An Introduction of New Simulation and Optimization Software Application for Long-Term Limestone Quarry Production Planning

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Abstract

Long-term limestone quarry production planning is essential to maintain the supply to the cement plant. In which, quarry planners usually attempt to fulfil the complicated calculations, which ensure a consistent supply of raw materials to the cement plant while guaranteeing technical and operational parameters in mining. Traditionally, the calculations are done on a spreadsheet or by trial and error procedure resulting in high additive cost and an increase in product variability. Modern quarry management relies on block models and mathematical algorithms integrated into the software to optimize the long-term limestone quarry production planning. However, this method is potentially sensitive to geological uncertainty in block modelling, resulting in the deviation of the supply production of raw materials. The need for mining intelligently raw material is, therefore, crucial and an increasing issue in the cement industry. In this research, a new simulation and optimization software application called Quarrier is introduced, allowing quarry planners to address the conflicting requirements of long-term limestone quarry production planning while forecasting and mitigating the effects of geological uncertainty on the supply of raw materials for the cement plant. The benefits of this software are demonstrated through a limestone quarry in Vietnam.

Keywords: *quarry, extraction plan, cement, optimization, simulation, geological uncertainty*

1. Introduction

Undertaking a long-term quarry production for cement manufacturing operations is not an easy task. Quarry planners usually struggle with the calculations required to blend the chemical characteristics and mining parameters and to maintain a consistent supply of raw materials. Additive materials such as high-grade limestone, bauxite, iron ore, and sand are often required to modify the raw mix quality. Frequently, the calculations are done on a spreadsheet or by trial and error procedure resulting in high additive cost and an increase in product variability. The results depend mainly on the experience and expertise of quarry planners rather than being objective and repeatable. The need for mining intelligently raw material is crucial and an increasing issue in the cement industry.

Various optimization commercial software is available in the mining industry, which is capable of determining the optimal long-term production planning. However, the applications are mostly applicable to metallic ore mining, which have different optimization objectives and starting input in comparison with cement raw materials mining. While metal production planning is driving NPV, quarry planning is driving the cost to maximize quarry lifetime to generate the highest possible return from the investment of the cement plant. Thus, the application of available software in quarry planning for cement production is much more limited and generates impractical results. Currently, the cement industry relies on manual methods such as trial and error approach using MS Excel or with the aid of computers like Autocad. One of the first software specialized is QSO Expert (Quarry Scheduling and Optimization) developed at Holderbank (now LafargeHolcim) in the 1980s and used internally within the group.

The current mine planning software operates based on resource models or block models that are constructed using estimation methods. Nevertheless, the estimation of a deposit is uncertain due to sparse geological data, and if this propagates to production, it can lead to a severe of not meeting production expectations and project failures (Dimitrakopoulos, Farrelly, & Godoy, 2002; Groeneveld, B., & Topal, 2011; Vallée, 2000). Conditional simulation algorithms are considered as the best method to characterize the risk related to geological uncertainty by generating a series of probable geological outcomes or realizations of orebody models with an equal chance to occur in practice.

The mine planning optimization group within the Freiberg University of Mining and Technology, Germany, has developed a mine planning optimization software called Quarrier. The concept of Quarrier specifically designed to optimize the long-term or life-of-mine quarry production planning, which is essential to ensure a consistent supply of raw materials to the cement plant. It provides quarry planners with a strategic planning tool to figure out the long-term quarry extraction plan, mitigate and control the risk of not supply raw materials at production targets due to geological uncertainty.

In this paper, we introduce the concepts and structure of Quarrier. We also present the application of Quarrier in a limestone quarry that supplies raw materials for a cement project in Vietnam.

