ARTICLE IN PRESS

Resources Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

The impact of variability and correlation of selected geological parameters on the economic assessment of bituminous coal deposits with use of non-parametric bootstrap and copula-based Monte Carlo simulation

Michał Kopacz*, Eugeniusz J. Sobczyk, Dominik Galica

The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Kraków, Poland

ARTICLE INFO

Keywords:
Hard coal mining
Bootstrap sampling
Gaussian copula
Empirical copula
Geological parameters interdependencies
Valuation
Risk
NPV
IRR

ABSTRACT

This paper presents an assessment of the impact of variability and interdependencies of selected deposit parameters on the net present value (NPV) and internal rate of return (IRR). The subjects of the analyses were three economically viable seams at one of the bituminous coal deposits in Poland. The source of information was the geological model and operational data of the mine "X". The simulation was developed based on non-parametric bootstrapping, where the influence of coal quality parameters, seam thickness, spatial density of coal, and waste rock derived from coal partings, floor cutting and dinting, and roof falls, was tested.

The interdependencies of geological and mining parameters were replicated in a simulation model using Gaussian and empirical copulas. In the model, the relationship between the amount of total waste rock and operating costs was associated with the use of elaborate mathematical formulas. Economic appraisal was based on an income approach, using the free cash flow for the firm (FCFF) analysis and discounting process.

Based on the Gaussian copula, in the X-1 and X-2 seams, the average NPV differences achieved were a maximum of 39%. In the case of IRR, the mean difference did not exceed 3.6% points (pp). The quantified spread between the correlated and uncorrelated average values of NPV was at most 45% and 4.8 pp for IRR. Empirical copula limits the range of variation of input and output parameters, resulting in different values for the average NPV, at a maximum of 11.8%, and IRR, 2.4 pp.

If the IRR reflects the level of expected return of investment, it can be stated that the additional risk premium resulting from the volatility and correlation of analysed deposits parameters of bituminous coal should be relatively low and less than 2.4 pp in similar cases. The analyses also revealed that the amount of available geological information is of secondary importance in the valuation process, as it does not negatively affect the regularity and symmetry of predicted outcomes.

1. Introduction

Hard coal mining is one of the key branches of the mining industry. According to the Polish Geological Institute (PGI), the documented balance resources of bituminous coal in 2016 amounted to about 56 billion Mg, while the balance resources of bituminous coal of the developed deposits were around 21 billion Mg. The share of economic resources of steam coal (types 31–33) amounts to about 60% (Industrial Development Agency IDA, 2016), (PGI, 2016). In Poland, the annual coal output (run-of-mines) is around 100 million Mg, of which the production of coal accounts for nearly 70% (IDA, 2016). Over the last 10 years, a downward trend in coal production has been observed, with a drop of nearly 30%, stabilizing at a level of 70–75 million Mg. This is due to the changing preferences of major consumers of coal (Kwaśniewski et al., 2015) and European Union (EU) climate policy regulations (Gawlik et al., 2015).

Uncertainty, volatility risk, and geological estimation errors are important components contributing to the value of mining investment projects, as indicated by, among others, Torries (1998a, 1998b), Roberts (2000) and Dimitrakopoulos et al. (2007). In Polish literature, this opinion is also shared by Uberman and Uberman (2008) and Saługa (2009). As indicated by Wanielista et al. (2002), these are not the only aspects that have a significant impact on the valuation of bituminous coal deposits. Khanzode et al. (2001) emphasized the importance of natural hazards, while Zhu (2011) points to faults, as their estimation plays an important role because they affect both the volume of extractable resources and the rhythm of production. Sobczyk (2009) points out the negative aspects of exploitation resulting from the

* Corresponding author.
E-mail addresses: kopacz@meeri.pl (M. Kopacz), sobczyk@meeri.pl (E.J. Sobczyk), dgalica@meeri.pl (D. Galica).

https://doi.org/10.1016/j.resourpol.2017.11.015
Received 16 May 2017; Received in revised form 4 October 2017; Accepted 28 November 2017

abnormal sedimentation, depth and thickness of a seam with partings, dip angle, the workability of coal, and roof and floor conditions. When it comes to the key technical risks, Park and Matunhire (2011) indicated the risk of quantity and quality of resources. Meanwhile, the impact of geological parameters is of great importance, which has been confirmed by Li et al. (2008) and Berry and McCarthy (2006).

Although all the above-mentioned aspects related to the geological structure of deposits are important in determining the success of mining projects, the influence of natural hazards, thickness of seams, and the quality parameters of coal have a dominant influence on coal deposits (Sobczyk, 2009). Preliminary information on the thickness or variability of the quality parameters of coal is obtained at the stage of deposit exploration using surface boreholes. Estimating the impact of natural hazards is usually a contractual issue (there are no reliable methods for assessing the probability of materialization and possible consequences). Heriawan and Koike (2008) confirmed that the variability of coal thickness, affecting the estimation of the volume of resources, is of decisive importance (Górecka, 1981); however, measurement errors must also be considered.

