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Design for worksystem safety using employees' perception about safety

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Abstract. In this paper, the predictors of work injuries based on Leamon's Man-Machine model are identified in a socio-technical framework. Several hypotheses are developed and tested to describe the accident/injury phenomena in mining work-systems. Possible designs for improving work-system's safety are specified using scaled Mahalanobis distance (MD). A case control study design is adopted. Five variables namely, age, negative-affectivity, physical-hazards, job-dissatisfaction, and safety-practice are emerged as significant contributors to work injuries for the mines studied. Two most interesting findings obtained through this study are (i) 36% of cases (injured employees) (MD < 1) are unlucky to meet an accident and (ii) 40% of the controls (non-injured employees) (MD > 1) are lucky to be able to avoid an accident. The most probable reason for the former case is the organizational ineffectiveness while that for the latter may be risky adventures of employees which are due to lack of education, awareness, and appropriate training. Based on the MD values for cases and controls, possible design guidelines are suggested. The study categorically identifies the accident situations where engineering control, education and training, and other organizational safety measures are to be adopted.

Keywords: Work injuries, case-control study, Mahalanobis distance

1. Introduction

Design for worksystem safety is traditionally an engineering issue where effective risk barriers are planned for, designed, and are kept installed during the operational phases of a system. The risk barriers are protective measures against functional disabilities of a system.

Although, the risk barriers are designed to safeguard the employees, it is seldom a practice to consider the employees' perception about safety to design for safety of a work system. The perception of safety and hazards might have significant influence on safety outcomes. For example, workers who work near the blast furnace know that their work is hazardous and they require coping up with the hazardous employment [1]. Hence, they become alert while working and some of them eventually never meet any accident/injury during their employment period. Similarly, mine workers who work at the face of a mine, might behave similar fashion. On contrary, workers who work in comparatively safer work[*] places may meet accident because of poor perception about the inherent hazards of their work places. Further, workers who perceive the management supportive enough for the cause of safety, behave positively which ultimately leads to increased safety.

Earlier studies showed that factors affecting safety can be broadly classified into three categories, (i) individual or human, (ii) process (plant/machine), where process refers to the technology and activities, and (iii) organization where organizational refers to the work organization which is responsible for creation of an effective work system [1-10]. Therefore, the author presumes that in order to improve safety three types of risk barriers are to be in place, (i) human risk barriers (ii) process risk barriers and (iii) organizational risk barriers. Human risk barrier main-

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tains human risk level within the acceptable level, when the risk level goes beyond the acceptable limit appropriate control measures are to be taken to bring back the risk level at the target. Process risk barrier provisionally deals with reduction of technical risk and organizational risk barrier promotes and strengthen both human and process risk barriers.

In this paper, an innovative approach is considered to design for safety of any work system through (i) identification of the components/factors of human, process, and organizational hazards, (ii) evaluation of these factors for design for safety, and (iii) recommendations for improved safety of a work system ensuring that the appropriate risk barriers are in place.

2. Methods

Based on Leamon's model [2], a worksystem can be defined as a system where people work with the help of machines and/or tools embedded in a local environment and controlled by work organization. The model divides a work system into three basic components – human, machine or plant, and environment (including physical environment and work organization). Leamon [2] stressed on design of interfaces (interactions) in line with the sociotechnical system theory [3]. Earlier studies advocate broadly examining the following ***hypotheses***: (i) H1: person as a cause (personal hazards), (ii) H2: process as a cause (plant and environment hazards), (iii) H3: organization as a cause (organizational hazards), (iv) H4: organization and process combined as a cause, and (v) H5: organization, process, and person combined as a cause. While H1, H2 and H3 indicate deficiency in the design of individual components of a work system, H4 and H5 pinpoint the lacuna in interface design. The variables considered, techniques used for testing these hypotheses as well as finding out design opportunities are explained below.

2.1. Data and Variables

A unique way of conceptualization and evaluation of a work system's safety is adopted here for design for safety. Workers' perception about their worksystem as a whole based on human hazards, process (plant and environmental hazards), and organizational hazards, if quantified can be indicative of the overall safety level of the work system. The possible hazards with their categories are listed in Figure 1. The variables considered in this study are primarily taken from the author's (and his colleagues') earlier study (Paul and Maiti [10]). A sample of 300 mine workers amongst the workers participated in the study (response rate 80%) was considered for analysis. The non-inclusion of 20% of the participants was mainly due to mismatched information. Case-control study with frequency matching criteria was adopted. On an average, the participants were 37.34 (SD = 9.00) years old, and held their current jobs for 14.58 (SD = 9.30) years. Of the injured, 65 were from the Mine 1 and 85 from the Mine 2. For more details about the instruments, please see Paul and Maiti [10].

