shifts of sampling must be conducted on each MMU. If blowing face ventilation is used, the face haulage operator (e.g., shuttle car operator) must also be sampled as another ODO, so a minimum of 45 sampling shifts must be completed for these MMUs.

3.3.2 Overview of CPDM Technology

Accurate real-time monitoring of coal mine dust has been an industry goal for a long time, with the first prototype personal dust monitor (PDM) funded by NIOSH in 1983 [62]. Although it was configured for end-of-shift measurements, the device was not a real-time monitor and had difficulty in achieving realistic wearability for workers [63]. Additional incidents of coal workers' pneumoconiosis (CWP) prompted the Secretary of Labor to convene an advisory committee in 1995 to study this issue, where the concept of personal dust monitors was given new attention and was undertaken again by NIOSH, but this time, in collaboration with labor, industry, and MSHA. NIOSH issued another contract to redesign and develop the PDM. The Thermo Fisher Scientific PDM 3600 was commercialized in 2009 and certified for use in underground coal mines by MSHA (safety) and NIOSH (performance) in 2011.

Components of the technology included a sampling inlet, Higgins-Dewell cyclone, air heaters, air sampling pump, dust sensor, battery for the sampler, battery for the cap light, electronic control and memory boards, and a display screen [63]. In addition, the technology also interfaces with computer software so the dust data that has been recorded each minute can be downloaded and viewed by workers and managers. This version of the PDM was field tested at ten mines [64], and a separate study completed 30 interviews with miners to understand their feedback, concerns, and uses with the PDM [65]. Eventually, a new version of the dust monitor, PDM 3700, was developed through another NIOSH contract with Thermo Fisher Scientific. This version was certified for use in underground coal mines by MSHA and NIOSH in 2014 and satisfies the compliance sampling requirements of a Continuous Personal Dust Monitor (CPDM) as specified in 30 CFR Part 74. This version was the same size but lighter due to the cap lamp and associated battery being removed. It provides near real-time readings, with workers being able to view cumulative exposure readings, 30-min readings, and the percent of the PEL that has been reached during their work shift by navigating through available screen views on the CPDM. Figure 4 shows the Model 3700 and available screen views.

3.4 CPDM Intervention

The current intervention initiated and enhanced conversations about the risks and potential occurrences of respirable coal

Fig. 4 PDM 3700 dust monitor (left) and information screens available (right). The screen view shown in the top right photo in Fig. 4 provides the average respirable dust concentration for the previous 30 min of sampling, in addition to the average cumulative concentration from the beginning of the sampling shift. The screen shown in the middle right photo identifies the PEL for the sampling shift (input by the user) and the percent of this limit that has been reached to this point of sampling. The last screen photo shows a bar graph of average dust concentrations for each 30-min period of sampling throughout the shift with the values of the highest and lowest measured mass concentrations also displayed

dust exposures on the job using the CPDM dust data output displayed on the screen. The data collection occurred in several stages during two separate visits, approximately 6–8 weeks apart at each mine site.

3.4.1 Surveys, Interviews, CPDM Use, and Dust Data Debrief with Coal Miners

In this case study, in addition to proactive scale measures, a "Learning Self-Regulation Questionnaire" (adapted from Williams and Deci [66] and Black and Deci [67]) was provided to participating workers each visit to better understand how using the CPDM aligned with their H&S values as well as how the technology was used to reduce exposure to respirable coal dust [68, 69]. The questionnaire measured internal (i.e., self-motivation) and external (i.e., motivated by others) motivation to take into account why coal miners may decide to learn or adopt a self-protective behavior. The 13-survey items were retained, but terminology was changed to reflect workers' use of the CPDM. The Cronbach's alpha for extrinsic regulation (7 items) was .85 and the Cronbach's alpha for intrinsic regulation (6 items) was .77. Both of these Cronbach alpha's rendered "good" internal consistency and considered a reliable measure for each scale [57]. In addition, similar interviews or focus groups, as detailed in the earlier Helmet-CAM discussion, occurred with workers.

After completing the survey and discussion, individual miners began their workday, wearing the CPDM as usual, as a part of the regulatory requirement (researchers visited the site while at least one DO or ODO was sampling). The next day or next visit, researchers reviewed the dust data output cards produced from the CPDM. Specifically, dust peaks were reviewed with the workers and members of management in an effort to initiate discussions about (1) possible scenarios that caused an elevation in dust exposure, (2) personal behaviors that can reduce exposure to respirable coal dust, and (3) potential engineering controls that can be explored by miners and management to improve current dust control methods.

3.4.2 Focus Groups and CPDM Debriefs with Management

Specific to managers, 15 members of mine management discussed current interventions at their respective sites in response to the CPDM dust data output. Conversations ranged from one to five participants per site and lasted anywhere from 30 min to 3 h. They shared ways that they help support dust control practices on site and how they communicate the CPDM dust data to their workforce. Leaders were asked to share specific efforts to ensure consistent site-wide communication about the CPDM, and how they communicate the dust data output to the workforce. In addition, feedback was provided to these members of management via e-mail between visits. NIOSH relayed information about worker's perceived dust data peaks, use of the CPDM, and considerations to possibly reduce exposures. During this process, site-level management could help facilitate communication efforts with the workforce about possible behaviors that may help reduce respirable dust exposure or the exposure of their coworkers.