Tab. 1. Constraints applied in Quarrier
Tab.1. Ograniczenia zastosowane w Quarrier

Constraint class	Constraint
Quarry	Minimum and maximum quarry production
	Maximum mining slope angles
Waste dump	Minimum and maximum waste dump production
	Type of materials removed to the waste dump
Blending stockpile	Minimum and maximum stockpile production
	Type of raw materials moved to the blending stockpiles
	Minimum and maximum quality required at blending stockpiles
Additive purchase	Minimum and maximum purchases of additive materials for blending at stockpiles

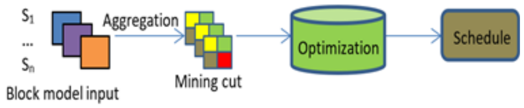


Fig. 1. Quarrier optimization procedure
Rys. 1. Procedura optymalizacji Quarrier

Tab. 2. Quality and cost of purchased additive materials
Tab.2. Jakość i koszt zakupionych materiałów dodatkowych

Additive	Cost	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	LOI
Clay	4	5.27	60	2.14	1.5	0.5	30
Laterite	6	0.72	8	47	19.4	1.06	20
High Quality Limestone	4	65	5	1	0.5	1.06	32
Iron Ore	8	1.69	10	1.07	70	1.32	10

Tab. 3. Production target parameters for evaluating the sensitivity of clustering schemes, penalty costs, and the capacity of the SMIP model
Tab.3. Parametry docelowe produkcji do oceny wrażliwości schematów klastrowych, kosztów karnych i wydajności modelu SMIP

Description	Value
Num. production periods	10
Mining capacity (Mt)	12 ÷ 15
Raw mix capacity (Mt)	10
CaO (%)	58 ÷ 69
SiO_2 (%)	14 ÷ 28
Al_2O_3 (%)	4 ÷ 10
Fe_2O_3 (%)	0.5 ÷ 5
MgO (%)	0 ÷ 3
$AM = Al_2O_3/ Fe_2O_3$	1 ÷ 3
$SR = SiO_2/(Al_2O_3+ Fe_2O_3)$	1 ÷ 3
$LSF = CaO/(2.8^* SiO_2+1.18^* Al_2O_3+0.65^* Fe_2O_3)$	0.485 ÷ 1

2. Quarrier Implementation

Quarrier has been developed to operate as a Matlab application and a standard-alone software package that have the following input/output features:

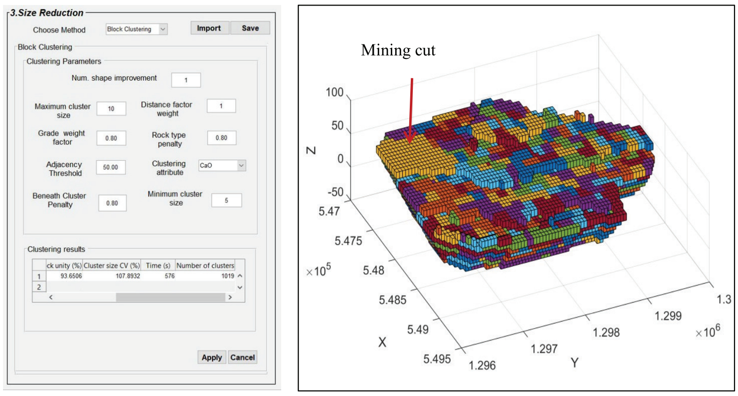
- A single block model or a series of geological realizations of the deposit as well as topography file are provided as ASCII files and text files, containing all block attributes which can be rapidly viewed through a 3D visualization tool.
- Cost data are calculated and assigned by Quarrier.
- Optimization parameters are entered through a graphical user interface.
- Schedule output data, including blending quality of raw materials at the cement plant, tonnage movement and costs, amount of additive materials purchased from outside sources, extraction sequence, is automatically reported via an ASCII file. Quarrier also provides a 3D and 2D graphical visualization tool to illustrate the output data.

3. Parameters and Setup

Quarrier's ultimate objective is to determine the optimum extraction sequence for the quarry for minimizing the cost of developing the raw mix for the cement plant and subject to blending and other operational constraints and mitigating the effect of geological uncertainty. Quarrier employs the commercially available CPLEX (CPLEX, 2009) mixed-integer linear programming (MILP) optimization solver from ILOG Inc to generate the final production schedule. The graphical user interface within Quarrier allows the planner to stop CPLEX solver using two standards: solution time limit and the MIP gap (EPGAP), which is an absolute tolerance of the gap between the best integer objective and the objective of the best node remaining. When the time exceeds the setup limit or the gap falls below the MIP gap, the solver is stopped.

The parameters within Quarrier applies a list of constraints, as shown in Tab.1, to generate the long-term quarry extraction plan. Other limits of Quarrier need to be considered as followings:

- Quarrier attempts to find an extraction plan that avoids using strategic stockpile capacity between the scheduled periods.
- The cost and quality of additive materials purchased from outside sources are assumed to be known in each scheduled period.
- Mining and haulage costs are attributed to each block corresponding to their position and rock types.



