Combining System Dynamic Modeling and the Datar–Mathews Method for Analyzing Metal Mine Investments

Jyrki SAVOLAINEN [a], Mikael COLLAN [b,*],
Pasi LUUKKA [c]

School of Business and Management, Lappeenranta University of Technology
Skinnarilankatu 34, 53851 Lappeenranta, Finland
[a] *e-mail: savoljyr@gmail.com*
[b] *e-mail: mikael.collan@lut.fi*
[c] *e-mail: pasi.luukka@lut.fi*

Abstract

This paper presents how a dynamic system model can be used together with the Datar–Mathews real option analysis method for investment analysis of metal mining projects. The focus of the paper is on analyzing a project from the point of view of the project owner. The paper extends the Datar–Mathews real option analysis method by combining it with a dynamic system model. The model employs a dynamic discount rate that changes as the debt-level of the project changes. A numerical case illustration of a nickel mining project is presented. The results show that using dynamic system models in real option analysis is not only possible with the Datar–Mathews method, but also that some previously identified problems of real option valuation can be avoided.

Key words: System dynamic model, Monte Carlo simulation, metal mining, profitability analysis, Datar–Mathews method, real option valuation.

2010 Mathematics Subject Classification: 65C05, 37M40, 90B30, 91B74

---

*Corresponding author.

1 Introduction

Metal mining investments are large investments with long economic lives that operate in an uncertain metal market price environment and can contain high project risks due to geological and technical uncertainties. The technical uncertainties are typically resolved only trough investment and revealed later. These characteristics underline the importance of through a priori investment analysis to support the decision-making surrounding starting new metal mining projects. Profitability level of metal mining investments is (highly) dependent on the market prices of the produced metals and on project specific issues, such as ore quality and the ability of managers to run the mine effectively by reacting correctly to market changes. In other words management can affect the value of a mining project through making correct choices with regards to, e.g., decisions to temporarily shut down the mine, when market prices of the produced metal are experiencing a temporary drop. Such operational choices that stem from the technical availability of the choices are commonly called operational real options. Interestingly the management ability to make operational decisions, such as temporary shut downs, is conditioned by the availability of liquidity that is needed to keep the mining operation "alive", while the shut-down lasts. Availability of liquidity is affected by fixed costs of the mining operation, this is where the question of the capital structure used to finance the mining investment comes to play, scheduled fixed debt amortizations have an effect on the available liquidity and hence condition management decision-making with regards to, e.g., production related decisions. Under ideal conditions, with perfectly functioning capital markets this kind of issues do not play a role, but under the real-world conditions this means that the form of financing has a value effect on metal mining investments. Management may have to keep operations running to avoid liquidity bankruptcy of the project, while the optimal production strategy would be to keep operations shut down. For this reason, in addition to the fact that the environment in which metal mining investments operate is not ideal, we posit that the capital structure and an adequate working capital level should be considered already in the planning and investment analysis phase of metal mining investments. This makes us what Brealey and Myers call "traditionalists" [7]. In other words we believe there is a capital structure that maximizes the value of the metal mining investment.

Furthermore, our focus is on the value of the prospective mining investment to the owners of the mining rights that is, to the organization that holds the equity of the investment project. Under these circumstances financing does matter, for if from the project NPV a part is paid as interest out to debtholders the value of the project to the "equity holders" changes with different debt levels. What also happens is that the discount rate for the equity holders changes as a function of the financial structure (see, e.g. [8]) that is, when the debt is amortized the discount rate changes—this has been modeled as a new feature in the dynamic system model. Figure 1 shows the general structure of the procedure.
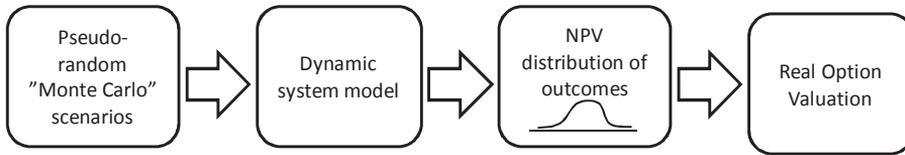
Figure 1: General structure of the analysis procedure

Analysis methods used should generally be able to account for as much of the complexity of the projects they are used to analyze in a way that matches real-world complexity with the analysis model complexity. Model—reality match in terms of complexity is referred to as requisite variety [9]. Here we approach this model—reality match by suggesting that by using dynamic system modeling in investment analysis we take new steps towards requisite variety in investment analysis and thus enter into previously untrodden territory and make a contribution. Using a DSM is a significantly less robust method than the traditionally used spread-sheet modeling based and static methods in the modeling the value of metal mining investments. Previously DSM has been applied for analyses in the mining industry, e.g., in [10, 11, 12, 13, 14].

