Access Optimisation Tools in Underground Mine Design

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ABSTRACT

Optimisation tools which determine the best layout for access and haulage in an underground mine address an important and difficult mine design problem. The complexity of the problem can be compared to the task of optimising the final pit design in an open pit, together with the pit haul roads required. The strategic design of an underground mine layout must address the location of haulage shafts, decline access, ventilation infrastructure, level development within the stopes, and stope access. By calculating optimal layouts corresponding to a range of cut-off grades, the economic viability of the various mining areas can be assessed, and the results may be a significant factor in maximising the net present value of the mine.

At the University of Melbourne, two software tools have been developed to address this problem: the Planar Underground Network Optimiser (PUNO) and the Decline Optimisation Tool (DOT). PUNO minimises the total production costs associated with the level layout within an orebody, using the theory of weighted Steiner networks. DOT optimises the haulage decline (or declines) under a reasonably comprehensive set of constraints, including turning circle, gradient and the avoidance of "no-go" regions. Both PUNO and DOT minimise total cost of development and haulage. This paper discusses the use of such tools as part of the mine planning process, and the methods underlying them. The tools have been applied in a number of industry case-studies. The long-term aim is to integrate the access design with other design tasks, such as stope optimisation, mine scheduling and strategic options evaluation.

INTRODUCTION

When developing a new mine, or an extension to an existing mine, the overarching aim is to maximise the value of the mine. A strategic evaluation of the choice of cutoff grades and mining methods must be undertaken and to help make an informed decision all the other aspects of mine planning must be brought to bear. In optimal planning of underground mines, there is a need for multiple scenarios to be evaluated in an efficient way and it is imperative to have a good procedure for this.

In this research project, we focus on optimisation in hard rock mines - gold, silver, lead, zinc, copper or polymetallic deposits. The planning of such underground mines can be viewed as a process that involves a number of fundamental decision and design tasks. Once exploratory drilling has been done to establish the initial block model, the key decisions are to determine the mining method and a cut-off grade or a series of cut-off grades (the *cut-off grade* for a region is the level of mineralisation that determines whether that region will be viewed as ore or waste). At a strategic level the most important design tasks include: designing the stopes (ie, the specific regions to be mined), designing the access to the ore bodies, and determining a schedule for extracting the ore. Traditionally, only a small number of feasible designs are evaluated; usually these underground mine designs are generated by hand, using the mine planners' expertise and experience. The complexity of each of the design steps makes it difficult to apply reliable optimisation techniques to any of the design tasks. Furthermore, decomposing the problem into a number of design tasks would not necessarily result in a global optimum, even if each of the individual tasks could be optimised. True optimisation involves considering the system as a whole.

It is instructive to compare the current underground mine planning process with the task of designing the final pit and pit haul roads for an open-cut mine. Throughout the mining industry, optimisation is recognised as an absolutely essential part of open-cut mine design. For open-cut mines there are a number of widely used optimisation software systems, mostly based on the Lerchs-Grossmann algorithm (Lerchs and Grossmann, 1965) and its improvements. For a recent survey on this see Caccetta (2007). No such software exists for underground mine planning, however, due to the different nature of the underground mine planning problem. In an open-cut mine, once the pit has been determined, everything within the pit shell is removed, and is either sent to the mill or discarded as waste. In an underground mine, the selection of ore versus waste must be made earlier in the planning stages, and is closely tied to the selection of cut-off grades and mining methods. Optimisation is also hampered, in the underground setting, by the enormous number of constraints. These range from environmental constraints relating to the geology of the ground and its stress fields, to technological constraints associated with the choice of mining methods and the type of transportation for taking ore from underground to the mill, to more general financial constraints such as current and forecast metal prices and production costs.

Within the above framework, there are three key optimisation tasks to be considered: stope optimisation, access optimisation, and scheduling. In this paper we focus on access optimisation, and our progress in this area which has lead to the development of two access optimisation tools, DOT and PUNO. We describe these tools in detail, including some of the practical features that have been recently added as part of a more general mine planning optimisation project (known as PRIMO). We also describe a current case study, Prominent Hill, where our tools are being applied and evaluated.

THE ACCESS OPTIMISATION PROBLEM

In underground mines, ore is reached and transported to the surface through a network of interconnected declines and shafts that provide access to designated ore bodies and a means of taking ore from these zones to the mill (usually via trucks, trains or road-trains). *Declines* are underground tunnels for accessing the ore bodies, navigable by haulage and access vehicles. A *shaft* is a primary vertical or near-vertical opening used for hoisting of personnel or materials, connecting the surface with underground workings. In addition the network may contain *ore passes*, which are near-vertical passages down which ore is dropped to a level where it is loaded onto trucks and then hauled to the surface.

