Optimisation in the design of underground mine access

M Brazil, D Lee, J H Rubinstein, D A Thomas, J F Weng and N C Wormald

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Contact author:

J Hyam Rubinstein,
Department of Mathematics and Statistics,
The University of Melbourne,
VIC 3010,
Australia

Phone: 61 3 8344 7887
Fax: 61 3 8344 4599
Email: H.Rubinstein@ms.unimelb.edu.au

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M Brazil,
ARC Special Research Centre for Ultra-Broadband Information Networks (CUBIN)*,
Department of Electrical and Electronic Engineering,
The University of Melbourne,
Victoria 3010
Australia

D H Lee,
Department of Mathematics and Statistics,
TheUniversity of Melbourne,
Victoria 3010
Australia

J H Rubinstein,
Department of Mathematics and Statistics,
TheUniversity of Melbourne,
Victoria 3010
Australia

D A Thomas,
ARC Special Research Centre for Ultra-Broadband Information Networks (CUBIN)*,
Department of Electrical and Electronic Engineering,
The University of Melbourne,
Victoria 3010
Australia

J F Weng,
ARC Special Research Centre for Ultra-Broadband Information Networks (CUBIN)*,
Department of Electrical and Electronic Engineering,
The University of Melbourne,
Victoria 3010
Australia

N C Wormald,
Department of Combinatorics and Optimisation,
University of Waterloo,
Waterloo ON N2L 3G1,
Canada

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ABSTRACT

Efficient methods to model and optimise the design of open cut mines have been known for many years. The design of the infrastructure of underground mines has a similar potential for optimisation and strategic planning.

Our group has developed two pieces of software to tackle this problem - UNO (underground network optimiser) and DOT (decline optimisation tool) over the last 5 years. The idea is to connect up a system of declines, ramps, drives and possibly shafts, to minimize capital development and haulage costs over the lifetime of a mine. Constraints which can be handled by the software include: gradient bounds (typically 1:7), turning circle restrictions for navigability, and obstacle avoidance. The latter constraint keeps development at stand off distances from ore bodies and ensures that it avoids regions which involve high cost, such as faults, voids and other geological features.

The software is not limited to only interconnecting fixed points. It has the useful feature that a group of points can be specified such that the development is required to connect to one member of the group. So for example, if an existing ventilation rise must be accessed at some level, then a group of points along the rise can be selected. Similarly this gives the opportunity to use variable length crosscuts from a decline to an ore body. The latter gives important flexibility and can significantly reduce the development and haulage cost of a design.

Finally the goals for the next phase of development of this project will be discussed, including speeding up the algorithms and allowing for heterogeneous materials, such as aquifers and faults, as additional costs rather than obstacles.

INTRODUCTION

There are several different basic forms for the layout of an underground mine. An underground mine can be viewed as a collection of ramps and drives connecting various points of access at each required level of the ore bodies to a surface portal. From this viewpoint the mine can be modelled as a mathematical network in which the nodes correspond to the access points, the junctions and the surface portal and each link corresponds to the centre-line of a ramp or drive. A mine containing a shaft together with ramps and drives for access and haulage can be modelled in a similar way. Other operational elements such as ore passes fit readily into such a description. If existing mine workings are to be extended to new ore deposits, a similar network can be constructed, connecting into the given structure at a convenient breakout point (or points). In all cases a major challenge for the mine designer is to construct a lowest cost feasible solution incorporating all operational constraints.

Key navigability constraints for mining equipment and haulage trucks include a gradient bound, m, where m is usually between 1/9 and 1/7 for declines and ramps. Also a minimum turning circle for curved ramps needs to be specified. Typically it will be in the range of 15m to 30m, again depending on the equipment to be used in the mine.

In addition, the design should take into account `no-go' regions that must not be intersected by the ramps or drives. These would usually include a stand-off region around the ore body (to avoid sterilization of the ore body) and regions of severe faulting or other operational or geological anomalies.

Moreover, future access to prospective new ore-zones may be included in the design. As more information becomes available, for example through in-fill drilling, designs may need to be modified. Having efficient software tools makes such updates much simpler and faster than previous approaches.

The Network Research Group, based at The University of Melbourne, has been developing techniques to find solutions to these design problems using new mathematical algorithms and software. In this paper, we will summarise our current methods and outline future plans to deal with extra geological features which are often encountered and to make the software faster and more flexible.

