Express Road Routing: The Application of an Optimal Haul Road Generator to Real World Data

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Abstract
The traditional failure of Lerchs-Grossmann based open pit optimization methods (e.g. Whittle 3D/4D/4X; MineMap LG) has been that the final result represents an abstract shell rather than a true design. While it is capable of delivering a pit shell based on a number of angular wall slope constraints, the addition of access and minimum mining width constraints make the true optimality of the final design questionable.

In 1997 Optimum Planit Pty Ltd released Express, an optimal haul road generator aimed at minimizing the loss of profit due to adding access roads to a previously optimal pit shell. This system is capable of juggling economic, geotechnical, and equipment constraints to quickly and interactively generate a system of roads from an ultimate open pit. The speed with which solutions can be generated allows the planner to examine a wealth of different scenarios and routes, leading to a more considered overall solution to the haul road planning problem.

This paper traces the application of the system on a real gold deposit. By allowing the designer to quickly find a transport system for the pit shell, a better design is reached in the time it would ordinarily take a planner to consider the location of their first few bench ascents. This then allows the engineer to instead focus on the more pressing demands of preparing their schedules.

Introduction
The ever-present need for increased efficiency in modern mining enterprises has led to a large amount of reliance on modelling and optimal planning in the mineral industry. Use of advanced optimization techniques such as graph-theoretic volume optimizers (e.g. Whittle 4X), are now often a pre-requisite for obtaining capital funding. However, while the problem of establishing an ultimate pit shell is now largely considered “solved”, methods for converting this abstract object into a true pit have been largely neglected.

A given pit shell obeys the required geotechnical and economic constraints to prevent it (in theory) from failing, but the addition of access roads and minimum working width constraints can lead to a large amount of degradation of the pit value - placing serious doubts on claims to the “optimality” of the resultant model. While the addition of minimum mining width generators to the Whittle family of optimizers has helped to alleviate the latter problem, the question of haul road routing has been largely ignored. Typical haul road placement methods consist of an iterative process of manual placement and re-optimization that can quickly confuse even the most experienced of engineers. An automated method of providing some form of optimal routing could free up the engineer from this time consuming task, allowing
more time to be spent on other aspects of the mine design process.

In response to this perceived need, Optimum Plant Pty Ltd sponsored a research program at Curtin University aiming to provide just such a system. Four years later, they have released Express — an automated haul road planning system capable of providing optimal haul road routes for a given pit shell. This paper provides a brief overview of the system and its methods, before presenting an example of it at work.

The Optimal Haul Road Routing Problem

As discussed above, the transport system is essential to the profitability of a real mine. The degradation of a typical pit shell can exceed ten percent of the value of the original optimal shell. The addition of haul roads by hand is a long and arduous process with a vast number of constraints. The choice of haulage equipment and the cost of building the road have to be juggled against the expected mine lifetime and long term pit schedule. Not surprisingly it is a task left to experienced engineers who evaluate a number of options in finding a solution.

Express is capable of handling a series of economic, geotechnical, equipment, and safety constraints into account when planning a transport system. It provides a series of solutions to the engineer, and feedback as to the relative merit of a variety of options. It is fully integrated with industry-standard optimization packages, and provides seamless data to the majority of software packages. By providing an overall guide to effective haul road placement, it forms a valuable aid to establishing the true worth (and often feasibility) of a given pit operation.

Existing Methods

![Figure 1: Varying the Wall Slope to Incorporate a Single Width of Road](image)

Manual planning methods make use of the wall slope constraints in allowing for the transport route. Once the ultimate pit shell is available the designer allows for a general route from the pit floor(s) to the surface. The width of the road(s) is then incorporated into the average wall slopes for those walls containing it, as illustrated in Figure 1. The pit is then re-optimized according to the new wall slopes that are then placed by hand by the designer. However, the net effect of these slope variations is not always cancelled out along the length of the road. If we consider that the building of the road could lead to the removal of some extra ore, then the locations of these blocks along the route would seriously affect the desired road placement. Similarly complex road systems involving varying road widths, multiple roads, switchbacks, and junctions would lead to major inaccuracies with this method.

The two other attempts at providing automated route planning tools have not been commercially implemented. The first was put forward by Dowd and Onur (1992) and consists of spiralling a path up the sides of the pit from the pit floor in a bench-by-bench fashion. By moving to each different point on the pit floor, the spiral direction is swapped from clockwise to anti-clockwise and the cost of the route recorded. While this could provide some useful information to the designer, it is too simplistic to provide any major benefits.
The second attempt is provided by Yun and Lu (1992). It takes a much more comprehensive approach, breaking each road up into "segments" consisting of single block height ascents. Each segment is then assigned a cost, given by equation 1, which can be simplified to "segment cost = building cost + bench extraction cost + rock removal cost", and a road is assigned a cost equal to the sum of the costs of the segments from which it formed. The set of all possible segments is then combined into a graph structure, which is then examined to find their solution road. However, the way in which this route is built up is in no way guaranteed to find an optimal (or even near optimal) solution (Gill, Robey, and Caelli, 1997).

