DEGREE PROJECT

# Medium term planning with Evolution

*Comparison with current method at LKAB Svappavaara*

Koen Vos

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Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering

LULEÅ UNIVERSITY OF TECHNOLOGY

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## Abstract

This thesis looks at the medium term mine planning process and tools in the Leveäniemi open pit mine operated by LKAB Svappavaara. The current planning process uses software, Chronos, which was previously used successfully to perform medium term planning for the Gruvberget mine, which is also operated by LKAB Svappavaara. Because of scale and geological differences this method is much less successful when applied in Leveäniemi, which has created the need to investigate other possible methods.

Since the Maptek scheduling solution Evolution is already available for use, this is the first candidate to be investigated. This report uses a case study approach, where both methods are evaluated in their intended operating environment.

Results obtained indicate that Evolution could be a viable replacement to conduct medium term planning. Testing indicates that Evolution is able to produce a schedule satisfying the planning criteria to the desired standard. The fact that Evolution is able to produce schedules with longer time horizons without having to sacrifice detail means that it could also improve the integration between long and medium term planning.

Besides replacing Chronos it was demonstrated that there are also some things that can be done using Evolution that are not possible using the Chronos module. From what has been demonstrated it can be concluded that there is a possibility to achieve significant benefit using these extra functions.

## Sammanfattning

Den här rapporten undersöker mellantidsplaneringprocessen och speciellt verktyg som används i processen i Leveäniemi dagbrott, som drivs av LKAB Svappavaara.

Nuvarande planeringsprocess använder mjukvara, Chronos, som använts tidigare för mellan och långtidsplanering i Gruvberget dagbrott. Då storlek och geologiska skillnader gör att den här metoden inte är lika effektiv i Leveäniemi dagbrott uppstod ett behov att undersöka andra möjliga metoder.

Mapteks planeringsprogram Evolution valdes ut för studien. Arbetet består av en fallstudie och två olika metoder studeras och utvärderas i blivande driftmiljö.

Resultaten visar att det är möjligt att använda Evolution för att göra mellan- och långtidsplanering för det studerade fallet. Testerna indikerar att Evolution kan ta fram ett plan som uppfyller ställda krav. Möjligheten att med Evolution skapa planer med längre tidshorisonter utan offra detaljnivå betyder också att det finns stor möjlighet att förbättra integreringen mellan mellan- och långtidsplanering, något som får positiva effekter för produktiviteten.

Resultaten visar också att det finns ett antal användningsmöjligheter med Evolution som inte är möjliga med Chronos. Från studien kan man konkludera att det finns möjligheter för märkbara fördelar med hjälp av dessa extra funktioner.

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## Definitions

Asl. – Above Sea Level

Period – Timespan in which the schedule is subdivided (i.e. a schedule for one year with data for each month has a one month period.)

Vkvot – Percent of Vanadium as percentage of iron content

fe_ok – Estimated iron content (obtained by ordinary kriging)

Bench – Level at which mining takes place (here named by elevation of the bottom)

Benchheight – Height difference between two benches

Pushback – See stage

Stage – Temporary pit geometry to be excavated, allows for increased net present value by deferring stripping)

Block model – Model representing geological situation of deposit in blocks (in Leveäniemi blocks are 15x15x15 m)

Mining block – Part of the bench that is used to schedule. Shape and size depend on geology and pit design. All mining blocks for a bench should allow for a logical way to mine the bench.

# 1 Introduction

This thesis presents research carried out at the Division of Mining and Geotechnical engineering at Luleå University of Technology, in accordance with requirements for the degree of Master of Science (Mining & Geotechnical Engineering). This was conducted at LKAB Svappavaara and data from LKAB forms the foundation for work presented in this thesis.

## 1.1 Background

The first pit to be opened when mining started again in the Svappavaara area was Gruvberget. Since the deposit here was quite homogeneous the planning was relatively uncomplicated, and the current scheduling method ,which is used in both pits, proved to be very capable of producing a manageable schedule. This involves cutting the mining blocks for each bench by hand, calculating reserves in the blocks block and scheduling them using the Chronos module in Vulcan.

Because of the different geological composition of the orebody in Leveäniemi it has been much more difficult to produce a good schedule. This difficulty has led to the search for an alternative scheduling method which should be able to produce a viable schedule taking into account the important variables: ore and waste tonnes as well as iron grade and level of vanadium inclusions.

Since Maptek products such as Vulcan are already used in the mine, and access to it was already available, Mapteks scheduling solution Evolution was the logical first tool to consider. The fact that it is made to integrate with other Maptek products, especially Vulcan, is an additional contributing factor to pick this program to look at first.

## 1.2 Objective

The objective of the project is to assess possibility to integrate the software Evolution into the operational planning for LKAB's Svappavaara operation.

To assess this some sub objectives have been formulated:

- Verify that Evolution is capable of producing a schedule satisfying the criteria demanded (tonnes and grades)
- Create schedules in Evolution mirroring current Chronos schedules, do side by side comparison and review benefits and drawbacks for each.
- Identify other benefits and/or drawbacks of using Evolution

## 1.3 Methodology

In order to reach the aim for the report the work has been broken up into the following parts:

- Literature review – Theory on mine planning and different scheduling algorithms as well as a brief discussion of some of the scheduling softwares that are available.
- Introduction to Evolution – Description of the different abilities and general workflow of the software. Besides introducing the functions of the software that will be used in later chapters, also contains a brief description of functions that were not used within this project but are available.

- Current planning process – Description of how planning is currently performed.
- Planning process with Evolution integrated – Description of what the planning process would look like when Evolution would be integrated into it.
- Comparing both methods: Discussion of strengths, weaknesses, limitations and advantages of both methods.

Apart from the literature review the makeup of these parts will be further discussed in the method chapter.

## 1.4 LKAB Svappavaara

LKAB Svappavaara is responsible for operations in three open pit mines in the area around Svappavaara, The main site just outside the small town of Svappavaara also houses a factory where iron ore is processed into iron ore pellets, which is then shipped to LKAB's customers. Currently the two pits on the main site, Gruvberget and Leveäniemi, are in operation, while Mertainen, which is about 15 kilometres away, is not. Gruvberget is expected to be mined out in the fall of 2017, and will therefore not be considered in this report.

### *1.4.1 Leveäniemi*

The Leveäniemi open pit was in operation from 1963 to 1983, after which it was closed and turned into a lake. Dewatering of this lake started in 2012 and was completed in 2014, after which mining started in 2015.

Mineralization in Leveäniemi consists mainly of magnetite, with some hematite, and can be divided into two distinct bodies. The western body consists of two relatively planar zones, typically 25-50 meters thick, dipping roughly 65 degrees towards the east. The Eastern zone is more planar and of higher grade and thickness (Bradley, 2014).

## 1.5 Evolution

Evolution is a mine planning and optimization tool developed by Maptek, focusing on medium to long term and life of mine planning in open cut mines. As well as scheduling production it can also optimize the haulage fleet and the filling of waste dumps. (Maptek, 2017)

# 2 Method & Methodology

## 2.1 Method

This thesis studies the implementation of a new process for medium term planning, which is to possibly replace the method currently in place, at the Leveäniemi open pit mine. In order to investigate this a case study approach is deployed. According to Yin (1994) a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.

Since this thesis focusses on selecting the best alternative for the specific operating context that is described, this research method is appropriate (Yin, 1994) and allows for the testing of both planning methods under actual operating conditions, which should produce results best resembling reality. This is especially important considering the challenging geological makeup of Leveäniemi. Secondly this allows to compare obtained scheduling data with measurement data where possible.

## 2.2 Methodology

As laid out in the introduction the research into the planning processes in Leveäniemi with and without Evolution is split in to four distinct parts. The methods by which results were obtained for each of these parts are described below.

### *2.2.1 Introduction to Evolution*

Before any evaluations can be made on how to integrate Evolution into the planning process it is necessary to understand the abilities of the software, as well as the workflow within the software. The programs abilities will be assessed with an extensive series of trial schedules using the different options and settings that are available. These trials will also be used to learn to work with the software, for which the support staff from Maptek will be available. From an earlier test with the software there is a manual still available. (Craig, 2015)

Learning the abilities of the software in this way should also make the proper workflow apparent, and expose the features incorporated into the software.

### *2.2.2 Current planning process*

To understand the planning process that is currently in place the process of making a quarterly schedule month by month will be documented step by step. Using this as a reference object the following aspects of the current process will become clear:

- Evaluation criteria (how the quality of the schedule is determined)
- Tools (which software/tools are used)
- Planning process
- Input (data required to create schedule)
- Process (operations performed on data)
- Output (information given on the schedule)

### *2.2.3 Planning process with Evolution integrated*

To illustrate the abilities of Evolution two quarterly month by month schedules will be created. The first schedule will strive to give the same information as is given on the current schedule, to see if Evolution can be used to do what the current process does, while with the second schedule as much information as possible will be generated, to see what additional information can be obtained. Of both schedules the following points will be discussed:

- Tools (which software/tools are used)
- Planning process
- Input (data required to create schedule)
- Process (operations performed on data)
- Output (information given on the schedule)

The evaluation criteria of the schedule will not be discussed here, since the evaluation criteria are the yardstick which is used to determine the quality of the schedules that have been created. This is assumed to be independent of the process that is used to create the schedule.

## 2.3 Comparing both methods

In order to discover the advantages and drawbacks of each method and the gain or loss involved with switching from one to the other a SWOT analysis will be used. SWOT analysis have been described and used by several authors, for instance (Ansoff, 1987) (Helms & Nixon, 2010) (Glaister & Falshaw, 1999).

In this the Strengths, Weaknesses, Opportunities and Threats (SWOT) will be discussed systematically. Since the main purpose of this thesis is to discover if replacing Chronos with Evolution is of overall benefit in this particular case this will be done using the following steps:

- Strengths (for Chronos and Evolution individually)
- Weaknesses (for Chronos and Evolution individually)
- Opportunities (of replacing Chronos with Evolution)
- Threats (of replacing Chronos with Evolution)

# 3 Mine planning theory

Mine planning can be split up in to different stages, with the level of detail increasing the nearer into the future the plan is considered with. Since this report is limited to the production side of planning, planning activities not related to production, while important for project success, will not be discussed here.

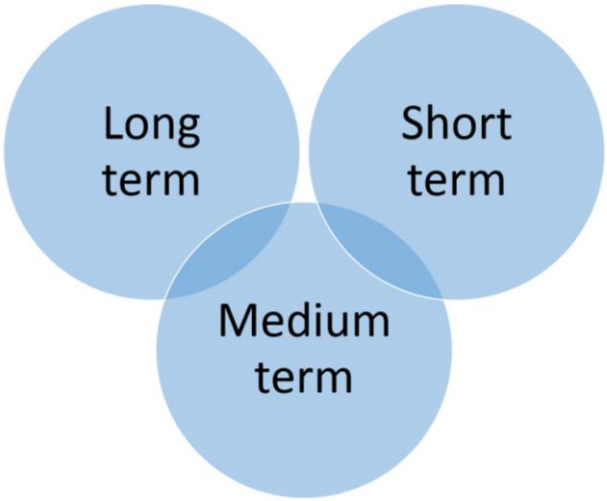


Figure 1 - Interactions of mine planning types, after (SRK, 2015), (SME, 2011) & (Hustrulid & Kuchta, 2006)

Mine planning can be split up roughly into three parts, within LKAB these used as defined by SRK (2015) (see also chapter 7), but can also be found more loosely defined by for instance SME (2011), Hustrulid & Kuchta (2006):

- Long term
- Medium term
- Short term/Operational planning

Long term planning is concerned with the far future: pit and pushback designs, sizing of the processing plant, waste dump design and equipment selection. In general this means that long term plans consider the life of the mine on a year by year basis (Hustrulid & Kuchta, 2006). Sometimes a fourth type of plan, the strategic plan is also considered (SRK, 2015), which concerns itself with mostly economic factors in the long term, and has been considered as part of long term planning for this report.

