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Application of Pit Optimisation Algorithms Beyond Open Pit Limits

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ABSTRACT: Pit limit optimisations are used extensively in open pit mine planning to determine the ultimate pit limits and open pit mining sequences. Various standard techniques for the analysis of pit limit optimisation results have been developed and accepted by the mining industry today. This paper presents two relatively new techniques employing pit limit optimisation algorithms beyond the definition of open pit limits: (1) optimisation of waste dump limits and (2) definition of optimum mining sequences through blending pit sequences from multiple optimisation runs.

I INTRODUCTION

Pit limit optimisations are integral part of open pit mine planning today combined with the other mine planning tools such as pit design generators, production schedulers and cut-off grade optimisers. Pit optimisation algorithms in various implementation forms are the only planning tools that can produce feasible optimum pit development geometries automatically utilising the given geology, grade, slope and economic information.

Pit optimisations can be used at almost every stage of a project, from exploration program definitions to the preparation of feasibility studies, and finally evaluation of development options in an operating open pit mine. Although pit optimisations are used widely in open pit mine planning, the use is rather limited in context to the determination of ultimate pit limits and a pit development sequence only. It is common that sensitivity analyses for variations of individual input parameters are also included in the analysis of the optimisation results for the selection of ultimate pit limits.

In current long-term planning practice, waste dumps, the largest surface structures in open pit mining, are usually designed manually without assistance of any computer tool for optimisation and sizing. Various rules of thumb are used through a trial and error approach for the calculation of volumes and minimisation of haulage and other related costs.

The importance of mining sequence definition is also usually not evident in long-term open pit planning procedures. Usually a mining sequence is derived from a simple selection of pit shells based on optimum pit limits parameterised by the variation of a single input parameter. The performance of the obtained mining sequence with respect to the production constraints is generally not questioned prior to the detailed production scheduling stage of a project.

Extending the use of pit limit optimisation algorithms in long-term mine planning, two techniques are presented in this paper. The optimisation of waste dump limits utilising standard pit optimisation algorithms will be discussed in the next section. The optimisation process provides the optimum waste dump limits that minimises the dumping costs for given cost, distance, area and topographic surface variables.

In the third section of the paper, a technique based on blending pit shell sequences from multiple optimisation runs will be introduced to achieve mining sequences that production constraints can be varied through time. This technique brings some degree of dynamism into the pit optimisations where the input parameters cannot normally be changed dynamically in the process.

Both techniques to be introduced for dump optimisation and mine sequencing were successfully applied recently in the development of open pit mining projects in Australia. The waste dump optimisations were used in three open pit gold mines to provide guidance in the mine designs. Syerston Nickel-Cobalt Project will be presented as a case study for the application of mining sequence definition technique in the fourth section of the paper.

2 WASTE DUMP OPTIMISATION

For large open pit mines, the haulage costs may constitute almost half of the mining costs. With reduced mining costs, lower grades and the added costs benefits of bulk mining, high stripping ratios ranging from 5:1 to 10:1 are common in surface mining today. This means that waste mining can make as much as up to 40% of the total mining costs. With the environmental issues and associated additional cost, waste dump design becomes an important task in today's open pit mining.

As established by Bohnet and Kunze (1990), important factors in the design of waste dumps are:

- Pit location and size through time
- Waste rock volumes by time and source
- Topography and property boundaries
- Existing drainage routes
- Reclamation requirements
- Foundation conditions
- Material handling equipment

Most of the design factors mentioned above can be quantified by assigning a cost factor which varies by surface topography and location. The ultimate objective of a dump design would normally be to minimise die total dumping cost, including haulage and other dump area related costs.

It is common practice that the CAD programs used for open pit designs are also employed to generate waste dump designs. No other computer tool or method was known until recently to assist, or most importantly, to improve the waste dump design process. Dincer (1997) introduced the application of a waste dump optimisation process in a case study. A custom computer program was developed to create a dump cost model and Whittle Four-D pit optimisation program was used in the case study, to optimise the waste dump limits.

2.1 *Dump v Pit Optimisation*

The dump optimisation problem can be described as a mirror image of the pit optimisation problem vertically. The slope constraints in dump optimisation are defined by using a set of structural arcs as in the case of pit optimisation. The slopes defined by the structural arcs are simplified in the form of cones in Figure 1 : an inverted removal cone for a pit and a dumping cone for a waste dump. In order to mine and ore block at the base of an open pit, the associated blocks within the removal cone should be mined first. In the case of a dump, the block within the dumping cone should be dumped first to be able to dump a block at the top of the cone.

