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**ABSTRACT:** Traditional mine planning is based upon maximizing the Net Present Value (NPV) of the forecast production outcomes from the mine. This methodology does not consider intrinsic uncertainty/variability of the mining system. Thus, when NPV oriented plans become operational there are large deviations with respect to the production rates, sequences and cut off grades, which derives in causing inefficiencies that lead to a lack of productivity and an increased operating cost.

Contemporary mining is moving towards a high-productivity system that identifies and quantifies uncertainty. SIMPLAN is a mine planning tool developed by REDCO Mining Consultants that uses the information from a base production plan to simulate the mine’s sequence constraint as a function of its individual operating units and process capacities. In addition to this, the tool has the capacity to run deterministic or stochastic scenarios, in order to emulate possible production performances. As a result of this exercise, it is possible to estimate a distribution of outcomes such as production, ore from different areas of the mine per period, utilization, operating costs, among other.

From the results it is possible to see how SIMPLAN is a valid tool to replicate the base plan of a mine and generate sensitivity scenarios with deviations of less than 3% in annual tonnage in comparison with traditional mining programs.

1 INTRODUCTION

Production rates define the life of the mine. This means that the production capacity at which a mine will operate plus its mining reserves must sustain the capital expenditure needed to start or continue the mine operation.

There are several “optimization” approaches to compute the first two steps of the planning process. The economic envelop and sequence are often two definitions that are paired and exposed as a result of a third definition denominated production capacity. Thus, for different economic envelops, a mining sequence is computed and simulated to different mining rates.

For low mining rates, the capital expenditure will be low, but the operating margin will not be able to pay the investment. On the other hand, when simulating a high mining rate, the cash flows will be brought upfront, but the capital expenditure would be higher, producing a low net present value. Figure 1 shows the evolution of NPV for different productions capacities (Rubio, 2006).
Figure 1. Net Present Value approach to define production target.

The above approach of an NPV driven mine planning, forces the operation towards a “push” approach rather than “pull”, i.e. intrinsically presumes that the production outcomes will be feasible regardless the integration design of geotechnical upsets, equipment configuration, mine layout and operational philosophy. Thus, production variability of the basic production units are often totally disregarded, resulting in a rather low overall equipment efficiency (OEE) of the mining system.

There are many sources of internal uncertainty that attempt towards the underlying concept of push planning approach. Some of these uncertainties are classified as the variability of the material handling systems, grades distributions, ore body continuity, geomechanical variability, operational events in the mining system, and the lack of integration: Mining Design ↔ Material Handling Systems ↔ Operational Philosophy ↔ Production Schedule. All these lead to having a mining system that is unreliable in terms of production outcomes.

Once there is an understanding that the potential outcome of the production schedule has a degree of compliance associated to it, then, mine planning under uncertainty is the way to approach the process of mine planning. In general, in all instances of mine planning, from strategic down to operational, mine planners should create several scenarios that are simulated in order to quantify the level of reliability. (Rubio, 2016)

Figure 2. Reliability assessments of different production scenarios when optimizing value.

2 SIMPLAN AS A MINEPLANNING TOOL

Planning under uncertainty consists on the first two gears of the strategic planning methodology defined by REDCO Mining Consultants (Figure 3).

Figure 3. Operating model integrated to represent the concept of Mining System.

The first gear called Mining System Design, defines a way to quantify the uncertainty of the inputs in the production plan. In simple terms, considering only the historical information of the productive parameters is not completely representative, since it does not consider the interaction that occurs between the different infrastructures and resources.

The second gear is Dynamic Production Schedules, which is defined by SIMPLAN. This mine planning tool developed by REDCO Mining Consultants uses the information from a base production plan to simulate the mine’s
sequence constraint as a function of its individual operating units and process capacities. This is done by allocating ore and waste in a rolling simulation depending on a set of reactive priorities. These priorities are based on a pattern recognition between multiple predefined objectives known as the operational philosophy of the mine.

Thus, for a given productivity, operational factors and grades, a complete multi period production schedule is computed being coherent with the sequence of excavation and fulfilling the production capacities. With this, several scenarios are simulated to emulate possible production performances, and as a result of this exercise estimate a distribution of outcomes such as production, ore extraction from different areas of the mine per period, utilization of main equipment, operating costs, among other.

Some of the main uses of the SIMPLAN are:
- Verifying a production schedule; it is frequent that there are differences between the production schedule and the declared inputs.
- Sensitivity study to a base production schedule: in the mine operation the evaluation of an alternative scenario (simplified) takes at least 4 hours.
- Variability study to a base production schedule: to have a good variability scenario it is necessary to have at least 100 replications, this is not an option in the traditional mine planning methodology.
- Quantify the compliance of a production schedule.
- Quantify the probability of occurrence of a production schedule.
- Quantify the reliability, volatility of a production plan.