UNO - UNDERGROUND NETWORK OPTIMISER

Our first project involved optimising mine costs by developing a mathematical network model of an underground mine layout where the links of the network correspond to the basic mine components such as ramps, drives, ore passes and shafts. Although a ramp or drive is generally curved, if it has constant gradient which is as steep as possible without violating the gradient bound then its length can be computed from the coordinates of its endpoints alone. This means that in the network model we can assume each link is a straight-line segment whose length is computed via a suitably defined metric, known as the *gradient metric*. If the link has gradient no greater than the specified maximum value m, then the standard Euclidean length L is used; however if the link is a straight segment with gradient greater than m, then the standard Euclidean length is replaced by the expression

$$L = z\sqrt{1 + \frac{1}{m^2}}$$

where z is the vertical displacement between the two ends of the link. It can be shown that any feasible path between such endpoints with constant gradient m will have length given by this expression.

The variable (that is, length-dependent) cost C associated with a ramp or drive of length L in metres, is given by a function of the form

$$C = (D + H_1 T + H_2 gT)L$$

where D, H_1 and H_2 are operational constants, g is the gradient of the ramp or drive, and T is the total tonnage of ore to be transported along this section of the mine over the life of the mine. We can view the first term DL as the development cost for this component,

the second term H_1TL as the haulage cost if we assumed the section of the mine was horizontal, and the final term H_2gTL as the haulage penalty associated with the gradient. In the case where the ramp or drive has maximum gradient m the cost function becomes

$$C = (D + H_1T + H_2Tm)z\sqrt{1+m^{-2}} \ ,$$

where z is the vertical displacement between the two endpoints.

A shaft with fixed surface portal (for simplicity), can be treated in the network model as a variable length vertical line segment with variable cost of the form

$$C_S = \left(D_S + H_S T\right)L$$

where the constant D_S is the per metre cost of the shaft of variable length L, H_S is an operational constant associated with the haulage costs and T is again the total tonnage to be hauled up the shaft over the life of the mine. We are also able to deal with cases where there is a choice of locations for the surface portal.

The only significant variable costs associated with ore passes are their development costs which can be assumed to be proportional to length.

Our mathematical algorithm proceeds to find the least cost connected network of such components, where the cost of the network is the sum of the costs associated with the links of the network, as described above. This is implemented in a software product called UNO - Underground Network Optimizer. Note that the network has to join up the given access points on the ore body to the surface portal. Alternatively, for an extension of an existing mine, the new development may join to one member of a set of possible breakout points in the existing decline system.

Mathematically, there are a number of key issues which need to be resolved to find an efficient algorithm to locate the least cost network. The *topology* of a network is the choice of segments of the network at the different junctions. In terms of the mathematical network, this specifies the pattern of connections in the network, or, equivalently, the

network's underlying graph structure. Classically, such networks are called *Steiner trees* (see Hwang, Richards and Winter (1992) for a good general introduction to this topic). In the network, all access points of the ore-zones, and the surface portal or breakout point, are called *terminals*, and all additional junctions are referred to as *Steiner points*. At Steiner points there are three incident segments. Links with apparent gradient more than m are realized, in graphical representations of the network, as bent links (zigzags) with each straight line section in the zigzag at maximum gradient m. In the actual mine a bent link will correspond to a curved, possibly helical, drive with constant gradient m. For more details, see Brazil *et al* (2001a).

A primary mathematical difficulty in constructing the optimal network is that the number of possible topologies grows extremely quickly with the number of terminals. So it is essential to have a very efficient method to find the least cost network for a given topology. We then use simulated annealing and genetic algorithm methods to systematically search through the huge number of possible networks.

To find the least cost network with a fixed topology on the links, the idea is to use a descent method, perturbing the locations of the Steiner points. This is not straightforward since the gradient metric places considerable restrictions on the ways in which Steiner points can move so that the length of the network is reduced. For example, if a link initially has gradient less than m, and after moving the Steiner points at its ends, the link has gradient more than m, then the cost function for the link changes. Making this problem tractable relies on a deep understanding of the geometric structure possible in a minimum Steiner Tree (Brazil *et al*, 2001a). Note that, for a large range of cost functions, the total cost of the network, with fixed topology, is a convex function of the positions of the Steiner vertices. See Brazil *et al* (in press).

