ARTICLE IN PRESS

Resources Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources Policy

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

A model robust real options valuation methodology incorporating climate risk☆

C. Dolan[a,*], J. Blanchet[b], G. Iyengar[b], U. Lall[c]

[a] Department of Statistics, Columbia University, USA
[b] IEOR Department, Columbia University, USA
[c] Water Center, Columbia University, USA

A B S T R A C T

Physical climate risk faced by companies is emerging as a significant concern for long term investors, such as sovereign wealth funds. For the mining sector, each physical asset may have a significant financial exposure to extreme climate events such as floods and droughts. Often, these financial risks are difficult to value given the paucity of data on climate extremes, and limited company assessment and disclosure of the associated financial liability. We propose a generalization of the Brennan-Schwartz approach to real option valuation to address this situation. A Poisson point process is used to model arrivals of extreme events that exceed the estimated design return period of the flood/drought mitigation infrastructure at the site. Using techniques from the field of robust performance analysis, we are able to calculate upper and lower bounds over all the probability models within a certain distance from the original model, that address the potential uncertainty of the risk and loss. We suggest two different approaches for mine valuation based on this technique. The first, and more direct approach, calibrates the distance of probability measures from a set of known mine transactions and prices a mine (with currently unknown value) relative to the training set of mines. The second approach uses historical precipitation data from a mine site, to calculate a "worst case" disaster arrival process from the actual physical data, and then the mine is priced using this process. Generalizations to a portfolio of assets are also considered.

1. Introduction

Concerns with climate change are now raising the question of how best to address the exposure of companies to physical climate risk (Bloomberg et al., 2017), that may be experienced at their physical assets and through their supply chain. Processes as to how such risks can be assessed, disclosed and used for the valuation of the companies are still at an evolutionary stage. A critical aspect is how to identify and price the exposure to extreme climate events, under current or future climate. Even where companies design infrastructure to protect against extreme climate events such as droughts and floods, the design criteria may not be disclosed, and in a non-stationary climate, the actual period of record used to estimate the likelihood of extreme events may alter the potential exposure risk. This level of detail and the re-appraisal of such risks is unlikely to happen. Calibrating this exposure is also difficult since by definition extreme events are rare, and their impacts may be highly location dependent. Hence, very little data may be available for relevant exposure and model calibration. This paper addresses this setting, and we choose the mining industry for an illustration of the ideas we develop. This industry has a high concentration of its valuation in a few assets or mines, with high potential exposure to climate risk, making it a particularly relevant sector for initial application and insights of our type of analysis.

We propose a simple extension to the Brennan and Schwartz (1985) model, that accounts for disasters using a Poisson point process. As usual, the mine is assumed to be open, and the operator is assumed to hold options to halt and resume production, and to abandon the mine permanently. Valuation is simple using the Longstaff and Schwartz (2001) technique, which was applied to mining operations by, Sabour and Poulin (2006) and Cortazar et al. (2008). Typically, in the construction of a mine, it is specified that the mine must be built to withstand a certain disaster specification, say a 1-in-100 year precipitation event will cause the mine to fail, which we advocate using as the rate of disaster arrivals in the model. While it is possible that one can glean useful information from the valuations produced by this model, the specification of the model is extremely basic (while computationally efficient and flexible), and moreover, the estimation of the probability of a disaster is extremely difficult, and was likely overly

☆ The authors gratefully acknowledge support from Norges Bank Investment Management.
* Corresponding Author.
E-mail address: cjd2119@columbia.edu (C. Dolan).

https://doi.org/10.1016/j.resourpol.2018.01.011
Received 2 July 2017; Received in revised form 19 January 2018; Accepted 23 January 2018
0301-4207/

Please cite this article as: Dolan, C., Resources Policy (2018), https://doi.org/10.1016/j.resourpol.2018.01.011

sanguine. We use this extension to Brennan-Schwartz instead as a baseline to produce "robust valuations" using techniques from the field of robust performance analysis.

Robust performance analysis is a body of techniques concerned with calculating the worst case performance (in our case, the value of a mine) among all plausible probability models, such as those within certain distance of a baseline model - namely, our extension of Brennan-Schwartz - which is believed to be reasonably reflective of reality, while being easy to compute or estimate. This can be challenging because it gives rise to an infinite dimensional optimization problem. When the distance is specified in terms of Kullback-Leibler divergence (Kullback and Leibler, 1951) (and other related notions, such as the Renyi divergence (Rényi, 1961)), this optimization problem is often tractable, and has been exploited in a range of literature in recent years, for example in control theory (Iyengar, 2005; Padoan et al., 2010; Nilim and El Ghaoui, 2005), distributionally robust optimization (Ben-Tal et al., 2013), finance (Glasserman and Xu, 2014), economics (Hansen et al., 2006; Hansen and Sargent, 2016) and queueing (Jain et al., 2010). In a sense, the basic idea of this field is to posit as simplified a model of the relevant phenomena as possible, and then come up with bounds of valuations, over all possible models within a "robustness bubble" around the baseline model.