Medium term planning is the step that translates the more abstract long term plan into concrete input data for the short term plan. This means that specific mining locations and material destinations are selected (Matamoros & Dimitrakopoulos, 2016) (Hustrulid & Kuchta, 2006) (SME, 1992), stockpiles are managed and checks are made to ensure that the fleet that is available is capable of handling the desired production. Generally, and for this report, the medium term considers periods of months, quarters or years, up to 5 years into the future, where the period length usually increases and detail decreases further into the future (SRK, 2015).

Finally short term planning is where the planning is turned into instructions for the people working in the mine. Blasts are designed and scheduled, if required recipes for blending are created, equipment is scheduled for deployment and short term stockpiles are managed (Shekhar, 2017) (SME, 1992). Short term planning is done on a week by week, day by day and sometimes even on an hour to hour basis.

For any type of planning it is important to keep in mind that choices in on part of the plan will affect the other parts, as illustrated in figure 1. Figure 1 also illustrate that the medium term plan is the linchpin in the whole process, connecting the longer term planning to the day to day operations. If for instance the production rate is increased, then this could lead to the need for bigger equipment, which in turn would require adapting the various designs to accommodate that. (Hustrulid & Kuchta, 2006)

## 3.1 Long term mine planning

### *3.1.1 Pit optimization*

Pit optimization is concerned with finding the optimal size of the ultimate pit to mine for the project to reach the maximum attainable project value. This value is usually expressed as the Net Present Value (NPV) (King, 2011). Various methods exist to obtain an optimized pit shell. Such as:

- Floating cone (Carlson, Erickson, O'Brian, & Pana, 1966)
- Whittle (Whittle, 1988)
- Lerchs-Grossmann (Lerchs & Grossmann, 1965)

The Net Present Value of a project can be used to evaluate the value of any project and compare it to other projects. It is a way to give investors the opportunity to compare projects that have nothing in common and decide which is the best one to invest in. The net present value of a project is calculated by taking the yearly result of the project and multiplying this by the discount factor. The discount factor allows for cashflows of any future years to be calculated back in to present day, thus creating a value for the project that is independent of the project duration (Hanafizadeh & Latif, 2011).

### *3.1.2 Pushback design*

Good pushback design pushes the mining of waste material further into the future, thus increasing the projects net present value. This is illustrated in figure 2 below, where it is very clear that mining the pit bench by bench will result in a lot of stripping in the beginning of the project, while the pushback design defers the mining of waste further to the end of the project. (Hustrulid & Kuchta, 2006) (SME, 2011)

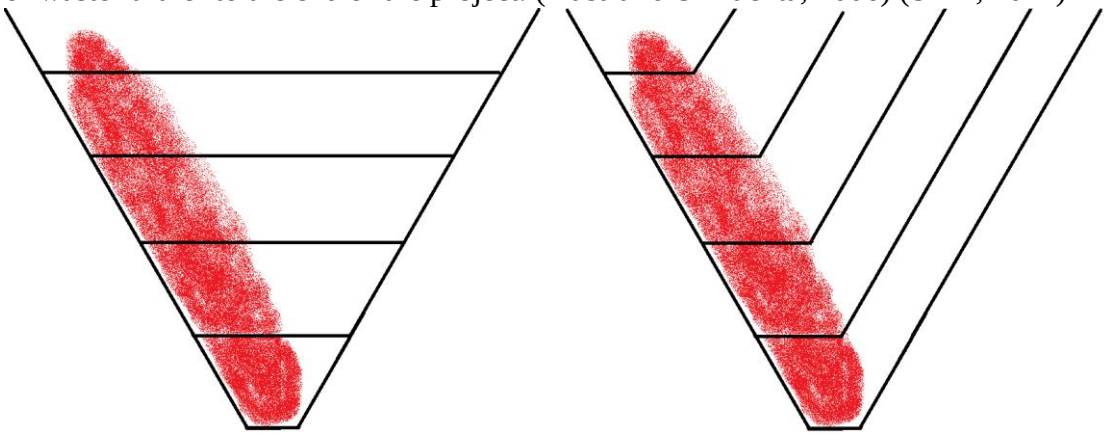

Figure 2 - Pit mined bench by bench (left) and pit mined by sequential pushbacks (right), after (Hustrulid & Kuchta, 2006)

### *3.1.3 Waste dump design*

Waste dumps can be split into two types: end dump and paddock dump. While end dumps are cheaper to operate, the paddock dump allows for more control over how the material is deposited and is safer (SME, 2011). Both options are shown in figure 3. In paddock dumping the material is deposited in horizontal layers, and spread out by a dozer, which gives good control over how the material is deposited and also gives good compaction and stability, since the haul trucks are driving over the newly made surface. For end dumping the trucks back up to the top edge of the dump and dump over it. Since here only the top surface has to be maintained this requires less maintenance, however the lack of control of material build-up increases risk for slope instability and because it is one continuous slope to the bottom the consequences are much worse if a machine does go over the edge (SME, 2011).

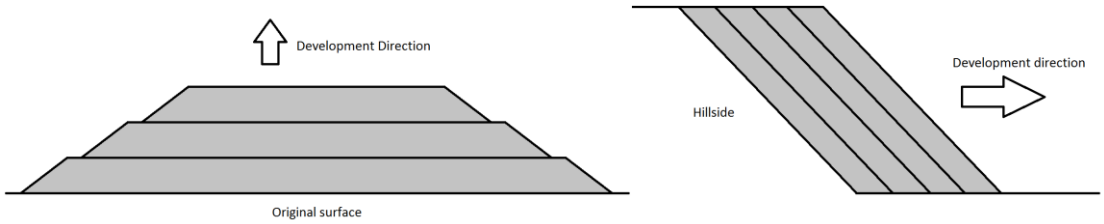


Figure 3 - Paddock dump (left) and end dump (right), after (SME, 2011)

Waste dump should be located as close to the pit as possible, but not so close that they will have to be moved to accommodate future pushbacks. It is generally considered to be good practice to locate waste dumps on a site with no underlying mineralization. (SME, 2011)

### *3.1.4 Processing capacity*

The sizing of the processing plant is highly dependent on the project lifespan, after all the desired processing capacity can be roughly calculated as:

$$Processing\ capacity(tpa) = \frac{Ore\ Reserves\ (tonnes)}{Project\ lifespan\ (years)} \quad [1]\ (\text{Taylor}, 1977)$$

Since the reserves are now known, from the pit optimization it is possible to determine the processing capacity required if the project lifespan, also known as mine life, is known.

Some rules of thumb considering mine life are provided by Taylor (1977). Operating on the basis that it requires total knowledge of costs, tonnes and grades over the mine life to calculate the optimum extraction rate mathematically, Taylor devised some rules of thumb to reasonably approximate mine life.

If the rate of extraction is too low, the project may miss out on possible economics of scale and defer potential profits to far into the future. Too high a production rate on the other hand could lead to unfeasibly high capital investment and could have the unwanted side effect of having all the production occur in the low part of the price cycle, which could seriously affect project viability (Hustrulid & Kuchta, 2006).

Taylor (1977) studied many actual projects, both planned and operational, and from that formulated the following equation:

$$Life\ (years \cong 0.2 * \sqrt[4]{Expected\ ore\ tonnage} \quad [2]\ (\text{Taylor}, 1977)$$

### *3.1.5 Equipment selection*

With the various designs and the production rate available the equipment that is to be used can now be selected. Decisions here also depend highly on the geology of the deposit and the processing requirements on the ore blend. Examples of this are given by Clark et al (1990), for limited bearing capacity, and Matamoros & Dimitrakopoulos (2016) for plant feed quality constraints. When material from multiple sources needs to be combined to satisfy these quality constraints, having one highly immobile shovel may not be the best option.

Requirements for different types of equipment need to be estimated. For drilling this is generally specified in drill meters for a certain time unit, while for loading and hauling this is done using tonnes. Now that there is a concrete target for each machine type, different options can be evaluated. For the loading and hauling fleet it is also important to make sure that these interact well with each other (Morgan, 1994) (Choawasakoo, Seppälä, Koivo, & Zhou, 2017).

The size of the equipment that is selected can have a big impact on the design, since the machine has to be able to effectively operate within it (Hustrulid & Kuchta, 2006). Machines also have their innate optimum rate of production, where they are most efficient, and machines should be selected so that they will be operated close to this point (SME, 2011).

## 3.2 Medium term mine planning

### *3.2.1 Mining areas*

In order to achieve the production targets from the Long term plan the areas that are to be mined within the specific period need to be designated. The benches designed in the long term plan are broken down into specific areas. For each period a combination of areas needs to be created that allow for the right production rates for waste and ore, as well as allow for producing a proper blend if that is required. While the targets need to be met it is also important at this stage to consider access to the areas that are to be mined, so that there are no major problems with creating access for drilling, charging, loading and hauling in the shorter term. (Matamoros & Dimitrakopoulos, 2016)

### *3.2.2 Waste dump development*

The final shape of the waste dump is decided on in the long term plan, but how the dump is filled from the current topography is still to be decided. It is important to plan this carefully, since major gains or losses in NPV can be achieved here. For this it is important to select the dump location that is most cost effective overall, so that costs for waste disposal are minimized without any negative side effects (Craig, 2014). If the operation is short on trucking capacity it is important to pick the location that allows for the shortest cycle time, in order to maximize the productivity of the haulage fleet. If there are enough trucks to satisfy the production requirement it is more important to pick the location that allows for the route with the lowest cost. (SME, 2011)

### *3.2.3 Stockpile management*

Stockpiles that have a lifespan that is longer than the short term planning horizon have to be accounted for in the long term planning. If above the cut-off grade and if it is possible stockpiles need to be recovered as soon as possible, since the investment into mining the material has already been made. Considering the material that is left in the stockpile will also make sure that stockpiled material will remain within acceptable levels and not grow out of control. (Hustrulid & Kuchta, 2006)

### *3.2.4 Equipment management*

Since there is a significant lead time for acquiring new trucks and shovels it is imperative that fleet numbers required are estimated some time into the future. This assures that extra vehicles are ordered in time, so that production is not hindered by a lack of machinery (SME, 2011).

During the lifespan of the mine equipment needs to be taken out of service regularly for scheduled maintenance, and sometimes for unscheduled maintenance (Choawasakoo, Seppälä, Koivo, & Zhou, 2017). For equipment with a major impact on the possible rate of production it is important to coordinate planning and maintenance efforts where possible. This could for instance prevent that the processing plant and the big waste shovel are out of service for maintenance at the same time, which would shut the majority of both waste and ore hauling down at the same time, leaving the truck fleet sitting idle. In short, maintenance activities cannot be seen separately from the rest of the operation (Topal & Ramazan, 2010).

## 3.3 Short term mine planning

### *3.3.1 Blast planning & design*

Planning of the individual blasts is where the planning process enters its final stage. In order to design the most optimal blast possible it is important to keep in mind that there are many factors that influence the design (Beyglou A. , 2016).

Within a single blast it is desirable to have only either ore or waste material, this to minimize the possibility for dilution to occur. If material is to be blended to get a constant ingoing grade into the processing facility it can also be practical to strive for a homogeneous grade distribution within the blast (Vojtech, 2017).

The geological makeup of the material within the blast is not only important for the grades that can be expected, but since different rock types have varying properties this also influences the behavior of the various rock types during the blast. Furthermore the way the rock is fractured, before blasting, also has major impact on the behavior during blasting (Beyglou A. , 2016) (Dolgov, 1976).