3.Size Reduction

Choose Method: Block Clustering

Block Clustering

Clustering Parameters

Num. shape improvement: 1

Maximum cluster size: 10

Distance factor weight: 1

Grade weight factor: 0.80

Rock type penalty: 0.80

Adjacency Threshold: 50.00

Clustering attribute: CaO

Beneath Cluster Penalty: 0.80

Minimum cluster size: 5

Clustering results

	ck unity (%)	Cluster size CV (%)	Time (s)	Number of clusters
1	93.6506	107.8932	576	1019
2				

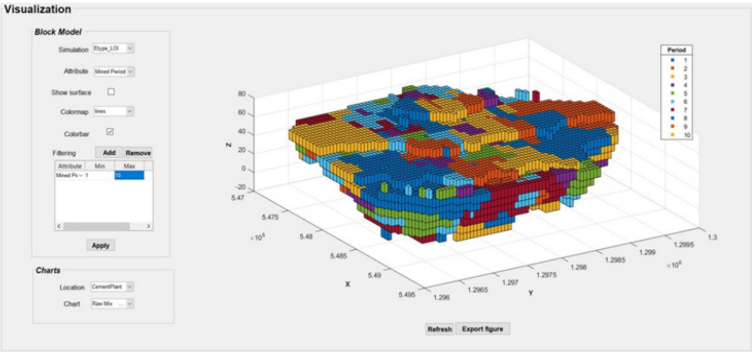
Fig. 2. Aggregation scheme on E-type model

Rys. 2. Schemat agregacji w modelu typu E

Tab. 4. Summary of expected production and quality of the raw mix in each period

Tab.4. Podsumowanie oczekiwanej produkcji i jakości surowca w każdym okresie

Period	**Production (Mt)**	**CaO (%)**	**SiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**MgO (%)**	**AM**	**SR**	**LSF**
1	10.00	58.00	17.45	5.00	5.00	2.28	1.00	1.74	1.00
2	10.00	58.00	17.45	5.00	5.00	2.05	1.00	1.74	1.00
3	10.00	58.00	17.45	5.00	5.00	2.51	1.00	1.74	1.00
4	10.00	58.00	17.45	5.00	5.00	2.50	1.00	1.74	1.00
5	10.00	58.00	17.45	5.00	5.00	2.87	1.00	1.74	1.00
6	10.00	58.00	17.59	4.78	4.16	2.24	1.00	1.84	1.00
7	10.00	58.00	18.10	4.00	4.14	2.18	1.00	2.26	1.00
8	10.00	58.00	18.10	4.00	4.01	2.13	1.00	2.26	1.00
9	10.00	58.00	18.10	4.00	3.92	2.10	1.00	2.26	1.00
10	10.00	58.00	18.10	4.00	3.67	2.27	1.00	2.26	1.00
Sum/Mean	**100.00**	**58.00**	**17.72**	**4.58**	**4.58**	**2.31**	**1.00**	**1.96**	**1.00**



Visualization

Block Model

Simulation: Etype_LOI

Attribute: Mined Period

Show surface ☐

Colormap: lines

Colorbar ☑

Filtering

Attribute	Min	Max
Mined Pe	1	10

Charts

Location: CementPlant

Chart: Raw Mix

Fig. 3. 3D quarry extraction plan generated by Quarrier

Rys. 3. 3D wygenerowany plan wydobycia z Quarrier

- All material in the quarry pit is allocated in selective mining cuts using a clustering algorithm and assumed to be of homogenous quality. The optimizer may extract any portion of a mining cut in any year.
- The extraction precedence of each mining cut is specified by the extraction precedence of its constituent blocks. First, predecessors for each block within a given mining cut are determined. Consequently, the mining cut that the block predecessors belong will be the predecessor of that mining cut. The extraction precedence is performed using the Eq. (1):

$$\sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \leq \left(z_i - z_j\right) tg\alpha \qquad (1)$$