The development of UNO was inspired by a case study provided by WMC Ltd based on Olympic Dam (see Brazil *et al*, 2001b). An example of an application of UNO to another recent case study is shown in Figure 1.

INSERT FIGURE 1 HERE

DOT - DECLINE OPTIMISATION TOOL

More recently, in work done based on case studies with Normandy and Newmont Australia Limited, we have developed a Decline Optimisation Tool, DOT, described in Brazil *et al* (2003). We give a quick summary of the key features of DOT.

The mathematical model consists of a surface portal or breakout point and a decline, which is modelled as a concatenation of straight and curved ramps, with variable length crosscuts attached at points which we again call Steiner vertices. We often assume that the crosscuts are perpendicular to the decline, although this condition can be varied. Moreover the crosscuts can access the orebody at a variable or fixed point on a given level. This extra flexibility can produce considerable savings in tightly constrained designs.

The cost functions associated with the different components of the network are very similar to those given previously. The important constraints are curvature (turning circle) and gradient constraints. The latter are exactly as before; the minimum turning circle (radius of the helical or circular segments) is typically in the range 15m to 30m, depending on the haulage equipment to be used in the mine.

Designing such a network so that it has optimal cost is an extremely difficult problem. In order to make the problem tractable, the algorithm focuses sequentially on each section between Steiner points where the initial and final directions of the path are determined in advance. Once a solution method has been developed for this modified problem, one can proceed with a dynamic programming methodology to solve the original problem, visiting the specified points and amalgamating the path entering a point and the one leaving it provided they have the same start and finish directions.

An abstract solution to the problem of finding minimal paths in three-dimensional space with given start and finish directions and a given minimal turning circle (but no gradient constraint) has been described in Sussman (1995). This solution, however, has the disadvantage of a continually varying gradient, which is an undesirable characteristic. It can be shown that if the additional constraint of an unchanging gradient is put on such a curve, then the shortest possibility is simply a segment of a circular helix. However if the gradient is both bounded and unchanging, then the shortest path consists of several helical and straight segments joined together smoothly.

The program DOT has several features which produce a good heuristic algorithm for finding low cost feasible designs. DOT is able to combine several helical segments together with some inclined straight segments or flat circular arcs, where the joins are smooth. By this we mean that at the junction between two curves, the incoming direction of the first matches the outgoing direction of the second. DOT then searches amongst such combinations to try to reduce costs.

DOT generates a three-dimensional image of the optimal decline's centerline and strings of co-ordinates which may be loaded into standard mine graphics systems.

OBSTACLES AND HIGH COST REGIONS

Obstacle avoidance is implemented by cutting off solutions which pass through barriers and recomputing using additional prescribed points on the decline where such intersections arise. Standard methods of dynamic programming then enable a sequence of efficient feasible solutions to be joined smoothly at such points and the shortening device in the previous section applied to check if any cost reduction is possible.

At present, highly faulted zones can only be treated as obstacles by our software. In the next phase of the project, to be conducted in conjunction with Newmont Australia Limited, our plan is to treat these regions as feasible regions but ones inducing extra

costs. Three different cases are highly fractured material, laminations and aquifers. In the first case, a law of cosines, similar to that for diffraction of light through materials of different density, gives a good method of treating the cost differential for extra reinforcement.

In the second case of laminations, the preferred direction for drives is perpendicular to the planes of faulting. So a cost function needs to be chosen which is direction sensitive. In the final case of aquifers, there is an initial cost to incorporate a pumping facility for each crossing. In all cases, these additional costs need to be incorporated into the software algorithms DOT and UNO.

SPEEDING UP DOT

Ultimately our plan is to incorporate some features of UNO in DOT, so that simple tree networks with multiple branches can be analysed. A major problem to be overcome in this project, is to speed up DOT since such a program would involve a large number of computations of low cost declines. To completely integrate UNO and DOT may be impractical, due to the huge number of steps required in such a program. However using UNO to determine the overall structure of a low cost network and then using DOT to design segments of the network, should work very well for even the most complex design problems.

Currently we have been studying how to construct paths which are several segments of helices, flat circular arcs or inclined straight lines, smoothly joined together. Our aim is to completely describe algorithms to find all least cost paths of this type, joining fixed initial and final terminals, with the initial and final directions also fixed. Then this can be inserted as a subroutine in DOT.