The general procedure used for the optimisation of waste dumps are provided in Figure 2. The procedure is similar to that of pit optimisation but the dump cost model is created through a computer program outside the modelling package. The area codes generated in the planning package can be used to divide the topographic surface into different cost areas. By using the dump area codes as the equivalent of ore types in a pit optimisation, it becomes possible to report and analyse the dump volumes and costs by different dump areas.

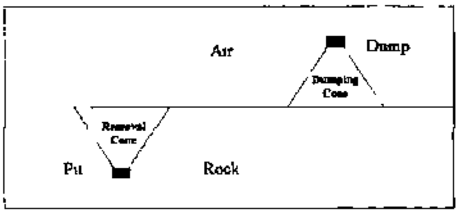


Figure 1 Removal v dumping cones

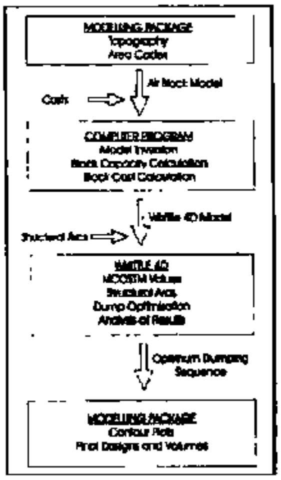


Figure 2. Flowchart for dump optimisation process.

The block model input to the optimisation is inverted around the horizontal plane so that the original air blocks transform into solid blocks. Conversely, the solid blocks in the original model becomes air blocks since they do not have any effect in the dump optimisation process. After model inversion, the slope angle constraints are defined by the creation of structural arcs in exactly the same way as for pit optimisation. Additional arcs (or slope constraints) can also be defined to represent surface structures, such as roads and drainage routes that will affect the waste dump limits.

2.2 *Dump Cost Model*

Haulage and area costs are the two main categories of costs that can be used to construct a model for dump optimisation purposes. The haulage cost is calculated for each block in the model depending on the block's location with respect to pit exit and dump access points. In the case of multiple pit ramp exits, the pit exit providing the lowest haulage cost can be selected for the calculation of haulage costs. Since the haulage cost depends on the vertical displacement as well as the total distance travelled, it is divided into horizontal and vertical components. The operating cost for the haulage equipment is also required in *the* calculation of the haulage *costs.*

The area costs apply to the blocks on the topographic surface. They can be allocated either as a direct area cost or lump sum cost assigned to a single block linked to other blocks in the area. The direct area cost is allocated on the basis of the unit area and can be used for such items as land acquisition, clearing and rehabilitation costs. In the lump sum cost assignment, the total cost would be incurred fully in order to access any of the blocks in the specified area. This method can be used to allocate the cost of diverting a drainage route or shifting a surface structure such as a road.

2.3 *Dump Optimisation ami Results*

After the calculation of the dumping costs and the available dump volume for each block, it is necessary to transform these variables into a form that can be used by the pit optimisation process. The open pit economic variables in the calculation of net block values are substituted in the dump optimisation model as follows:

- Dumping cost in dump optimisation replaces the mining cost in pit optimisation. Processing cost becomes redundant in dump optimisation since all the costs are represented in the dumping costs.
- The dumping capacity (block volume) in dump optimisation replaces the product (metal or mineral) in pit optimisation.
- Product price in dump optimisation becomes a factor applied on the dump volumes to generate net block values used in the optimisations. The magnitude of revenue factors to be applied in the dump optimisations depends on the magnitude of the cost values stored in the dump model.

With fee application of a range of revenue factors, the resultant dump increments from the optimisations are ordered from the best, having the lowest dumping costs, to the worst, having the highest cost. As well as the determination of an optimum dumping strategy, the original case study (Dincer, 1997) showed that the dump optimisations can also be used for the evaluation of options for the placement of major surface structures. The optimum dumping cost curves such as shown in Figures 3 and 4 can be generated for the evaluation of mine design options for major structures.

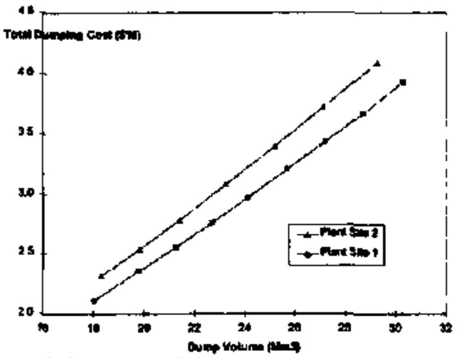


Figure 3. Comparison of plant site options.