The desired fragmentation of the material after blasting has also a major impact on the blast design, where a finer material will generally lead to a higher specific charge. For fragmentation considerations differ between waste rock and ore. For the ore, which has to be processed the desired fragmentation depends on the processing setup. Since waste rock is not processed, fragmentation has to be so that the waste material can be moved out of the pit at minimal costs, which is generally possible at a more coarse fragmentation profile than the ore (Johansson, 2016) (Beyglou, Johansson, & Schunnesson, 2017).

Since both the possible burden and spacing have a direct relation to the hole diameter and the design has to be drilled with the machines that are available to the mine, there are some limits on the designs that can reasonably be used.

### *3.3.2 Blending recipes*

When a constant grade into the further process is required but the ore has variations in grade some different materials have to be blended together in a certain ratio. This can be done by combining materials from different blasts or stockpiles or a combination of these. The blending recipe informs the operators in the mine how much of each material has to be taken in order to get the grade that is required. Depending on the production rates and the amounts of material that is available this can involve changing the recipe within weeks, days or even hours (Vojtech, 2017) (Sormunen, 2017).

### *3.3.3 Stockpile management*

Stockpiles in the short term can serve various functions. In most mines there will be a stockpile between the primary crusher and further processing, this serves to even out any fluctuations both in the supply of ore to the primary crusher and in the demand of ore from the processing plant (Robinson, 2004).

A second type of stockpile contains material that cannot delivered to be processed when it is being mined. There can be several situations where this type of stockpiling can occur. Firstly there could be a problem with the material itself, if the material is very wet for instance it may lead to problems in the process if it is fed in in large quantities. If this material is in a place in the mine from where it needs to be taken

from the mine for some reason then it can be stockpiled for recovery later. Secondly there could be a problem with the processing facility, where it is unable to receive material for a while, for instance during breakdowns. Instead of waiting until the breakdown is been dealt with, material can be stockpiled close by and then fed in later (Vojtech, 2017). This allows the haulage fleet to keep working, although in case of a major breakdown it could be a good idea to switch to hauling waste material if possible.

Thirdly stockpiles could be a part of a grade targeting effort, where the one or more stockpiles are used to combat grade variations within the material fed into the process (Robinson, 2004).

Some operations store waste material with grades close to the cut-off grade in separate piles from the rest of the waste material. This material may in the current situation be unrecoverable from an economic standpoint, but may well yield a positive cash flow in the future. However, since there is no reclaim from these stockpiles they can be considered waste dumps, all be it with a specific grade requirement, for the short term planning. (Hustrulid & Kuchta, 2006)

### *3.3.4 Equipment deployment*

Part of the short term planning is deciding which machines are to work at which area. This can have great influence on the productivity. With productivity defined as the production rate multiplied by the efficiency factors, with the production rate defined as the theoretical maximum production per unit of time (SME, 2011). While for drilling and charging this assignment of machines should be fairly straightforward, with little variation between machines that are able to carry out the same tasks, on the loading and hauling side of things this can be much more complicated.

Different machines for loading have different operating properties and therefore should be deployed in a different way. Big shovels require a large area to operate efficiently and can fill a lot of trucks very quickly, if a blast does not allow for this space to operate, or the ramp to access it is not able to accommodate the traffic to allow the shovel to operate effectively, it may be better to deploy it where it can work effectively, or redesign the blast so that it is better suited to the shovel. (Hustrulid & Kuchta, 2006)

With multiple shovels operating it could also be a concern not to operate the entire loading capacity at the same time, to allow the truck fleet to keep up with the machines that are working (Choawasakoo, Seppälä, Koivo, & Zhou, 2017). Since it takes a lot of time to move these big shovels from one face to another the movement of these machines should be staggered timewise, so that as one is moved the others are working. Smaller excavators and especially wheel loaders are much easier to move from one place to another, and thus are more suited to load smaller amounts of material here and there.

Trucks must be assigned first and foremost to a loading tool that fits their size. A big shovel cannot load a little truck, since the impact of the material falling onto the dump bed could do serious damage to the truck. Similarly a little machine cannot load a big truck if it is not able to reach over the sides (Morgan, 1994).

# 4 Planning & Scheduling software

To accomplish the same tasks as Chronos or Evolution, many other software packages are available. Some of those alternatives are discussed here, as well as some theory on the selection of software. Finally we take a look at some cases where similar scheduling problems were addressed.

## 4.1 Available software

Available software can roughly be split in two categories, where one has resemblance in form and function to Evolution and the other one is more like Chronos, bolting on to a CAD program. Many different programs are available, too many to list, so listed below are some examples.

In the Evolution-like camp there are for instance

- Geovia MineSched (Dassault Systemes, 2017)
    - Algorithm: Proprietary
- MineMax Scheduler (MineMax, 2017)
    - Algorithm: MILP (branch and bound method (Gonzales, 2016))

More like Chronos are for instance:

- Hexagon Minesight (Schedule Optimizer, Atlas Optimizer and Atlas Scheduler) (Hexagon Mining, 2016)
    - Extensions of Hexagon Minesight 3D
- Deswik Software (Different modules for different functions) (Deswik, 2017)
    - Extensions of Deswik.CAD and Deswik.Sched

## 4.2 Software selection

The choice of using one piece of software over another can have far reaching consequences. Therefore a lot of research has been conducted into the selection of software, for instance: Blanc & Jelassi (1989),Hlupic & Paul(1996) and Collier et al. (1999). Bouras et al (2013) propose a six step methodology for the software selections process:

1. Form a special group of experts
2. Identification of possible software solutions
3. Study of existing reviews
4. Defining technical areas and required components
5. Comparison of the leading programs' attributes to specific needs
6. Analysis of the top selected software solutions

Another stage based methodology for the selection of software packages is proposed by Jadhav & Sonar (2011), and also contains six steps:

1. Requirement definition
2. Preliminary investigation of availability of software packages
3. Short listing packages
4. Establishing criteria for evaluation
5. Evaluating software packages
6. Selecting software package

While these two lists have been formulated independently from each other, with no references in common, they are very similar. While Jadhav & Sonar define the objective of each step, Bouras et al define the action that has to be taken in each step. Jadhav & Sonar further show that this methodology or something very similar can be found within many other papers within this particular field of study, suggesting it is broadly applicable for software selection processes.

If these criteria would be applied to this project it starts with step three completed, with the shortlist consisting of Evolution and Chronos. Step four, the establishment of the criteria, and step five, evaluating of the software packages, are then carried out. The project ends with a recommendation for the package selection.

### *4.2.1 Evaluation methods*

After the criteria and the acceptable software packages are known the best package has to be selected. The analytical hierarchy process and weighted scoring method have been widely used to evaluate competing software packages (Jadhav & Sonar, 2011).

Zaidan et al(2015) studied variations of these two methods in a comparative study, showing that there could be wide variations in the valuation of the different software packages studied based on the method chosen, however their respective ranking of the alternatives was much more similar (Zaidan, o.a., 2015). Applying and comparing multiple of these various methods could be used to reduce bias introduced by the evaluation method.

Aldea & Olariu discuss the application of a weighted scoring method in a situation where uncertainty exist, applying Laplace's criterion. This criterion states that in a situation where there is insufficient certainty about what the weights of the different evaluation criteria should be, their weight should be identical. They however note that while this methodology arrives at the best mathematical solution this may not lead to the best practical solution (Aldea & Olariu, 2014). This paper also highlights that the practical outcome of any of these methods is highly dependent on how well the criteria reflect the reality in which the package evaluated has to function.

# 5 Scheduling algorithms

In this chapter some fundamentals of linear programming are discussed as well as the differences between some of the algorithms used in scheduling software.

## 5.1 Introduction to Linear Programming

Linear programming concerns itself with the maximizing or minimizing of an objective function under a certain set of constraints, in a mathematical way. This is also what a scheduling algorithm does, it tries to maximize the objectives of the operation (be that total ore tonnage, profit, NPV, etc.), by selecting the optimal mining sequence, while respecting the limitations of the operation. For linear programming this objective function is a linear equation. (Taha, 2011). Problems can be written in their general form as:

$$Minimize\ or\ maximize\ z = F(x), x \in S \quad [3]$$

Where the objective is to minimize or maximize z, a function of x, where x has to be in the solution space S. This solution space is defined by the constraints set for the problem.

For simple problems this is quite straightforward to do with minimal computing power (Shekhar, 2017), however for problems with more variables and more constraints finding the optimal solution becomes much harder, this has led to the development of different algorithms and strategies to find the optimal solution (Holzhauser, Krumke, & Thielen, 2017).

A subsection of Linear Programming concerns itself with Integer Linear Programming (ILP), where all variables are integers (designated as pure ILP problems) or there is a mix of both integer and continuous variables, known as Mixed ILP problems (a.k.a. MILP) (Taha, 2011).

## 5.2 Algorithms

### *5.2.1 Branch and bound*

The branch and bound algorithm was developed to solve ILP problems. First it solves the problem as a continuous linear problem. Then one of the variables that is not an integer at this continuous optimum is taken and used to split the problem into two new problems (the one problem branches out into two). For example if at the continuous optimum $x_1 = 2.4$, then the two new problems are faced with all the old constraints plus the new constraints $x_1 \leq 2$ and $x_1 \geq 3$. The space $2 < x_1 < 3$ contains no integer values for $x_1$, and is deleted. This process is then repeated with these 2 new problems, and their new problems and so on, until all variables have become an integer, which is called fathoming (the branch can't improve any more by creating new sub problems), or the problem has resulted in an unfeasible solution. The most optimal value is then chosen from the results. (Taha, 2011) (Przybylski & Gandibleux, 2017) (Morrison, Jacobson, Sauppe, & Sewell, 2016)

### *5.2.2 Genetic algorithm*

Genetic algorithms are a subset of Heuristics, which are designed to find approximate solutions to complicated combinatorial problems, which cannot be solved by conventional algorithms (Mohammadi & Nakhaei Kamal Abadi, 2012). Major advantage of Heuristics in general is that they are able to find good solutions quickly, downside is that the quality of this solution in regards to the optimum is generally not

known. Early heuristics were based around the greedy search rule, which demanded improvement with each search move through the solution space. Newer, so called metaheuristics, improve on this by creating a possibility for the solution to escape a local optimum (Taha, 2011).

Genetic algorithms mimic the biological evolution process. Each feasible solution of a problem can be thought of as a chromosome, coded by a set of genes (variables). At the start of the solving process a population of feasible solutions is created. Two of these are then selected and genes are exchanged to make two children, who will displace the weakest chromosomes (Taha, 2011).To maintain genetic diversity within the population, a mutation operator is often part of the genetic algorithm, which mutates some of the genes of the offspring (Myburgh, Deb, & Craig, 2012) (Nemati, Braun, & Tenbohlen, 2017). While rules over how parents are selected or children are created vary, this is the general concept of the algorithm. After there is no improvement on the solution, or a certain amount of iterations has taken place, the algorithm is stopped.

# 6 Introduction to Evolution

Within Evolution there are three different modules with three different functions: Phase, Strategy and Origin. For this project there was access to both the Strategy and Origin modules, but only the Origin module was used. In this chapter there is a short description of the abilities of the Phase and Strategy modules, to give a sense of their capabilities and why they were not really suitable for use within this project, as well as a detailed look into the abilities and workflow of the Origin module. This should provide the knowledge of Evolution necessary to motivate decision making when it comes to integrating it into the planning process (Maptek, 2017).

## 6.1 Phase

Evolution Phase is a tool to aid in practical pushback design. It allows the user to turn a number of optimized pit shells made in Vulcan into a practical pushback design. This function was not available during the project and therefore the understanding of this function is very limited. (Britton & Barker, 2017)

## 6.2 Strategy

The strategy module concerns itself, like the name suggests, more with the strategic side of mine planning, with its main purpose being the optimization of cut-off grades for the entire operation, which could contain one or more mines. Access to run schedules from this module was not available during the project, but people from Maptek were made available to talk about the functionality of this module. Like the Origin module Strategy schedules are run on a cloud based server. (Britton & Barker, 2017)

## 6.3 Origin

The Origin module is the detailed scheduling module within evolution. Unlike Strategy, which can only produce annual schedules, Origin has a variable period length. This means that schedules can be made for periods ranging from one day to years. Just like the Strategy schedules Origin schedules are run on a cloud based server.