Note that the least cost solutions for the corresponding problem in the plane (related to vehicle navigation) have been determined in a classical paper of Dubins (1957).

AN APPLICATION OF DOT

This section illustrates the application of DOT to a small design example. The data is based on a recent Newmont investigation into an extension of a gold mine. It describes a mine extension on 9 levels with vertical separations between different levels varying between 10 and 14metres.

Two snapshots of the DOT generated decline centerline are shown in Figures 2 and 3. These figures show, respectively, a side view and plan view for the same design. The dots in the figures indicate the access points, at which the decline must meet the crosscuts. At two of the levels there are alternative access points nominated.

INSERT FIGURE 2 HERE

INSERT FIGURE 3 HERE

An important capability of DOT is the facility to perform 'what-if' testing of alternative designs. While not part of the original Newmont exercise, the following table indicates the cost variation of this design as the turning radius is varied from the original 25metres to span the range 20m to 30m over 2.5m intervals. These values were simply generated by a single parameter change at run time. The cost referred to is the sum of development plus haulage through this segment of the decline

Min. turning radius	20	22.5	25	27.5	30
Cost (A$million)	3.32	3.75	3.93	4.35	4.60

The table illustrates the design is fairly sensitive to the nominated minimum turning radius and the changes are not linear – there may well be mine regimes where there is little change in cost for a larger radius and on the other hand very significant changes near certain critical values. DOT provides a means of testing designs for this sensitivity. Figure 4 below illustrates (in plan view) the design corresponding to a 30m turning radius; it is qualitatively similar to the 25m radius design in Figure 3 but significantly more expensive.

INSERT FIGURE 4 HERE

The versatility of DOT has been further demonstrated by Carter, Lee and Baarsma (2004), who apply the program to design and cost the infrastructure to serve a nominated tabular ore-body mined by the Open Stope method.

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Sussman, H J, 1995. Shortest 3-dimensional paths with prescribed curvature bound, in *Proc 34th Conf on Decision and Control*, pp 3306-3312. (IEEE: New Orleans, L A).
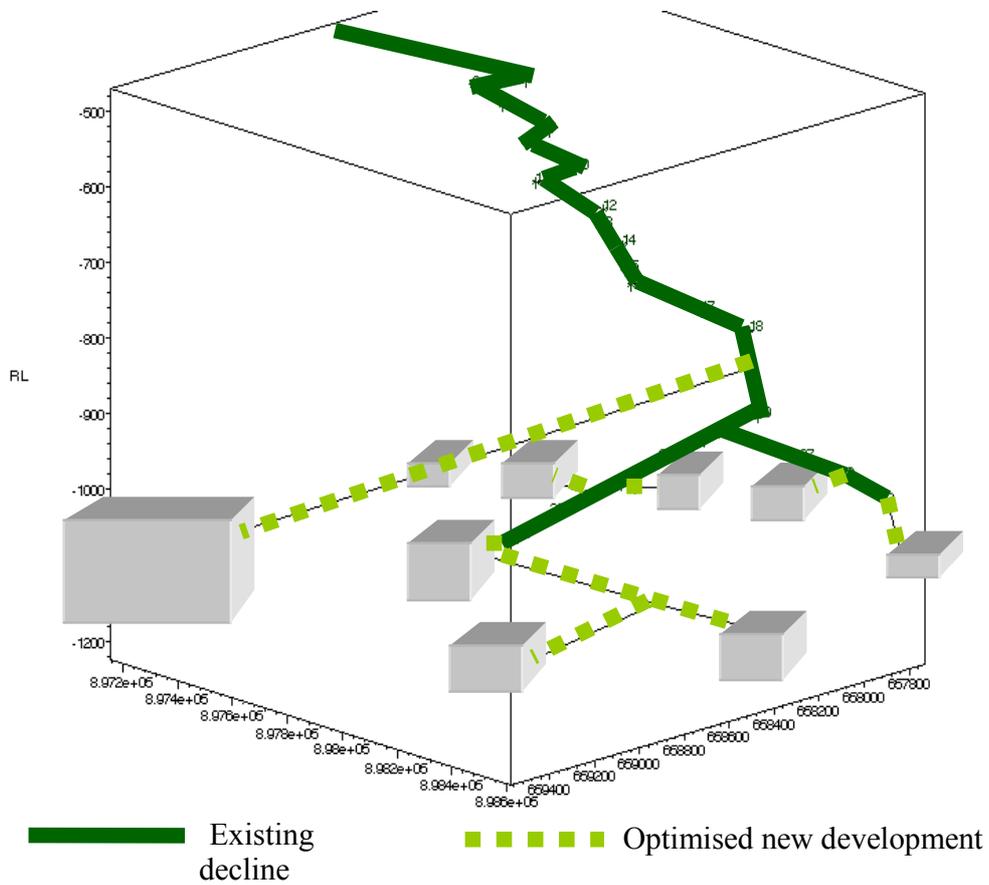
List of Headings