Follow-up visits occurred approximately 8 weeks later at each site in order to reevaluate if any new dust sources had been identified via the CPDM or any new dust controls were put in place. Participants discussed changes in response to the CPDM dust data output. The same workers were asked if they continued using information gleaned from the CPDM to sustain protective work practices, even when they did not have to wear the technology to comply with the regulation. Individual responses were linked to workers' surveys.

3.4.3 Participants

The study recruited 35 workers who wore and responded to the dust data provided via the CPDM (note that additional participants were recruited, but only provided qualitative and not quantitative feedback and therefore, are not included in the case studies). Workers from these three locations shared repeated situations in which respirable dust was higher, their thoughts on sources of higher exposure, common actions taken to reduce exposure, and what actions, if any, had been maintained over time. There were usually three to four workers from a crew present for the focus groups. Of the 35 underground coal mineworkers, all were male, and 37% ($n = 13$) were continuous mining machine operators; 37% ($n = 13$) were shuttle car operators; and 26% ($n = 9$) were roof bolters. Regarding age, 8% were 18–24 years old; 33% were 25–34; 25% were 35–44; 8% were 45–54; and 25% were 55–64.

3.5 Analysis of Quantitative and Qualitative Data

For both case studies, the surveys were entered into a statistical software "Statistical Package for the Social Sciences" (SPSS). For the purposes of this paper and the smaller sample sizes, only averages and basic pre and post differences are reported. The interview data for both case studies was analyzed and coded in a series of stages. Initial coding of the data occurred while typing the interview and focus group notes. Then, researchers engaged in a more focused effort to identify codes under respective themes from both worker and manager perspectives [70–72]. Once the worker and manager data was organized, the codes and examples that supported the overarching themes were compared to the theoretical constructs used to develop the data collection instruments [73]. This allowed us to better understand the forces driving perceptions and decisions of workers and management. The coded data was then reviewed with the meta-design principles in mind to determine areas specific to individual participation, organizational adaptability, and communication [7, 26]. The coded data was sorted into these three meta-design areas to inform social processes around these two technologies.

4 Results

For specific results related to engineering controls and other fixes identified via the two technologies to reduce workers' exposure to respirable dust, see [74–78]. Because this paper focuses on the "socio" factors of STS with an emphasis on collaborative participation, the two case studies are debriefed within three sub-sections to accurately examine how regulated and non-regulated technology implementation may have impacted social aspects within the meta-design process. Broadly, the meta-design principles are centered around participation, adaptability and flexibility, and communication. The quantitative and qualitative data is used to contribute to these three overarching areas.

4.1 Participation in Identifying Sources of Respirable Dust

As discussed earlier, a culture of participation is important in recognizing individuals' contributions and even in fostering intrinsic motivation to take action [7]. Both interventions fostered a culture of participation via workers and managers engaging with the technology from both a usability perspective as well as using the information to reduce personal exposures. Engaging individual workers and managers fostered greater participation and contributions to technology implementation by the end of the intervention as well. For example, the pre- and post-surveys with workers from both case studies indicated that, regardless of whether a technology is regulated or not, engaging users in what the technology is communicating about their personal health can be used to motivate workers' performance.

Although the surveys varied slightly, the constructs measured were similar. In the Helmet-CAM pre- and post-survey results (Table 1), workers reported higher levels of personal proactivity, compliance, engagement, and coworker communication about health and safety. Figure 5 shows the Helmet-CAM results for the proactivity questions in more detail, illustrating a significant increase in proactive behaviors from time 1 ($M = 4.84$) to time 2 ($M = 5.10$), $t\ (33) = -2.545$, $p < .016$ (two tailed). The mean increase in proactivity scores was .268 and the eta squared statistic (.16) indicates a large effect size. The data below met the assumptions of paired t test data, including the inclusion of continuous variables, the matched data pairs followed a normal probability distribution, albeit highly skewed, and the samples were random, meaning that any of the employed workers could have been chosen for this study.

The same proactivity questions were asked of coal miners who participated in the CPDM interventions. Statistical significance, using the same paired t test option, was not obtained within this sample, but the averages improved in all but one item, as shown in Fig. 6. For both tests, the small sample size, even though responses were distributed normally between the first and second visit, limited the ability to perform in-depth statistical analyses, but for the purposes of this paper, and examining results within an STS framework, it was deemed appropriate to share these pre and post intervention results regardless of statistical significance.

