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Predicting seismic events in coal mines based on underground sensor measurements

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ABSTRACT

In this paper, we address the problem of safety monitoring in underground coal mines. In particular, we investigate and compare practical methods for the assessment of seismic hazards using analytical models constructed based on sensory data and domain knowledge. For our case study, we use a rich data set collected during a period of over five years from several active Polish coal mines. We focus on comparing the prediction quality between expert methods which serve as a standard in the coal mining industry and state-of-the-art machine learning methods for mining high-dimensional time series data. We describe an international data mining challenge organized to facilitate our study. We also demonstrate a technique which we employed to construct an ensemble of regression models able to outperform other approaches used by participants of the challenge. Finally, we explain how we utilized the data obtained during the competition for the purpose of research on the cold start problem in deploying decision support systems at new mining sites.

1. Introduction

Coal mining is one of the most important branches of heavy industry in the world. According to the report by IBISWorld, it employs over 3.5M people worldwide (IBISWorld, 2016). There are many countries – even in Europe – which produce most (e.g., 83% in 2012, Poland) or almost half (e.g., 45% in 2012, Germany) of its energy from coal. Miners in underground coals mines can face many threats, such as methane explosions, rock-bursts or seismic tremors, etc. To provide protection for people working underground, systems for active monitoring of coal extraction processes are typically used. One of their fundamental applications is to screen seismic activity in order to minimize the risk of severe mining incidents. To facilitate this task, data exploration and decision support tools can be employed.

Coal mines are well equipped with monitoring, supervising and dispatching systems connected with machines, devices and transport facilities. There are also systems for monitoring natural hazards. Such systems are provided by many different companies, which causes problems with data quality, integration and interpretation. If someone is able to overcome these issues, the collected data can be used for ongoing visualization of conditions in particular places of a mine (Mu and Ji, 2012). Moreover, by utilizing the domain knowledge and patterns derived from integrated historical data (Fontes and Pereira, 2016), one can construct forecasting models to enrich the upcoming sensory data with additional predictions. This way, it is possible to considerably improve both the safety of miners, as well as work efficiency (Zhang and Zhao, 1999; Moczulski et al., 2016a). For example, thanks to short-term prognoses related to methane concentrations, combined with information regarding the location and work intensity of a cutter loader, it is possible to prevent emergency energy shutdowns and maintain continuity of mining (Janusz et al., 2015a). This, in turn, allows for increasing the production volume and reducing the wear of electrical elements whose exploitation time largely depends on a number of switch-ons and switch-offs (Sikora and Sikora, 2012).

An important aspect of safe and efficient coal mining is the prediction of seismic hazards (particularly those related to high-energy destructive tremors which may result in rock-bursts). Safety refers to saving workers from accidents and injuries, while efficiency refers to unplanned shutdowns of longwall systems. From this perspective, analysis and proper prognosis of potentially dangerous methane concentration (Sikora and Sikora, 2012; Zagorecki, 2015a) and seismic events (Kabiesz et al.,

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2013; Leśniak and Isakow, 2009) constitutes one of the most important challenges that should lead toward improving the safety and reducing the costs of underground coal mining.

Processes related to seismic activity are often considered the hardest types of natural hazards to predict. In this respect, they are comparable to earthquakes. Seismic activity in underground coal mines occurs in the case of a specific structure of geological deposits and due to excavation of coal. Factors which influence the nature of seismic hazards are diverse. Relationships between those factors are very complex and still insufficiently recognized. Such a situation occurs in the Upper Silesian Coal Basin where the additional conditions are related to the multi-seam structure of the coal deposit.

In almost all mines in this region, there are systems which detect and assess seismic activity degrees. The current industry standard in this regard (and the regulations imposed by the Polish law) involves manual assessment of hazards by mining experts. However, the question remains whether the existing systems and expert methods take full advantage of the available data in order to provide their users with the maximum possible prediction accuracy. Moreover, it is important to design seismic hazard prediction methods that can adapt to new conditions. There is also a question of whether the way in which currently deployed systems work is sufficiently clear and comprehensible, so the users can properly interpret their results and react in case of possible false emergencies.

In order to facilitate the above requirements, we decided to work with prediction models which, on the one hand, can perform well for partially noisy, incomplete and inaccurate input data, and, on the other hand, are simple enough for domain experts, analysts and end-users to understand and interact with. Put more precisely, we assumed that incoming sensory data streams will be processed by means of possibly overlapping time windows (Fu, 2011) and that prediction models will be fed with basic statistics derived from those windows. The reason for working with such statistics was the need to compensate for the effects of isolated noises, sensory hardware differences and missing values in the data. We further assumed that it is worth applying efficient feature selection methods (Guyon and Elisseeff, 2003) in order to simplify prediction models and to provide users with additional information about the importance of particular sensors in space and time (Han et al., 2015).