2.2. Analyses

The analyses were conducted in two stages. First, logistic regression was used to identify significant variables contributing towards work injuries. The hypotheses from H1 to H5 were analysed sequentially. Secondly, the significant variables were used to highlight improvement requirements using scaled Mahalanobis distance.

Logistic regression is a well adopted and useful technique for safety studies. The logistic model allows the estimation of a probability γ ($0 < \gamma < 1$) of an injury to an individual worker with given characteristics (**X**) representing personal, process and/or organizational characteristics (see, Figure 1). In order to understand the modelling process, a binary variable is used. A binary variable z assumes a value of 1, if a worker had an accident that resulted in an injury during a period of employment or 0, otherwise. The probability is defined as [11]:

$$\gamma(z) = \Pr(z = 1 / X) = \frac{e^{\beta' X}}{1 + e^{\beta' X}} \;.....(1)$$

Where, the parameter vector β represents the contribution of each characteristic (**X**) on the probability of work injury. The e^{β} (Eq.1) is called odds ratio representing the risk of getting injured for a particular category of a categorical variable with respect to reference category.

In order to derive appropriate safety promotional measures, a composite risk level for the mineworkers based on workers' perception about safety was computed using average Mahalanobis Distance (MD). The scaled MD values as described by Taguchi et al. [12] were computed separately for the cases and controls using the variables emerged as significant in logistic regression modelling) (the first stage).

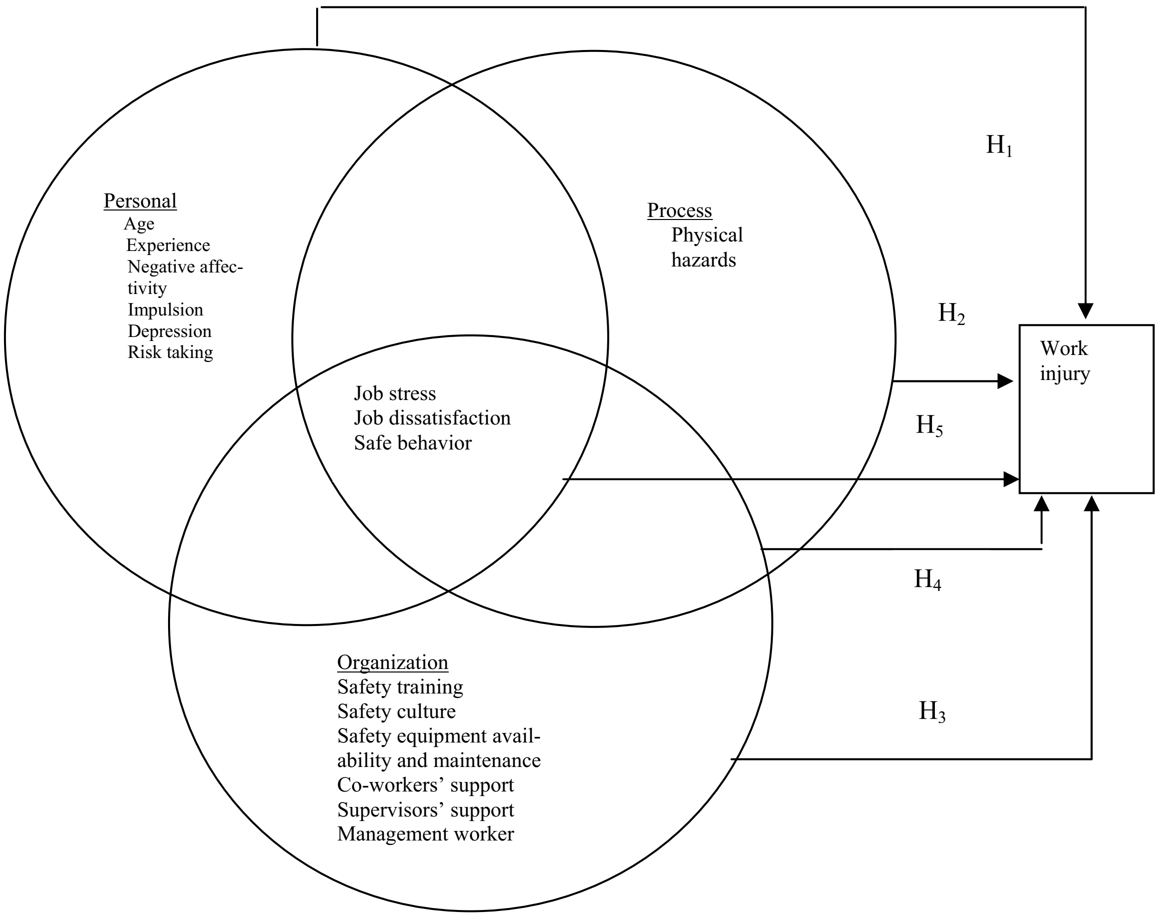

Fig. 1. Personal, process and organizational level predictors of work injuries (adopted from Paul and Maiti, 2008)

The scaled Mahalanobis Distance was calculated using the following formula [12]:

$$MD = \frac{1}{p}(z_0^T R^{-1} z_0) = \frac{D_0}{p} ....(2)$$

Where, z_0 is a column vector of standardized variables for controls, R is correlation matrix of variables for controls, and p is the number of variables.