The potential of the SIMPLAN Mine Planning Tool is that once the base production schedule is loaded it only takes one minute (1min) for each scenario to run. This results in a maximum error of 2% of the total copper production per year between a traditional planning method and SIMPLAN.

3 APPLICATION EXAMPLES OF THE USE OF SIMPLAN

The use of SIMPLAN has been applied mostly in open pit mines. For this case, mines “A”, “B”, and “C” (real mines) will be analyzed where all of them extract copper, producing cathodes and concentrate. The required inputs for the tools are:
- Production plan (period, origin, destination, material, attributes)
- Calendar definition
- Equipment information (cycle times, allocation by period, productivity, etc.)
- Initial stock information (grade, tonnage, material)
- Operational factors by period (availability, utilization, productivity)
- Operational philosophy (operation’s predefined objectives)

In addition, the user can add variability to the inputs in order to perform a stochastic analysis.

3.1 “A” Mine – Base Case: discrete scenarios

Once the information required by SIMPLAN is uploaded, it is important to define the Key Value Drivers (KVD) or the main parameters that define the results of the production schedule of mine “A”. In this case the relevant metrics are; mine extraction tonnage, re-handling tonnage, mine movement (mine extraction + re-handling), mill throughput, mill copper grade, mill recovery, mill production, cathodes and total production.

As a result of the calibration and validation process of the tool for mine “A”, there are two main reports. The first one is the simulated tonnage profile per month (Figure 4) compared against the planned tonnage, ore and process capacities, where no relevant differences are appreciated.

![Figure 4. Mine extraction of the base case “A” mine.](image)

Here it is possible to see that there are no significant differences between the extracted tonnage and the production schedule tonnage. Figure 4 also shows how the drill and blasting
unit operation is not a bottleneck, since it was entered with excess capacity.

The second report is a KVD comparison (Table 1) where it is possible to see how the simulated extracted tonnages are equal to the production schedule for both Fiscal Years, FY1 and FY2.

Table 1. Principal KVD of the base case “A” mine.

<table>
<thead>
<tr>
<th>Mine</th>
<th>FY1 (6 Months)</th>
<th>FY2 (12 Months)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production Schedule</td>
<td>SIMULATION</td>
</tr>
<tr>
<td>Exit</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>KVD</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Movement</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Throughput</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Grade</td>
<td>86%</td>
<td>86%</td>
</tr>
<tr>
<td>Recovery</td>
<td>86%</td>
<td>86%</td>
</tr>
<tr>
<td>Production</td>
<td>53</td>
<td>53</td>
</tr>
</tbody>
</table>

With the base case defined, a shovel is added (adjustment/perturbation of the base case) in a pushback of interest to evaluate the impact of its incorporation at end of FY1.

As it can be seen in Figure 5, this results in an advance of the pushback of interest and delaying the pushbacks of sterile according to the ranking of priorities previously established.

Figure 5. Mine extraction of the sensitivity analysis to the production schedule “A” mine.

The priority ranking is a numerical setting inputted in SIMPLAN which in this case decides which pushback has priority over another.

Delayed tonnages are those that according to the plan should be extracted on a certain period, but due to a capacity restriction they ended up being extracted later. On the other hand, advanced tonnages are those that in the simulation are extracted earlier than in the plan. In a numerical basis, Table 2 shows how the incorporation of this new shovel affects the results of FY1 and FY2.

Table 2. Principal KVDs of the sensitivity analysis to the production schedule “A” mine.

<table>
<thead>
<tr>
<th>Mine</th>
<th>FY1 (6 Months)</th>
<th>FY2 (12 Months)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production Schedule</td>
<td>SIMULATION</td>
</tr>
<tr>
<td>Exit</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>KVD</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Movement</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Throughput</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Grade</td>
<td>0.72%</td>
<td>0.72%</td>
</tr>
<tr>
<td>Recovery</td>
<td>86%</td>
<td>86%</td>
</tr>
<tr>
<td>Production</td>
<td>53</td>
<td>53</td>
</tr>
</tbody>
</table>

The main result is that for FY1 there is a 1% increase in mine extraction and a re-handling delay of 11%. This is due to the fact that even when there is an increase in loading, the hauling capacity is the bottleneck of the mining system, therefore the effect of increasing the hauling fleet should be evaluated. For FY2, there is a 6% increase in mine extraction, associated with a higher hauling capacity than in FY1. This has an effect in the grade being fed to the mill which has a decrease of 3% due to the progress/advance of pushbacks with lower grade.

The result of this sensitivity analysis is discrete, because it does not incorporate the variability in the inputs declared in the production schedule. Under this concept, it is relevant to consider that this scenario has a probability of occurrence, higher or lower, depending on the decisions of the miner. This means that this could be one replication within a set of N replications.