At its most fundamental level, the *access optimisation problem* involves designing this network of declines so as to optimise an associated cost or value function. The network is composed of a system of ramps and cross-cuts (horizontal drives) that connects the access points (points which must be accessed for drilling and blasting operations) and draw points (from which the ore is drawn) to the surface portal or breakout from existing mine infrastructure. The problem assumes that some degree of stope optimisation has already taken place. Hence, it is assumed that the locations and geometries of the stopes are given and that the stoping data has been used to determine groups of choices of access and draw points at each of the levels and the tonnages of ore to be transported to the surface from each of the draw points. Like the draw points, the surface portal can also be assumed to be predetermined, or strongly constrained, to a discrete set of possibilities.

There are a number of important constraints that the network must satisfy. First, the decline must be navigable by trucks and mining equipment. This constrains the gradient and curvature of the decline. In addition, the decline must stand off from the orebody by some specified minimum distance to avoid stress fields and possible sterilisation of the ore and to allow a minimum working length in the cross-cuts. The aim is to minimise the cost of the decline subject to these constraints, where the cost is a combination of both development and haulage costs.

A secondary task within the access optimisation problem is to design the layout of the infrastructure within the stoping regions on each level of the mine. This infrastructure determines how each individual stope is to be accessed by bogging and blasting equipment, and how the ore is carried to the appropriate cross-cut.

Current industry practice on both of these design tasks involves no rigorous optimisation. The usual industry approach is to rely on the experience of mining engineers to find “good” feasible design solutions. Mining engineers are assisted in this task by the use of computer-aided 3-dimensional visualisation software for underground mine design. These software packages, however, do not incorporate any systematic optimisation capability for underground layout design. Such a capability is important not only for producing better mining layout designs, but also for enabling good decision-making by mine management in underground mine planning. Deciding whether a proposed mining project is economically viable or how to maximise the value of the mine depends on being able to accurately model and optimise costs associated with competing designs.

As described above, the access optimisation problem is divided into two sub-problems: the decline optimisation problem and the level layout problem. The two software tools that we have developed to address these sub-problems are described in detail in the following two sections.

DECLINE OPTIMISATION (DOT)

Our approach to the decline optimisation problem has been to model the decline as a mathematical network that captures the operational constraints and costs of a real mine, and then solve the associated network optimisation problem. In Brazil *et al* (2003), the first version of the Decline Optimisation Tool, DOT, was described. The heuristic methods of this early version have been replaced and substantially improved in the current version of the tool by a method based on an understanding of exact solutions to a constrained 3-dimensional path optimisation problem, which then are employed within a dynamic programming framework. The underlying method is described in this section, after we describe the mathematical model.

The decline is modeled as a mathematical network in which the nodes of the network correspond to the access and draw points at each level of the orebody and the surface portal (or breakout point from existing infrastructure) of the mine. The links in the network model represent the centerlines of sections of ramps and drives. The absolute value of the gradient of each ramp is constrained to be within a maximum working limit for trucks, typically in the range 1/9 to 1/7. Hence, the decline network is gradient-constrained, with a given maximum value for the slope. In addition there is a minimum turning radius for curved ramps which is typically in the range 15m to 40m.

Access to the orebody from the decline is via cross-cuts. These connect the decline to the given access or draw points which lie on a sequence of levels. Each cross-cut should meet the decline at an angle of approximately 90 degrees for geomechanical stability. At each access level a set of candidate nodes, representing a discrete choice of junctions at which the cross-cut can meet the decline, is specified. Each of these nodes has an associated fixed cost that is proportional to the length of cross-cut and is dependent on the cost of development of the level layout, and haulage costs through the level, which in turn are dependent on the tonnages at that level. These fixed costs associated with each node are determined by optimising the level layout design, which can be done using PUNO, as described in the next. The decline is required to pass through one node from each group. This provision of choice for the node locations provides design flexibility and optimisation opportunities.