Table 1 Workers' H&S perceptions pre and post Helmet-CAM intervention

Workers' self-reported attitudes and behaviors	Pre Helmet-CAM Assessment (on 6-point scale)	Post Helmet-CAM Assessment (on 6-point scale)
H&S Proactivity	4.8	5.1
H&S Compliance	5.4	5.5
Engagement	4.6	4.7
Coworker communication	4.9	5.2
Personal H&S knowledge	5.5	5.5
Personal H&S motivation	5.7	5.7

As indicated earlier, coal miners within the CPDM interventions participated in a self-regulation survey. These results, shown in Tables 2 and 3, revealed a one-point difference between an intrinsic (4.33 on a 6-point scale) and extrinsic (3.38) motivation scale.

This large difference between the two scale averages illustrates first, that mineworkers are more intrinsically rather than extrinsically motivated to use and respond to the CPDM dust data to protect their health. For example, the question that received the highest agreement score (i.e., 4.76) was "it's good to try and improve my health," indicating that workers want to learn as much as they can about the CPDM technology to reduce their exposure to respirable coal dust. Second, the results show that extrinsic motivation does not play a large role in mineworkers' dust-related decisions on the job, with the "not true" average being below a 4.0. To illustrate, the survey item that received the lowest agreement score (i.e., 2.66) was, "Others would think badly of me for not using the CPDM," illustrating that workers do not care as much about what others think of them, or rely on regulatory pressures to use the technology, as much as their own motivation influencing their behavior. The qualitative results further show how technology, when implemented appropriately with social factors in mind, can enhance participation and buy-in from workers.

4.1.1 Participation in Using Helmet-CAM and EVADE

The Helmet-CAM case study illustrated that a technology in which workers have the option of using can serve as a risk assessment tool to build knowledge and awareness. This was evident as the interventions at each site progressed. For example, during the first visit at each of the participating Helmet-CAM sites, mineworkers had initial awareness of RCS, but did not have a sense of urgency to reduce their exposure. This was particularly prevalent among younger workers, who felt that dust was well controlled on site. Attitudes during the first visit included comments such as, "I think about dust exposure and trying to reduce it but I generally don't worry about it being a problem in the future in terms of my health. People have worked here for 35+ years and they're fine." Many workers acknowledged their exposure to RCS but did not feel it was a serious health threat. For example, one worker said, "I know that I'm exposed but I don't think I'm overexposed. So, I tend to not worry about it." Often workers just said

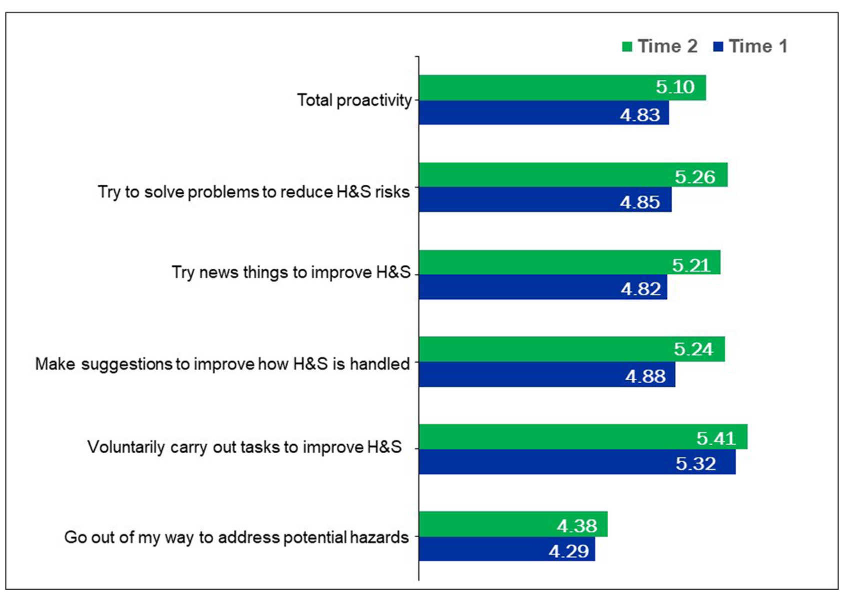

Fig. 5 Workers' levels of proactivity on the job pre and post Helmet-CAM intervention