In this paper we use a dynamic system model of a metal mine as the basis for investment analysis of a prospective metal mine project. System dynamic modeling may be used to deal with some previously identified problems with real option analysis, such as the "black box" problem, problems with being able to utilize the available data, and the problem of modeling real option interaction, see [1, 15, 16, 17, 18]. Firstly, the "black box" problem related to complex mathematical equations is not a problem, because SD models present application specific (graphical) function block diagrams, where simple algebra and "if-else" coding are applied. Secondly, SDM is not restricted by the type of data used; all types of data from fuzzy expert knowledge to stochastic processes can simultaneously be incorporated into and used in a single model, without making compromising changes to the quality of the data. Furthermore, this means that multiple and interdependent sources of uncertainty can be modeled simultaneously. Thirdly, simultaneously modeling multiple and interacting real options is not a problem with system dynamic models. For these reasons we believe it is a good idea to use SDM in real option analysis. The system model used is based on the technical structure of an existing metal mining investment and includes modeling of technical and financial aspects of the said mine. Monte Carlo simulation (MCS) is used to "run" the DSM and to generate a net present value (NPV) distribution of the possible outcomes of the investment. We are interested also in the RO valuation of the prospective metal mining project and illustrate how the DSM can be used in RO valuation with the Datar–Mathews method [6]. We follow the "footsteps" of the Datar–Mathews method very closely and construct our analysis framework in line with the original Datar–Mathews models. The Datar–Mathews model uses the commonly accepted discounted cash-flow (DCF) method to neutralize the risk connected to future cash-flows and to make them comparable with riskless cash-in-hand

at the present time. What is expected is the ability to estimate relevant yearly discount rates for the stream of uncertain future cash-flows that is utilized in the discounting. In this paper we use, as is used in the original Datar–Mathews method, separate discount rates for revenues and costs as the risks of these are assumed to stem from different sources. We simplify the world and use only two discount rates, one for the investment cost stream and one for the revenue, or operational cash-flows stream. According to the Datar–Mathews [5] method the real option value is calculated from the net present value distribution of the investment simply by:

$$ROV = (1 - P_n)\mu_p \tag{1}$$

where P_n is probability of negative outcomes and μ_p is expected value of the positive values.

Using the Datar–Mathews method as the background method for this research is our choice as modelers that is based on the simulation based Datar–Mathews method fitting well together with using a dynamic system model. We understand the discussion about the construction of new risk-neutral valuation models through matching the stream of estimated future cash-flows to a traded index that is assumed to follow, and that can be modelled with, a stochastic process [19], but such modeling falls outside the scope of this research. Figure 1 shows the general structure of the analysis procedure used. To the best of our knowledge there are very few previous attempts to use a dynamic system model together with simulation to study the use of (Datar–Mathews) real option analysis in metal mining investment valuation, typically the used models have been much simpler. The focus that is taken in this paper, that is to look at the valuation from the subjective point of view of the organization that "owns" the project and considering the effect of choice of financing with a dynamic discount rate modelled into the DSM is a fresh approach in the metal mining valuation and real option analysis landscapes. Real option analysis has previously been applied to mining investments in, e.g., [20, 21, 22, 23].

The following chapter contains an introduction to the applied profitability simulation model and the results of a numerical case illustration. The paper is closed with discussion about and conclusions based on the attained results. Future avenues for further research are identified.

2   Short presentation of the DSM and of a numerical case illustration

2.1   Model description

The techno-economic dynamic system model that combines technical and economic aspects of the metal mining investment used in this work is built in Matlab Simulink and the underlying reality behind the model is the structure of a real-world metal mining investment. The high-level structure of the model is illustrated in Figure 2. The four sub-models are interconnected and their mutual parameters are inputted into a common Matlab workspace, allowing the

formation of feedback loops between input variables and the resulting calculated values. The benefit of the proposed approach is that a single model can be used to detailed modeling of multiple sources of uncertainty, imprecision, and feedback loops connected to industrial investments instead of considering the effects of multiple sources of uncertainty in separate analyses.
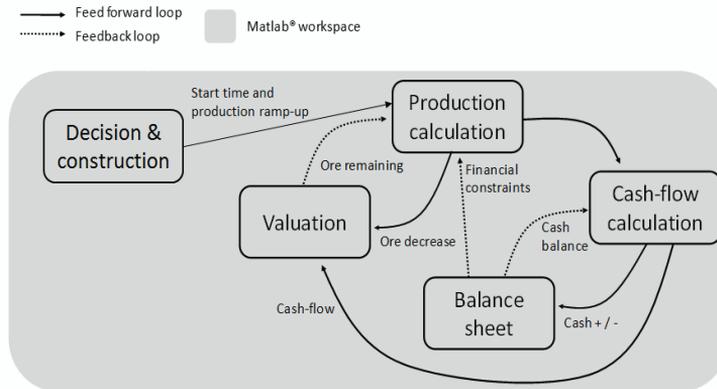

Figure 2: Conceptual illustration of the applied SD-model (adopted from [24]).

In Figure 2 (see also Appendices 2–4), the "Decision & construction" sub-model simulates the projects construction and ramp-up times, which trigger the "Production calculation" sub-model. "Production calculation" models the technical mining system used for revenue generation including the modeling of multiple uncertainties, such as the uncertain metal world market price and the production rate. The output values from the sub-model are used as inputs in the "cash-flow calculation" sub-module, where other (financial) costs are further subtracted and the current cash balance is re-calculated. "Cash flow calculation" sub-model is linked to the "Balance sheet" and "Valuation" sub-models that perform the cash-flow calculations and the generation of the project balance sheet that includes the final valuation of the project. The model operates in discrete time with a one month time-step. Function block descriptions of the detailed model are listed in Appendix 1 and block diagrams of the dynamic system model used are shown in Appendices 2–4.