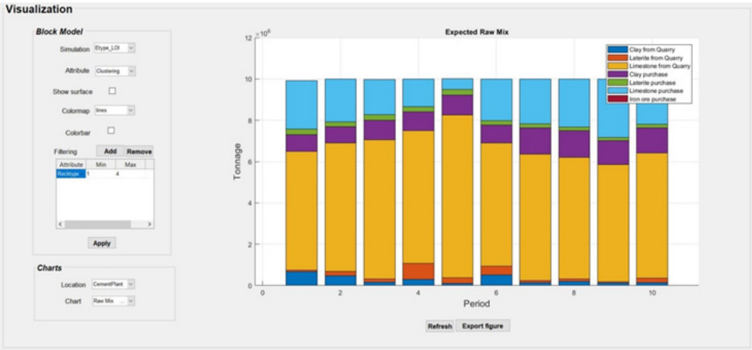
where: (xi, yi, zi) and (xj, yj, zj) are the coordinates of centroids of blocks i and j, respectively; α is the safety slope applied on the centroid of block i

- A series of block models or realizations is assumed to represent probable geological outcomes of deposit with an equal chance to occur in practice.
- Uncertainty costs are applied and multiplied to their corresponding amount of deviation to control the risk of occurrence of these deviations due to geological uncertainty.
- An approximate discount rate is used all over period costs.
- The optimization is global over all the scheduled periods.

4. Quarrier Optimization Procedure

The Quarrier optimization procedure consists of two primary steps: block aggregation and optimization, as shown in Fig. 1. The input for Quarrier can be a single block constructed using any estimation method such as Inverse Distance or Kriging. Also, the planner can construct a series of block models to capture the geological uncertainty of the deposit.

In the following section, we present each step of this procedure in more detail.

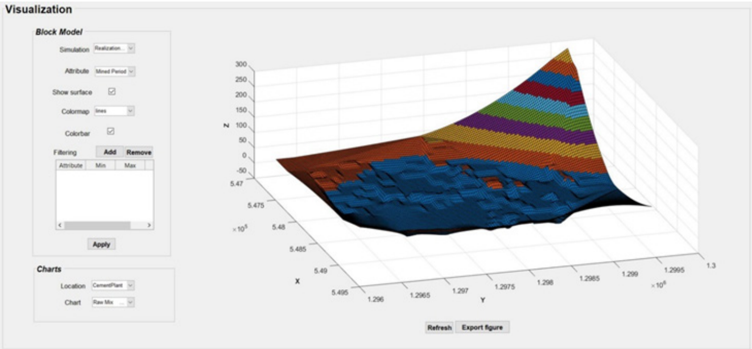


Simulation: Etype_LOI
Attribute: Clustering
Show surface ☐
Colormap: lines
Colorbar ☐

Attribute	Min	Max
Rocktype	1	4

Location: CementPlant
Chart: Raw Mix

Fig. 4. Composition of the raw mix suggested by Quarrier
Ryc. 4. Skład surowej mieszanki przetwarzanej przez Quarrier



Simulation: Realization...
Attribute: Mined Period
Show surface ☑
Colormap: lines
Colorbar ☑

Attribute	Min	Max

Location: CementPlant
Chart: Raw Mix

Fig. 5. The topography of the study area after finishing mining
Rys. 5. Ukształtowanie terenu po zakończeniu eksploatacji

4.1 Block aggregation

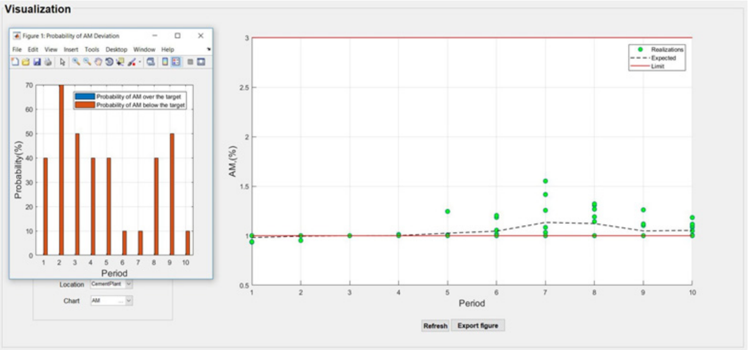
The main engine in Quarrier is the MILP algorithm. For a large block model, the size of the MILP model is often too large to be solved in a reasonable time, using CPLEX solver. Hence, it is necessary to aggregate blocks into some mining cuts to reduce the size of the MILP model. Two conventional aggregation methods are available in Quarrier: reblocking and clustering. The first method resizes blocks and is common in many mine planning software. The second method is a hybrid clustering approach, named KHRA, using k-means and agglomerative hierarchical clustering algorithm (AHCA) (Tabesh & Askari-Nasab, 2011; Mohammad Tabesh, Mieth, & Askari–Nasab, 2014). Quarrier implements the KHRA bench by bench, from the bottom to the top, considering all over realizations of the deposit. KHRA deploys k-mean function in Matlab (2007) to group blocks with a similar grade, rock type, and location into MCs. Then, to avoid aggregating the high uncertainty blocks with low uncertainty blocks, KHRA uses AHCA (Tabesh & Askari-Nasab, 2011; Tabesh et al., 2014) to aggregate blocks based on their frequency of being in the same MC. Finally, KHRA improves the shape of MCs to be minable in practice. The clustering parameters used in Quarrier are as followings:

- Minimum/maximum cluster size: is the minimum/maximum number of blocks in each mining cut.
- Distance weight factor: is applied on distance measure to calculate the distance similarity between blocks.
- Grade weight factor: is the value that is applied to the primary grade difference to calculate the grade similarity between blocks. It should be noted that if the clustering attribute is not the grade attribute, then this grade weight factor is not be used.
- Rock-type penalty: is the penalty value for blocks that are different in the rock-type attribute.
- Adjacency threshold: is the limit value to determine the adjacency between blocks to avoid forming
  Fragmented clusters:
- Clustering attribute: is the attribute of blocks that are selected to be used in the clustering process.
- Beneath cluster penalty: is the penalty value for the blocks located above the different clusters.

Notably, decreasing the number of mining cuts can decrease the solution quality while increasing the solution time.

4.2 Optimization

In the second step, Quarrier automatically feeds the result mining cuts into the optimization model and call CPLEX solver to generate the final production schedule. The optimization tool within Quarrier is formulated using both deterministic and stochastic models. The deterministic model employs a single block model input and assumes that it is the reality of the deposit. Whereas, the stochastic model uses a series of block models and considers as equally probable occurrences of the deposit in practice or geological uncertainty. This model applies the uncertainty cost to penalize the deviation of not meeting the production targets due to geological uncertainty. Generally speaking, the increase of the penalty cost results in the decrease of the deviation from the corresponding production targets or produces a lower risk, while rising the total discounted cost for developing the raw mix and purchasing additive materials.

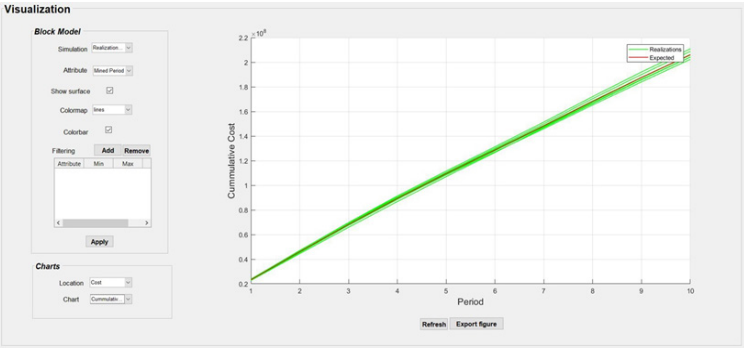


Location: CementPlant

Chart: AM

Fig. 6. AM Indice forecast under geological uncertainty

Rys. 6. Prognoza wskaźnika AM w warunkach niepewności geologicznej



Simulation: Realization...

Attribute: Mined Period

Show surface ☑

Colormap: lines

Colorbar ☑

Attribute	Min	Max

Location: Cost

Chart: Cummulativ...