The decline can be modeled as a network with the system of ramps having a path topology if we ignore ventilation infrastructure and alternative means of egress. The theory of paths in 3-dimensional space that are optimal with respect to gradient and curvature constraints is described in Brazil *et al* (2007) and Brazil *et al* (2008), where we present a dynamic programming algorithm for designing underground mine declines so as to minimise the associated life-of-mine costs, based on a mathematical analysis of minimum length curvature-constrained paths. Essentially, the method involves designing links that can be shown to be minimum in cost for the positions and directions at their endpoints, using an extension of the geometrical theory of Dubins (1957), and building the entire the decline, link by link from the bottom up, using dynamic programming. This exact approach substantially improves on our previous heuristic methods, described in Brazil *et al* (2003), in terms of both speed and accuracy. The efficiency of the current version of DOT means alternative decline designs can be generated and displayed within a few seconds, which allows the mining engineer to quickly explore and consider multiple alternative scenarios.

A number of additional features have been added to DOT as a result of our work with the mining industry. It is desirable to reduce the occurrence of adjacent curves on the decline with opposite senses (i.e. left-turning versus right-turning). Such features are usually avoided by mining engineers, as far as possible, because of the physical problem of reversing the direction of camber of the road surface at the position of change in turning direction, as well as the difficulty it causes for the truck drivers. We have modified the algorithm to take account of this “opposing arcs” constraint, by ensuring there is a straight section of length at least 10 metres (or some other length nominated by the user) between such curves. It is often also important, for reasons of ventilation and safety, to minimise the percentage of curved sections within the decline. DOT provides the capacity for doing this by allowing the user an option of adding a cost penalty to curved sections of the decline, which means that design with longer straight sections get favoured in the dynamic programming.

We have also introduced a barrier avoidance capability into the optimisation problem solved by DOT. There are a number of types of region underground that the decline must avoid. The decline must avoid the ore bodies and standoff regions around them where the geological rock stresses caused by extraction of the ore could compromise the integrity of the decline. In addition there may be underground faults, aquifers and areas that contain existing workings or where future workings may be planned that must be avoided. The introduction of barriers significantly increases the complexity of the optimisation problem. We have developed a heuristic algorithm, described in Brazil and Grossman (2008), which gives near-optimal solutions in the presence of barriers and has been shown to work well in practice.

DOT also has the capability of optimising mine layouts where there are a number of interconnected navigable declines in a tree structure. For example, suppose we have a main decline and want to breakout from this decline to a subsidiary decline. It is a requirement that the subsidiary decline meet the main decline at an angle of approximately 90 degrees for geomechanical stability. The problem is to optimally determine the best position for the breakout point or junction of the two declines. We have solved this constrained optimisation problem by considering the three access points adjacent to the junction as having given, fixed positions and using the method of simulated annealing to find the best position for the junction. We have been able to extend this technique to the situation where we have a number of adjacent junctions. DOT calculates optimal or near-optimal locations for the junctions using the method of simulated annealing in combination with dynamic programming.

In future work we plan to improve the barrier avoidance algorithms within the software, and to add the capability for DOT to handle inhomogeneous ground. For example there may be bad ground regions in parts of the underground environment which cannot be avoided by the access network but where the cost of developing infrastructure is significantly higher due to extra structural support needed for the tunnels. Another problem currently under consideration is that of ventilation. An important part of the planning process is to decide where to put the ventilation rises. As these need to link into the declines, there is an obvious interaction between the two and to achieve an optimal design, the two should be designed together. Currently, given the position for the ventilation rises, we can ensure that the decline is situated so that it connects with the rises, but optimising both design problems together could give significant savings.

PLANAR UNDERGROUND NETWORK OPTIMISATION (PUNO)

The objective of the level layout problem is to design a layout to access and mine the stopes on a level at a minimum total cost. We have developed a software tool, PUNO, which estimates the cost of access and haulage relating to a set of stopes to be drawn to a given cross-cut. It does this by finding schematic representations of the possible layouts, and associating a cost as best as possible to the representation. The representation comes from joining the central points of the stopes by a least cost network. This representation is well optimised according to a cost function involving haulage and access construction costs.

The optimisation method here uses the theory of weighted gradient-constrained Steiner trees. A Steiner tree is a network that optimally interconnects a set of given nodes (with given locations), but may contain extra nodes (not in the original set). A general optimisation tool, UNO, for constructing such networks for underground mines, without constraining radius of curvature, was described in Brazil *et al* (2000). It uses an understanding of the geometry of optimal solutions to rapidly construct an optimal solution for any given topology, and a heuristic framework to sort through the possible topologies. PUNO has been formed by taking the parts of the UNO algorithm that were relevant to the case where all access points have roughly the same *z*-coordinate (the planar case). Modifications to the algorithm have made PUNO considerably faster than UNO for planar case, and allow it to accurately model level layout costs.