2.2 Case description

In our illustrative numerical example, we model an early stage nickel mining project with a promising new metallurgical technology. The project is subject to both market uncertainty (market risk) and more importantly the uncertainty of production technology (project risk). We assume that the mining site has proven mineral resources in terms of metal tonnage, but it is questionable to what extent and the mineralization can be exploited at an industrial scale using the given technology. There is no guarantee of the recovery rate of metal, which

may have an undermining effect on the project economics. The estimated construction time, cost, and ramp-up time of the project are uncertain. A number of "in the real world" uncertain variables are assumed to be fixed, and selected "key uncertainties" are considered variable. Random initial values for key uncertainties are drawn randomly from triangular distributions. To simplify the analysis, we assume that all the variables are independent of each other. The key uncertainties are listed in Table 1, where also the estimated volatilities for dynamic parameters are given. With dynamic parameters is meant the parameters that can change during each simulation round as a function of time within the set volatility "around" the randomly drawn initial value. The model is run 10000 times.

Table 1: Key variables of the mining project with their triangular distributions and connected volatilities (for dynamic parameters)

Variable	Unit	Pessimistic	Most Likely	Optimistic	Type	Volatility %
Reserve size	Tons	72000	140000	210000	Static	−
Metal yield	Tons/month	1000	1200	1400	Dynamic	10
Production ramp	Tons/month	50	100	200	Static	−
Unit cost	€/ton	4000	3500	3000	Static	−
Fixed cost	€/month	3000000	2500000	2000000	Static	−
Construction time	Months	36	24	12	Static	−
Construction cost	€	80000000	60000000	40000000	Static	−
Unit price	€/ton	14000	16000	18000	Dynamic	5
Exchange rate	USD/EUR	1.2	1.1	1.0	Dynamic	2

The metal (unit) price and the exchange rate are modeled as stochastic processes that are assumed to be mean reverting towards the initially drawn value on the long run. In the general form, the used mean reversion (MR) equation can be written as (for details, see [17, 25, 26]):

$$\frac{dP}{P} = \eta(P' - P)dt + \sigma dz \tag{2}$$

where, P is the stochastic variable, P' is the long run mean to which the values revert, η is the speed of mean reversion, δ is the volatility of the process, and dz denotes the increments of the standard Brownian motion process. The reversion speeds of the mean reverting processes, η, are set to 0.5 for metal price and 0.75 for the exchange rate respectively. Volatilities are assumed remain constant. Table 1 presents the parameter details. The proposed modeling approach allows us to use any type of stochastic processes to model the dynamic uncertainties. Modeling of metal prices and exchange rates is left outside the scope of this paper, however we observe that mean reverting processes are commonly used to model them (see, e.g., [24, 27, 28, 29]).

Because the focus of the paper is to look at the investment from the point of view of the owner of the project the discount rate used should adjust dynamically to the changes of the financial structure of the project. Here we have modeled this by using a variable discount rate for the project revenues that is assumed to follow a linear relationship with the debt to equity ratio of the project. The

linear relationship is assumed to be such that at full equity financing the discount rate used is ten percent and at limit to full debt financing the discount rate used is fifteen percent. The discount rate used is updated for each time-step within each simulation round run. In line with the original Datar–Mathews method a separate 5 % discount rate is applied to the costs, the cost-side discount rate is assumed to remain fixed.

The project is funded with a 40 $M\mathord{\in}$ debt and a varying amount of equity, which depends on the randomly drawn total investment cost (see Table 1). Loan interest payments start to from the beginning of the investment and their present value are added to the total operating costs. Loan amortization is assumed to start in the beginning of the fourth year and the loan pay-back schedule is set at four years and four yearly instalments of 10 $M\mathord{\in}$ each. Initial working capital is set to 40 $M\mathord{\in}$. If the cash balance of the project drops under 10 $M\mathord{\in}$ a credit line will be used. The credit withdrawals are assumed to be made in 10 $M\mathord{\in}$ installments and the total amount of available credit is assumed to be 100 $M\mathord{\in}$. If the project runs out of both cash (≤ 0) and the credit line (≤ 0) the mine is assumed to go to into liquidity bankruptcy and it is assumed that it will immediately be abandoned. In reality, if the value of the mine is above zero refinancing would most likely take place. If at the time of ore depletion or the abandonment of the mine, the working capital (cash) less the credit limit is larger than zero the discounted value of the remaining working capital is added to the NPV. The simulations are run with two different initial capital structures, the situation where the project is initially financed with fifty percent debt and the situation where the project is initially fully equity financed.

2.3   Simulation results

The project value for the owner as histograms for the two cases of financial structure and the development of the value as a function time is illustrated in Figure 3, where in addition to the mean the 20th and the 80th percentiles are shown as "placeholders" for the optimistic and the pessimistic cases. Histograms for the discounted revenues and the discounted costs are presented in Appendix 5.

Visual inspection of Figure 3 shows that under the assumed circumstances using the initial financial structure of fifty percent debt financing entails a significantly larger downside risk to the project value for the owner than financing the project fully with equity. This is confirmed by the expected values of the NPV distributions, with fifty percent initial debt financing the expected value of the project is $-2,7$ $M\mathord{\in}$ and with full initial equity financing $+14,3$ $M\mathord{\in}$.