In short, scaled Mahalanobis Distance is the regular Mahalanobis Distance (D_0) for the standardized variables, divided by the number of variables. The benefit of using scaled Mahalanobis Distance as a measure for baseline multivariate space is that for controls (healthy population as per Taguchi et al. [12]), the average scaled Mahalanobis Distance is approximately equal to one. This property can be effectively used to establish a baseline space for the controls in the present experiment.

Next, the scaled Mahalanobis Distance for cases (unhealthy observations as per Taguchi et al. [12]) is computed using Eq. 2 replacing the values of column vector z_0 with that of the cases. It is expected that the scaled Mahalanobis Distance for the cases will be significantly higher than one.

3. Results and discussion

Several interesting findings were obtained from logistic regression analyses (Table 1) and Mohalanobis distance. First, the 'person as a cause' hypothesis (H_1) indicates that aged, highly negatively affected, and risk-taking workers are more injurious. Older workers (>mean years) are 2.12 times more risky than young workers (<mean years). The only process level variable, physical-hazards, is positively related to work injuries and significant (H_2). It is implied that workers who perceive the work system more hazarders, have a chance of more injuries (odds ratio: 2.39). The 'organization as a cause' hypothesis (H_3) extracted only one variable namely 'safety practice' to be statistically significant contributor for reducing work injuries in mines. Safety practice has direct impact on work injury, and it is observed that workers who perceive better safety culture, performs/execute work more safely (odds ratio = 1/0.40 = 2.50). The 'organization and process combined as a cause' (H_4) retained both safety practice (from organizational level variables) and physical hazards (process level variable) as significant contributors to work injuries in the mines studied. However, their strength of prediction has been decreased slightly. This is because of shared variances by the organizational and process level variables. Interestingly, in the final hypothesis 'organization, process, and person combined' as a cause (H_5), most of the variables that emerged significant in earlier models remain significant in the more complete model. Negative affectivity emerges the most significant contributor (odds ratio: 3.14) followed by age (odds ratio: 2.23). Job-dissatisfaction is significant at 0.13 probability level of significance (odds ratio: 1.61).

The design specifications for the above-mentioned variables may be thought of from Table 2. The mean score for negative affectivity of the injured workforce is more (22.70) than the non-injured workers (19.10), while the standard error of means is almost same (0.46). An average shift of 3.60 (22.70 – 19.10) in negative affectivity makes the worksystem unsafe. Reducing this drift for negative affectivity is of primary concerns and appropriate risk barrier should be placed for that. Similar logic can be put forward for physical-hazards, job-dissatisfaction, and safety-practices. The average drifts for these influencing variables are 1.7, 3, and 4.31, respectively. Appropriate interventions are required, can be started with a pilot study.

As stated earlier, in order to derive appropriate safety promotional measures, a composite risk level for the mineworkers based on workers' perception about safety is computed using average Mahalanobis Distance (MD) separately for the cases and controls. The five influential variables were considered in this calculation (see Table 2). The distribution of MD values for both the cases and controls are shown in Figures 2a and 2b.

Table 1

Significant variables with odds ratios

Hypothesis tested	Significant variables (at ≤ 0.05 probability level except job dissatisfaction)	Parameter estimate	Odds ratio
H1 (Person as cause)	Age	0.75	2.12
	Negative affectivity	1.03	2.81
	Risk taking	0.59	1.80
H2 (Process as cause)	Physical hazards	0.87	2.39
H3 (Organization as cause)	Safety practice	-0.90	0.40
H4 (Organization and process combined as cause)	Safety practice	-0.80	0.45
	Physical hazards	0.55	1.73
H5 (Organization, process and person	Age	0.80	2.23

combined as cause)	Negative affectivity	1.14	3.14
	Job dissatisfaction (p=0.13)	0.48	1.61

Table 2

Means and standard errors of means of the significant variables for cases and controls

Influencing variables	Cases (Injured)		Controls (not injured)	
	Mean	Standard error of mean	Mean	Standard error of mean
Age	39.40	0.77	35.40	0.66
Negative affectivity	22.70	0.46	19.10	0.47
Physical hazards	25.00	0.34	23.30	0.36
Job dissatisfaction	25.04	0.48	22.04	0.49
Safety practice	37.50	0.58	41.81	0.60

