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Sustainable management of mining operations with accidents: A mean-variance optimization model

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ABSTRACT

Sustainable management of mining operations requires careful considerations of environmental sustainability, economic sustainability and corporate social responsibility (CSR) related issues. Motivated by prior studies on accidents associated with mining operations, this paper builds a formal optimization model to address the above three sustainability related issues for a mining operation with the optimal decision on mining quantity. To be specific, we model the number of accidents as a Poisson distribution with a quantity dependent distribution parameter. We formulate the objective function via the mean-variance approach, and incorporate analytical constraints which relate to environmental sustainability and CSR into the model. We analytically derive the algorithm which can find the globally optimal solution for the optimization problem. After that, we further analyse when the mining company should consider implementing (i) the pollutant reduction technology, and (ii) the accident reduction technology. It is interesting to find that the mining company's degree of risk aversion affects the choice of pollutant reduction technology, but not the choice of accident reduction technology. Several other important insights are also analytically derived.

Introduction

Mining is an influential industrial sector which has huge economic and social effects. The raw materials obtained by mining are critical for all kinds of manufacturing industries which include (but not limited to) energy, chemicals, jewellery, fashion and textiles, electronics, alloys, etc. Over the past decade, this sector has rapidly expanded in countries such as China (Yin and Chen, 2013). Despite its importance, mining operations are notorious for having a lot of accidents. In the US, coal mining is well regarded as the most dangerous occupation (Poplin et al., 2008). The average rate of serious fatal injuries in the US coal mining industry in 2006 was 49.5 per 100,000 workers, which is over 10 times the rate for all other private industries (Sari et al., 2009). In Turkey, among all industries, the coal mining industry leads to the largest number of cases associated with severe occupational diseases (Sari et al., 2009). Undoubtedly, accidents do a lot of harm to both the mining company and the workers. For the company, accidents lead to heavy loss in the costs associated with both (i) the injured workers and (ii) the broken devices and disrupted operations. For the society, accidents lead to many social problems because they are painful and influential to the casualties and their families. Thus, accidents management is a crucial element of corporate social responsibility (Metaxas and Tsavdaridou, 2013) and is a factor critically important for achieving a sustainable management of any mining operation.

At the same time, mining operations create a lot of wastes and pollutants, which pose serious threats to the environment. According to Phillips (2012), four types of wastes can be created by mining operations, namely "overburden (soil and rock being removed)", "waste rock (rock wasted because it does not contain the target materials)", "tailings (ground-up ore as a residual)", and "heap leach spent ore (small chunks of processed rock and soil)". These wastes, together with the other potential environmental hazards such as damaging the natural land and water environments, create concerns on environmental sustainability associated with mining operations. Nowadays, with the global awareness of environmental sustainability, a lot of governments impose regulatory measures on mining operations which helps limit the amount of pollutants and wastes created by the mining industry.

As a business operation, the mining companies must also strive hard to attain economics sustainability with very careful consideration of profit risk. As such, we argue that the sustainable management of mining operations in the presence of accidents should consider

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three important dimensions: economics sustainability, environmental sustainability, and social responsibility (with respect to limiting the number of accidents). Motivated by the observed industrial practices and pinpointing these three dimensions, this paper builds a formal analytical optimization model to explore the sustainable management of mining operations with a focus on "mining quantity" decision in the presence of stochastic occurrence of accidents. To be specific, following the real empirical data based statistical analysis reported by Sari et al. (2009), we model the number of accidents occurring under a mining operation as a Poisson distribution with a quantity dependent distribution parameter. In order to model economic sustainability, we formulate the mining company's optimization objective function by adopting the classical mean-variance approach (Markowitz, 1959; Choi and Chiu, 2012) which captures benefit by the expected profit, and profit risk by the variance of profit associated with the mining operation. In addition, the model includes analytical constraints on both environmental sustainability and corporate social responsibility. After formulating the model, we analytically develop and derive the algorithm which can guarantee to obtain the globally optimal solution for the optimization problem. By exploring deeper into the algorithm, we analytically reveal how the optimal mining quantity decision relates to various critical parameters. Moreover, we include further analysis on the situations in which it is desirable for the mining company to implement enhancement technology to respectively reduce: (i) the pollutant emissions associated with the mining operations, and (ii) the number of accidents. Among other findings, it is interesting to find that the mining company's degree of risk aversion affects the choice of pollutant reduction technology, but not the accident reduction technology.