Figure 4 shows the project pay-off distributions, when it is considered to be a real option (to start the project) for the two financing cases. With the initial fifty percent debt funding the real option value of the project is 22,4 $M\mathord{\in}$ and with full initial equity financing 31,9 $M\mathord{\in}$. Table 2 summarizes the results of the numerical case illustration.
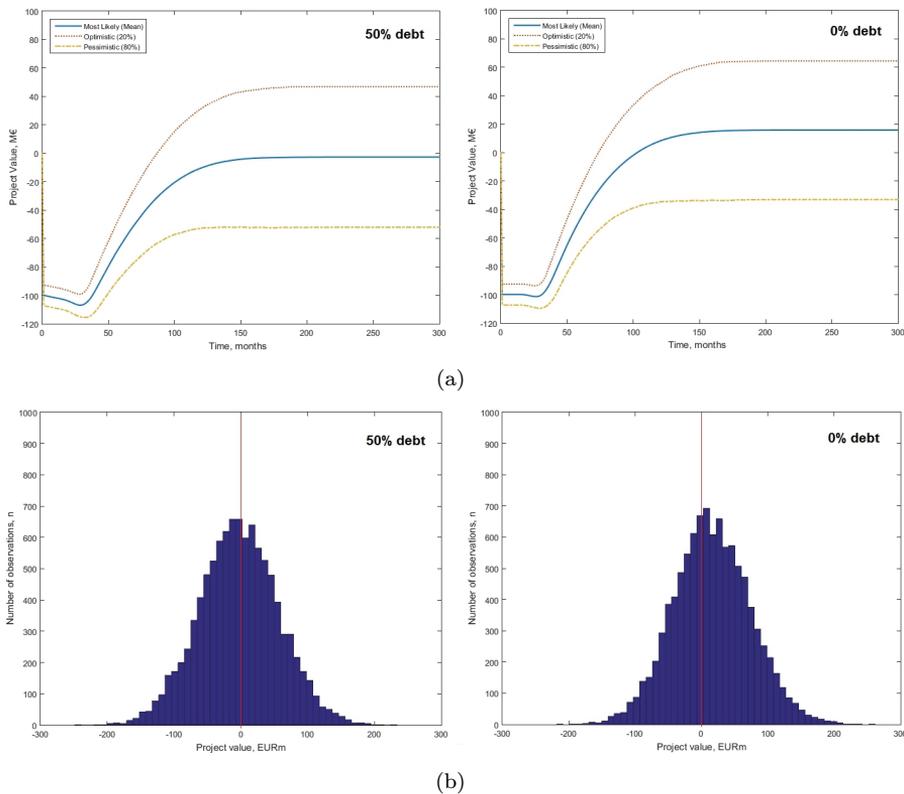
(a)

(b)

Figure 3: Value of the project for the owner as a function of time and the final value for the owner histograms. Left side: 50 % debt, mean value −2,7 *M€*; Right side: 0 % debt, mean value 14,3 *M€*.
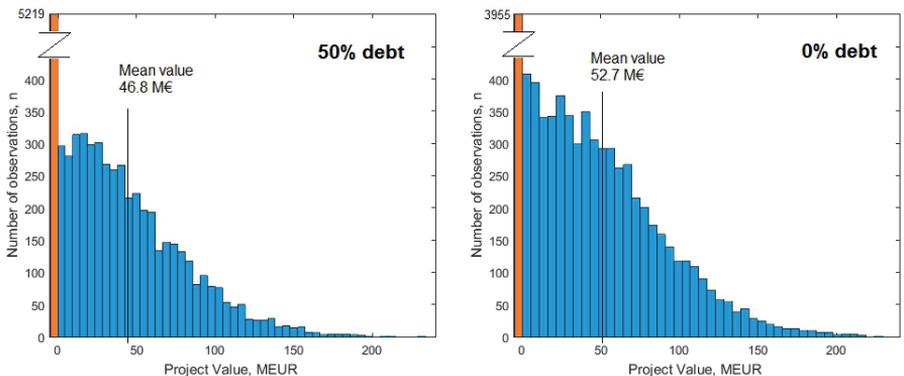

Figure 4: Project as a real option pay-off distributions, with the mean value of the positive side indicated for the two initial financial structures.

Table 2: Summary and comparison of the results

NPV Calculation	Unit	50% debt	0% debt	Diff.	Diff, %
Discounted revenue	$M€$	623,9	631.8	−7,9	−1,3
Discounted cost	$M€$	626,6	617,5	9,1	1,5
Mean NPV	$M€$	−2,7	14,3	−17,1	630,7
Negative outcomes	%	52.2	39.6	12.6	24.2
Positive Mean NPV	$M€$	46,8	52,7	−6,0	−12,8
Real Option Value	$M€$	22,4	31,9	−9,5	−42,6

What the results show is that under the assumptions of the case illustration financing of the project with full equity is a more profitable choice for the project owner in both cases, when the project starting decision has been already done and also when the project is considered to be a real option to start the project. Under the net present value investment rule the project can be started immediately with full equity financing, but there may be value in waiting. In the fifty percent debt financing case the project should be postponed.

3 Discussion and conclusions

Using system dynamic modeling in real option valuation is a rather new avenue of research that opens interesting new research opportunities. System dynamic modeling does not have the previously identified "black box" problem of real option valuation modeling, because the models typically mimic the real world closely. Also other previously identified problems can be solved by using system dynamic modeling.