Traditionally, mining projects (and many corporate investment projects in general), have been valued using Discounted Cash Flow Analysis (DCF). These valuation techniques have been shown to consistently mis-value investment opportunities, as they do not account for managerial flexibilities and the inherent uncertainty in commodity prices (Samis et al., 2005, 2007; Cairns and Davis, 2007). Over the last several decades, real options valuation (ROV) has emerged as the preferred technique of valuation and risk management for mining operations, both in the academic literature and, increasingly, in industry. Starting with the seminal paper by Brennan and Schwartz (1985), the literature has gone on to cover a number of different areas and different embedded options within the mining structures, including commodity prices (Trigeorgis, 1996, 1993; Cortazar et al., 2008), changes in cost of production (Nelson, 2009; Wang, 2016; Zhang et al., 2017), stockpiling (Zhang and Kleit, 2016), and the length of time to establish a mining operation (Zhang et al., 2015, 2017; de Almeida and Zemsky, 2003). Of particular note is the idea of private risk, that is, risks that cannot be hedged using financial market instruments, but whose levels will still influence the decisions made by the mine operator, and which affect valuation (Borison, 2005; Smith and McCardle, 1998; Smith and Nau, 1995). Our approach is not dissimilar from that of Espinoza and Rojo (2017), in that we are concerned with the impact of private risks that do not have hedging instruments in the financial markets. Their approach, Dynamic Net Present Value (DNPV), effectively incorporates the cost of a premium from a risk-neutral insurer. However, this method still depends on a specific model from which risk-neutrality is inferred. Our framework, in fact, can easily be applied to DNPV, to "robustify" DNPV estimates.

Using these techniques, we propose two distinct methods of valuation. In the first method, the degree of robustness (i.e. the distance between models) is calibrated from a portfolio of known transaction prices, i.e. M&A transactions that have been publicly announced. For each mine in the portfolio, we establish a baseline model using knowledge of the disaster threshold to which the mine was initially built. Then, for each mine, we calculate a series of robust prices (both upper and lower bounds), expanding our tolerance region until we match the observed transaction price. Once the tolerance region has been found for every mine in the portfolio, for mines with unknown values, we produce upper and lower bounds for mines with unknown values, using, for example the largest region of the known mines, or some other quantile thereof, depending on the view of the investor.

The second method calculates the degree of robustness from the observed physical processes at the mine site. In this case, we use the highly simplified example that disasters are caused by an extreme rainfall event. We assume the mine was built to withstand a 1-in-x year event, as calculated from an N-year time series of annual 24-h precipitation events, from when the mine first underwent construction. Using this time series, we calibrate an appropriate GEV model, and search over all models within the distance between the fitted GEV model and the actual time series, and use results from robust extreme value theory (Blanchet and Murthy, 2016) to find a worst-case probability of exceeding the threshold to which the mine was built. The mine is then valued with this worst case annualized probability using the simplified disaster model. Both of these methods produce a range of values that reflect the uncertainty in the risk associated with the mining project, as has been suggested by regulators, most notably CIMVal.

This paper is structured as follows: in Section 2, we propose our simple extension of Brennan-Schwartz, and briefly compare the results from this model to those of the more traditional model. Section 3 develops our first pricing technique, estimating the robustification parameter using a collection of observed prices, and provided results on a smaller portfolio of known mining transactions. Section 4 develops the second pricing technique, which robustifies against misspecification in the climate risk, and re-prices the same portfolio of mines using this technique. Finally, we conclude in Section 5.

2. Baseline model for catastrophe risk

While the real options framework provides many new insights into the optionality and true value of a mining operation, it fails to account for one major uncertainty in the cash flows of a mine: natural and man-made disasters. Perhaps the most significant of these are tailings dam failures. A tailings dam is used to create a tailings pond, where the byproducts of ore refinement are stored. The tailings pond is retained permanently behind the tailings dam. A tailings pond frequently contains toxic metals such as iron and mercury, which if released into the environment, can cause major environmental damage and can be deadly to local human and animal populations. Increasingly, tailings dams are being viewed as a liability, in that they fail at a much higher rate than conventional dams. A tailings dam failure will cause significant economic damage to the owners of the mine, as they will be forced to suspend operations until a new tailings dam can be built, and they will be forced to pay to clean up the damage that the failure and ensuing flooding have caused, incurring substantial fines and legal dues.

We propose to incorporate the risk of natural disasters into the real options framework. We assume that disasters arrive according to some process, and that when a disaster happens, the operator of the mine suffers a loss, and the mine is forced closed for some period of time (or permanently). This approach to real options valuation is the "Integrated Approach" from Borison (2005), which was originally developed by Smith and McCardle (1998); Smith and Nau (1995). In this case, there are two different types of risk - one is a market-traded, hedgeable risk, and the other is an idiosyncratic, non-market-traded risk, the so-called "private risk." For the former risk, we can and should use market inputs - namely, the value of the underlying, and the implied volatility from the corresponding options markets. The other risk here is the failure of the mine due to some exogenous risk factor - this cannot be hedged with a replicating portfolio of the underlying. Instead, we are typically forced to use a holistic approach to deal with private risks - using subjective probabilities that attempt to closely replicate the real world.

The model presented in this section is a "toy model" (or baseline model) that will be subjected to robustification techniques in Sections 3 and 4 used to produce valuation ranges - upper and lower bounds on the price of the mine. In a sense, it is the simplest (reasonable) continuous-time model that accounts for the risk we are interested in evaluating: commodity price risk, and idiosyncratic disaster risk.