Scheduling within Origin is done block by block for the block model or models that are put into the schedule setup. While this is being done it can also optimize the haulage fleet requirement and waste dump development.

A schedule setup within Origin contains one of two primary objective and up to two optional objectives. These objectives define the required input that is required to create the schedule and what output will be generated.

Primary objectives:

- Material Movement: Move a fixed amount of material every period, does not account for haulage or waste dump development.
- Equipment: Specify equipment production rates and hours, schedule indicates required haulage equipment and ideal waste dump development.

Optional objectives:

- Min-Max: Gives additional control for keeping variables within a specified range. Unable to use stockpiles and blending. Min-Max and Blend are mutually exclusive objectives.

- Blend: Gives additional control for keeping variables within a specified range. Can make active use of stockpiles and blending to stay within the boundaries specified.
- Net Present Value: Allows for NPV calculations.

Since the nuts and bolts of how to setup a schedule will be covered in chapter 8, it will not be discussed further here, also because it cannot be explained properly without proper input data.

### *6.3.1 Running and reviewing*

When the setup is completed it needs to be validated, to discover if there are any problems with it, after passing it can be uploaded to the server in order to run it. While server is running the schedule its progress can be monitored, as well as the two extreme schedules. When the server has completed the run the results can be downloaded as a schedule file. For each schedule setup that is run a number of schedules will be returned, the preferred amount for this can be set, although less schedules may be returned if insufficient schedules are located on the trade-off front. The fit of these schedules to the set objective is displayed on the overview page for the schedule file (with 0 being optimal). For each individual schedule there are also charts displaying the fit for each objective per period.

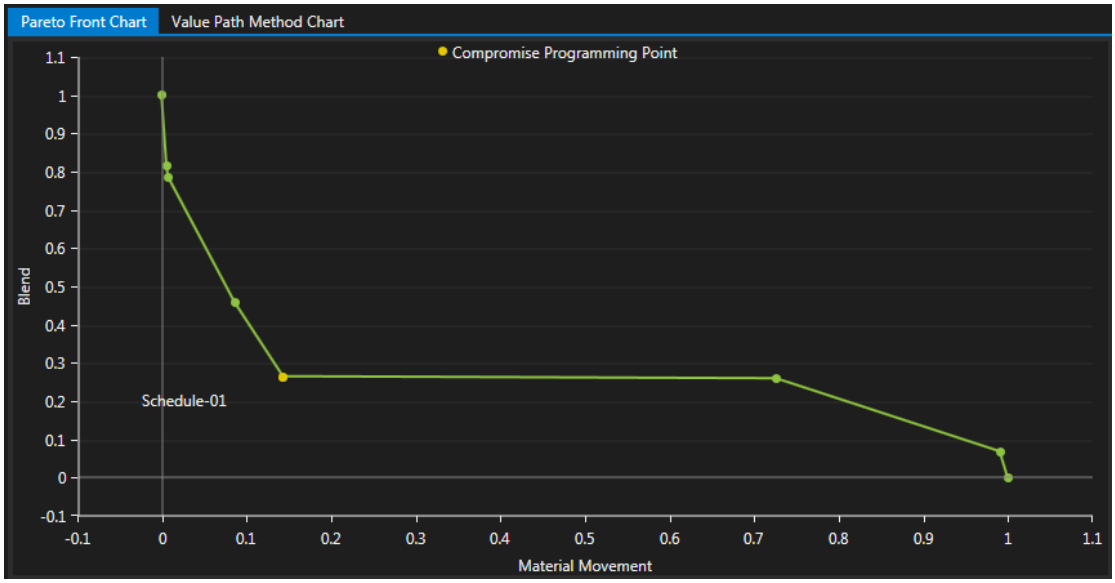


Figure 4 - Pareto front chart displaying fit of 8 schedules for blend and material movement objectives

After selecting the schedule that fits best with the users objectives, there are several possibilities to review the schedule in more detail.

The first option is the schedule report, which gives a table with figures per period on tonnes and grades, fuel burn, trucks required etc. (depending on selected objective). It also displays tonnes, grades and haulage hours in charts, which allow you to quickly determine if a schedule satisfies the objective(s) set in an acceptable manner.

The second option is to create your own table, this can be done in two ways, a Pivot-table or a Schedule Report Formula. With the Pivot-table option, the user can combine all variables in any which way to create the table with the information of interest. The Schedule Report Formula is more advanced, allowing for computations and the introduction of new variables. Both of these can be exported or copied from Evolution and used in other applications.

Finally the schedule can be monitored in the 3D view mode, where the mining sequence can be observed, as well as the filling of the waste dumps, if they are included.

### *6.3.2 Exporting a schedule*

Schedules can be exported as CSV or DXF files. Exporting as a CSV results in a table with all the information for each individual block model block (location, tonnes, grades, scheduling period, ramp assigned, etc.). This is particularly useful if the schedule is used to code a block model in Vulcan, or if it is used to code an Evolution block model in order to hour stamp the schedule. Exporting a DXF returns surfaces or solids to be used in Vulcan.

## 6.4 Discussion

In short Evolution offers a range of planning solutions. From pushback design and cut-off grade optimization all the way to monthly planning. For the more detailed planning with Origin a lot of different factors can be considered at the same time (tonnes, grades, haulage, NPV) making sure that the result is optimized for the entire operation, not just for one factor.

# 7 Planning in current situation

## 7.1 Planning in Leveäniemi

The current planning process in Leveäniemi can be split into three distinct categories:

### *7.1.1 Long term planning*

Planning on the life of mine level, pushback design, year by year production targets.

### *7.1.2 Medium term planning*

Planning up to a maximum of about 5 years into the future. Within these plans the areas to be mined for each planning period are made specific and the expected tonnes and grades for these areas are calculated. Smallest period timespan for which is planned is one month, with periods increasing further into the future (i.e. three months, three quarters and 4 years making up a plan for 5 years).

### *7.1.3 Short term planning*

Within short term planning the mining areas are split into blasts and recipes are made up to blend material from multiple blasts to the grades specified in the medium term plan. Planning horizon has a maximum of about 3 months.

## 7.2 Evaluation criteria

In order to create a valid schedule it is necessary to first establish the criteria that the schedule is judged by. For the purposes of creating a medium term schedule there are two main categories to evaluate the schedule, which are tonnes mined and ore grade. A schedule is considered acceptable if it provides proper tonnes and grades, these are important since ore from Leveäniemi goes into LKABs pelletizing process where it is important to have enough material of a certain grade to keep producing pellets of proper quality. While the ability to access the material is certainly a factor this is not considered when evaluating the schedule, since this is already assessed by the planner when selecting the possible mining locations, which has to be done manually.

### *7.2.1 Tonnes*

There are two important tonnages to plan for: waste tonnes and ore tonnes. Firstly mining enough waste is important to keep enough ore exposed to be able to not hinder production in the future. Targets for this are set in the long term plan, it is up to the planner to pick the best places to achieve these targets. For planning in Leveäniemi any material below 25% iron content is considered waste.

Ore tonnes are the other important tonnage. These work much like the waste tonnes, in the sense that there is a tonnage target given and it is up to the planner to pick the proper mining areas. For the ore tonnes it is not just important to achieve the target tonnage, there are also grade considerations.

### *7.2.2 Grades*

For planning in Leveäniemi two grades are used: iron content and vanadium content. Iron content is expressed as a percentage of total tonnage. Vanadium

content is usually expressed as a percentage of the iron in the material (vkvot), since it is included into the magnetite (and thus can't be separated before the material enters the processing plant)

Iron content in the ore has no fixed target value and can be adjusted somewhat, it generally is somewhere within the 40% range, average within current design is about 45,5%. For the medium term plan it is important to keep the grade quite constant and have changes in the grade be quite gradual, in order to not cause problems with the processing of the material.

Vanadium is an undesired inclusion into the magnetite. It has an upper limit of 0.5% (vkvot), since the current design has an average vkvot of about 0.41% percent it is undesirable to low, because that will make planning for an acceptable grade in the future very difficult.

## 7.3 Tools

Currently the planning in Leveäniemi is all done within the Maptek program Vulcan (Maptek, 2017). To accommodate the planning the Chronos module is used, which produces an excel sheet with tonnes and grades for each period as well as the locations that those tonnes are sourced from. In Chronos tonnes are used to make the schedule, after which grades are used to assess if the schedule is acceptable.

## 7.4 Input

In order to create a schedule using Chronos the following data is needed:

- Final pit or pushback topography (mine design)
- Topography at schedule start
- Block model
- Production targets (tonnes)
- Knowledge of accessibility requirements (in pit logistics)

## 7.5 Process

All actions taken are carried out within Vulcan. The flow and general parts of the process is displayed in figure 5. In the rest of this section these parts will be described in more detail.

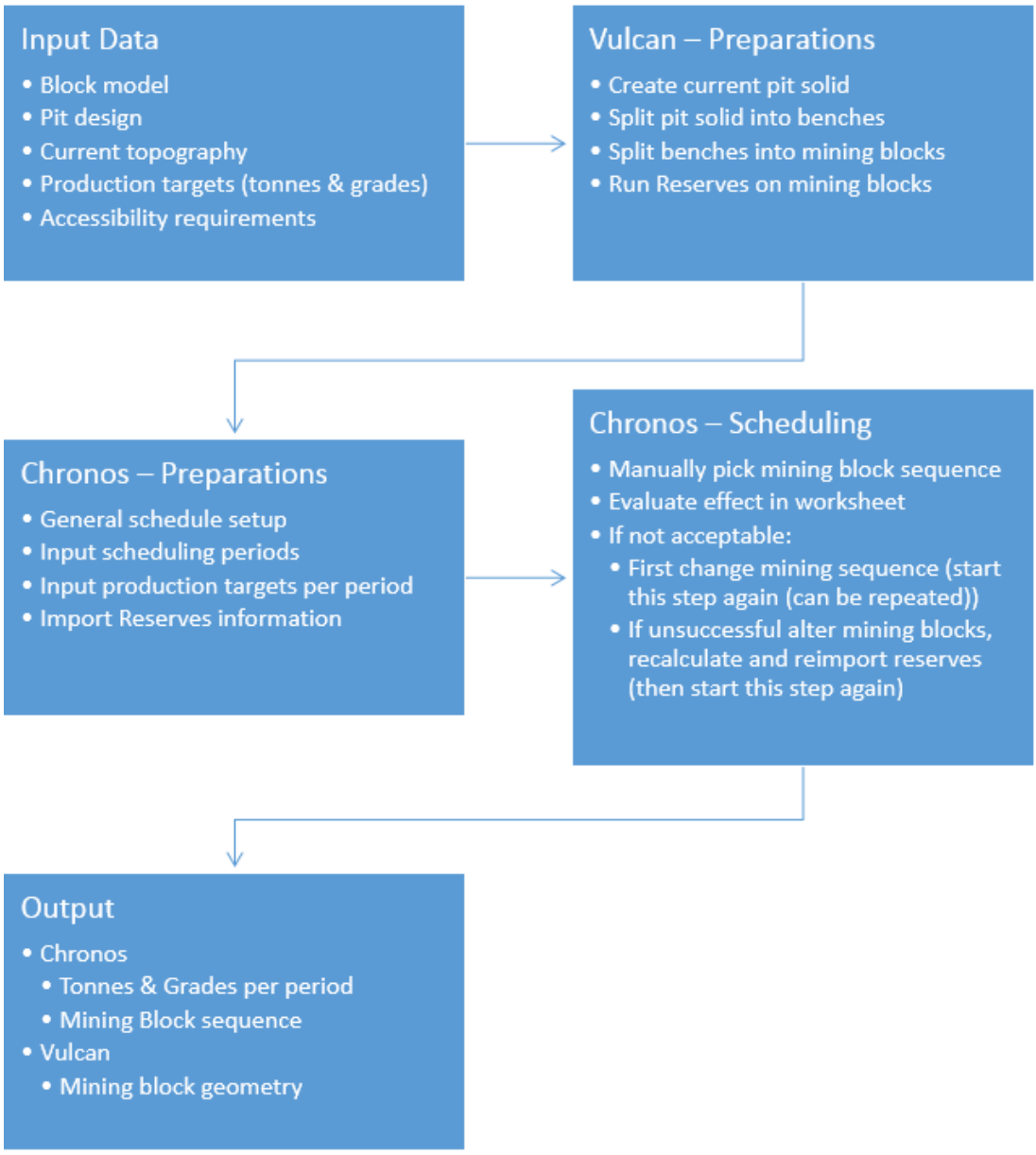


Figure 5 - Process flow of the current planning process

### *7.5.1 Vulcan Preparations*

The first step to making a schedule is the creation of a solid triangulation in Vulcan, which contains all the material that is left to be mined.