Here we have combined the structure of the Datar–Mathews real option analysis method with a system dynamic model for the purpose of valuing a metal mining project from the point of view of the project owner. The model used includes both the technical and the economic structure of the project. As a novelty we use a dynamically changing discount rate for discounting project revenues that follows the changes in the capital structure of the project, this is in line with the focus of the paper.

We have studied the effect of two different capital structures of the project to the value of the project to the owner and how much the project is worth to the owner as a real option under the two capital structures. The illustrative results showed that capital structure is an issue that may be of great importance for metal mining project owners and thus should be considered when investments are planned.

The obtained results not only show that the Datar–Mathews real option analysis is usable with a dynamic system models for metal mining investments, but also indicate that the combination may bring additional benefits over the typical Datar–Mathews models that are based on using cash-flow scenarios.

Future research directions include studying the effect of operational real options that may be found in metal mining projects with the presented model,

studying better (than linear) representations for the connection between the discount rate used for the revenues and the debt level of projects, and optimizing investment timing.

References

[1] Collan, M.: *Thoughts about selected models for real option valuation*. Acta Univ. Palacki. Olomuc., Math. **50**, 2 (2011), 5–12.

[2] Collan, M.: The Pay-Off Method: Re-Inventing Investment Analysis. *CreateSpace Inc.*, Charleston, NC, 2012.

[3] Collan, M., Fullér, R., Mézei, J.: *Fuzzy pay-off method for real option valuation* Journal of Applied Mathematics and Decision Systems **2009** (2009), 1–14.

[4] Datar, V., Mathews, S.: *European real options: an intuitive algorithm for the Black Scholes formula*. Journal of Applied Finance **14** (2004), 7–13.

[5] Mathews, S., Datar, V., Johnson, B.: *A practical method for valuing real options: The Boeing approach*. Journal of Applied Corporate Finance **19**, 2 (2007), 95–104.

[6] Mathews, S., Salmon, J.: *Business Engineering: A Practical Approach to Valuing High-Risk, High-Return Projects Using Real Options*. In: Tutorials in Operations Research (2007), 157–175.

[7] Brealey, R. A., Myers, S. C.: Principles of Corporate Finance. Mcgraw Hill Series in Finance, *Mcgraw-Hill*, 1996.

[8] Esty, B. C.: *Improved techniques for valuating large scale projects*. J. Proj. Financ. (1999), 9–25.

[9] Ashby, W. R.: *Requisite variety and its implications for the control of complex systems*. Cybernetica **1**, 2 (1958), 83–99.

[10] O'Regan, B., Moles, R.: *A system dynamics model of mining industry investment decisions within the context of environmental policy*. Journal of Environmental Planning and Management **44**, 2 (2001), 245–262.

[11] O'Regan, B., Moles, R.: *Using system dynamics to model the interaction between environmental and economic factors in the mining industry*. Journal of Cleaner Production **14**, 8 (2006), 689–707.

[12] Savolainen, J., Collan, M., Luukka, P.: *Modeling Profitability of Metal Mining Investments as Dynamic Techno-Economic Systems*. In: Workshop on Sustainability and Decision Making, 25.–26. 2. 2015 *RWTH*, Aachen, Germany, 2015, p. 15.

[13] Sontamino, P., Drebenstedt, C.: *Decision Support System of Coal Mine Planning Using System Dynamics Model: Introduction and Reviews*. 6th Freiberg–St. Petersburg Kolloquium junger Wisseshaftler 15–17 Juni, 2011, Freiberg, Germany (2011), 1–6.

[14] Tsekrekos, A. E., Shackleton, M. B., Wojakowski, R.: *Evaluating natural resource investments under different model dynamics: managerial insights* European Financial Management **18**, 4 (2012), 453–575.

[15] Triantis, A.: *Realizing the Potential of Real Options: Does Theory Meet Practice?* Journal of Applied Corporate Finance **17**, 2 (2005), 8–16.

[16] Lander, D. M., Pinches, G. E.: *Challenges to the practical implementation of modeling and valuing real options*. Q. Rev. Econ. Financ. **38**, 3 (1998), 537–567.

[17] Smith, J. E., McCardle, K. F.: *Options in the real world: Lessons learned in evaluating oil and gas investments* Oper. Res. **47**, 1 (1999), 1–15.

[18] Borison, A.: *Real options analysis: Where are the emperor's clothes?* J. Appl. Corp. Financ. **17**, 2 (2005), 17–31.

[19] Jaimungal, S., Lawryshyn, Y.: Incorporating Managerial Information into Real Option Valuation. In: R. Aïd, M. Ludkovski, R Sircar, Eds.: Fields Institute Communications **74**, Commodities, Energy and Environmental Finance, *Springer*, New York, 2015, 213–238.

[20] Abdel Sabour, S., Poulin, R.: *Valuing real capital investments using the least-squares Monte Carlo method.* Eng. Econ. **51**, 2 (2006), 141–160.

[21] Cardin, M., De Neufville, R., Kazakidis, V.: *A process to improve expected value of mining operations.* Min. Technol. **117**, 2 (2008), 65–70.

[22] Haque, M. A., Topal, E., Lilford, E.: *A numerical study for a mining project using real options valuation under commodity price uncertainty.* Resour. Policy **39** (2014), 115–123.