The quality parameters of steam coal (calorific value, sulphur and ash content) affect its price and the possible revenues available (Lorenz et al., 2002). The coal calorific value or lower heating value (LHV) is one of the lesser variable parameters of coal, while its influence on the value of mining investment projects (in the group of quality parameters) is dominant (Mucha et al., 2008). The impact of the remaining quality parameters (e.g., ash content), after considering coal processing, is reduced and in some cases can be even omitted (Blaschke, 2009), (Grudziński, 2012). It should be highlighted that the impact of geological parameters is only partially negative. A negative impact on the deposit is observed when the calorific value and the thickness of the deposit (without coal partings) is below the average, while the ash and sulphur content, and partings thickness, are above the average. The impact of spatial density is debatable. In practice, it is generally accepted that spatial density plays a less important role and is considered as constant (Nieć, 1990; Mucha et al., 2007). Generally, higher coal density has a positive impact on the amount of resource estimation, while strong correlation with the ash content can provide information about the increased amount of production waste.

According to Smith (2000) and Olea et al. (2011), the accuracy of the estimation of geological parameters and the amount of resources, which is a part of the risk and uncertainty in the assessment of mining investment projects, is of great importance. The estimation of deposit parameters is associated with some errors, which can occur during sampling, measurement, processing, data management and interpretation, estimation, and reporting (JORC Code, Guidelines Review Committee, 2014). Vose (2008) points out that the total impact effect should be considered as a combination of uncertainty and volatility, for which identification and quantification requires a comprehensive approach. The need to pay attention to the accuracy of the evaluation of deposit parameters, considering the future development and high-performance exploitation, has already been highlighted by Kozubski (1962).

Modelling of volatility, uncertainty, and interdependence of deposit parameters depends on the method used and is different in the scope of Monte Carlo methods or geostatistical ones (Wasilewska, 2007). In the case of methods based on the distance of points, correlation and autocorrelation of the observation are understood as the distances to which the mutual correlation of the value of the specified deposit parameter is observed (Chilès and Delfiner, 2012; Journel and Kyriakidis, 2004). The ranges of correlation and autocorrelation can also be used to determine the balance between the random and constant components in the model (Kokesz, 2014). Spatial variability of the geological parameters can be reproduced with use of variograms (semi-variograms); the shape depends on the character of the variability observed in the deposit (Naworyta, 2015). In comparison, in simulation (Monte Carlo) methods based on the sampling of statistical distributions created in geological data sets, where the content has already been interpreted (e.g., using interpolators of the digital geological model), the spatial location of the measurement point is lost. The variability and/or uncertainty can be described only in terms of mass or probability density. The correlation of deposit parameters is treated as a method of measuring the interdependence of variables, allowing transfer of the observed dependencies to the simulation, to use them in the applied valuation methods.

Knowledge of the nature of volatility, uncertainty, and the correlated impact of deposit parameters is very important at the valuation stage and when selecting the risk premium, usually considered in the discount rate (Graham and Harvey, 2001). In discounting methods, the volatility and uncertainty are usually associated with risk and loss, while they may constitute a chance to obtain results that are better than expected (Pera, 2010). It is also worth mentioning that the influence of the variability of deposit and qualitative parameters of coal can be estimated at a level of few percent (Smith, 2000) or at several times higher level (Mucha et al., 2008), while the aspect of co-occurrence of specific deposit parameters and the impact of coal processing on the structure and quality of mining products is often overlooked. In some cases, the risk and uncertainty (about the deposit parameters) premium are arbitrarily taken from a certain range, depending on the stage of deposit development, and can take the form of a declining discount rate (Runge, 2003; Rudenno, 2012), which makes interpreting the rate of return more complicated or even senseless. As indicated by Gollier et al. (2008), there is no clear solution to this problem in the professional literature. Relatively less attention has also been paid to the question of total correlated impact of geological parameters on the estimated values and risks, which is due to the complexity and multidisciplinary nature of the research problem. The authors believe that the presented paper, which discusses the impact of variability, uncertainty, and correlated influence of the deposit parameters, will contribute to a better understanding of these aspects during the valuation of hard coal mining projects.

2. The research methodology and scope of work

The aim of the analysis was to assess the impact of variability and forms of coexistence of the selected geological (deposit) parameters on the value and profitability of coal mining projects measured by NPV (net present value) and IRR (internal rate of return). The analysis was conducted using Monte Carlo simulation, bootstrap sampling and copulas. NPV and IRR are two of the most popular methods for making capital-budget decisions belonging to the income approach.

The research (simulation) procedures included:

(1) Preparation of data derived from the geological model for further economic analysis.
(2) Selection of empirical distributions and consideration of the uncertainty about the characteristic parameters of the distributions.
  (2a) Correlation of geological parameters in the simulation model with empirical copulas.
(3) Generating random observations and estimation of NPV and IRR values and the differences determined because of their application.
(4) Probabilistic and quantitative analysis of the obtained results.

To extract the net effects of *volatility* and *correlation*, a differential approach was used. The explanatory (input) variables in the simulation models were (Fig. 1):

- Seam thickness (without partings), ST (m);
- Coal partings, P (m);
- Coal calorific value or lower heating value (LHV), Q^r (GJ/Mg);
- Sulphur content in coal, S^r (%);
- Ash content in coal, A^r (%);
- Roof fall and ripping, R (m);