In order to arrive at a valid schedule it is important to have the right data to start off with. Even if a current height map of the surface within the mine is available this is not a proper input for the topography at the schedule start, which will be some time in the future. Since the mine is a working environment there will be heaps of blasted material, which will show up in the height map, but should not be scheduled again. The same goes for mining blocks that are earmarked to be mined

before the new schedule will start. This material will have to be removed either before or after the solid is created. The removal of this extra material is most important in areas where mining is going to take place within the schedule that is to be created, if the schedule is not going to touch the area in which this extra material is then it can be ignored (for the purpose of creating that specific schedule).

Assuming the height map is adjusted to reflect the situation at the start of the schedule the pit solid can be created. The easiest way to do this is to use the option Pit topography, with 2 triangulations loaded, the current height map and the design, where it is important the design protrude above the height map. Constructing the enclosed volume triangulation will result in a solid triangulation that contains all the material that is left to be scheduled.

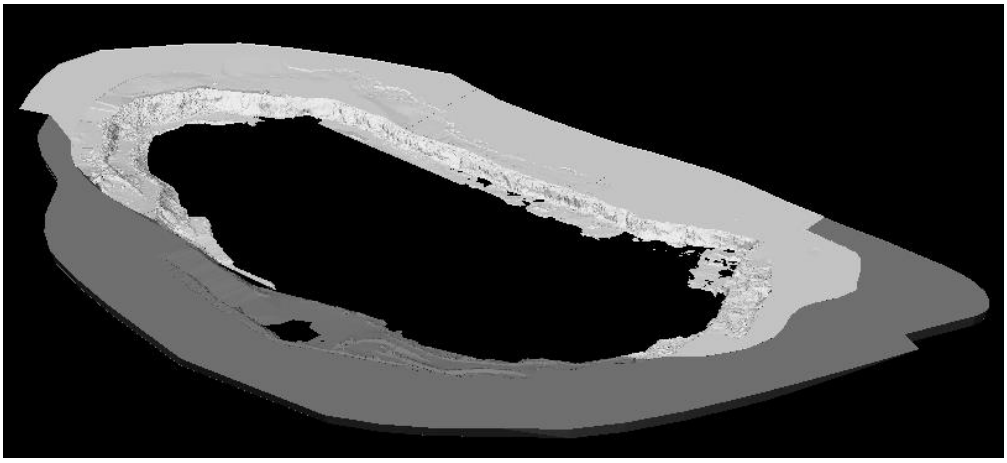

Figure 6 - Leveäniemi bench 280 (from 295 to 280 asl., pushback 1 light grey, pushback 2 dark grey)

The second step is to subdivide the solid into blocks that can be mined. In order to do this the pit solid needs to be cut into individual benches first. The option Shells can be used for this. With a known bench level and the bench height the solid triangulation for the entire pit is split into separate solid triangulations for each bench. The bench 295-280 from Leveäniemi is displayed in figure 6, divided into two for the two pushbacks currently planned.

The bench triangulations can then be cut into mining blocks. This can be done automatically in the same way as the benches, but in order to get blocks with a similar grade throughout and to separate blocks containing waste and ore it requires cutting by hand ideally assisted by an overlay of the block model.

For the mining blocks containing only waste the size does not really matter, Chronos will spread it out over multiple periods if the tonnage is too high to be mined in one period. For mining blocks containing ore size is more important, because most likely material from 2 or more places is needed to achieve a proper blend. This may require dividing some mining blocks into several parts, to get a proper blend in each period, especially when the scheduling period is quite short compared to the block size.

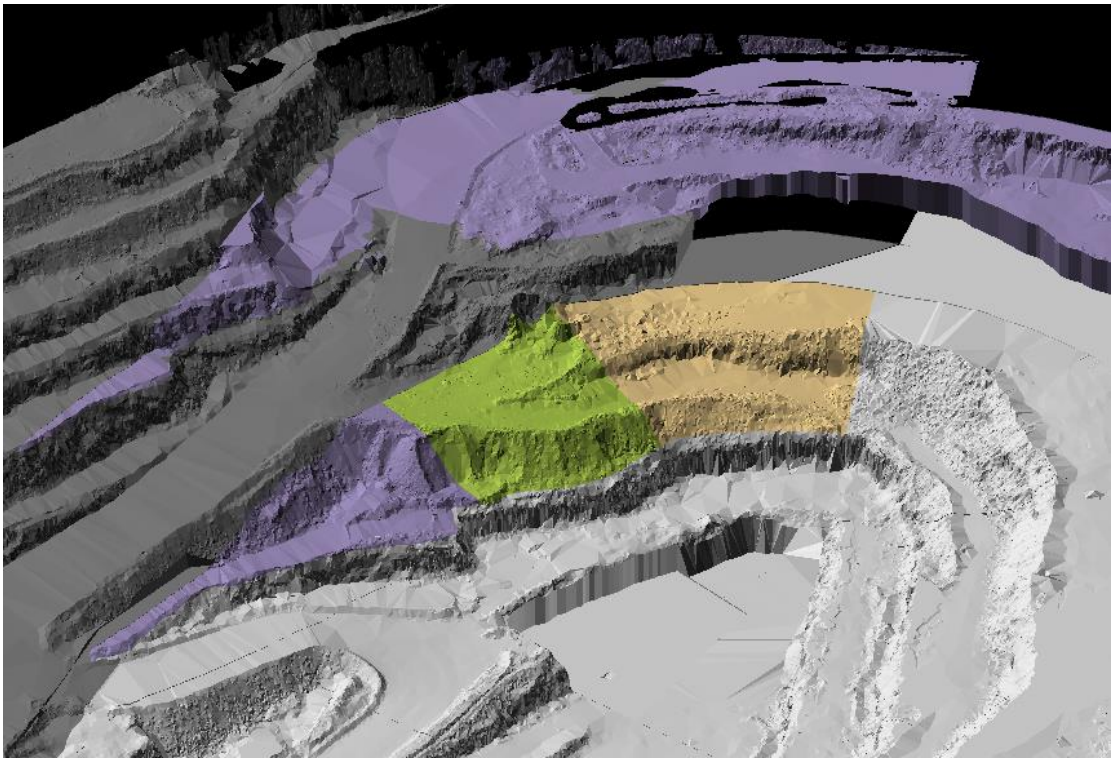

Figure 7 - Mining blocks (coloured by schedule period, grey colours for unscheduled blocks)

An example of hand cut mining blocks can be seen in figure 7, with a row of ore blocks below one big waste block.

After the mining blocks have been drawn we have to establish how many tonnes and what grade can be expected in each block. For this the option Advanced Reserves is used, which calculates grades and tonnes for both ore and waste based on the block model and the mining block geometry. This data is saved and will be used as input for the Chronos scheduling module. In figure 8 a mine block with calculated reserves is displayed. While the tonnes and iron grade of the block can be clearly seen, the importance of cleaning up the topography is also apparent.

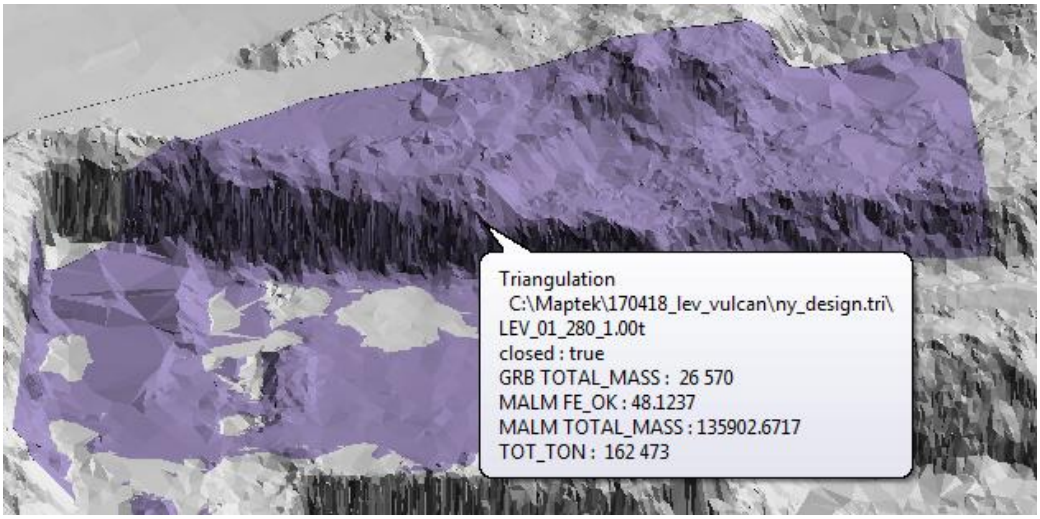


Figure 8 - Mining block(purple) with calculated reserves

### *7.5.2 Chronos preparations*

Now that the input data is prepared the schedule itself needs to be prepared, for this there are some general things that need to be configured. These consist of material routing, variable(s) targeted, material destinations and material routing. This is quite straightforward and has to be done only once, and therefore has no major impact on the time and effort required to produce the schedule.

When the general setup is been completed it is time to put in the input data. Firstly the periods that are being scheduled need to be defined, after which target tonnes can be set for the period. Finally the reserve file that was made earlier needs to be imported into the Chronos worksheet, so that the tonnes and grades for each block are available to the module for scheduling.

### *7.5.3 Chronos scheduling*

With all the preparations complete it is time to actually do the scheduling of the blocks. In order to do this the blocks are manually picked in sequence and send to the mining task. While this is being done the progress can monitored in the Chronos workbook. If the sequence does not lead to the desired results it is necessary to remove the sequence and start picking again from the beginning. If there is no sequence to be found which satisfies the schedulers objective then the mining blocks need to be adjusted, after which reserves have to be rerun and reimported into the Chronos module. With the complex nature of the geology in Leveäniemi it is common to have this happen several times while creating a month by month schedule, which makes the entire process very time consuming.