[23] Samis, M., Davis, G. A., Laughton, D., Poulin, R.: *Valuing uncertain asset cash flows when there are no options: A real options approach.* Resour. Policy **30**, 4 (2006), 285–298.

[24] Savolainen, J., Collan, M., Luukka, P.: *Using a dynamic system model in ex-ante operational and profitability analysis of a metal mine through simulation.* In: Book of abstracts of the ECCOMAS CM3 Thematic Conference – New Challenges for the Greening of Transport, 25.–27.5.2015, Jyväskylä, Finland, 2015, 97–100.

[25] Dias, M. A. G., Rocha, K. M. C.: *Petroleum concessions with extensible options using mean reversion with jumps to model oil prices.* In: 3rd International Conference on Real Options, Wassenaar/Leiden, June 6–8, 1999, L. Trigeorgis, Eds., *Oxford University Press*, 1999.

[26] de Magalhaes Ozorio, L., Shevchenko, P. V., De Lamare Bastian-Pinto, C.: *The Choice of Stochastic Process in Real Option Valuation II: Selecting Multiple Factor Models.* In: 7th International Conference on Real Options, Tokyo, 2013.

[27] Slade, M.: *Valuing managerial flexibility: An application of real-option theory to mining investments.* J. Environ. Econ. Manage. **41** (2001), 193–233.

[28] Lemelin, B., Abdel Sabour, S. A., Poulin, R.: *Valuing mine 2 at raglan using real options.* Int. J. Mining, Reclam. Environ. **20**, 1 (2006), 46–56.

[29] Abdel Sabour, S. A., Dimitrakopoulos, R. G., Kumral, M.: *Mine design selection under uncertainty.* Min. Technol. IMM Trans. Sect. A, **117**, 2 (2008), 53–64.

Appendix 1. Functional block description of model and numerical values. Note that, for brevity, the tables A1–A4 do not include basic function blocks, such as: link-("goto"/"from"), algebraic-(plus/minus/multiply/divide), logic-("greater than", "equal or greater than", etc.), integration/derivation and delay signalfunction blocks which are visible in Appendices 2–4.

Legend for tables A1–A4: SP = Sub Process; D&C = Decision & Construction; Prod = Production; CF = Cash Flow; BS = Balance Sheet; MV = Mine Valuation

Table A1. Simulation input blocks.

SP	Block Name	Type	Output uni	Value	Function
D&C	Building time	Constant	months	12…24…36	Actual value is drawn from triangular distribution
D&C	RampUp	Constant	tn/mth	50…100…200	Production ramp-up rate; drawn from triangular distribution
Prod	Open_FixedCost	Constant	EUR/mth	(2.0…2.5…3.0)*10^6	Monthly fixed cost in operation; drawn from triangular distr.
Prod	MineCapacity_Variation	Constant	-	-	Creates variation to monthly production rate +/-10% of capacity
Prod	VariableCost	Constant	EUR/tn	3000…3500…4000	Variable unit cost of produced metal; drawn from triang. distr.
Prod	VariableCostExp	Constant	EUR/tn	N/A	Not in use (needed for capacity expansion modeling)
Prod	MineCapacity	Constant	tn/mth	1000…1200…1400	Mine capacity; drawn from triangular distribution
Prod	MineCapacityExp	Constant	tn/mth	1 200	Production rate after cut-off grade increase
Prod	PaymentRatio	Constant	-	0,6	Payment ratio of customer compared to LME-price
Prod	NiPrice_t0	From Workspace	USD/tn	(14…16…18)*10^3	Nickel price at t=0 and the mean reversion level; triang. distr.
Prod	Constant FX	From Workspace	EUR/USD	1.0…1.1…1.2	Exchange rate at t=0 and mean reversion level; triang. distr.
CF	CashMinimum	Constant	EUR	10 000 000	Input value for required minimum cash balance during simulation
CF	Constant IR	From Workspace	%	2	Interest rate (fixed)
CF	IL_Margin	Constant	%	4	Interest rate margin for initial investment loan
CF	CL_Margin	Constant	%	7	Credit limit loan margin
CF	Initial cash	Step	EUR	40 000 000	The initial cash balance of company
CF	LoanPayment	From Workspace	EUR	4*10^6	Yearly loan payment schedule for initial investment
CF	Amortization	From Workspace	EUR/mth	N/A	Not in use; amortization
CF	CapexReplacementRatio	Constant	-	N/A	Not in use; replacement investments
CF	CapexNew	From Workspace	EUR	N/A	Not in use; Planned new capital investments monthly
BS	CreditLimit	Step	EUR	100 * 10^6	Initial credit limit
BS	Credit Limit Withdraw	Constant	MEUR	10 000 000	Amount of credit limit withdrawal per one installment
BS	Covenant time 0	Step	-	N/A	Not in use
BS	Initial Investment	From Workspace	EUR	(40…60…80)*10^6	Initial capital investment; drawn from triangular distribution
BS	Initial Loan	From Workspace	EUR	4*10^6	Initial liabilities
MV	Initial reserve size	Step	tn	(72…140…210)*10^3	Initial reserve size in terms of metal tons; drawn from triang. distr.
MV	AbandonCost	Constant	EUR	5 000 000	Abandonment cost of mine after depletion of ore
MV	AbandonTreshold	Constant	MEUR	-50*10^6 or -inf	Abandon option treshold
MV	DiscountRate_Rev	Constant	-	0.10	Revenue discount rate used for NPV-calculation
MV	DiscountRate_Cost	Constant	-	0.05	Cost discount rate used for NPV-calculation