The true cost of a design that schematically has the same network as an optimised PUNO solution is a little different to that computed by PUNO due to the fact that the costs associated with parts of the network vary depending on whether those parts are in ore or in waste. PUNO has been designed to attempt to take this difference into account when evaluating the total cost associated with a given layout. The aim is to use a representation that can be efficiently computed and yet gives a fairly realistic cost comparison of different layouts for whatever purposes are required.

The schematic representation itself is not intended as a final level layout design, but can be used as a template for one. These layouts are particularly useful for cut and fill mining methods. In this case, up to four levels are associated together and the sum total cost is evaluated, in order to compute the total cost associated with each cross-cut, as required by DOT.

A CASE STUDY – PROMINENT HILL

Prominent Hill is a copper-gold deposit in South Australia, and is currently under development by OZ Minerals. Current ore production is from an open pit, but ongoing drilling below the pit has identified further resources that are the subject of a feasibility study for underground mining. The aim of the case study was to demonstrate how to apply the optimisation tools (in particular, DOT), and their strategic role in choosing and constructing an efficient mine layout.

Preliminary work identified two zones below the pit that appear amenable to sublevel open stoping (SLOS), as shown in Figs. 1 and 2, termed the eastern and western SLOS zones. Two portals are planned for underground access; one from the pit and one from a boxcut located about 1.3 km west of the pit. According to current plans, most ore will be trucked to surface via the western decline and a remote boxcut to the west of the final pit limits. The pit and underground operations will be mined concurrently, so this remote boxcut access will minimize interaction between the two operations.

We were provided with the locations and tonnages of the stoping blocks based on a 30 metre sublevel interval and a 40 metre subinterval level. Currently we only have access to stoping data at a single cut-off grade, but eventually data will be provided at a range of different cut-offs, which will allow us to determine optimal access costs over a wide range of strategic options. For the 30 metre case the production levels were to occur every 90 metres, for the 40 metre case they were to occur every 80 metres. The stope shapes were used to construct footwall drives (horizontal drives along strike for access and ventilation) at each sublevel at a standoff distance of 22.5 metres. A minimum stand-off distance of 50 metres was required from the stope footwall to decline.

For the access evaluation, it was decided to consider three possibilities for the topology of the decline: a single decline servicing both ore bodies, a twin decline where each half d services an orebody, and a “split decline” which starts off as a single decline and at some point splits into a twin decline. A group of three access/draw points was chosen on each footwall drive, one at each end and one in the middle, to give DOT a choice for optimization. Barriers were built at a 50 m stand-off from the ore zone which the decline had to avoid. These three topologies were explored for the 30 metre sublevel case, and a single decline design was also generated for the 40 metre sublevel case.

One of the particular challenges arising from this case study lies in the nature of the cross-cuts. The cross-cuts, especially in the single decline case, are long and not constrained to being horizontal. Here we modeled the cross-cuts as subsidiary declines, breaking out from the main decline at variable junctions, whose locations are to be determined (using the simulated annealing method within DOT discussed above). The cross-cuts each meet a footwall drive at one of a small specified set of points on the drive.

With such a large number of subsidiary declines, it was immediately evident that the simulated annealing method within DOT could not accurately do the optimisation (which involved simultaneously optimising the positions and directions of 27 junctions and more than 50 sections of decline) in one step. Some sort of decomposition of the problem was required. It was decided to first do an initial design that included only the main decline/s and the haulage cross-cuts at the 90m levels. This can be justified by the observation that the total per metre costs associated with development and haulage on these parts of the network will be far greater than the cost for the access development to the other sublevels (which includes no haulage). This first strategic phase required DOT to simultaneously optimise the positions of nine junctions, a task that the simulated annealing methodology was able to handle well.

The access-only development was then added on later, essentially as a secondary optimisation objective. The initial strategic design formed a "base solution" in each of the three cases, which DOT used as a starting point for constructing the more detailed strategic design. The standoff region constraints for the decline were taken into consideration through the use of barriers. The role of these designs is to act as a template to inform the final design which needs to take into account a range of more detailed constraints such as ventilation. Adding this further layer of detail will not significantly change the relative costs of the different designs.