FIGURES

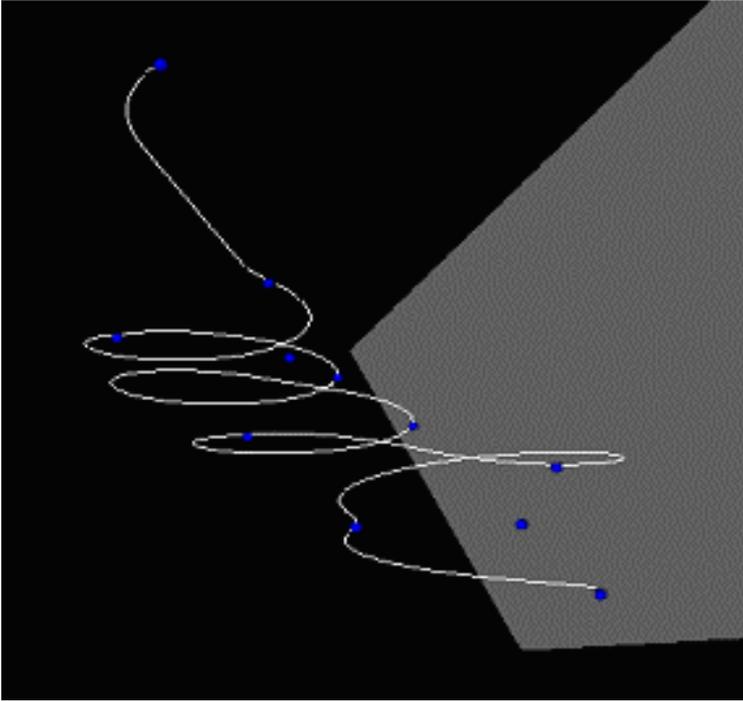Figure 1: This figure, from a live case study, illustrates the capacity of UNO to design an optimal network extending an existing mine and accessing new orebodies.
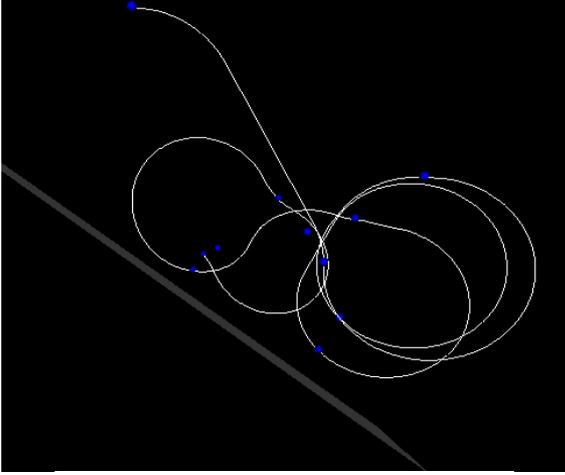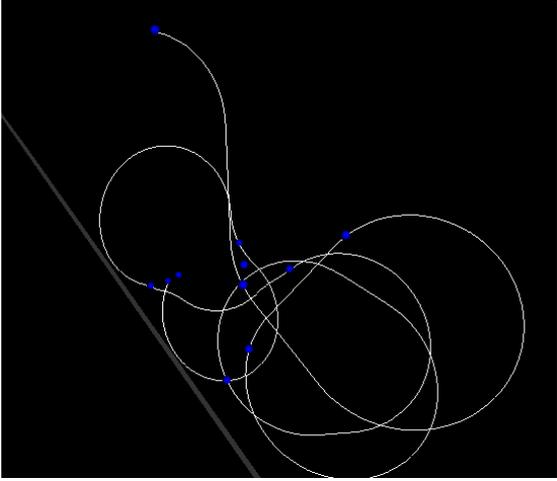
Figure 2

Figure 3

Figure 4