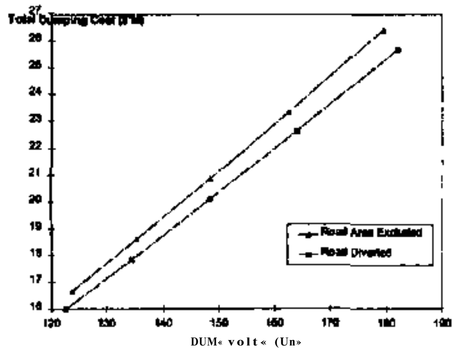


Figure 4. Comparison road diversion options.

3 MINING SEQUENCE DEFINITION

In current long-term open pit planning practice, mining sequence definition is usually based on the pit shell selections from a family of nested optimum pit shells valid for one set of technical and economical parameters. This approach might be valid for relatively simple deposits with short mine life but probably will not provide the optimum mining sequence in the case of the following:

- Deposits containing multiple elements with revenues factored by product categories;
- Deposits with significant lateral extent and multiple mining areas;
- Massive relatively uniform grade deposits with pit economics depending on the surface geometries and slight variations m grade; and
- Long-term projects requiring the inclusion of risk factors, market limitations and other corporate objectives.

3.1 *Pit Limit Parameterisation*

The process of obtaining the family of nested pit shells for a range of parameters through pit limit optimisations is called "pit limit parameterisation". The pit optimisation process, and consequently the parameterisation process, is static so that the parameters can vary İn the calculation of the block values within the optimisation model but they cannot be changed dynamically through time. Repeated runs are required to determine the optimum pit limits for a range of parameters that can be used for sensitivity analysis purposes and definition of a mining sequence for incremental mine development.

The previous work for the parameterisation of pit limits and development of a mining sequence can be summarised as follows:

- Lerchs and Grossmann (1965) highlighted the complexities in defining intermediate pit contours and suggested the parametric analysis of the optimum pit shells to determine an optimum digging partem to achieve the final pit limits.
- Bongarcon and Maréchal (1976) assumed a constant cut-off grade and used a parameter *(X)* defined by the ratio of mining cost to unit price of the metal to parameterise the open pit limits.
- Whittle (1988) produced a pit parameterisation program (Four-D) based on a parameter defined by the ratio of the product price to the mining cost (1/A). This parameter was utilised in the optimisation such a way that the resultant pit shells were basically parameterised by price.

Besides the techniques involving parameterisation of open pit limits, there are also some other approaches to determine the optimum mining sequences (and in part the production schedules). These approaches can be summarised as dynamic programming techniques (Wright 1989, Dowd and Onur 1992), heuristic search methods (Wang and Sevim 1992) and artificial neural network method (Tolwinski and Underwood 1992).

In the case of a single element or product, simple parameterisation of pit limits and other approaches would probably be sufficient to determine an optimum mining sequence. Even in die single element case, depending on the type of the deposit and the grade distribution, the varying cut-off grades and metal prices may require further analysis of the optimum pit shells. The mining sequence to be adopted may also be affected by the factors associated with die production constraints and risk such as confidence levels on die resources. Palma (1997) provided such a case in which several mining sequences were studied for the same deposit. The selected sequence from the study was one of the sequences (not the original price parameterised sequence) that would satisfy the corporate risk management policy.

3.2 *Mining Sequence and Production Schedule*

Prior to preparation of the detailed production schedules, definition of the mining sequence is a critical stage of a project's development since it combines geometry, volume, tonnage, grade, time and economic dimensions for a project as follows:

- *"Geometries"* in the form of pit shells partly addressing mining practicality and accessibility issues

  "Quantities" reported within the geometries (bench volumes, tonnages and grades)
- *"Economic"* evaluation of the quantities based on cost and revenue factors

  "Dependency" of geometries and mining *"order"* of quantities
- inclusion of *"time dimension"* in the preliminary schedules and option evaluations

As schematically shown in Figure 5, me mining sequence would constrain the production scheduling process by defining die bench quantities and dependencies as main input to the schedules. The production scheduling process does not usually have the geometrical concept and the dependency relationships defined by the pit slopes and access considérations used in die generation of the mining sequences. As the production schedule is mainly driven by the input data, this will in turn will have a fundamental effect on the mine and mill production rates, cut-off grades, ore quality and stockpiling strategies. If the mining sequence does not account for me production schedule constraints, then major alterations to the mining sequence (pit stage designs) are often required to improve and optimise the resultant production schedules.