Equation 1:

\[ S_n = d_n l_n + Q_n l_{ns} C_1 + d_n C_2 \sum_{j=1}^{N} Q_j \]

Where:

- \( S_n \): the cost of segment \( n \)
- \( d_n \): the length of the segment
- \( l \): the set-up cost of building the path per unit length
- \( Q_n \): the amount of ore and rock to be removed in bench \( n \)
- \( l_{ns} \): the distance between the segment start point and the center of mass for this bench
- \( C_1 \): the horizontal hauling cost
- \( C_2 \): the haulage cost at the defined grade
- \( N \): the number of benches in the model

Road Planning with Express
In contrast to the above methods, Express is capable of finding the true optimal route through a pit shell. There are a large number of these constraints on the haul road(s) - including equipment-based constraints, safety constraints, geometric constraints, and economic issues. These are examined in more detail below.

Economically, Express can be crucial to modern pit designs. Low mineral prices have made many operations marginal. Express is capable of quickly assessing how deep a haul road can go and still provide useful profits by quickly evaluating all possible valid routes through the pit as to the cost of their design in terms of degradation of the original pit plan. It also provides intuitive interfaces to import models directly from Whittle 3D/4D/4X and MineMap optimization packages, to ensure that it always deals with the same economic block values as the original pit shell design system. In addition, it is capable of exporting its final results as Whittle results files, MineMap models and strings, Surpac strings, or straight ASCII text. This then provides an easy guide to engineers when they are preparing their final designs.

Express is capable of rigorously optimizing a given route from a floor region to a surface region. It is capable of converging to the optimal solution for a given ramp while honouring a range of constraints including:

- Road grade and width by RL.
- Road Curvature, and switchback curvature.
- Limited floor access points
- Limited pit daylight points
- Avoidance of buildings, works, unstable areas, etc.
- Saddles and multiple ramps

It also provides mechanisms for planning complex transport systems made up of multiple ramps spanning a range of floors, saddles, and exit points.

How Does it Work?
A full technical analysis of the internal workings of Express is beyond the scope of this article (and is proprietary information), but a simple overview will be attempted. A more complete analysis of road planning as a form of search can be found in the paper by Gill, Robey, and Caelli (1997).
Figure 2: A Ramp Can Be Modelled by a Series of Straight Segments

A ramp can be thought of as being made up of a series of single block height ascents, or road segments, which are fitted together to span the pit model (see Figure 2). If we view a single road segment in plan view, we can see that it can be further broken down as a set of blocks in a “step” shape. By using a series of these “steps” we can then model the ramp as a series of blocks in the model. The safe wall slopes around the segment can then be modelled as an extraction cone (must consist of air blocks above the segment), and a refill cone (must consist of solid blocks below the segment). A two-dimensional example of this is shown in Figure 3. The problem of placing the ramp then becomes one of modifying the original shell to place a series of safe road segments (“steps”) from the desired exit point to the floor of the pit.

Figure 3: A Two-dimensional Model of a Single Road Segment

We have now established that each segment now consists of a series of changes to the original model that can then be assigned a cost (equal to the effects of these changes). A ramp consists of a series of consecutive segments with a cost equal to the effect of the union of the individual changes. The optimization process can be defined as a search through the space of all possible ramps. This can be expressed more simply as follows:

Suppose that we wish to start the road at a certain point in the model. Given that we have to ascend from the floor at a certain grade we then have a finite number of possible road segments available to us as the first segment of our road. This set of segments is shown in Figure 4(a). In contrast, once we have ascended a number of benches we have a more limited set of options available to us, as we are now limited by the amount of curvature we can place in the road. The route taken to reach this point now restricts the range of exit points available to us. This range is illustrated in Figure 4(b). In real terms, these ranges are further restricted in that the ramp is not able to cross or fill over itself, and there can be restrictions due to geotechnically unstable or economically undesirable regions in the model.
The space of possible roads consists of taking our starting set and expanding each of the initial segments through all possibilities until we reach the desired exit points. This space suffers from combinatorial expansion (the majority of tested sets consist of 20-30 segments at each case similar to Figure 4(b) and is further complicated by massive interdependence between the segments. For example, one route to a given point may involve changes that preclude a given option from the point – while other routes may not. These factors make generation of the entire solution space non-feasible. We therefore have to rely on intelligent techniques to traverse the solution space in search of the optimal solution. Artificial intelligence techniques (Rich and Knight, 1991) have long been available to rigorously perform this task on traditional graphs, but the interdependence of the data in this case makes these methods unusable. Dynamic graph search (Gill, 1997) provides methods to allow the use of traditional search algorithms in massively interdependent and changing data sets. The use of these techniques allows us to reliably converge on the optimal solution in a realistic time frame. Furthermore the rigorous nature of the algorithms in use means that there are no random elements to become stuck on diverse locally optimal solutions in the search process.