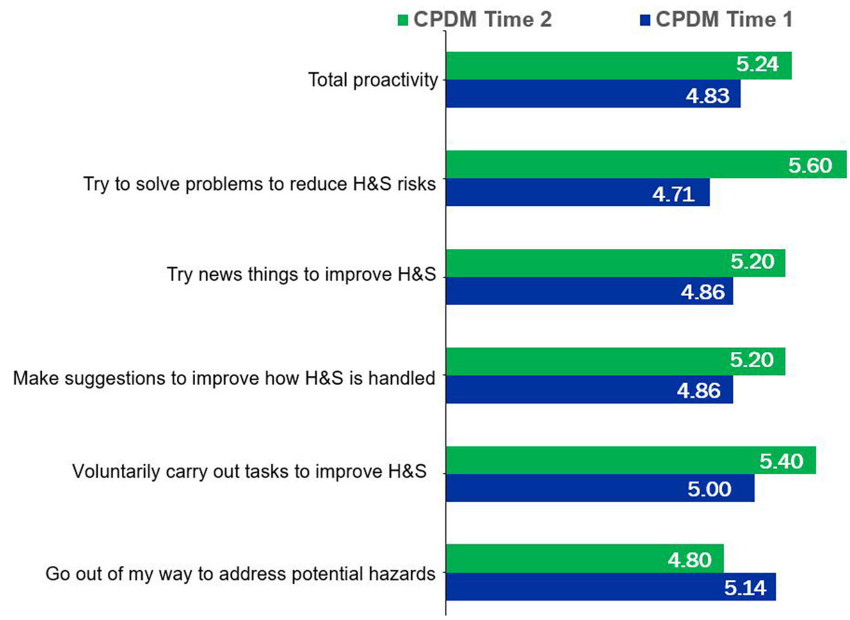

Fig. 6 Workers' levels of proactivity on the job pre and post CPDM intervention

something along the lines of "You can't eliminate everything. In some cases there's nothing you can do." Other workers justified their exposure by saying they might just be in a dusty situation for a few hours and not their whole shift. This is not to say that workers were not concerned about their exposure, but they had a more relaxed attitude. A common development in those who were concerned is that they were older and nearing retirement.

However, we also learned that workers did not have a strong sense of first, where their exposures came from, and second, what they could do to reduce their exposure. After workers wore the Helmet-CAM and saw their footage their perceptions shifted. Conversations with workers quickly turned into knowledge-building sessions where workers were given an opportunity to use the EVADE software and navigate to their highest dust exposure peaks. During this time, workers were also encouraged to ask questions about their exposure levels, to either the NIOSH researchers or the managers present during these conversations. These discussions allowed workers an opportunity to better understand their exposures, and they were provided immediate action items to reduce their RCS exposure, if desired.

On the follow-up visits, workers' attitudes changed significantly. Not only did workers' proactivity increase, as evident in the survey, but workers wanted to learn more about their exposure to RCS. Workers asked things like, "So what is the silica standard? Is that exposure over time negative? How much is too much before it affects you?" One young employee even asked, "If you're exposed to 100 mg/m^3 your whole life will you get silicosis?" In addition, workers expressed interest to continue participating in using this technology, even though it was not requested or required by the mine. Workers said things like, "I'd like to wear the Helmet-CAM again, during certain times, to identify tasks that have higher dust elevations," while some managers of the participating mine sites purchased their own Helmet-CAM equipment and downloaded the EVADE software for organizational use upon completion of the study. Therefore, the intervention illustrated that voluntary use of the Helmet-CAM was often received well by the workforce to protect their personal health rather than to comply with a higher-level regulation.

Table 2 Average of DOs and ODOs autonomous motivations

Autonomous survey items	Average (on 6-point scale)
• I feel like it's a good way to improve my skills and my understanding of exposure to respirable dust.	4.38
• Learning to use my CCPDM is an important part of being a coal mineworker.	4.26
• I believe my supervisor's/organization's suggestions will help me better use my CPDM.	4.21
• It's good to try to improve my health.	4.76
• It's hard to identify sources of respirable dust.	3.76
• It's helpful to use my CPDM to identify my main sources of respirable dust.	4.61

Table 3 Average of DOs and ODOs extrinsic motivations

Controlled survey items	Average (on 6-point scale)
• Others would think badly of me if I did not [use my CPDM].	2.66
• I would feel bad about myself if I did not use my CPDM.	3.03
• I would receive praise if I do what is suggested.	2.75
• I want others to think I am a safe worker.	3.91
• It's easier to do what I am told than to think about it.	3.03
• I would probably feel guilty if I did not comply with my supervisor's/organization's suggestions.	3.70
• I would feel proud if I continued to lower my exposure to respirable dust.	4.55

4.1.2 Participation in Using the CPDM

Obviously, due to the requirement of workers who were in a specific job role to wear the CPDM each quarter, workers participated in the use of this technology. However, because technology use was mandatory, their actual buy-in and adoption of the technology could have taken slightly longer if a mandated regulation to use the CPDM did not exist. To put this in perspective, it is highly unlikely that every mine organization would have bought several CPDMs for thousands of dollars unless they were required to for compliance purposes. While not surprising, the initial difference in experiences offers considerations for all technologies thought to be regulated at some point. First, coal miners had a more serious view of their exposure to respirable coal dust. This could be because coal mining has long been associated with CWP and coal mining is a generational occupation. Many workers indicated that they knew someone who had CWP or assumed that they had it themselves. As one worker said, when you start working in a coal mine "you sign up for Black Lung too." Surprisingly, workers were not initially motivated to reduce their exposure to respirable coal dust, similar to the previous case study. Many workers said that their mine did a good job and if anything more water sprays or water pressure could be added. Broadly, workers often referenced action taken to comply with the law rather than to protect their own health. For example, one worker said, "Supervisors take care of (reducing the exposure) to keep us from shutting down. The mine and us, we do things required by law."