Table A2. Simulation output blocks

SP	Block Name	Type	Output uni	Value	Function
Prod	Costs and revenue	Scope	MEUR, ktn		Revenue and production diagrams
Prod	Costs scope	Scope	MEUR		Cost diagrams
Prod	Price and FX-rate	Scope	EUR/USD, USDt/tn		Average price and exhange rate diagrams
Prod	Unit Cost Scope	Scope	MEUR, tn		Cost and production diagrams
Prod	Out3	Outport	USD/tn		Simulated nickel price
Prod	Out5	Outport	ktn		Cumulative production of nickel in kilotons
CF	Cash Scope	Scope	MEUR		Diagrams of cash flows and cash balance
CF	Out4	Outport	MEUR		Cumulative undiscounted cash flow
CF	Out7	Outport	MEUR		Cash balance
BS	Key Figures	Scope	%, MEUR		Diagrams of balance sheet key figures
BS	Debt Scope	Scope	MEUR		Diagrams of debts
BS	Out8	Outport	MEUR		Remaining credit limit
MV	Out1	Outport	MEUR		Cumulative cash flow assuming single discount rate
MV	Out2	Outport	MEUR		Cumulative cash flow without debt assuming single disc. rate
MV	Out6	Outport	months		Life of mine
MV	Out9	Outport	MEUR		Cumulative discounted cost
MV	Out10	Outport	MEUR		Cumulative discounted revenue
MV	Out11	Outport	MEUR		Cumulative discounted value
MV	Out12	Outport	-	1/0	Negative project value indicator

Table A3. Simulation calculation blocks

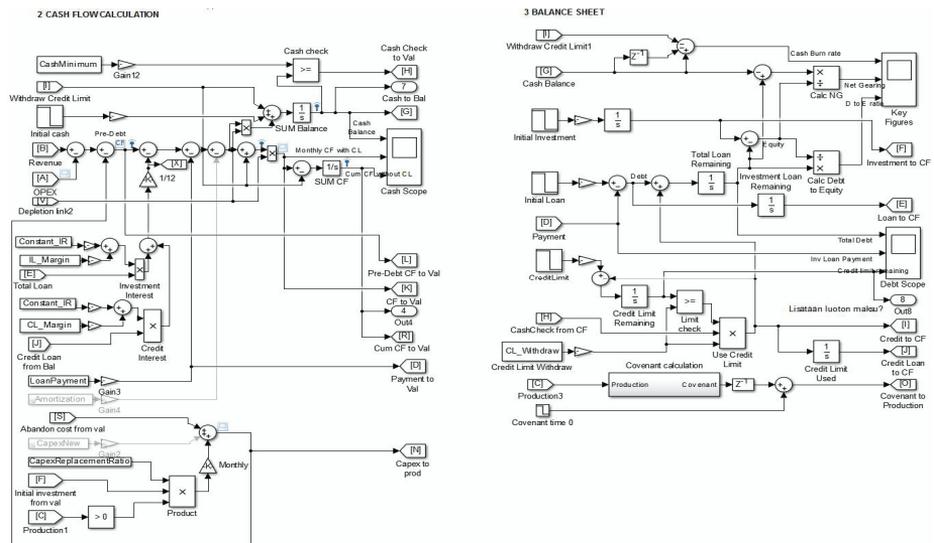| SP	Block Name	Type	Output unit	Function; ∑ refers to cumulative sum
D&C	Limit	Integrator (limited)	tn/mth	IF ∑[Ramp-up] < [Production Rate], THEN [Ramp-up] otherwise [Production Rate]
Prod	Production function	Function block	tn/mth	IF [construction] = 1 & [reserve] > 0, THEN [production] = [capacity]
Prod	AVG Price	Product	$/tn; €/$	∑[price & FX-rate] / ∑[Time]
Prod	Unit Cost	Product	EUR/tn	[OPEX+CAPEX]/[Monthly production]
Prod	Cost EURm	Product	MEUR	[Production rate] * [Production unit cost]
Prod	Revenue USDm	Product	MUSD	[Production rate] * [Output price] * [Payment ratio]
Prod	USDm to EURm	Product	MEUR	[Revenue USDm] / [FX_rate]
Prod	SUM cost	Integrator	MEUR	∑[OPEX]
Prod	SUM revenue	Integrator	MEUR	∑[Revenue]
Prod	MR1	Subprocess	USD/tn	[Nickel price at t=0] * [MR-SDE (vector)]
Prod	MR2	Subprocess	EUR/USD	[Exchange rate at t=0] * [MR-SDE (vector)]
CF	Cash check	Relational operator	1/0	IF [SUM Balance] >= [Cash Minimum], THEN 1, OTHERWISE 0
CF	Investment Interest	Product	MEUR	[Remaining investment loan] * [Total interest rate (incl. margin)]
CF	Credit Interest	Product	MEUR	[Credit loan] * [Total credit loan interest rate (incl. margin)]
CF	SUM CF	Integrator	MEUR	∑[Cash flow]
CF	SUM Balance	Integrator	MEUR	∑[Cash balance]
CF	1/12	Gain	MEUR	[Yearly total loan payment (investment +credit loan)] / 12
CF	Payment to Val	Goto	MEUR	Routes signal from subprocess to another
BS	Limit check	Relational operator	1/0	IF [Credit Limit Remaining] >= [Credit withdraw installment] THEN 1, OTHERWISE 0
BS	Calc NG	Product	-	[Cash balance] / [Invested equity]
BS	Calc Debt to Equity	Product	-	[Total loan (inv. +credit)] / [Invested equity]
BS	Use Credit Limit	Product	MEUR	[Limit check (0 or 1)]*[Credit withdraw installment]*[Cash Check (0 or 1)]
BS	Credit Limit Used	Integrator	MEUR	∑[Credit withdraws]
BS	Payment	From	MEUR	Routes signal from subprocess to another
BS	Investment Loan Remaining	Integrator	MEUR	∑([Initial loan]-[Loan payments])
BS	Loan to CF	Goto	MEUR	Routes signal from subprocess to another
MV	Revenue discount factor calc.	Function block	-	[rate]^[time]
MV	CF	Product	MEUR	(∑[Cashflows]-[Initial investment])/[Revenue discount factor]
MV	CF1	Product	MEUR	(∑[Pre-debt cashflows]-[Initial investment])/[Revenue discount factor]
MV	Return on Investment	Scope	%	Displays diagram
MV	CF Scope	Scope	MEUR	Displays diagram
MV	Reserve depleted	Relational operator	1/0	IF [Mine Capacity] >= [Metal Reserve], THEN 1, OTHERWISE 0
MV	End of LOM disc. cash	Function block	MEUR	Sub-process: returns the discounted amount of initial capital at the end of simulation
MV	DtoE ratio	Function block	%	[Debt]/[Equity]*100
MV	Debt-to-Discount rate table1	Look-up table	%	Match D-to-E ratio to Revenue discount rate (see fig. 3 in text)