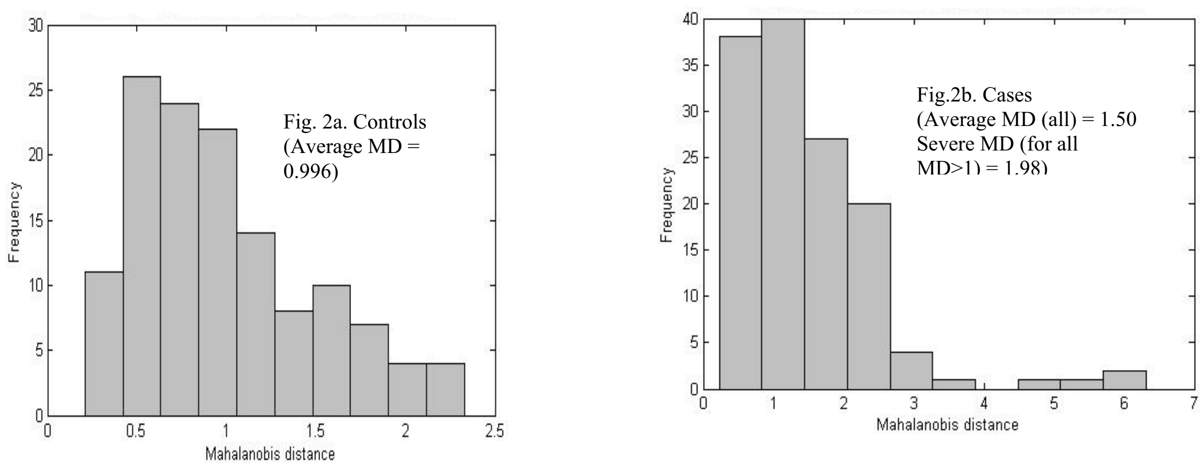

Fig. 2. Distribution of risk based on Mahalanobis Distance (MD) for controls and cases

From Figure 2a, it is seen that the MD values for controls are approximately normally distributed with a mean of 0.996, which is close to 1. Therefore, the scale for the base space is established. The distribution for MD values for cases is right tailed (Figure 2b) with an average value of 1.5. Further, considering the cases with MD >1, the average MD calculated is 1.98, which is quite high (double) than the desired value (MD ≤ 1).

As stated earlier, MD values are departures from the base space (using controls), the MD value for a participant (case or control) can be treated as an inherent risk level for that participant. Further, Taguchi et al., (2001) stated that the average scaled MD for controls (healthy population) should be close to 1. Considering the above, a classification scheme has been developed using MD values for cases and controls to find out appropriate control measures for the participants. The risk control scheme is presented in Table 3. From Table 3, it is seen that 36% of cases whose MD < 1, are unlucky to meet an accident. The most probable reason for their injuries is organizational ineffectiveness. This is perhaps due to the insignificant contributions of the organizational risk barriers except safety practice.

	MD ≤ 1	**MD > 1**
Cases (injured)	**36%** (Unlucky) [Increase organizational effectiveness]	**64%** (Risk level beyond acceptable limit) [Enhance engineering and organizational controls. Compare with with 60% controls whose MD≤ 1]
Controls (Non-injured)	**60%** (Risk level within acceptable limit)	**40%** (Lucky but can meet accident any time) [Ensure awareness and training]

Table 3

Composite risk measure (MD) and risk control measures

Interestingly, 40% of the controls who's MD > 1 did not meet an accident. It is very much alarming for the mine management because this group of persons is expected to meet an accident at any point of time and eventually this will push the accident rate of the mines further upward. Possible reasons for their risky adventures are lack of education, awareness, and appropriate training. As a result, these workers should be imparted to effective safety promotional campaigns. The accident situations faced by 64% of the cases (see Table 3) who's MD > 1 should be compared with the worksystem situations perceived by 60% of the controls (MD ≤ 1) for appropriate safety promotional measures to be introduced. It is anticipated that by modifying and/or strengthening the organizational measures along with instituting engineering control based on the comparison would lead to a definite pathway for safety improvement in the mines studied.

4. Conclusions

Although several studies were conducted in the recent past to establish the correlates of work injuries in a work system, they were not focused towards design of work system's safety as a whole. In this study, an attempt has been made to use employees' perception about safety in designing safety guidelines. Based on this study, it is concluded that the 'person as a cause' hypothesis can still explain substantial injury occurrences in a worksystem. Particularly, the aged and negatively affected individuals are of primary concern. Physical hazards require engineering solutions to overcome the situations. The design guidelines based on Mahalanobis distance (MD) derived in this work can be used by the mine management for effectively design for safety for their worksystem.

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