Even though the motive for using the CPDM was in response to a regulation, and workers were initially frustrated with new obligations, they eventually saw the positive effects of this technology. On our first visits, when mines were just starting to use the CPDMs, workers felt like they knew where their exposures came from and were in some ways blindsided by the new technology. For example, one worker said, "We haven't really been told anything about the CPDM, just that we had to wear it." These workers also had concerns about how the dust data could be used in the future and if their dust data would be compared to other workers' levels. However, as time went on and for those who were motivated to learn from the technology, the workers and organization welcomed the dust data. By the follow-up visit, after going through one dust data debrief with workers, they expressed that they were looking at their CPDM output more often to see what they might be able to learn and that they are still learning, even after wearing the CPDM multiple times. For example, one worker said, "I like looking at my readout. It's nice to see what the feedback is so you can prevent exposure later. .. if I know where or when I got a spike last time, and if that means I can stand in a different spot or something."

Most workers indicated that they look at their output and ask questions about their exposure to their fellow coworkers or direct managers. Specific corrective actions that mineworkers learned are outlined elsewhere [i.e., 76]. Managers also noted printing out and discussing the dust data cards with their employees more as a result of the intervention. One manager learned that most of his workers' exposures were happening due to maintenance of the continuous mining machine prior to the shift starting. The mine site changed its housekeeping practices after realizing that the operators needed to clean them at the beginning of every shift.

A noticeable difference was observed in workers' responses to the CPDM once they learned that their dust data cards were posted and available for them to see, and once they learned how to interpret the dust data and received guidance from their supervisors. Notably, this communication path was not explicitly built into the original implementation of the CPDM, and seeing workers' change perceptions toward the technology showed the value of consistent communication about the capability of the technology and what the workers can do to reduce exposure levels and thus, comply with the regulation much easier. In a sense, providing workers with knowledge about the technology also provided them with a sense of control, which has been shown to increase participation in an activity [69].

4.2 Empowerment for Adaptation to Dust Control Technology and Evolution in its Design and Use

This section debriefs results for the underdesign, empowerment, and evolutionary growth principles. These principles address the importance of adaptability within an STS in order to allow flexibility on behalf of end users. This area is where more differences existed between the two technologies from both a design and implementation perspective.

4.2.1 Flexibility During Helmet-CAM Implementation

Although EVADE 1.0 was successful, it was not without its challenges during the first phase of implementation. Because NIOSH engaged in formative research to identify growing pains with the first version of EVADE, such as saving and retrieving files and then uploading them to simultaneously synchronize and play on the platform [52], many of these issues were fixed for subsequent users. The ability to add other real-time contaminant devices to EVADE 2.0 (by contacting NIOSH) has also helped the second phase of the technology's implementation. To illustrate, web tracking data from Omniture indicated that, between June 2015 and August 2018, EVADE 1.0 was downloaded 124 times and EVADE 2.0 was downloaded 751 times [79]. The difference in these downloads shows that users prefer the adaptable features of EVADE 2.0, including the ability to perform multiple assessments as once, and being able to upload data and footage that can be synchronized in the software.

In addition, because the Helmet-CAM technology was not regulated and served as a voluntarily assistance or learning tool, its use was more casual and designed to serve the specific needs of the organization rather than a mandated policy. Therefore, workers and managers could experiment with the technology in a variety of areas including their preferred method of fit (i.e., using a backpack or miner's belt to house the equipment); how long they wanted to wear the device; what tasks they wanted to do; and length of time they wanted to wear it. In addition, if the technology malfunctioned, it did not affect the organization or the worker because the sampling effort was voluntary and performed as a proactive activity on site.

4.2.2 Flexibility during CPDM Implementation

The initial development of both technologies was discussed earlier, and although both had initial feedback from workers and stakeholders, because the CPDM technology was required to be worn a certain amount of time to comply with a regulatory requirement, there was less flexibility in its implementation. The initial constraints perceived by workers and the organization caused hesitation at the onset of CPDM implementation, but were eventually overcome. Specifically, the development and design of the technology was more of a concern for workers because they had to wear the technology in combination with many other devices around their miners' belts for consecutive work shifts. For example, one shuttle car driver (an ODO position) stated, "We're on our second round using these. I mean, it's bulky to me – the size is very big. But I shouldn't complain because I can just hang it up in my car or put it next to me and he [pointing] can't do that." Similarly, managers discussed wearability as a general issue that they have to address during the initial integration period. One manager said, "Now that miners seem to be getting used to the device a little more, an ongoing issue is to determine how individuals prefer wearing the CPDM."

As a result, the wearability and comfort of the device was the biggest obstacle that workers had to overcome and a focus of discussion during the first visit. However, by the second visit and after learning how to interpret their dust data, workers had a more positive perception of what the CPDM could offer. After becoming more familiar with their CPDM screens, workers felt more comfortable about their exposure levels. One continuous mining machine operator shared about one experience wearing the CPDM, "That day I was at 38% after a cut and a half. We were being safe so I wouldn't be overexposed. So that's nice that we can check where we're at." Many workers shared similar sentiments, expressing that there is usually "plenty of room to play with if something happens" that causes a lot of dust.