3.3 *Blending Optimum Pit Mining Sequences*

As die complexity of tile mineral deposit and scheduling process increases, it is important that more attention should be paid to the mining sequence definition process. The proposed mining sequence definition methodology can be summarised as follows:

- Define a set of pit optimisation runs that will investigate the critical factors and areas for the definition of the mining sequence;
- Combine and examine the families of the nested pit shells from the set of pit optimisations for:
  - o The change in physical quantities for defined mining areas and/or ore types,
  - o The schedule objectives, blending and likely stockpile build up requirements,
  - o The variation in operating costs and cash flows,
  - o The variation in any other constraint or schedule objective that would affect the Mining Sequence,

  Select individual pit shells from the pit optimisation runs that suit the constraints and criteria for each option;
- Rationalise the pit shell surfaces to create a Wended mining sequence; and

- Prepare a preliminary production schedule to verify the sequence with the inclusion of the time dimension.

In this method, the pit shells obtained from pit optimisations are treated simply as shapes that are analysed and manipulated to obtain a practical mining sequence that will maximise the project cash flow within production and corporate constraints. In addition to the definition of the optimum mining sequence for the project, further advantages and contribution of the proposed methodology might be summarised as follows:

- Definition of the ultimate pit limits can be carried out dynamically taking into account the product specifications, blending requirements and variation in input parameters.
- Earlier analysis and development of the pit development strategy with various options and preliminary schedules save time and cost in the development of the project.
- Problem areas and periods can also be identified and various measures can be taken to solve the production problems in the mining sequence.
- As in real mining practice, the mill feed would be physically controllable in the source defined by the mining geometries rather than trying to deduct meanings from the behaviour of a scheduling tool.
- A comprehensive understanding of the mineralisation provided in terms of contribution of different ore types, geology and areas.

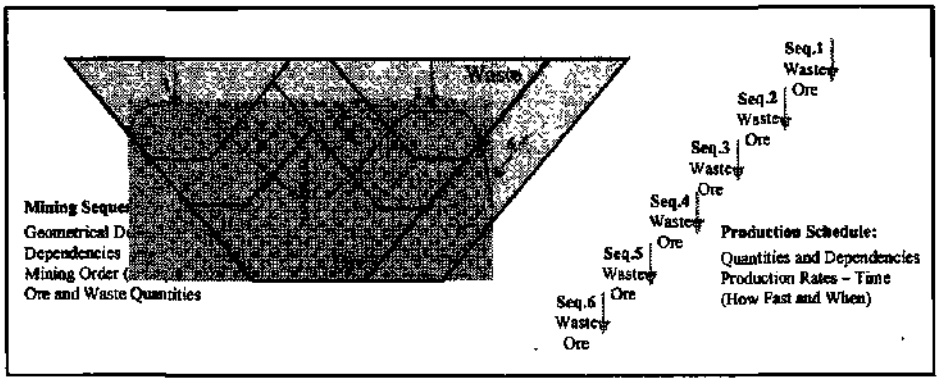


Figure 5. Comparison of mine sequencing and production scheduling processes

4 *CASE STUDY- SYERSTON NICKEL-COBALT PROJECT*

Syerston Nickel-Cobalt Project (Syerston) is located 400km west of Sydney in central New South Wales, Australia (Figure 6). The Syerston mineralisation is a limonitic nickel-cobalt latérite containing a resource of 100 million tonnes at 1.06% Nickel equivalent. The relatively compact resource at Syerston, covering an area of some 2 kilometres by 3 kilometres, is suitable for low-cost open pit mining.

The Syerston processing plant has been designed at a nominal capacity of 2.0 million tonnes per annum autoclave feed following a ramp up period of two years. The capacity in terms of metal production is 20,000 tonnes nickel and 5,000 tonnes cobalt (platinum by-product). The required mining rates per annum for a sustainable mill feed rate of 2.0 million tonnes vary between 6-10 million tonnes (ore and waste).

4.1 *Syerston Feasibility Study*

The feasibility study schedule for Syerston was based on a pit shell sequence selected directly from a Whittle Four-X optimisation run. A linear programming tool was used to schedule the quantities calculated within the optimum pit shells.