A comparison of costs was done for four choices of declines as shown in Table 1. The single and split declines have similar costs whereas the two decline option is more expensive, even though it has the least development cost. Figures 1 and 2 illustrate the three optimised strategic designs for the 30 metre sublevels in section views. (The design for the 40 metre case is similar in appearance to the first of the 30 metre cases.)

[Insert Table 1 here]

Table 1. A comparison of relative costs for the three design options. The total costs are in the range of about $100M.

[Insert Figure 1 here]

Figure 1: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the single decline option (top) and double decline option (bottom) with 30 metre sublevels.

[Insert Figure 2 here]

Figure 2: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the split decline option with 30 metre sublevels.

The results indicate that for this case study the choice of sublevel interval is a much greater factor in the total access cost than the specific topology, once the design have been optimised. This is important information to be included in the options analysis, which determines the maximum value of the mine by also taking production and scheduling constraints into account.

CONCLUSION

We have described two access design optimisation tools fro underground mine planning that have been developed at the University of Melbourne: the Planar Underground Network Optimiser (PUNO) and the Decline Optimisation Tool (DOT). PUNO minimises the total production costs associated with the level layout within an orebody, using the theory of weighted Steiner networks. DOT optimises the haulage declines under a comprehensive set of constraints, including a turning circle constraint, a gradient constraint and the avoidance of "no-go" regions. Both PUNO and DOT have the objective of minimizing the total cost of development and haulage for the mine.

It is important to appreciate, however, that although being able to optimise individual mine planning tasks, such as access design, is a necessary condition for achieving an overall optimal design, it is not sufficient. Maximising the net present value of an underground mine ultimately requires the simultaneous optimisation of a range of different design tasks, including the determination of mining methods and cut-off grades, the design of stopes, and the design of production schedules. A major industry project, PRIMO, is currently working towards this goal by facilitating integration between a number of new underground mining optimisation tools (including PUNO and DOT) and studying the interaction of the mine planning tasks. Currently we are working closely with a number of the industry sponsors on case studies in order to establish an efficient tool-chain for the design tools on a common platform, and to explore the effects of iteration and combined optimisation between sets of tools within this tool-chain.

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Figure Captions:

Figure 1: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the single decline option (top) and double decline option (bottom).

Figure 2: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the split decline option.

Table Captions:

Table 1. A relative comparison of costs for the three design options. The total costs are in the range of about $100M.

Tables:

	Development	Haulage	Total
Single decline 30m levels	0.48	0.52	1.00
Two declines 30m levels	0.47	0.56	1.02
Split decline 30m levels	0.48	0.52	1.00
Single decline 40m levels	0.57	0.56	1.13

Table 1. A relative comparison of costs for the three design options. The total costs are in the range of about $100M.

Figures:

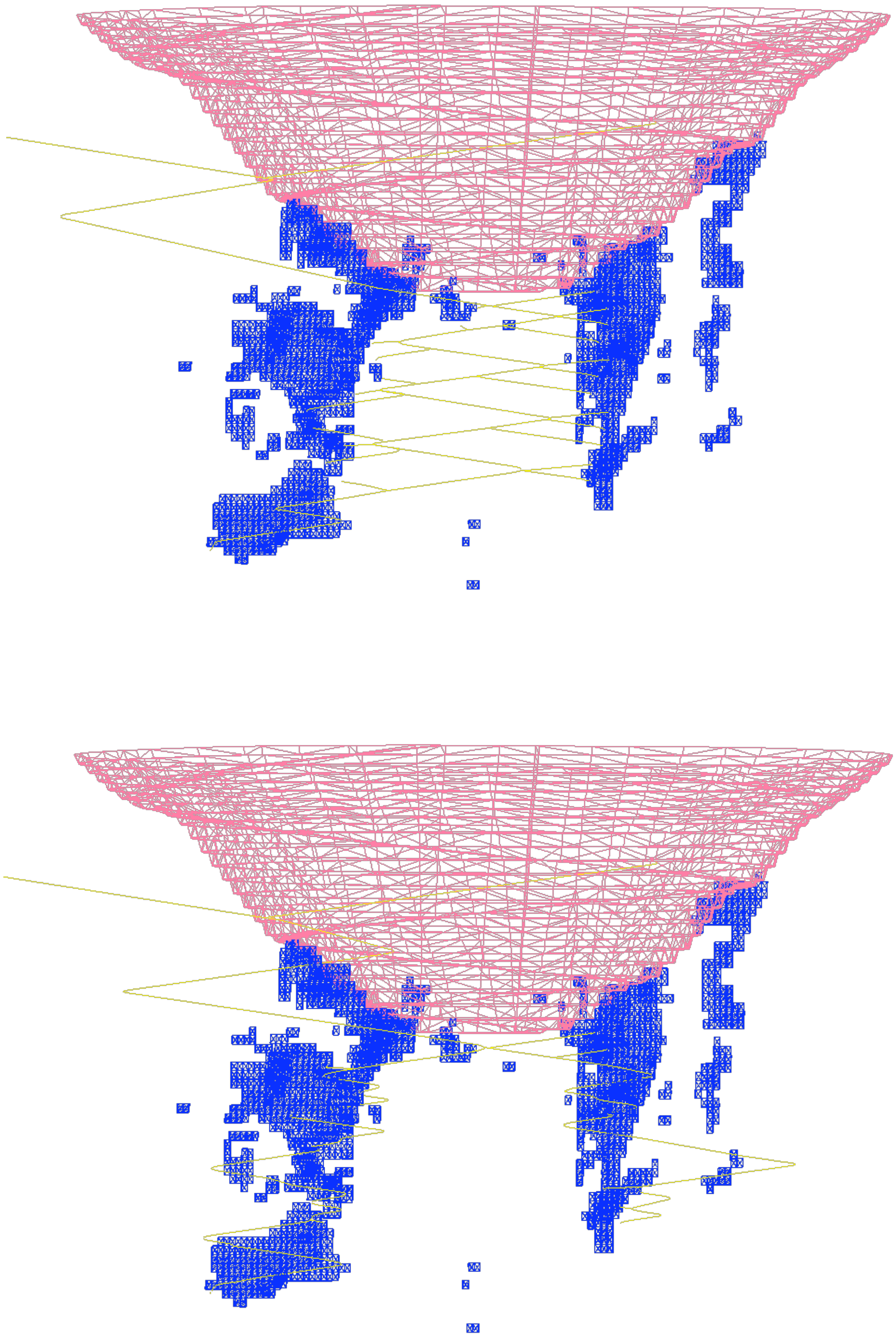

Figure 1: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the single decline option (top) and double decline option (bottom).

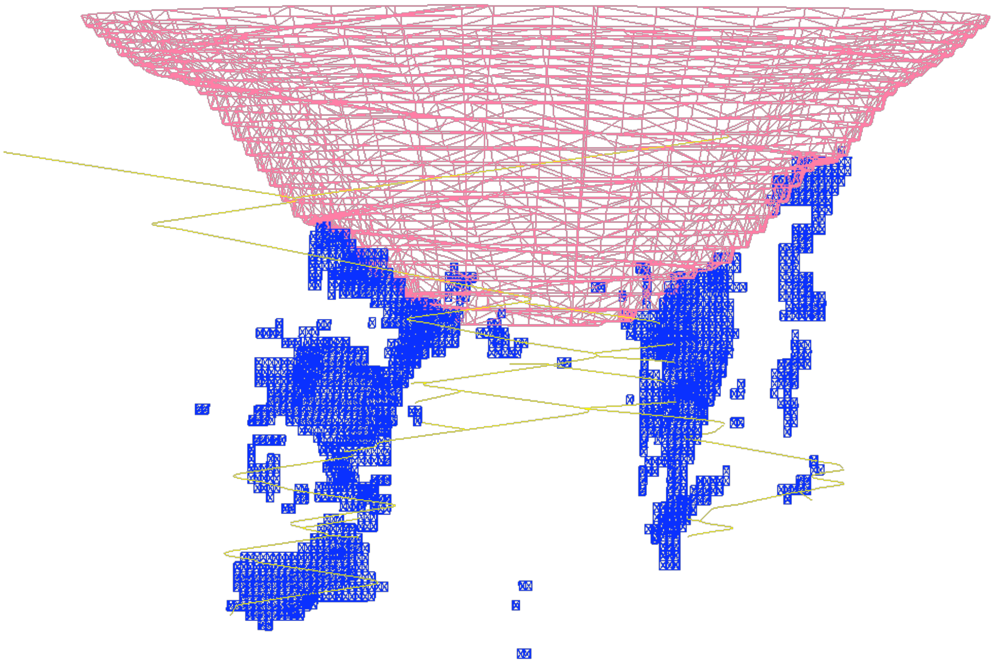

Figure 2: Long-section from west (left) to east (right) showing the final pit and potential eastern and western SLOS zones and development layout for the split decline option.