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Segmented point process models for work system safety analysis

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ABSTRACT

This study proposes a new scheme for measurement of safety performance in work systems using segmented point process models that can capture the points of changes in the working conditions as well as changes in safety initiatives. Data, collected from an underground coal mine, were analyzed using homogeneous (HPP) as well as non-homogeneous (NHPP) point process models. Time between occurrences (TBO) and number of occurrences (NOC) were modeled followed by the development of loss functions. The methodology can be used to monitor safety performance and to check safety program effectiveness. The findings of the case study application showed that the injury occurrences data fit the models for (i) 'all incidents' and 'first aid' cases with one change point at 458 days, (ii) 'near-miss' case with one change point at 441 days, and (iii) 'minor' injury case with two-change points at 11 days and 375 days, respectively.

1. Introduction

A comprehensive measure of the safety performance is critical for effective safety management of hazardous facilities and operations. In addition to setting out safety objectives and targets for the safety management systems, a rational framework is needed for evaluation of safety performance in order to assess and improve the effectiveness of accident prevention programs over time.

Several measures exist for the measurement of safety performance. Accident rate has been used as a safety performance index and measuring performance by the number of studies (see Khanzode et al., 2012 for a comprehensive review). Similarly, *incident rate* has been used as a safety performance index. It has also been indexed in the form of risk.

Several methods exist for measuring the safety performance of a work system, such as, accident control chart, Safety Performance Evaluation (SPE) framework, System-Theoretic Accident Model and Processes (STAMP), risk indicator, and attitude scale, etc. Each method has its own merits and demerits. The attitude scale is rather subjective and provides only qualitative rather than quantitative measures on safety management. SPE framework improves the organizations' safety standards by continuous monitoring and review of their safety performance but several questionnaire surveys need to be conducted. Leveson (2015) proposed a new approach namely, System-Theoretic Accident Model and Processes (STAMP) to identify system-specific leading indicators that, in turn, could guide a risk management system. Øien (2001) proposed a risk indicator development methodology for identification of risk influencing factors (RIFs), assessment of potential change in RIFs, assessment of effect of change in risk, and selection of risk indicators. Although the proposed methodology is comprehensive, it lacks in implementation in real scenario. Past researchers have focused on identification of general leading indicators, like maintenance backlog, or on identification of system specific leading indicators that are characterized by hazard analysis techniques (Leveson, 2015; Sinelnikov et al., 2015; Koivupalo et al., 2015; Khawaji, 2012). But, unfortunately, there is a dearth of literatures that could provide the evidences of the usefulness of these general indicators in practical or real world applications (Khawaji, 2012).

Here we recommend the use of statistical approaches for safety performance analysis, notably by taking advantage of the resources offered by modeling. Statistical analysis of the work system safety performance measures facilitates safety management. Mingyan et al. (2011), Maiti et al. (2009) and Khanzode et al. (2011) have carried out statistical analysis for ascertaining safety performance in coal mines in China and India, respectively.

Maiti (2010) has proposed a new way of analyzing and evaluating work system safety based on probability models, control charts, loss functions and safety capability index. The development starts with the adoption of process approach to model safety. Effective combination of quality engineering concepts into safety study is the major attribute of the development.

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Nomenclature

HPP	Homogenous Point Process
NHPP	Non-Homogenous Point Process
ARI	arithmetic reduction of intensity
PLP	power law process
TBO	time between occurrence
NOC	number of occurrence
α, β	model parameters (scale and shape parameter respectively) ($\alpha > 0$, $\beta > 0$)
λ	injury rate
t_k	development test time ($t_k > 0$)
n_k	number of occurrence of incident
$L(\theta)$	likelihood function
T	predetermined observation time
i	change point location
$\lambda(t_i, \theta)$	conditional intensity process

All the above methods deal with a work system under stable conditions. They will not work well for work systems under changing environments. Changing work environment can be on account of changes in the workforce, changes in occupational safety and health systems, etc.

In all such cases the usual statistical approach defined above will not apply. The performance measures have to be treated as a stochastic process and the changes in the process on account of changes in the environment of the work system are to be incorporated to properly analyze the safety measures of the work system.

Such an approach has been applied to the data set of British coal mining disasters given in Maguire et al. (1952) and corrected by Jarrett (1979). The data set lists the times between 191 instances of mining disasters leading to ten or more deaths during the period 15th March 1951 to 22nd March 1962. Akman and Raftery (1986), Loader (1992), West and Ogden (1997), Raftery and Akman (1986), Achcar et al. (2007) and a number of other authors have analyzed this data set and conclusively showed that a change-point approach is suited to this data set. The change-point problem in software failure process was considered by Zou (2003) and some Non-homogenous Point Process (NHPP) software reliability models with change-point have been proposed. Muralidharan (2010) reviewed various point process model exclusively in parametric setup and provided the methods and applications of these models under different repairable policies.

Syamsundar and Naikan (2007) developed a point process methodology based on segmented point process models to model maintained systems with a fair degree of accuracy when the systems are operating under varying environment. This paper extends the work carried out in Maiti (2010) by applying segmented point process models developed in Syamsundar and Naikan (2007) to the safety performance measures when the work system safety is subjected to varying environment. This notion is considered here from the standpoint of how to develop its use in practice for safety performance analysis.

The motivation of this work came from the fact that there is a definite lack in the availability of the methods dealing with changes in performance with passage of time in the domain of work system safety performance measurement. The scope of this paper encompasses three main objectives. The first objective is to analyze the injury data set associated with a given industrial setting. Second objective is to develop loss functions for models used for analysis of work system performance. Final objective is to derive necessary conclusions from the results about the safety status of the work system.

This study is organized as follows. Section 2 describes the modeling of the work system safety performance and determination of the loss function. Section 3 provides the application of proposed methodology in an existing industrial situation. Section 4 discusses the key observations and the results followed by the conclusion and future scope of research.

2. Methodology

The purpose of the present paper is to assess the work system safety performance by modeling the injury or failure data using suitable point process models and also detect the presence of trend or pattern in the respective data. As given in Atwood et al. (1992) a trend means a steady increase or decrease over time, for example, a trend in a failure probability. A pattern means any deviation from an initial hypothesis, resulting from some cause more fundamental than mere randomness of the data; examples could be a step change in reporting rates, caused by issuance of a rule, or a high failure rate in one year, caused by discovery of a generic problem and a backlog of previously unrecognized degraded components.

This paper uses point process modeling to analyze and identify:

1. Trends and patterns associated with safety performance measures.
2. Developing loss functions for these measures.
3. Assess safety performance and take corrective and preventive measures if necessary.

A framework has been proposed for the development of work system safety performance scheme as shown in Fig. 1.

This section defines the segmented point process models as well as parameter estimation technique using the method of maximum likelihood, followed by the development of scheme for safety performance evaluation and decision making.

2.1. Segmented models for varying work system environment

In an industrial setting work systems designed for operation over long periods of time are subject to changes in the environment in which they operate. Changes in the environment bring about changes in the trend or pattern of performance of the systems.

Stochastically the changes in trend are modeled using non-homogeneous Poisson processes. For changing patterns in the maintenance processes of work systems, Syamsundar and Naikan (2007) have developed segmented point process models. In order to take into account the changes in the environmental conditions, a point process model is separated into segments at times where a change occurs in the process with each segment being modeled by a separate point process intensity model independent of the others forming segmented point process models.

Various point process models related to repairable and maintained systems can be easily extended to the case of work system safety performance without loss of generality.

2.1.1. Segmented models

The usual point processes used are the renewal process and the non-homogeneous point process. Renewal process (RP) is used for systems which undergo major changes and after change can be