Although workers appreciated information that the technology could offer, the rules behind its use were still in the back of their minds. Mainly, workers discussed the responsibility that comes with wearing the costly CPDM. As one worker said, "What I hate the most is it's a lot of responsibility… I'm responsible for taking care of an expensive piece of technology. It's something extra I have to worry about and keep up with. I'm a miner, I didn't think I'd be having to worry about this, it just makes me uneasy when I have to have it with me." Along with workers worrying about keeping the technology in working order, managers also had preliminary concerns about workers being distracted by the technology, posing a risk to workers' personal safety. To illustrate, one manager said, "I think these guys are so distracted when they're wearing it to make sure they're not out of compliance that knowing when they're going or might be going over would be good. It would limit their distractions on the job."

This feedback illustrates that there was more on the mind of these workers who were using the CPDM to comply with formal rules than simply protecting their health. In other words, the results between the two technologies regarding the flexibility of use on site showed that the implementation of a regulated technology is a little more complex at first and can disrupt social processes on site. Eventually, however, perceptions of the technology improve, especially after realizing the health information and protection being provided.

4.3 Structuring of Communication for Designing the In-Between

Results also showed the importance of clear communication paths among social factors, including among coworkers and between workers and managers. Providing a structured mechanism for workers to interact with and learn from the technologies was critical, as was managers supporting these efforts among their employees. Results showed that it is critical for the organization and management to provide space for everyone to learn how technologies work and what the output means. In both cases, after workers learned new information that could be used immediately to reduce their exposure to respirable dust, their perceptions of the technology improved as well as their protective health behaviors.

4.3.1 Coworker Interactions and Behavior Maintenance

Even if unpredictability exists when organizational changes are introduced, workers that are part of any STS are still working toward common goals [11]. Although a common goal was not as established during the Helmet-CAM case studies, workers did say that the information would help crews perform their jobs safer. For example, one worker said, "We can use this [dust information] to make decisions that are best for us, because our supervisors don't do the jobs, we do." There was a stark contrast in the CPDM studies, however; the sense of a collective goal was particularly evident because everyone wanted their coworkers to be in compliance so that the sampling period for each quarter would go more quickly. Specifically, wearers of the CPDM mentioned learning and informing each other about dust hazards, which rarely occurred prior to the CPDM [78]. One worker said that communication has definitely increased among his coworkers to help comply with the new regulation: "We definitely communicate more. We (the roof bolter) all talk to each other before and after shifts – when we're changing out – we'll say what we were in the time before. We try to help each other." These extra interactions were prevalent especially during shift changes, to prevent out-of-compliance samples for the incoming crew. For example, these workers indicated that they often look at each other's posted dust data cards after being off for a day so they can be aware of what might be going on underground. In response to this technology, "Everyone in the mine is more aware of each other's behaviors and how it can affect each other underground."

Although workers wearing the CPDM discussed an enhanced awareness and communication among their work crews, their end goal was to stay in compliance while wearing the CPDM rather than adhering to any sort of internal value. For this reason, when asked if workers would continue dust-reducing practices when they did not have to wear the CPDM, of the 33 responses from the CPDM case studies (2 were not present on our follow-up visits), 21 workers (64%) said "yes" and 12 workers (36%) said "no." In contrast, workers who had tried the Helmet-CAM all said that they would wear it again in the future, and during follow-up assessments with managers they reported changes made by all of the participating workers. These results support the notion that workers' intrinsic H&S values can be a greater motivator in behavior maintenance than external pressures by the organization or regulatory measures in place.

4.3.2 Management and Worker Interactions around Technology

Although most workers had no complaints about their supervisory support for dust control resources, they also had little to report about communicative support and information from their management. Regarding the CPDM case studies, when asked what he knew about the CPDM, one worker said, "We weren't really told anything, just that we were going to have to wear it." There was consistent feedback from workers about minimal planning, communication, and coordination on behalf of organizational management about the upcoming regulatory change that was requiring this technology. Then, upon wearing the CPDM, these same workers expressed minimal communication and feedback about their dust data cards. In addition, some workers were disappointed in the lack of a coordinated response plan to maintain low exposures. For example, one worker discussed his ongoing stress about being overexposed while wearing the CPDM. He provided this example: "I was in at 9:00 a.m. and was already at 20% [exposure for the day] so I called my manager. I thought it might not be working right. It seemed like an excessive concentration value to me. It wasn't and I was fine that day. I didn't realize how much exposure you get just going in the mantrip and my manager just had to help me understand the readings."

Workers' feedback regarding the Helmet-CAM had a similar tone, but because it did not impact workers' abilities to perform their jobs, the Helmet-CAM did not receive as much censure among workers. However, room for more structured communication was evident during these interventions, and the Helmet-CAM technology was shown to be a viable method to improve communication between workers and managers. For example, one worker discussed how the enhanced communication with his supervisor has increased his awareness and personal behaviors on the job when he said, "I've become much more aware through personal interactions with my supervisors on site. When I first started here I hadn't given dust much thought. I've been made aware and understand the consequences." In addition, workers noticed and appreciated when their supervisors took action based on feedback displayed in the EVADE software. Actions included purchasing newer work equipment such as haul trucks, H&S equipment such as a clothes cleaning booth, or reminding workers of increased exposure during trigger work practices such as housekeeping activities. As a result, workers noted improving work practices.