Fig. 7. Predicted cumulative cost

Rys. 7. Przewidywany łączny koszt

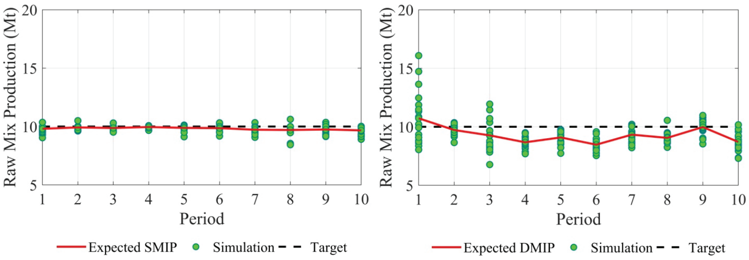


Fig. 8. Risk profiles of raw mix production generated in Test #1 (left) and Test #2 (right)

Rys. 8. Profile ryzyka produkcji surowej mieszanki wygenerowane w Teście #1 (po lewej) i Teście # 2 (po prawej)

5. Case Study

In this section, we demonstrate the ability of Quarrier through a real case study, which is a limestone deposit located 80 km south of Ho Chi Minh City in Binh Phuoc province of Vietnam. Currently, Ha Tien cement company has extracted the deposit, using the open-pit method to supply raw materials for Binh Phuoc cement plant, which is situated about 7.5 km far away. The deposit consists of four main rock types, including soil, laterite, clay, and limestone, in which the soil aims to strip and stockpile for use in the rehabilitation of the quarry, although we can use this material for the raw mix. The waste dump was considered for disposing of waste. The quarry is extracted by the open-pit method with bench height of 10 m and the overall slope angle of 20 degrees. A recovery rate of 80% and a discount rate of 8% were applied in the optimization process. The cost for extracting each block depends on their rock type and location. The quality and cost of the additives are assumed to be known and fixed (Tab.2). In Tab.3, we summarize the production targets for optimization. We have tested the case study on a Dell Precision M6800 with a processor of Intel (R) Core ™ i7-4800MQ CPU 2.80 GHz and a RAM of 32.0 GB. The CPLEX solvers used the gap of 5% to terminate the solving process.

The input was obtained by a hierarchical simulation method in which rock-type domains was simulated first using Sequential Indicator Simulation (SIS) to generate the layout for grade simulation using Sequential Gaussian Simulation (SGS) afterwards. GSILIB (Deutsch, C.V., Journel, 1998) software was deployed to construct 20 realizations of grades and rock types. Two tests were run with Quarrier using this input. In the first test (Test #1), we averaged 20 realizations to construct a single average block model (E-type model) and fed it to Quarrier to demonstrate the ability of the software in optimizing the quarry production planning problem. In the second test (Test #2), we took all 20 realizations to Quarrier to forecast and mitigate the effect of geological uncertainty on the generated quarry production plan.

The resource model contains 14554 blocks which are too large to solve in a reasonable timeframe using the commercial solvers such as CPLEX. Quarrier employs the KHRA, as mentioned in section 4.1, to aggregate all blocks into 1019 mining cuts to decrease the solving time of Quarrier. Fig. 2 illustrates the aggregation parameters and resultant scheme on the E-type model.

5.1 Test #1

In this test, Quarrier generated the solution in 480 seconds using CPLEX solver. The solution to the case study demonstrates the ability to supply an average of 100 million tons of raw material to the cement plant over ten periods. It also ensures the quality of the raw mix fluctuating within the required ranges, as shown in Tab. 4. Fig. 3 shows the feasibility of the mining sequence of the solution through the 3D plan view. As opposed to the manual method, Quarrier demonstrates the ability to consider block precedence and sequencing to achieve a proper blend. Fig. 4 presents the composition of the raw mix, allowing better management in negotiating future agreements with additive suppliers. In many cases, the quarries often consider limestone as a component of the raw mix and the other materials as waste. As given in Fig. 4, the solution minimizes the use of costly additive materials and the amount of waste by adding both clay and laterite from the quarry in the raw mix. The visualization tool within Quarrier also allows the planner to view the topography of the study area after the mining finishes, as shown in Fig. 5.

5.2 Test #2

Test #2 aims to generate an optimum quarry extraction plan that captures and reduces the effect of geological uncertainty. We set the uncertainty costs for quarry production, cement plant production, and quality targets at 1 \$/ton, 3 \$/ton, and 0.1 \$/ton, respectively, to understand how geological uncertainty influencing those production targets.