With this mentioned, a second case is considered where the intrinsic uncertainty of the mining operations and processes is used based on a historical information database.

3.2 “A” Mine – Case 2: variability scenarios with real extraction information

By adding variability to the inputs, it is possible to run 20 replications, Figure 6, and obtain a tonnage histogram, Figure 7, in under one minute.
As a main result, it was possible to identify that there is variability in each period, which depends on the previous period’s extraction, generating a difference between the minimum and maximum of up to 10% in the average mine movement.

With this said, the estimation of the fulfilment of the production schedule will depend on the number of replications. Then, by analyzing the set of 100-replications, it was possible to see how 0% of the replications obtained a higher tonnage, meaning that the plan compliance was not possible. But this information is incomplete without knowing the risk-free tonnage of 43.3Mt, which translates in a total risk of the plan of 8% in mine extraction.

Similar to mine extraction it is possible to do the analysis with the copper production as seen in Figure 8 and Figure 9.

In this case the probability of compliance is 5%, with 4kt of fine copper at risk, being higher than the mine compliance. This result is due to the extraction philosophy of mine “A”, where the mine movement priority of the pushback depends directly on the grade of the main product.

With this mentioned, as a side note, SIMPLAN has the possibility of incorporating different operational philosophies depending on the analyzed mine.

For, instance Table 3 shows three Chilean mines (different to mines A, B, and C) and their different operational philosophy weights:
Table 3. Operational Philosophies.

<table>
<thead>
<tr>
<th>Operational Criteria</th>
<th>Mine X</th>
<th>Mine Y</th>
<th>Mine Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Planned Destination</td>
<td>90%</td>
<td>80%</td>
<td>70%</td>
</tr>
<tr>
<td>from Origin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Grade</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>Material</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Each row represents different operational criteria and the weights given to them depend on the mine’s operational philosophy, which may vary between mines.

These weights can be obtained by expert criteria or by iteration until the results of the tool match the budget plan (elaboration of the base case). In this case, Mine Z has an operational philosophy in which they prioritize higher grade in a 30% in comparison with mine X in which high grades only weight 10% in the planning strategy.

3.3 “B” Mine – Variability scenario to define the investment on the mine

The analysis of mine "B" has a different approach than the one of mine "A" because it is an analysis that decides the possible investment in a mining project. In this case the mine operation knows that there is an inherit variability and needs to quantify it.

The methodology considered the study of 10 sensitivity scenarios, each one with 100 replications. All the scenarios present different inputs in the operation chain of extraction and production of the mine, having a greater implication in the operations of loading and hauling. Only Scenarios 7 to 10 additionally consider adverse factors due to the winter condition that decrease operating days and productive factors such as availability, utilization and equipment performance.

Once the 10 scenarios are simulated, the box-plot graphs of Figure 10 and Figure 11 are obtained, comparing the tonnages of movement and production of fine copper respectively between the scenarios and the production plan budget.

As a result, it is obtained that the only scenario that has fine copper compliance (less than 100%, because the minimum is less than the plan) is scenario S4, which considers the incorporation of an extra shovel into an ore pushback with high grade. All the rest of the scenarios are below the plan, especially the scenarios S7 to S10 due to the winter conditions.

3.4 “B” Mine – Probability study to define the investment on the mine

Once the scenario that represents the operating conditions of the mine is chosen, in this case scenario S7, it is possible to generate based on the 100 replications the histogram of mine extraction tonnages, where each replication has a production schedule with a different probability of compliance. Therefore, if one chooses a set of scenarios, one could, for example, identify a plan with 80% compliance probabilities (P80), P50, P20 and P09, thus having different main parameters for each one.
In this case the most aggressive scenario is the P09 while the most conservative one is the P80. The results are exposed in Table 4.

Table 4. P80, P50, P20 and P09 production schedule replications.