The rest of this paper is organized as follows. First, a brief literature review related to mining operations, sustainable operations management, and mean-variance operations models is presented. Then, the analytical optimization model for the sustainable management of mining operations is shown. After that, further analyses on the pollutant reduction technology and the accident reduction technology are reported. Finally, the paper is concluded with discussions on future research directions. To enhance presentation, all proofs and technical derivations are placed in the Appendix.

Literature review

This paper relates to three major research areas in operations management, namely mining operations with accidents, sustainable operations management, and mean-variance operational models. We review some recent representative works in the following.

For safety and accidents management for mining operations, prior studies have focused mainly on risk related assessment and some enhancement measures. For example, Sari et al. (2009) propose a methodology to establish stochastic modelling of accident risks associated with mining operations. With the use of real empirical data from Turkey, they build statistically verified analytical models. One important finding is that the number of accidents follows a Poisson distribution. Understanding the severe consequence brought by accidents in mining, enhancement measures such as those accident analysis methods have been proposed (see Staley and Foster (1996), Sari et al. (2004)). In addition, there are also discussions of some risk assessment measures which may help establish efficient risk management schemes in the presence of accidents. These studies include Rowell (1996), Staley (1996), and Joy (2004). Recently, there are also discussions on how some innovative measures, such as providing government funding and technical support to small economic agents, can effectively enhance mining safety and tailings recycling (see Milanez and de Oliveira (2013)). This paper follows the statistically proven analytical distribution (by Sari et al., 2009) to model the number of accidents associated with a mining operation. Similar to many related studies such as Simpson and Moult (1995), this paper also discusses the situations in which it is beneficial for the mining company to deploy accident reduction technology. However, different from all of them, this paper examines the topic via an operations research optimization approach with analytical explorations. In terms of the research approach, this paper is in the domain similar to Kamrad and Ernst (2001).

Nowadays, sustainable operations management (OM) is a hot topic. In the related OM literature, the previous studies focus mainly on issues such as closed loop supply chains (e.g., Govindan et al., 2009, Govindan and Sasikumar, 2009) and the recent studies extensively consider the issues on sustainability measures which include both environmental sustainability and economics sustainability (Choi and Chiu, 2012). In addition, measures governing the operational issues around carbon and other pollutants emissions are also widely explored. For example, Sundarakani et al. (2010) explore the carbon footprint modelling in green supply chains, Gemechu et al. (2012) study the imposition of environmental tax on the pulp and paper products and services, Phillips (2012) applies an analytical modelling approach to study the sustainability associated with coal mining tailing dumps, and Choi (2013a) examines via a dynamic optimization model on how the carbon footprint taxation system can improve environmental sustainability on a fashion quick response system. Since sustainability related OM is a huge topic, we do not exhaustively review the related works. For more details on the establishment of a sustainable mining operation, we refer readers to a recent discussion paper by Laurence (2011).

As we discussed above, sustainability in the mining industry refers to more than just the environment and the social issues. In fact, for any mining company, in order to survive, it must achieve a high level of economics sustainability. Since the mining industry is full of risk, a mining company must carefully deal with profit risk in order to be economically sustainable. To model profit risk, the mean-variance theory (Markowitz, 1959), which originally applied in finance, has now been widely adopted in operational analysis nowadays. To be specific, under the mean-variance theory, we focus on examining two important measures, namely the "mean" (e.g., the expected profit) and the "variance" (e.g., the variance of profit). Here, the "mean" represents payoff and the "variance" represents risk. Under the assumption that companies are risk averse, a lower "variance" (i.e. risk) and a higher "mean" (i.e. payoff) will be preferred. In fact, Lau (1980) is the first piece of work employing the mean-variance objective in conducting inventory analysis. After that, a lot of studies have applied the mean-variance objective in exploring supply chain operational problems. They include Agrawal and Seshadri (2000), Tsay (2002), Choi et al. (2008), (2011), (2013b), (2013c), Vaagen and Wallace (2008), Wu et al. (2009), Chiu et al. (2011), Choi and Chiu (2012), Li et al. (2013) and Shen et al. (2013). For a recent review of the use of mean-variance theory in OM analysis, see Chiu and Choi (2013). Following the above literature, to capture the concern of profit risk, this paper also formulates a mean-variance optimization objective function for the mining company.

As discussed and reviewed above, there is no doubt that it is critically important to study the sustainability related issues in mining operations with accidents. Notice that even though the existing literature has examined accidents and risk related issues in mining operations, there is no discussion on the full sustainability management scheme with the comprehensive considerations of environmental sustainability, corporate social responsibility, and economics sustainability. The reviewed literature also does not conduct the sustainability analysis on mining operations with accidents via an operations research based optimization approach. Thus, to the best of my knowledge, this paper is the first in the literature which analytically examines the sustainable management