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The application of quantum computing to the optimal design of open-pit mines

1. Overview

The optimal design of open-pit mines is an ongoing optimization problem in the mining industry since the 1960's, where incremental improvements through new algorithms and/or better heuristics result in greater economic value, environmental value, and safety.

2. Detailed Objective

Read the 2 short embedded/linked referenced papers to develop a good understanding of the problem: the original problem statement and algorithm, *Lerchs-Grossman (L-G)*, and today's best-known heuristic, *Pseudoflow*. Then, start with a simple version of *L-G* modelled as a binary optimization problem, e.g., Figures 3-5 in *L-G* indicate the problem can be modeled as a graph problem with:

i. **dependencies**, e.g., remove everything above a certain block before removing the block itself
ii. **cost**, i.e., of extraction, and
iii. **value**, i.e., of the extracted ore.

A binary variable would determine which block to extract at what time. This will give an indication of the number of variables (qubits) to model something realistic. Then, constraints need to be added to guarantee that all physical and temporal bounds are satisfied.

IBM's Qiskit can be used in a straight-forward manner to start with very small test cases:

i. model the problem using Qiskit's high-level language, *docplex*,
ii. automatically translate it into an Ising Hamiltonian,
iii. use the Hamiltonian directly in quantum optimization heuristics (VQE, QAOA) to try to find optimal solutions.

See the following Jupyter notebook as an example, https://github.com/Qiskit/qiskit-iqx-tutorials/blob/master/qiskit/advanced/aqua/optimization/docplex.ipynb.
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3. Requirements

The stated objective is challenging, yet feasible, in terms of understanding the two algorithms—*L-G* and *Pseudoflow*—and an approach using quantum computing—Ising Hamiltonians—as a start for finding a quantum algorithm for a more optimal business solution.

At the same time, connecting theory & experiments to real-world practice is a requirement, and the team will also need to understand how a quantum computing solution would fit into the business processes and workflows of the realities of open-pit design today. IBM would need to connect the team to experts and data in this field.

4. Project Success Criteria

The delivery of a quantum algorithm for the design of open-pit mines based-on and measured-against past real-world open-pit mining designs and data. The algorithm doesn't necessarily have to outperform today's classical counterpart, since it's not known if one exists.

5. Points of Contact

Mario Motta will be the IBM technical lead. Joe Latone will be the business strategy lead.
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Optimum Design of Open-Pit Mines

Joint C.O.R.S. and O.R.S.A. Conference, Montreal, May 27-29, 1964

Transactions, C.I.M., Volume LXVIII, 1965, pp. 17-24

ABSTRACT

An open-pit mining operation can be viewed as a process by which the open surface of a mine is continuously deformed. The planning of a mining program involves the design of the final shape of this open surface. The approach developed in this paper is based on the following assumptions: 1. the type of material, its mine value and its extraction cost is given for each point; 2. restrictions on the geometry of the pit are specified (surface boundaries and maximum allowable wall slopes); 3. the objective is to maximize total profit — total mine value of material extracted minus total extraction cost.

Two numeric methods are proposed: A simple dynamic programming algorithm for the two-dimensional pit (or a single vertical section of a mine), and a more elaborate graph algorithm for the general three-dimensional pit.

Introduction

A SURFACE mining program is a complex operation that may extend over many years, and involve huge capital expenditures and risk. Before undertaking such an operation, it must be known what ore there is to be mined (types, grades, quantities and spatial distribution) and how much of the ore should be mined to make the operation profitable.

The reserves of ore and its spatial distribution are estimated by geological interpretation of the information obtained from drill cores. The object of pit design then is to determine the amount of ore to be mined.

Assuming that the concentration of ores and impurities is known at each point, the problem is to decide what the ultimate contour of the pit will be and in what stages this contour is to be reached. Let us note that if, with respect to the global objectives of a mining program, an optimum pit contour exists, and if the mining operation is to be optimized, then this contour must be known, if only to minimize the total cost of mining.

Open-Pit Model

Besides pit design, planning may bear on questions such as:

- — what market to select;
- — what upgrading plants to install;
- — what quantities to extract, as a function of time;
- — what mining methods to use;
- — what transportation facilities to provide.

There is an intimate relationship between all the above points, and it is meaningless to consider any one component of planning separately. A mathematical model taking into account all possible alternatives simultaneously would, however, be of formidable size and its solution would be beyond the means of present knowhow. The model proposed in this paper will serve to explore alternatives in pit design, given a real or a hypothetical economical environment (market situation, plant configuration, etc.). This environment is described by the mine value of all ores present and the extraction cost of ores and waste materials. The objective then is to design the contour of a pit so as to maximize the difference between the total mine value of ore extracted and the total extraction cost of ore and waste. The sole restrictions concern the geometry of the pit; the wall slopes of the pit must not exceed certain given angles that may vary with the depth of the pit or with the material.

Analytically, we can express the problem as follows: Let v, c and m be three density functions defined at each point of a three-dimensional space.

$v(x, y, z)$ = mine value of ore per unit volume
$c(x, y, z)$ = extraction cost per unit volume
$m(x, y, z) = v(x, y, z) - c(x, y, z)$ = profit per unit volume.

Let $\alpha(x, y, z)$ define an angle at each point and let S be the family of surfaces such that at no point does their slope, with respect to a fixed horizontal plane, exceed α.

Let V be the family of volumes corresponding to the family, S, of surfaces. The problem is to find, among all volumes, V, one that maximizes the integral

$$\int_V m(x, y, z)\, dx\, dy\, dz$$

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