Quarrier generated the solution within 178 seconds using the same CPLEX parameters as in Test #1. One of the main advantages of Quarrier in comparison with the currently available software is the ability to predict the performance of production and quality targets. For instance, Fig. 6 shows the AM predictions along with its probability above or over the targets through ten periods. The predictions provide valuable information for the planners to react or prepare for the uncertainty of production and quality targets. In terms of project evaluation, Quarrier allows the planner to evaluate a series of critical economic indicators. Fig. 7 shows the predicted cumulative cost produced by risk analysis. The cumulative costs go from \$203 to \$222 (M), which corresponds to a range of -4.63 to +4.34% concerning the expected value.

To emphasize the ability to mitigate the geological risk of the optimization model within Quarrier, we made a comparison of the risk profiles generated in Test #1, which uses the E-type deposit model, and Test #2, which uses a series of deposit simulations. The risk profiles of Test #1 were constructed by deploying the quarry extraction plan to apply back to 20 realizations of the deposit sequentially. The results from each run represent the possibility of implementing the extraction plan in reality and are averaged to get expected results. It is clear from the risk profiles that Test #2 outperforms Test #1 in the capability of mitigating the geological risks. In Fig. 8, the plan in Test #1 shows an unstable supply of raw materials to the cement plant. The plan in Test #2 ensures a more stable supply by minimizing the deviation of not meeting the raw mix production target. Also, the deviations of raw mix production of the plan in Test #2 (the red line) tend to increase towards the later periods while that is randomly distributed in Test #1 over the production periods. As expected in the model within Quarrier, it tends to mitigate the geological risks by delaying mining the risky parts of the quarry.

6. Conclusion

Quarrier provides a digital tool for and support quarry planners at different levels:

Understand the characteristics of the deposit. The software allows planners to import deposit realizations generated from geostatistical simulation software and visualize qualities inside the deposit in the form of a 3D block model or cross-sections.

Figure out the long-term quarry extraction plan. A plan that is feasible, achievable, and meets all conflicting requirements in cement production.

Simulate and access the risk of supplying raw materials to the cement plant. Quarrier calculates different scenarios of raw materials production that the deposit can produce, depending on the quality and other constraints set up by users, including the use of additive materials. Simulation results can provide valuable information to the feasibility of the cement project.

Have a tool to mitigate and control the risk of not supply raw materials at production targets due to geological uncertainty.

However, the current model and framework within Quarrier do not consider the situation that multiple quarries such as a limestone quarry and a clay quarry feed raw material to a single or multiple cement plants. For future development, the proposed framework and model within Quarrier can be extended to deal with this situation.

Acknowledgement

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Wprowadzenie nowej aplikacji do symulacji i optymalizacji długoterminowego planowania produkcji w kamieniołomach wapienia

Długoterminowe planowanie produkcji w kamieniołomie wapienia ma zasadnicze znaczenie dla utrzymania dostaw do cementowni. W którym planiści kamieniołomów zazwyczaj starają się wykonywać skomplikowane obliczenia, które zapewniają stałe dostawy surowców do cementowni przy jednoczesnym zagwarantowaniu parametrów techniczno-eksploatacyjnych w górnictwie. Tradycyjnie obliczenia są wykonywane manualnie lub metodą prób, co skutkuje wysokimi kosztami dodatków i zwiększeniem zmienności produktu. Nowoczesne zarządzanie kamieniołomami opiera się na modelach blokowych i algorytmach matematycznych zintegrowanych z oprogramowaniem w celu optymalizacji długoterminowego planowania produkcji w kamieniołomie. Jednak metoda ta jest potencjalnie wrażliwa na niepewność geologiczną w modelowaniu bloków, co skutkuje odchyleniem w zakresie dostaw surowców do produkcji. Potrzeba inteligentnego wydobywania surowca jest zatem kluczowym i rosnącym problemem w przemyśle cementowym. W ramach tych badań wprowadzono nową aplikację do symulacji i optymalizacji o nazwie Quarrier, umożliwiającą planistom kamieniołomów sprostanie sprzecznym wymaganiom długoterminowego planowania produkcji kamieniołomu wapienia, jednocześnie prognozując i łagodząc skutki niepewności geologicznej na dostawy surowców do cementu. roślina. Korzyści płynące z tego oprogramowania są widoczne w kamieniołomie wapienia w Wietnamie.

Słowa kluczowe: *Quarrier, plan wydobycia, cement, optymalizacja, symulacja, niepewność geologiczna*