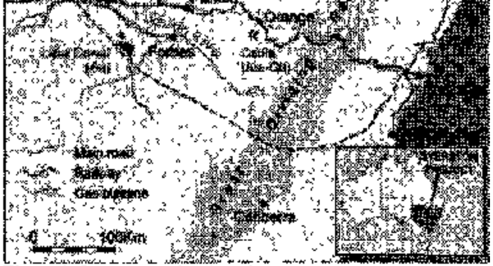


Figure 6. Syerston project location.

The operation has initially been planned for a 20 year mine life in high grade ore (+1.0% Nickel equivalent). The total operating life is expected to be in excess of 35 years including treatment of the low grade ore mined and also that rehandled from the stockpiles built during high grade operation.

The distribution of metal production during 20 years of high grade ore treatment Is shown in Figure 7. The total metal production varies between 21,000 and 27,000 tonnes in the initial 10 years of the high grade operation with an average nickel to cobalt production ratio of 4.6:1.0. The production starts to decline slowly after 10-12 years of the operation down to 15,000 tonnes of total metal at the end of the 20 years with the treatment of gradually lower grade ore. Figure 8 shows the amount of stockpile re-handling during the first 20 year's of operation as a percentage of mill feed. As seen in the figure, the stockpile re-handling can comprise up to 30% of the mill feed in some years with the overall average ratio of approximately 20%.

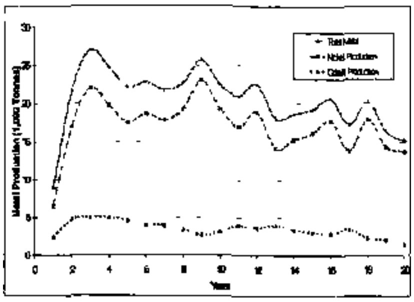
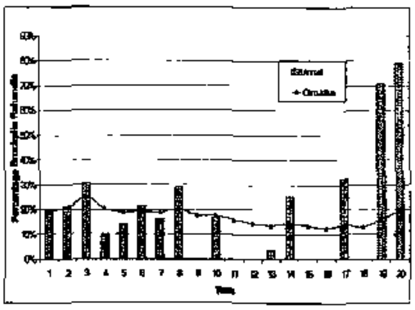


Figure 7. Syerston feasibility study metal production schedule.



After the review of the Conventional Schedule and the quantities in the pit limits, possible areas

Figure 8. Syerston feasibility study production schedule stockpile «handling.

4.2 *Redefinition of Syerston Mining Sequence*

After the review of the feasibility study results, the possible areas for improvement in the Syerston production schedules were recognised as follows (Dincerand Peters, 2001):

- Definition of relatively larger/continuous mining areas for the improvement of the mining widths and access ramp configurations;
- Decrease in high grade ore stockpile movements with mining larger areas which would provide more flexibility with ore and waste mining rates; and
- Increase in metal production in the early years of the operation by concentrating on areas with relatively high nickel and low cobalt grades.

To achieve these objectives, further pit optimisation runs were planned for systematic analysis of the optimum pit sequences. The base case pit optimisation using only high grade ore at study nickel and cobalt prices indicated a high rate of cobalt production in the early years. This was not desirable as the marketing analysis indicated that the total world production of Cobalt is approximately 35000 tonnes per year and the Syerston Study should target 5 000 tonnes per year. Four additional optimisation ruas were completed for a range of nickel/cobalt price ratios resulting in five different optimum pit shell sequences. As expected, the cobalt production was decreased in the early years of the sequences obtained from optimisations with higher nickel/cobalt price ratios.

The pit shell sequences obtained from each optimisation run were analysed together for the following indicators in the given order of importance:

- Nickel/cobalt production ratio of more than four (20,000 tonnes of nickel and less than 5,000 tonnes of cobalt) in the initial 3-5 years of the operation. The ratio is normally lower in the pit shell sequences for later years.
- While achieving the nickel and cobalt production limitations, maximise the early cash flow to provide early return from the operation as much as possible {maximum NPV)
- To achieve the above, the smaller pit shells for the mining sequence were selected from the higher nickel/cobalt price ratio optimisation. The price ratio was gradually decreased with the selection of the larger shells so that the ultimate pit limits from the base case optimisation were at the study nickel and cobalt prices.