Table A4. Simulation calculation blocks not in use

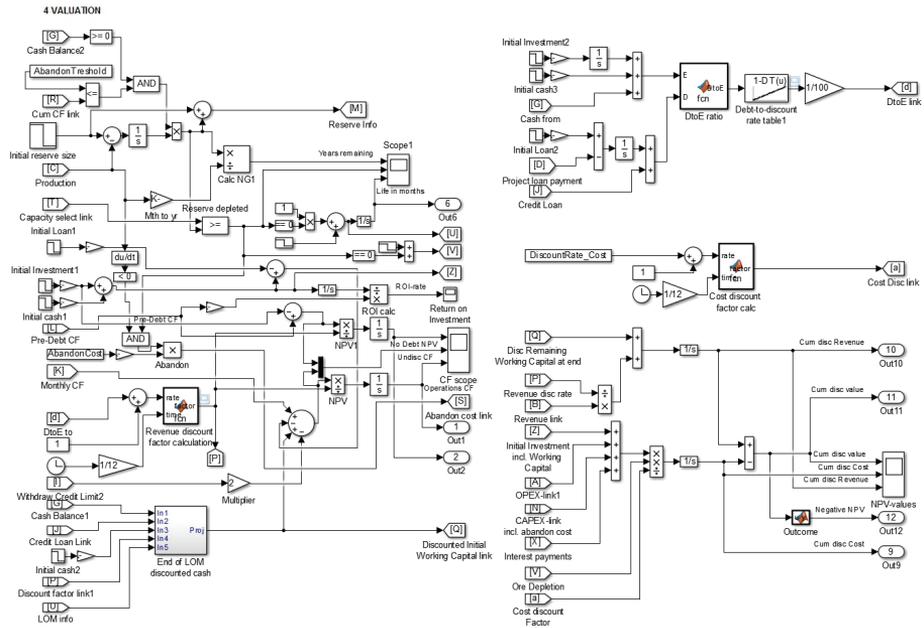| SP	Block Name	Type	Output unit	Value	Function
Prod	Select Var-cost	Subprocess	EUR/mth	N/A	Not in use (needed for capacity expansion modeling)
Prod	Select Fixed-cost	Subprocess	EUR/mth	N/A	Not in use (needed for capacity expansion modeling)
Prod	Open-close status	Subprocess	EUR	N/A	Not in use (needed for temporary closing modeling)
Prod	Open_FixedCostExp	Constant	EUR/mth	N/A	Not in use (needed for capacity expansion modeling)
Prod	Closed_FixedCost	Constant	EUR/mth	N/A	Not in use (needed for temporary closing modeling)
Prod	ClosingCost	Constant	EUR	N/A	Not in use (needed for temporary closing modeling)
Prod	OpeningCost	Constant	EUR	N/A	Not in use (needed for temporary closing modeling)
Prod	Price 3-month	Subprocess	USD/tn	N/A	Not in use (needed for temporary closing modeling)
Prod	Volatility calculation	Subprocess	%	N/A	Not in use
BS	Covenant calculation	Subprocess	1/0	N/A	Not in use; special conditions for debt payment

Appendix 2. Simulation model from Matlab Simulink: decision making and production calculation modules.

Appendix 3. Simulation model from Matlab Simulink: cash flow and balance sheet calculation modules.

Appendix 4. Simulation model from Matlab Simulink: valuation module *right*: separate discount rate calculation for costs and revenues as applied in this paper.

Appendix 5. Discounted revenue (up) and discounted cost histograms (down) using the two initial financial structures.