5 Discussion

Specific to the mining industry, STS research has shown that internal regulation of a work system is preferable to external regulation of individual workers by their supervisors [3]. This finding is further validated by the current intervention results for both technologies, where workers reported intrinsic values having a greater impact on their maintained technology use and subsequent decision making than external regulation by their supervisor, organization, or rulemaking, which tended to have an eventually positive, but short-term impact on changes to work practices. However, there are still implications from these two case studies that inform how more stability in an STS's social processes can aide in the implementation of new technical factors at a mine site while also adhering to changes in the overall environment.

Specifically, when any new technology is introduced on site, the choice that organizations and workers make is not a choice between adopting and not adopting; rather, the choice is between adopting now or deferring until later [80]. The results show that the technologies were adopted by workers at different rates, due to issues such as regulatory measures, design of the technology, and organizational support. The subsequent discussion focuses on using principles of meta-design to adopt new technological products and processes sooner rather than later.

5.1 Establishing a Collective Social System

The comparison between these worker-technology-organizational interventions shows how social factors can be impacted in two different work environments. It is not surprising that any new regulation, technology, or procedure can disrupt social processes when trying to meet a new requirement. However, the current results demonstrate that the interplay of the social factors (i.e., the *inter*-organizational interactions) are seldom given as much attention as just the worker-technology interaction (*intra*-organizational interactions). We argue that focusing on the interplay of the social processes to improve communication and participation during technology development and implementation may be useful. This argument is consistent with other research, showing that technical designs or developments that are flexible and facilitate social processes can create a stronger system during times of change [81, 82]. Some considerations to undertake such an approach are outlined below.

5.2 Maintaining Underdesign and Flexibility When Possible

The differences in the implementation and openness toward the two technologies provide keen insights into the benefits of underdesigning a system to be adaptable, allowing the technology to serve as an emergent property of the organization [83]. Much research on new technologies in mining has discussed either the organization's or workers' abilities to "work around the technology" to ensure compliance [65, 84–86]. According to Coiera [83], any workaround is essentially an implicit signal of a need by users and shows the strengths and weaknesses of a technical factor already impacting workers' behaviors to make do with the technology. Coiera [83] went on to argue that workarounds most often occur when there is a pressing need to make something work that is not functioning consistently or correctly. This may be an issue when a regulation is present, requiring workers to make a technology work, or appear to be using it, to comply with the rules.

Notably, there are effective options to aid in the underdesign of a system at mine sites. First, research has shown that when appropriately designed, environmental policy can strongly affect both technological progress and the diffusion of less invasive technologies [87]. Regulatory agencies already abide by this suggestion, providing ample time to provide public comments on proposed rules. Also, reliable technology development can take a long time, and obviously if a regulation comes before the technology is available, maintaining an adaptable system is not always possible. However, results from both case studies lend themselves to the positive outcomes of increased participation from workers during technology design and even pre-implementation. For example, workers were able to give feedback on the Helmet-CAM and CPDM during the initial design phases and during the development of their respective updated versions. In addition, for the CPDM, the MSHA regulation allotted a grace period of 18 months for the industry to integrate this technology. Even this grace period written into regulations provides some initial flexibility for organizations to identify and mitigate potential problems. Allowing workers to use a technology prior to a regulation or formal work rule being established may aid in participation later. This is a practice that regulatory agencies and mine companies can work together on, to ensure organizations and workers have time to learn how to use and respond to information from the technology. Other research in mining has discussed this approach while examining unintended consequences of new technologies [88].

5.3 Improving Management Interactions

Of importance is the identified missing link of managers' roles within the entire STS and, specifically, within social processes. Results showed that active participation on behalf of workers and managers is imperative whenever any new process is implemented on site. More so, new technology can even function to improve and facilitate social processes on site about H&S, creating a collective evolution of knowledge and action [81]. Specifically, when managers took a more active role in the implementation of the technology at the ground level, particularly following up with workers about dust exposure and asking for their expert feedback in mitigating exposure sources in the future, workers perceptions changed, as evident in both the quantitative and qualitative case study feedback.

Although not emphasized in previous research, STS theory espouses a view that supervisors or even veteran workers have a role in designing organizational processes [20]. This is because STS processes, particularly in meta-design, are not predetermined and supervisors have some choice in how their system is implemented [88]. These results show that building in more structured interaction points throughout the day would be helpful for workers whether trying to use a technology for compliance purposes or not. Mainly, an increase in site wide communication during the development and implementation of a new technology can aid technology integration while leveraging workers' intrinsic health values. However, this takes persistence among mine management, as understanding where each worker is at in his or her awareness of a specific health risk, and knowledge of the specific technology, are both important to structuring tailored communication efforts that resonate with employees.