## 7.6 Output

After the schedule has been completed to satisfaction the creation of the output is very straightforward. From Chronos there is a report stating tonnes and grades for each period, as well as the sequence in which to mine the blocks. The blocks are already in Vulcan, ready to be worked with for the short term planning.

| Period | | 1 | 2 | 3 |
|---|---|---|---|---|
| Start Date | Start Date | 1-JUL-2017 | 1-AUG-2017 | 1-SEP-2017 |
| End Date | End Date | 31-JUL-2017 | 31-AUG-2017 | 30-SEP-2017 |
| | TOT_TON | 1 330 000 | 1 330 000 | 1 251 430 |
| | MALM FE_OK | 45.17 | 41.91 | 46.82 |
| | MALM VKVOT_OK | 0.31 | 0.37 | 0.41 |
| | MALM TOTAL_MASS | 386 897 | 476 979 | 475 291 |
| | GRB FE_OK | 13.23 | 13.16 | 11.78 |
| | GRB TOTAL_MASS | 943 103 | 853 021 | 776 139 |
| | | | | |
| | SR | 2.44 | 1.79 | 1.63 |
| | | | | |
| | MALM | 386 897 | 476 979 | 475 291 |
| | GRB | 943 103 | 853 021 | 776 139 |

Figure 9 - Chronos report output, with tonnes and grades for ore (MALM) and waste (GRB)

# 8 Planning with Evolution integrated

## 8.1 Evaluation criteria

Changing the scheduling tool does not change the requirements of the schedule that is being created, so for scheduling with Evolution the same criteria as in the current situation apply.

## 8.2 Tools

To plan with Evolution naturally Maptek Evolution is used to create the schedule. Before that can be done the data first has to be prepared using Vulcan, and Vulcan is also used to generate the inputs required for short term planning from the schedule.

## 8.3 Input

In order to create a schedule using Evolution the following data is needed:

- Final pit and/or pushback topography (mine design)
- Topography at schedule start
- Block model
- Production targets (tonnes & grade bandwidth)
- Knowledge of accessibility requirements

This is the same information as is required to create a schedule using the current method, the only change being that the desired grade of material is put into the program instead of evaluated manually. In addition to this information on the haulage fleet can also be put in to the program to get an estimate of the haulage capacity required to execute the schedule, this however is not a requirement.

## 8.4 Process

The flow and general parts of the process using Evolution are displayed in figure 10. In the rest of this section these parts will be described in more detail.

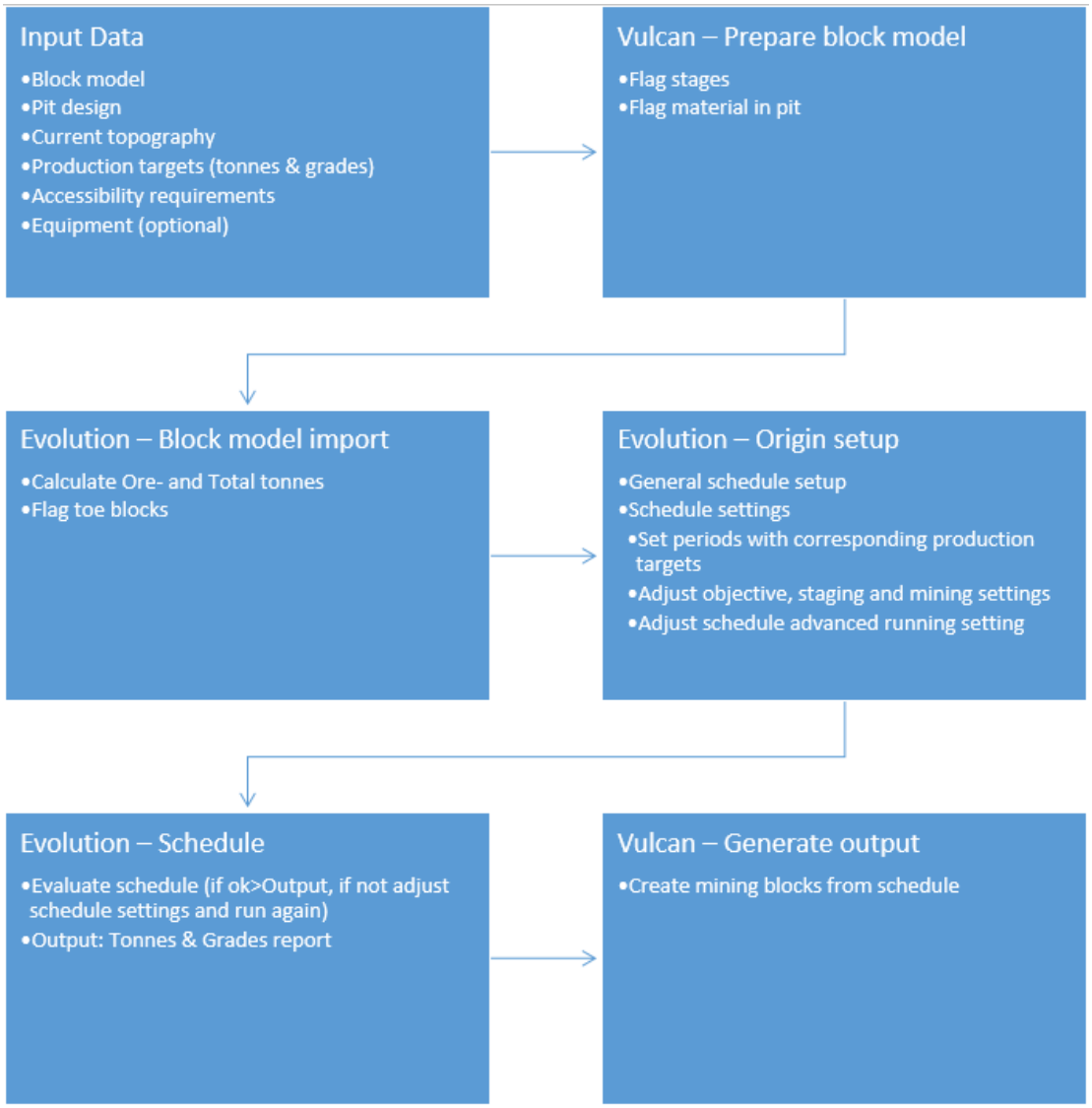


Figure 10 – Flow of planning process using Evolution

### *8.4.1 Vulcan – Prepare block model*

Before the block model can be used in Vulcan two variables need to be added to it. Firstly there is the material that is to be mined, the material below the surface and within the final pit design. This is flagged into the block model using the Mine function, which calculates how much of the block is left to be mined based on the current topography and the pit design. Result of this can be seen in figure 11 below.

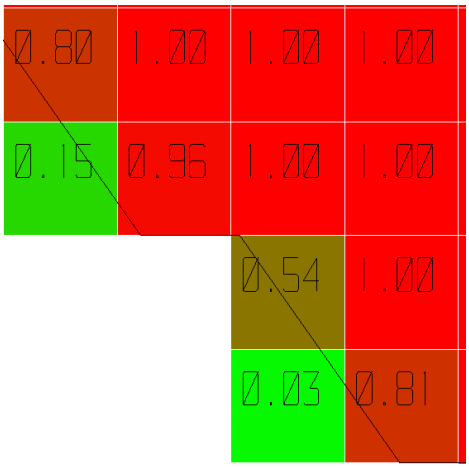


Figure 11 - Block model with remaining material flagged (design as black line from bottom right to top left, numbers represent fraction of material left)

Much the same do the different stages within the pit need to be put into the block model. Because Evolution can only process one stage per block, these are flagged by majority volume, which means that the block will get assigned to the stage in which most of its volume is.

Finally if haulage will be considered then the routes the trucks travel have to be drawn. There are four types of route that can be required, all are drawn as a single line (strings) representing the center line of the road. In the pit there are strings per ramp and per stage simulating the ramp for each stage. Outside the pit there are the so called expit strings, these start where the inpit strings end and lead to the different locations the material can travel (Crushers, stockpiles and waste dumps). The third type are the waste dump strings, they are similar to the inpit strings in that there is one for each of the ramps of each waste dump. The final type is the stockpile string, which is a route from a stockpile to a crusher.

### *8.4.2 Evolution – Block model import*

After the block model is prepared in Vulcan it can be imported into Evolution. Here some more preparations have to be done. Firstly the blocks to be mined need to be selected out of all blocks. For this the block model is filtered using the remaining material variable, and all blocks that are not to be mined are discarded. For the blocks left ore tonnes and total tonnes are calculated.

The second thing required to prepare the model is to assign one or more toe blocks to each level, shown in figure 12. This sets the starting point or points on each level from which mining can start. If this step is omitted Evolution will pick a point which is most convenient from a scheduling standpoint, but might not be practical.

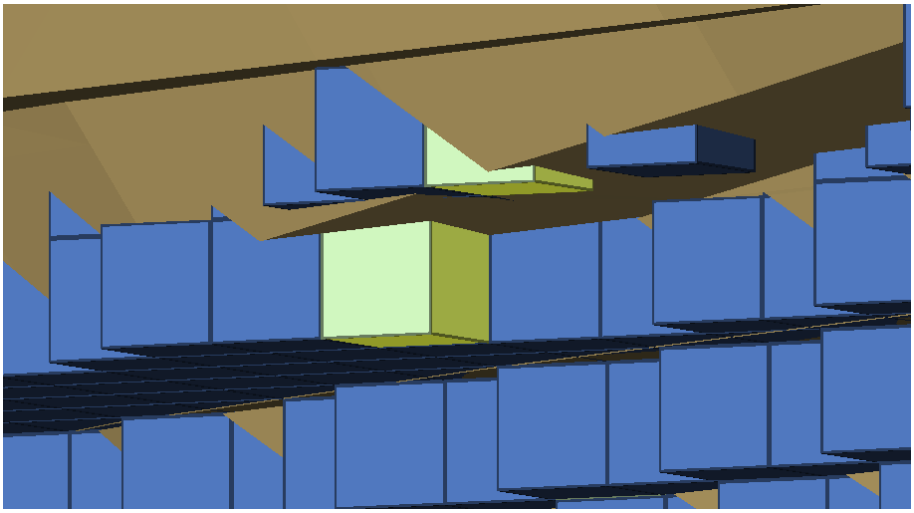

Figure 12 - Marking toe blocks in Evolution (toe blocks in yellow, other blocks in blue), looking from outside of the design(in beige), ramp coming down from top right corner.

Creating an Origin setup can be split into two parts. First there is the general setup, which makes sure that the schedule will run properly and that the results that are given at the end are of use. These settings are not (usually) subject to change while the schedule is being optimized. The general setup consists of creating the proper flowchart for the mine, an example can be seen in figure 13 , which defines the origin(s) and destinations of materials. Tonnage variables also need to be assigned to these different entities. Secondly there are some reporting variables that can be set, to make sure that the required information is available when the report is generated.

With these general settings completed the schedule specific settings can be put into the setup. Firstly the periods to be scheduled are added in the calendar tab and production targets are set for each period. After that settings are done for the objectives. Since the main focus of this report is to plan for proper tonnes and grades the focus here will be on blend and material movement, for more information on the haulage objective see chapter 11.

For the material movement the only option that needs to be set is the allowable variance, which allows for some margin of error. It is recommended to give the schedule some leeway, depending on the period length and block tonnage, so that there is at least one full block covered by the variance percentage. Irregardless of the setting, Evolution will still try to minimize the deviation.
For the blend objective (for min-max this is almost identical), blend variables need to be selected, and they need to be assigned a relative importance percentage (with total importance 100%). For each period the blend variables also need a lower and upper limit, between which Evolution will try to keep them.

For each period the stages available for mining need to be selected. Excavation capacity also needs to be set for each period, it is recommended to set it only slightly higher than the target for the period, this insures a similar rate of mining through the period (no peaks in required capacity within the period).

Finally mining settings and schedule running settings need to be done, these are not period specific. Mining setting define the distance between successive benches, required mining width, number of active mining areas, minimum blocks excavated

between excavator moves and vertical aggressiveness. Schedule running settings define which periods to optimize, how many schedules are evaluated and how many are returned. While using the blend objective one of the most important settings, especially when using short periods, is the number of snapshots. This setting dictates into how many pieces the period is subdivided for the blend objective. The blend objective will try to achieve the proper blend within each of these sub periods, but since Evolution mines whole blocks at once then if the period of time is too small the program cannot blend multiple blocks together.