In our case study, we extended the available set of features by adding some more static attributes reflecting assessments of particular mining locations made by experts and some general characteristics of the mining sites. We did this for two reasons. Firstly, we wanted to evaluate a degree in which sensor-based information improves prediction accuracy compared to purely expert-based models—this could be done by comparing prediction quality of models trained using all features and only expert-based features, respectively. Secondly, we wanted to address the so-called cold start problem, when a decision support system is installed in a new location and it does not yet have a sufficient amount of data to fit into the new environment (Son, 2016).

In order to verify whether our approach to seismic hazard prediction is valid, we decided to organize an open data mining challenge whose participants had access to the same data set as the one which we used in our own study (Janusz et al., 2016). This data set was built in a way which reflected the diversity and possible inaccuracies of measurements acquired from sensors. The cold start problem was investigated by means of providing increasingly more data over time and observing how the efficiency of participants' solutions evolves when they can be trained using more information. It is worth noting that, although the competition winners applied quite a sophisticated and computationally expensive approach (Milczek et al., 2016), our own solution turned out to be comparatively accurate. Moreover, some other well performing solutions were based on rather simple models (Boullé, 2016) which – in the case of rapid situation changes – could be manually controlled by experts.

One of the main objectives of this paper is also to discuss how to embed the acquisition of sensory information and seismic hazard prediction methods into a bigger decision support framework. In this respect, we refer to our previously-developed system called DISESOR (Moczulski et al., 2016b) which combines sensory data processing and knowledge engineering solutions in order to integrate different and specialized monitoring systems within a more standardized environment. We demonstrate how our own prediction model fits into that environment and compare its outcomes with the most successful contributions from our competition.

The contribution of this paper can be divided into the following areas:

- a reliability evaluation of expert methods for the assessment of seismic hazards,
- an extended description of a data mining challenge related to the task of seismic activity prediction in coal mines and a summary of its results,
- a comparison of performance between the expert and machine learning methods,
- a description of a prediction model developed in the frame of the DISESOR system, whose performance matches that of the best solutions from the data mining challenge,
- an extended analysis of the cold start problem in the context of a predictive model deployment at new longwalls or working sites.

These areas are reflected in the structure of the paper. After the introduction and overview of related works in Section 2, we briefly describe selected expert methods in Section 3.1. Then, in Section 3.2, we discuss the scope and results of an open data mining competition which we organized to facilitate our research. In Section 4, we present details regarding our prediction model for the assessment of seismic hazards. This section is followed by Section 5, where we perform an extensive analysis of the cold start problem. It aims to answer the question whether it is possible to use models trained on data from many working sites in order to make accurate predictions for a different longwall. Finally, in Section 6, we conclude the paper and set some directions for future research.

2. Related works

The typical environments deployed in a coal mine are monitoring and dispatching systems. These systems collect a large number of data which can be utilized in further analysis, e.g., on-line prediction of the sensor measurements. This research area was surveyed in Kalisch et al. (2014). Such analysis can address different aspects of coal mine operation such as, e.g., equipment failure or natural hazards (Janusz et al., 2015a, 2016).

There are examples of research in the field of natural hazard assessment in underground coal mines, e.g., prediction of methane concentration and seismic hazard analysis. For example, the prediction of methane concentrations was discussed in Sikora and Sikora (2012), Kalisch et al. (2014) and Simiński (2015). An application of data clustering techniques to seismic hazard assessment was presented in Leśniak and Isakow (2009). There are also approaches to the prediction of seismic tremors by means of artificial neural networks (Kabiesz, 2006) and rule-based systems (Kabiesz et al., 2013). However, each of the above-listed works presents a stand-alone approach that is not incorporated into any integrated system. Moreover, the experiments which they describe were conducted on much smaller data sets than the one described in our paper.

Analytical methods mentioned above require data that was extracted, cleaned, transformed and integrated. In practice, decision support systems utilize a data repository of some kind, e.g., a data warehouse. The critical dependence of the decision support system on a data warehouse implementation and the impact of data quality on prediction performance is discussed in March and Hevner (2007). Moreover, some initial concepts of a system that processes data streams delivered by monitoring systems were presented in Grzegorowski (2014). However, to the best of the author's knowledge, the currently existing integrated