Figure 7 presents a modified STS model to emphasize interaction points and relationships that can occur during technology implementation to better stabilize and prepare mines for new innovations. As Fig. 7 shows, the added red arrows illustrate that an STS is not linear, meaning that the environmental system does not strictly push down to the social and technical factors to later push down to individual and organizational outcomes. Rather, the results and differences in both case studies demonstrate the need for a flexible system that

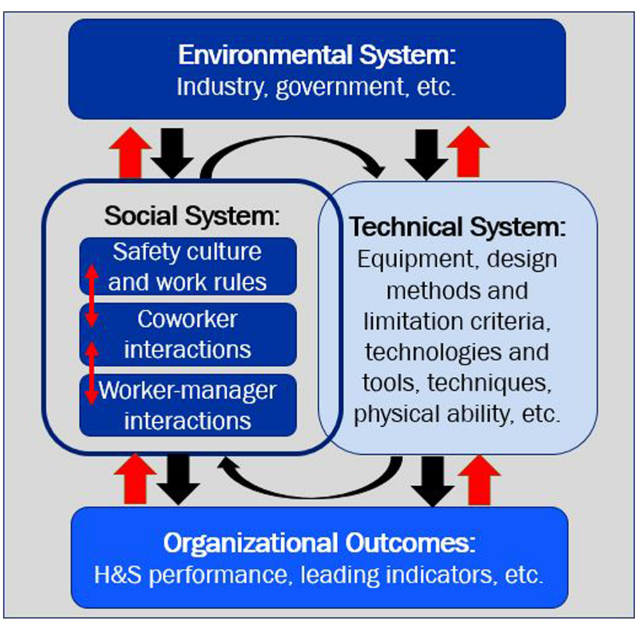

Fig. 7 Proposed meta-design STS framework for mine organizations

allows action-based participation from workers and managers to make improvements to technology and, as a result, may influence certain regulatory guidelines. Providing the organization an opportunity to inform rules and processes that may impact them is helpful in tailoring innovations for any environment [17]. In addition, Fig. 7 also distinguishes various social processes that are important to maintain when any technological or environmental change is introduced at a mine. Although the original figure depicted these implicit connections, results of the current research show that organizations may not always remember the roles that these varying individuals and groups have in the success or failure of technology implementation. Finally, this figure fuses the social and technical factors to depict the truly interdependent relationship among workers, the organization, and technologies.

6 Conclusion

This paper sought to extend STS theory through applying principles of meta-design to analyze the results of two technology-based case study interventions. Results revealed gaps in the *inter*-organizational communication necessary to address challenges to introducing new technologies, especially if and when accompanying a new regulation or formal work process.

6.1 Limitations

Although the results showed promise in using meta-design to improve the stability of an STS to prepare for changes to the system, there are limitations. First, these two case studies addressed a similar health issue but in different circumstances including the commodity being mined, regulations around dust control and exposure, and the use of regulated or compliance-assistance technologies. Specifically, the CPDM, although a lengthy implementation, was ultimately a required technology in comparison to the Helmet-CAM technology, which had the space to evolve without the constraints of a regulatory requirement. Due to the timeline and usability differences with these two technologies, it is obvious that there are more differences beyond that of the organizational issues discussed and are beyond the scope of this paper. However, pertaining to the organizational issues, because the adoption processes for workers was similar regarding the stages of using and responding to the technology output, it is likely that comparing these two case studies was a valid approach to studying meta-design STS. Still, with the small sample and absence of formal design and wearability issues, these results cannot be generalized to the greater mining industry, and rather should be considered by individual mine organizations as a potential learning tool when a new technology or process is introduced on site.

6.2 Future Directions

Ultimately, these results argue for the necessary attention to the social and organizational factors within the STS through the inclusion of metadesign principles. The results show that, regardless of whether a technological innovation is regulated or not, factors of the STS eventually coevolve until they fit into the mine environment. However, because the development of technology appears to occur as a single event while the dissemination of the technology is a continuous, slow process [80], a meta-design framework is an important consideration. Although an iterative process to technology design may occur, there are aspects that can be improved through equal involvement on the social systems side. Mainly, it is important to take time to proactively prepare the social factors for upcoming changes in the technical factors. This can be done through soliciting active participation from workers, which improved personal proactivity and intrinsic values in the current case studies. In addition, any level of flexibility that can be afforded to workers when implementing a new wearable technology—from how they wear to how long they have to wear the unit—can be useful at the initial onset of learning the technology's capabilities. Finally, managers should play a more active role in maintaining the social processes within the STS through increased communication about the technology, including its purpose and what the outputs of the technology communicate to workers about their health. Through using the meta-design STS principles to improve the identified inter-organizational communication gaps, it is possible that mine organizations can foster a more adaptive culture and be better prepared for not just new assessment technologies, but other integral innovations such as advancements in automation and big data analytics.

Compliance with Ethical Standards

Disclaimer The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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

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