**Search Algorithms in a Nutshell**

Search algorithms can be loosely classified according to two extrema - breadth first and depth first algorithms. If we imagine our search as a series of possible road segments starting from our initial starting point, it takes the shape of a tree such as that shown (for two benches) in Figure 5. A breadth first solution would traverse this structure by expanding each branch one segment at a time, never stepping up a bench until all of the possible segments at that depth have been examined. In contrast a depth first approach would take the first branch and step up a bench at a time until it reached the surface. It would then select a new branch and repeat the process. In both cases, the search would not terminate until all of the branches in the tree had been examined.
Express makes use of a range of different dynamic search algorithms, alternating between depth-based and breadth-based algorithms according to the current range of solutions presented. These methods also make use of cost information to quickly prune down the solution space while still guaranteeing convergence on the global optimum. The use of depth-based algorithms enables the package to present a range of solutions while optimizing, while the breadth-based methods enable it to quickly identify beneficial routes at crucial points, such as at the base of the pit.

**Constraints**

The previous pit had experienced a wall failure on the southern end of the east wall (highlighted bottom right). This made this area of the pit out of bounds to the ramp. In addition, haulage constraints required that the ramp exit from the northern end of the pit, preferably close to the existing ramp exit. To allow for these constraints, the bounds and surface were used as shown in Figure 7.

**Case Study Example**

The following is a simple example of Express at work. It requires the optimization of a real world data set, using a single floor and exit point region. All of the following figures consist of direct screen dumps from the running package.

The initial surface topography (shown in Figure 6) shows that we are dealing with an optimized shell cut into an existing pit. The previous haul road is highlighted (top right) in the north-east corner of the pit. A manual design had previously been prepared for the new shell and costed at approximately $2,000,000, to give a pit value of approximately $17,250,000. The model was directly imported from the Whittle 4D results file, given the required pit number.
Single Floor Planning

The ramp was required to have a width of 22m from the surface to 360RL, then narrowing to 18m from this point to the floor. The ramp grade was set to a ratio of 1:9 throughout. Optimizing on these parameters led to the solution presented in Figure 7. This pit has a reported final value of $18,337,000 (the road therefore cost $1,260,000 to place), however there are a few problems in accessing the rest of the pit. The regions highlighted in Figure 7 would be very hard to reach in this shell. It was therefore decided to repeat the optimization with these regions explicitly flagged as floors.

![Previous Ramp – will require widening and a new switchback](a)
![These regions have access problems](b)

Figure 7: (a) Surface (North East region) and bounds region (shaded white) used for run

(b) The single optimal solution has access problems to higher floor regions. The new switchback is located higher on the old ramp, but is much further from the unstable region

Multi-Floor Planning

The floor regions used for the multi-floor planning are shown in Figure 8 (a). The road constraints used were the same as for the single ramp case, above. The ramps for the northern floors fitted nicely, providing the overall solution shown in Figure 8 (b), but the southern region required a “stage one” ramp to the saddle with the deeper floor to the north. The overall solution value was $18,753,000 – a saving of some $500,000 over the single ramp solution, providing more access throughout the pit. This was due to the ability to relax the grade at the floor regions, giving a better overall fit to the pit walls. In an attempt to find the worth of the “stage one” area to the south of the pit, it was refilled to the existing topography to give a pit value of approximately $15,000,000. This made the addition of the stage one pit an obvious inclusion, especially if the final design factored it in as an in-pit waste dump.
The final design represented a drop in value of $1,153,000 over the shell after it was modified to place the floors. It should be noted however, that this cost does not include the value of the possible goodbye cuts which were conservatively estimated at around $500,000. The manual design (which cannot be shown here) was costed at approximately $2,000,000 including goodbye cuts. At this time no design has been prepared from the Express results, but the majority of cases have shown a decrease in the final road cost due to the use of relaxed grades, curved road segments, and the fitting of switch-backs into safety berms.

![Figure 8: The floor regions (a) and the ramp system linking them to the surface (b). The final solution had a value of $18,355,000 representing a net cost of $1,153,000 over the original pit using these floors](image)

**Conclusions**

*Express* is the only automated haul road design system currently available that uses mathematically proven rigorous optimizing techniques to home in on the optimal placement of haulage ramps. Based on new Dynamic Graph Search techniques, it converges to the optimal path from a given floor region to a given surface region, whilst balancing operating constraints including road widths, grades, curvatures, unstable areas, and switchback placement. Although *Express* has only been available for some 9 months at the time of writing, it is already in use on approximately half a dozen Australian mine sites, and has used data from more than fifteen for testing and evaluation. It is yet to report an increase in cost over previous manual designs.
References


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