4.3 *Syerston Case Study Results*

After the analysis of the mixed list of optimum pit shell sequences, two final mining sequences were blended each composed of 7-9 pit shells selected from different optimisations. The pit shells in the blended mining sequences were rationalised to provide a new family of pit shell surfaces. The metal production charts for the preliminary production schedules based on Mining Sequences 1 and 2 are provided as a percentage of the initial feasibility study schedule in Figure 9.

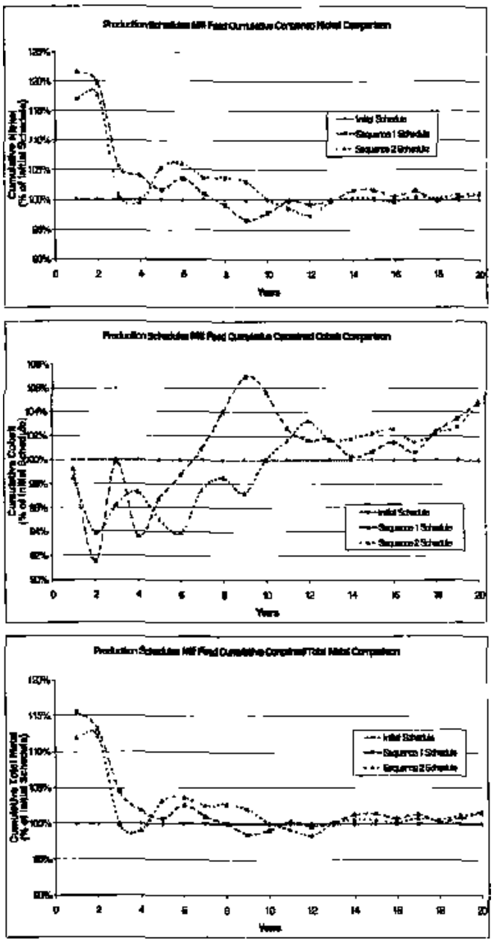


Figure 9. Production schedule cases- Comparison of metal production.

Comparison of the charts above shows the following improvements with the development of the blended mining sequences:

- The cumulative nickel production is increased by approximately 15-20% in the initial two years of the operation and 4-6% in the first six years.
- The cumulative cobalt production is decreased by 6-8% in the in the initial two years of the operation and 1-6% in the first six years.
- The cumulative total metal production is up by 12% in the initial two years and 3-4% in the first six years.
- The cumulative total metal production is very similar for all schedule cases after 10 years of operation. The metal production in the Mining Sequence 1 and 2 schedules are slightly higher at the end of the 20 years due to treatment of high grade ore only. No high grade ore stockpiles are allowed in the generation of Mining Sequence 1 and 2 schedules.

5 CONCLUSION

Two applications of pit optimisation algorithms beyond the definition of open pit limits have been discussed in this paper. Further to the standard application of pit optimisation algorithms, these applications significantly improve the main long-term planning tasks of dump designs and detailed mining sequence definition.

The dump optimisation process introduced in the second section of the paper is a useful planning tool especially where:

- The topographic surface is variable;
- The operation size is large with a high stripping ratio;
- There are multiple dump areas and these areas depend on the location of other surface structures; and
- The costs are variable between the dump sites due to differences in clearing, reclamation and acquisition requirements, and

In addition to the direct assistance to the dump design process with the definition of the minimum cost dump boundaries, dump optimisation can also be effectively used for mine site design purposes. The site options for major surface structures can be analysed with respect to die dumping costs using the optimisation results. The options for pit ramp exit positions can be evaluated iteratively to reduce the waste haulage costs.

As shown in the third and fourth sections of the paper, mining sequence definition is a critical stage of project development combining the geometrical definitions from pit optimisations and the time dimension from production schedules. With the proposed methodology, the production constraints and other factors that cannot be quantified in the pit optimisation models can be addressed in the generation of the mining sequences.

The application of the proposed methodology in the Syerston Nickel Cobalt Project was able to show practical mining sequences that can facilitate the control of different production rates for multiple elements and management of stockpiles. Preliminary production schedules of mining sequences showed that favourable results are achievable compared to a production schedule generated by using a single optimum pit shell sequence and a linear programming tool.

It is considered that the proposed mining sequence definition technique is applicable and bring significant benefits to the projects where there are conflicting and competing constraints, including nickel latente, iron ore, polymetallic, base metal and mineral sand deposits.

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