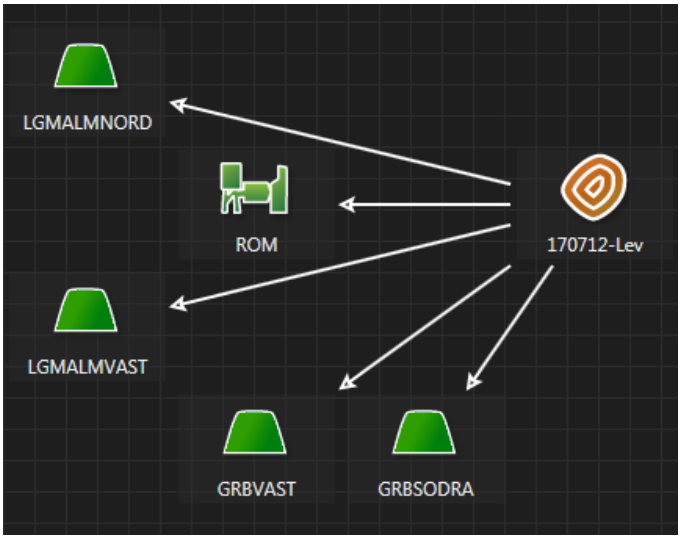


Figure 13 - Origin setup flowchart (Leveäniemi on the right, 2 waste dumps at the bottom, 2 low grade waste dumps or the left and ore processing (ROM) in the middle)

When all this is set the setup can be verified, to make sure there are no mistakes, and uploaded to the server in order to be run.

### *8.4.3 Evolution – Schedule*

When the setup has been run a schedule file is returned. This file contains, with some exceptions, multiple schedules, and a chart displaying how well the each of the schedules satisfy the objectives set.

Each individual schedule has a schedule report, which contains tonnes and grades information in a table format. There are also charts displaying tonnes and grades, see figure 14, for a quick evaluation of the schedule.

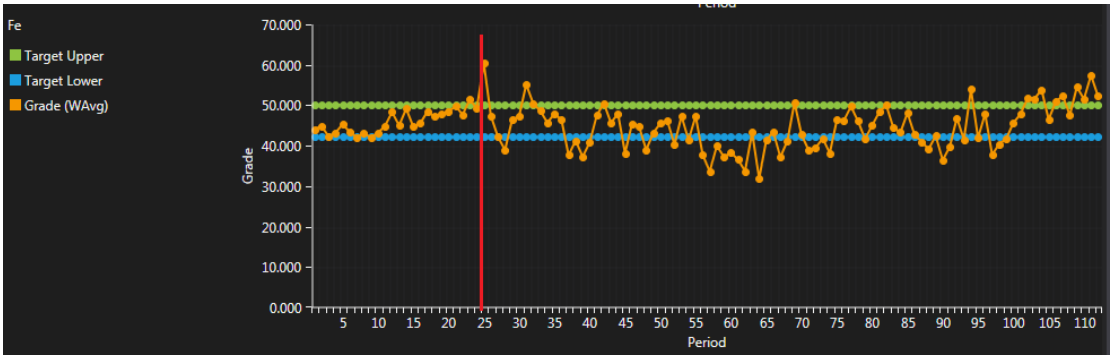


Figure 14 - Iron grade (schedule optimized in first 24 periods, left of the red line)

To check if the schedule can be executed in a practical way the 3d view can be used, see figure 15. Here the blocks can be made to vanish in sequence one by one. It is also possible to forward period by period and watch the blocks disappear.

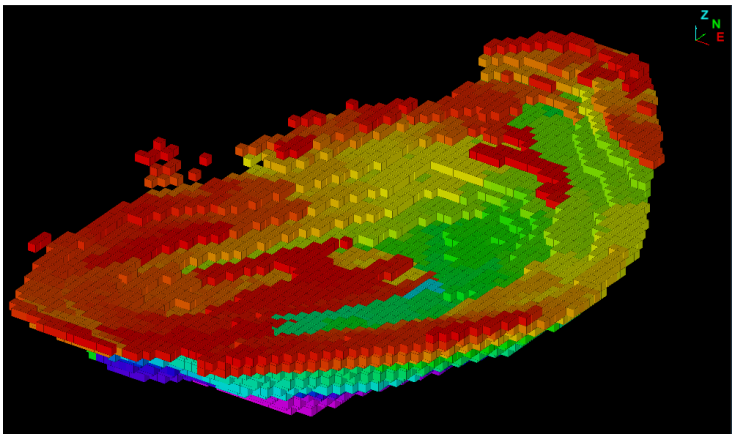


Figure 15 - 3D schedule display, blocks colored by period from red to purple.

### *8.4.4 Vulcan – Generate output*

There are several ways to visualize the schedule within Vulcan in order to plan for the more short term, in order to plan blasts for instance. There are some functions within Evolution to export solids or surfaces directly. Currently these functions are under development and not quite free of flaws, so recommendation from Maptek is to export the schedule data as a csv and then import it into a Vulcan block model. This is an easy and quick process and consists of exporting a csv, editing out the data that is not relevant and importing the csv it into the Vulcan block model of your choosing. Then you can use the options within Vulcan to review schedule information, much like you would for grade variables. This can then be used to cut the mining blocks, if they are required. For viewing these options are especially suited for this:

- Block model slice
  A block model slice displays one (or more) cuts through the block model on the screen as flat surface. This can be seen in figure 16. In addition it is possible to set up text both in the blocks (on the surface itself) and as a tooltip when the cursor is pointed to a specific block. These options allow to quickly access a large amount of information on the specific block, without even having to interrupt the option that is being used.

- Block model intersection
  To make an intersection a copy of the original triangulation is created onto which the colours of the contained block are painted, this new triangulation is for visualization only and cannot be edited. It is however possible to have both triangulations loaded at the same time and edit the original. As of now this option is quite sensitive if the edge of the original triangulation is exactly on the boundary between blocks. Also this has to be created separately for each triangulation. Figure 17 shows the same bench as was sliced (in figure 16), where also the interference from overlying blocks can be observed.

- Dynamic model
  The dynamic model allow the user to view properties from the block model in a 2d(using section view) or 3d. For this application the 2d option is most relevant, which results in a view very similar to the block model slice (figure 16), but the user can scroll through the entire block model, although only one level at a time can be seen. Downside for this can be that the view also slices through any triangulations that may be loaded so that it can be difficult to see what you are doing (no triangulations are harmed in this process).

- Grade shells
  Grade shells are intended for geological purposes, where they can be used to produce a triangulation that encloses a volume above a certain grade. Since there are now variables for the schedule period in the block model it is possible to use this option to make a shell containing the blocks for a single period instead.

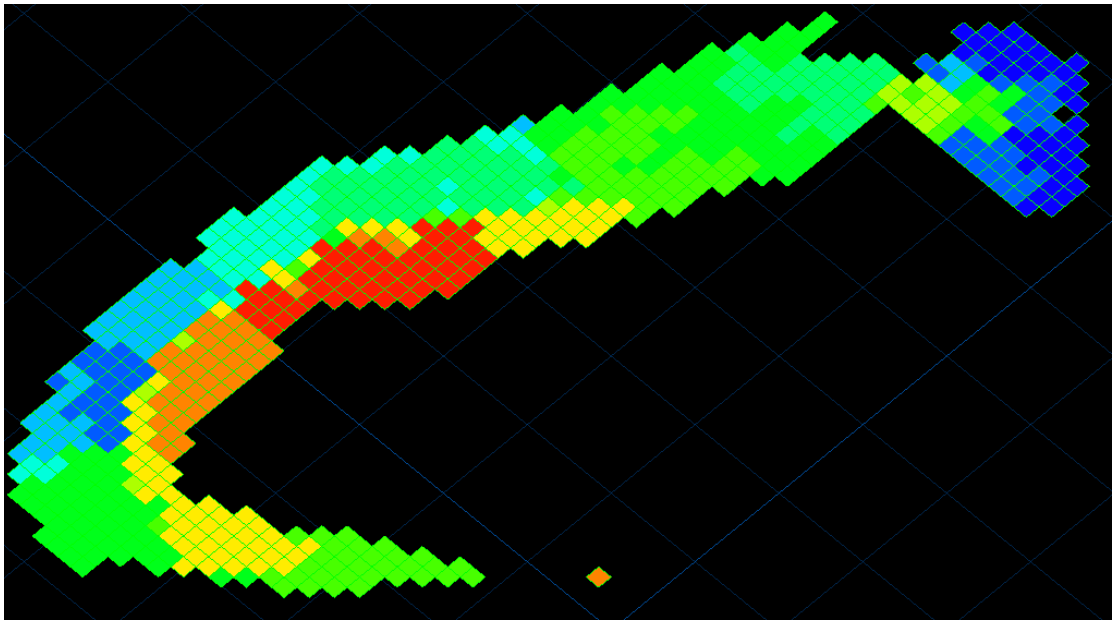

Figure 16 - Block model slice for one bench, different colours represent different scheduled periods (display limited to first 12 months of the schedule).

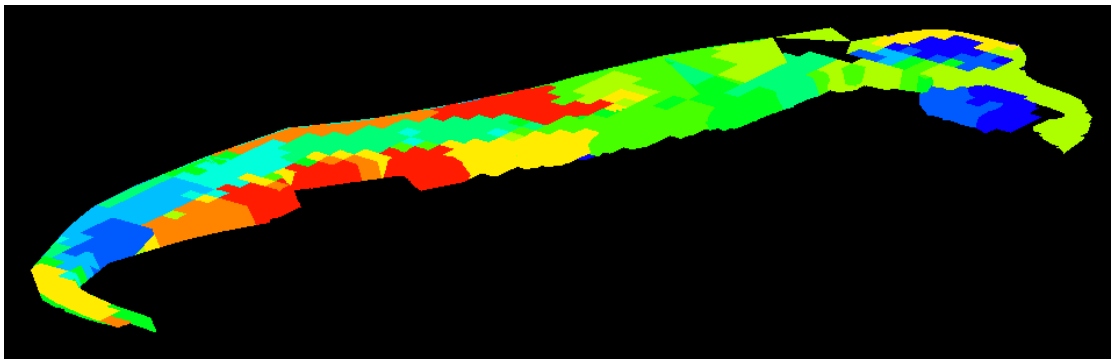

Figure 17 - Block model intersect

### 8.5 Output

For Evolution a similar report to the Chronos report is available specifying the results per period. Also for Evolution it is possible to export the scheduling results into the block model. This will code the blocks so that the schedule can be viewed in Vulcan, as discussed above.

# 9 Planning example

To illustrate the processes described in the last two chapters there will be a look at the two planning methods in action in this chapter. Using both methods a month by month plan will be evaluated for the third quarter of 2017 (Q3). For the Cronos plan the actual Q3 plan for the mine will be used, while for Evolution a brand new plan is made.

Production targets for Q3 from Leveäniemi are displayed in table 1. For vanadium there is a maximum of 0.5% (vkvot), and iron grade should ideally be between 42% and 46% and be fairly constant.

Table 1 - Targets for Q3 2017

| | July | August | September |
|---|---|---|---|
| Ore (kton) | 400 | 475 | 475 |
| Waste (kton) | 930 | 855 | 855 |
| Total (kton) | 1330 | 1330 | 1330 |

Since there is a thorough description on how to schedule with both methods in previous chapters the main concern here will be the results that were obtained by the respective methods.

### 9.1 Chronos

The results for Q3 are shown in table 2. As can be seen all the criteria for the period are satisfied, although the iron grade is a bit bumpy. The shortage of waste in September is due to the fact that no block was selected to complete the months target, this to avoid spilling the rest of that block over into October. Locations of the different blocks can be seen in figure 18.