<table>
<thead>
<tr>
<th>Production Schedule</th>
<th>P80</th>
<th>P50</th>
<th>P20</th>
<th>P09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expit</td>
<td>48</td>
<td>40</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Rehandling</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>118</td>
</tr>
<tr>
<td>Movement</td>
<td>50</td>
<td>45</td>
<td>44</td>
<td>87</td>
</tr>
<tr>
<td>Throughput</td>
<td>17</td>
<td>15</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Grade</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Production</td>
<td>109</td>
<td>101</td>
<td>101</td>
<td>101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mine</th>
<th>Simulation</th>
<th>Diff</th>
<th>Simulation</th>
<th>Diff</th>
<th>Simulation</th>
<th>Diff</th>
<th>Simulation</th>
<th>Diff</th>
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</thead>
<tbody>
<tr>
<td>In-pit</td>
<td>48</td>
<td>40%</td>
<td>41</td>
<td>8%</td>
<td>42</td>
<td>1%</td>
<td>41</td>
<td>8%</td>
</tr>
<tr>
<td>Rehandling</td>
<td>3</td>
<td>2%</td>
<td>3</td>
<td>2%</td>
<td>3</td>
<td>2%</td>
<td>3</td>
<td>2%</td>
</tr>
<tr>
<td>Movement</td>
<td>50</td>
<td>45%</td>
<td>44</td>
<td>6%</td>
<td>44</td>
<td>6%</td>
<td>44</td>
<td>6%</td>
</tr>
<tr>
<td>Throughput</td>
<td>17</td>
<td>15%</td>
<td>16</td>
<td>6%</td>
<td>16</td>
<td>6%</td>
<td>16</td>
<td>6%</td>
</tr>
<tr>
<td>Grade</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Production</td>
<td>109</td>
<td>3%</td>
<td>101</td>
<td>3%</td>
<td>101.9</td>
<td>3%</td>
<td>102</td>
<td>3%</td>
</tr>
</tbody>
</table>

3.5 “C” Mine – Assessment of various operational risk and opportunities with variability

For Mine “C” the objective was to evaluate different operations risks and opportunities and see their effect on total movement, ex-pit tonnages and copper production.

For this mine, the evaluation contemplated the assessment of 12 operational risks and two opportunities, for example: A failure in the conveyor belts, a restriction in the water supply, a 2% positive deviation in the reserves estimation, or others.

The analysis was done with variability considering 100 replications. The histograms of the results can be seen below:

From the results it is possible to see how the risks affect the expected tonnage. This can be seen by noticing that the risk dots are always to the left of the 5YP bar, which is the budget. On the other hand, there are certain risks that have a lower impact on the extracted tonnage or production than others, for instance, R7 whose impact is almost null compared to the budget, versus R4 which causes approximately 14 [Mt] less of total movement, 14 [Mt] less of ex-pit tonnes, and 80 [kt] less of copper fines.

Regarding the opportunities, it was possible to conclude that their impact was not as evident as the risks. For instance, O1 was below the budget’s expected copper fine production by approximately 8 [kt], mean while O2 was above by approximately 6 [kt].

Together with these risks and opportunities assessments, it was possible to evaluate the reliability of the mine movement, ex-pit, and copper fine tonnages versus the budget, which were 15%, 25% and 0% respectively.
Therefore, SIMPLAN allows to do an exhaustive and efficient analysis depending on the mine’s needs, which may be deterministic or stochastic depending on the tool’s inputs.

4 CONCLUSION

The SIMPLAN tool has shown to be a valid model to replicate the base plan of a mine, under some considerations on the mine/process capacities and the operational philosophy of the mine. Generating sensitivity scenarios where deviations of less than 3% in annual tonnage are obtained by comparing the results with other programs of known use in mining.

By performing sensitivity analysis on the inputs that define the extractive capacities the tool is able to obtain results that facilitate quick comparisons and allow strategic decisions in the operation of a mine. Now, since this analysis is discrete, because it does not incorporate the variability in the inputs declared in the production schedule, it is relevant to consider that the scenario’s probability of occurrence.

4.1 “A” mine results

As the main result, it is possible to identify that there is variability in extraction capacity on each period, which depends on what materials are extracted in the previous period and that it is possible to have a difference between the minimum and maximum of up to 10% the average mine movement. This variability is based on the historic information and makes the probability of occurrence of this plan is 0%, with a risk in tonnage of the plan of 8% in mine extraction and a risk-free tonnage of 43.3Mt.

In this case the probability of compliance is 5%, with 4kt of fine copper at risk, being higher than the mine movement, which is due to the extraction philosophy of mine “A”, where the mine extraction priority of the pushback depends directly on the grade of the main product.

4.2 “B” mine results

When the planning tool allows to generate a set of productions schedules it is possible to build a histogram with the tonnage of mine extraction or copper production, where each interval will have a different probability of occurrence. A chosen scenario, for example, with 80% occurrence probabilities (P80) can define the goal of the company in a form where an informed and strategic decision is used.

The tool shown in this paper outlines a methodology that integrates the operational variability as part of the inputs of the planning process. It is recognized that operational hedging needs to be declared and optimized in order to mitigate the production risk resulting from operational variability.

4.3 “C” Mine results

The flexibility and efficiency of the planning tool allows the generation of various scenarios that include variability and different risks and opportunities. Each scenario is analyzed by looking at the KVDs of interest and by observing how far the risk’s tonnage is from the budget’s expected tonnage. With this, it is possible to take decisions regarding which risks have a higher impact on the KVDs and take the corresponding preventive actions or decide where to pursue on an opportunity or not.

REFERENCES