### 9.2 Evolution

Results from the Evolution simulation are shown in table 2. From the table it is clear that both tonnes and grade criteria for the period are met, and although the iron grade drops after period 1 it stays well between acceptable limits. The areas for this plan are displayed in figure 18.

Table 2 - Results Q3

| Chronos | | | |
|---|---|---|---|
| | July | August | September |
| Total Tonnes | 1,330,000 | 1,330,000 | 1,251,430 |
| Waste Tonnes | 943,103 | 853,021 | 776,139 |
| Ore tonnes | 386,897 | 476,979 | 475,291 |
| fe_ok(WAvg) | 45.17 | 51.91 | 46.82 |
| vkvot_ok(WAvg) | 0.31 | 0.37 | 0.41 |
| | | | |
| Evolution | | | |
| | July | August | September |
| Total Tonnes | 1,336,812 | 1,332,927 | 1,330,076 |
| Waste Tonnes | 936,491 | 857,642 | 855,718 |
| Ore tonnes | 400,321 | 475,285 | 474,358 |
| fe_ok(WAvg) | 45.13 | 42.29 | 42.16 |
| vkvot_ok(WAvg) | 0.35 | 0.34 | 0.46 |

## 9.3 Comparison

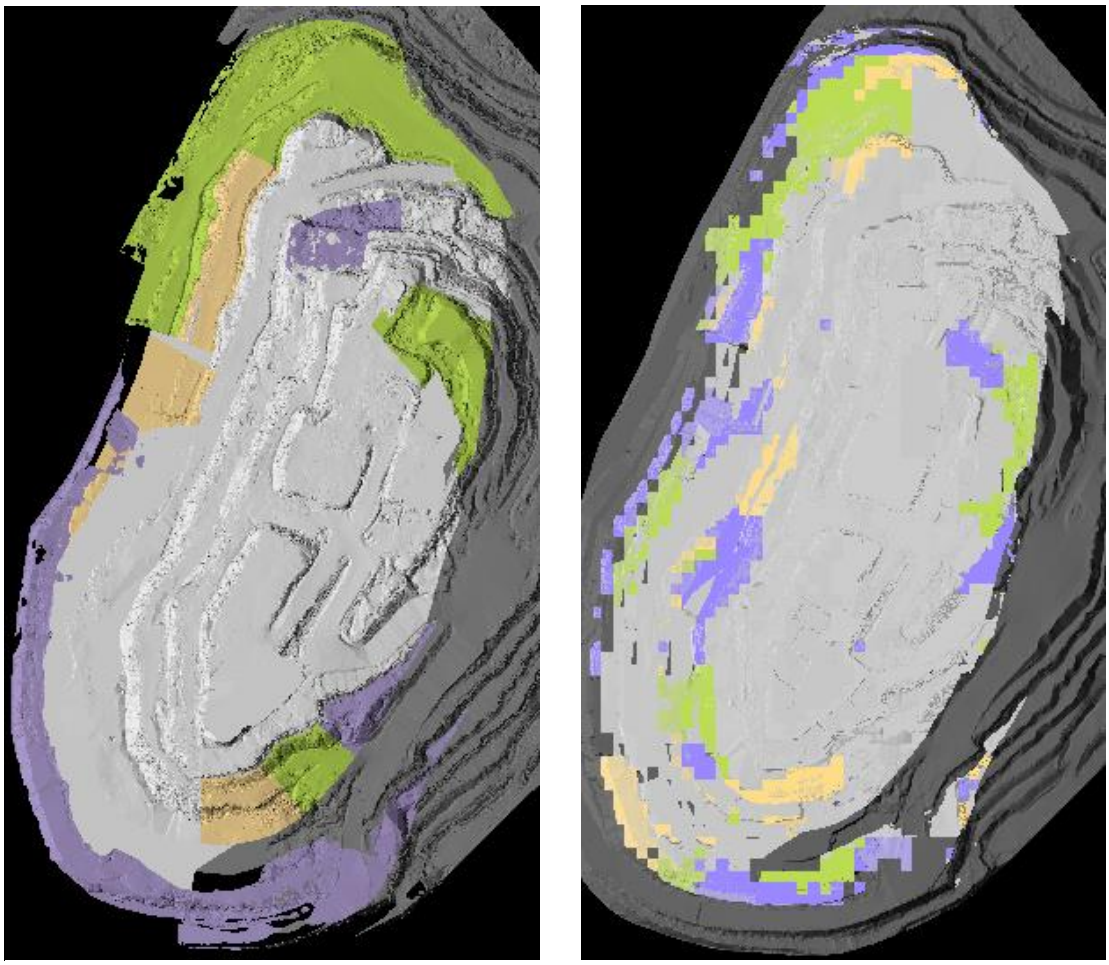

Figure 18 - 2017/Q3plans, Chronos on the left and Evolution on the right (visualized with Block Model Intersections), July in purple, August in green and September in beige

From the production report in the previous sections it is clear that both methods have produced a schedule satisfying the criteria. Looking at the visualization of the schedules in figure 18 above it is obvious that for both methods it is important to have a clean topography, which in the picture manifests itself best in the thin purple sections along the western wall. These sections are part of the final wall and should not be scheduled, and should have been cleaned in both.

Mining areas are fairly similar, which is to be expected. Exception to this is the mining low in the southeast corner, which has been relocated, mostly to the southwest corner.

# 10 Comparing planning approaches

In this chapter the methods are compared with each other. This is done in a SWOT-analysis format (Strength, Weaknesses, Opportunities & Treats). First strengths and weaknesses of each of the methods are discussed, after which the opportunities and threats associated with changing to a method that has Evolution integrated into it are evaluated. In this comparison Evolution will be treated as a one on one replacement for Chronos, for any other tasks that can also be performed see chapter 11.

## 10.1 Strengths

### *10.1.1 Chronos*

Looking at the workflow for scheduling with Chronos, figure 5, there are very few new skills required if the person using the scheduler is familiar with the basic Vulcan program. This low barrier to entry makes it easy for someone else to jump in if the regular scheduler is not available.

Because the picking process is purely manual it is also possible to steer the development in the mine to the precise wishes of the scheduler.

Results from Chronos are good, provided the scheduler sticks with it long enough, because, theoretically at least, there is no limit to the accuracy that can be achieved. Since results from Chronos have their basis in solid triangulations or mining blocks from Vulcan, this will provide the short term planning with all the input required. Thus when the schedule has become acceptable there is little to no work afterward to create the input for short term scheduling.

Chronos does also provide some options for modeling stockpiles, these however have remained unused, and were considered outside the scope for this thesis.

### *10.1.2 Evolution*

Looking at the workflow for scheduling with Evolution, figure 10, the process of preparing input data in Vulcan for Evolution is, much like Chronos, a quick and simple process for someone familiar with the Vulcan program. Further preparations in Evolution itself are also fairly straightforward.

Creating an Origin Setup is a fairly quick process, depending on complexity. Setups can be copied to eliminate the bulk of manual setup that is involved, especially useful if one wants to explore a small change but keep the original.

Since the scheduling is done by on a cloud based server this allows the user to create schedules from several different setups at the same time and while those are being calculated work on something else, since the scheduling algorithm does not put any stress on the scheduler's computer.

From the schedule report, especially the charts section, it is simple and quick to determine if the schedule meets the standards set for it. For a three month schedule this may not be so relevant, but as the amount of periods evaluated increases it becomes unpractical to wade through a table for every schedule.

Inspecting the schedule in 3D to make sure it is practical to mine is also straightforward, especially if some designs are imported as an imaginative aid.

## 10.2 Weaknesses

### *10.2.1 Chronos*

One of the strengths of Chronos is also its inherent weakness. It's not just that the planner gets to make all the decisions, all decisions have to be made by the planner. This can make it a very time consuming process to get the blocks in the proper sequence even if the blocks are cut to the correct size. When the blocks need to be altered, this whole process basically starts over from where the altered blocks fit in the sequence.

It is quite a lot of work to produce a schedule, especially if the periods are short, on a month by month basis for instance. This makes it very difficult to make a detailed plan with a long horizon, for instance a month by month plan for one year. This limitation makes it difficult to evaluate if the medium term plan complies with the long term plan, other that by tonnes and grade measurements. Since the plan is not optimized beyond the horizon for which it is used, it could lead to the operation mining itself into a situation where there is no access to ore.

Results from Chronos are broken down to a set of triangulations for each period, usually 1 month for medium planning, this can leave a lot of freedom for the short term and operational planning, resulting in a different sequence than planned for, which can lead to serious problems in the next period.

Any change in criteria means that the whole process has to start over again, this means that Chronos is really not suited for doing any kind of scenario study.

Finally support for Chronos is coming to an end, which makes it not an ideal product to depend on.

### *10.2.2 Evolution*

The addition of a completely new piece of software brings with it the necessity for new skills to be learnt. Depending on how this is handled by the organization this can lead to dependency on very few or even one person who possess the knowledge required to create a schedule, which could give problems if these people are for some reason not available.

Since the scheduling itself is done by an algorithm it can be difficult to focus on development in specific areas. Development starts at the ramp(s), where the bench can be accessed, this means that the schedule can only be as good as the pushback design. A series of well-designed pushbacks allows for designed ramps to be put in, so that the algorithm can arrive at a good solution. Temporary ramps that are not in the pushback design specifically pose a serious problem, since they usually are near an active face, and are not on a pushback boundary, which means the algorithm has no way to know that it should leave the blocks making up that specific ramp. To take these things into account is not impossible, but requires a certain skill and familiarity level on the part of the scheduler.

Finally, since triangulations are not directly produced as output, there is a fair bit of work involved with going from the Evolution schedule to the input required for the short term planning.

### 10.3 Opportunities

In Evolutions the bulk of the effort on the part of the planner is in preparing, importing and exporting the data. The making of the Origin-Setups is very quick, which allows for many to be created in a short time. Assuming the start point is the same, meaning everything but the Origin-Setup, and the elaborate output for short term planning is not required, a study of different scenarios could be carried out very quickly. Results for this could provide valuable insight for decision making, for instance on the following issues:

- Determining appropriate stripping ratio for the coming year
- Examine effect of design changes
- Evaluating stockpiling possibilities

Furthermore switching over to a system which makes use of Evolution in some capacity will allow for a better integration between the long term and the medium term plan, since it is much easier to plan in quite some detail for a few years ahead, so not only can the goals for the immediate future be assessed, but it is also possible to get to know if goals for the long term are attainable.

### 10.4 Threats

Both input data and schedules coming back need to be thoroughly evaluated. If this is not done there is a risk that decisions will be based on erroneous information. Since Evolution is much more of a black box than Chronos this could easily happen if thorough checks for anomalies are not conducted.

Scheduling with Evolution requires an additional skillset to be acquired by members of the planning staff. Since most members of this staff have no need to use Evolution with any kind of regularity there is the risk that Evolution will only be used by one or two people, which could cause serious problems when those people are not available for one reason or another.

This last threat can be mediated by training more staff members than strictly necessary to use the software, building some redundancy within the planning department. This should be accompanied by a combination of instructions and manuals, so that out of practice staff members have something to refresh there memory when the time comes. Furthermore there is also support available from Maptek both for training purposes and to resolve scheduling problems.

# 11 Other features in Evolution-Origin

Besides the basic tonnes and grades planning within the pit there are some other options in Evolution that can be used.

## 11.1 Haulage optimization

Haulage is one of the big costs within any open pit mining operation. It is estimated that haulage account for around half of the costs of a surface mining operation (SRK, 2015) (Craig, 2014). This means that if improvements in haulage are made this can have a big impact on the operation.

If instead of the Material Movement the Equipment option is selected when choosing a schedule the scheduler will try to optimize the schedule in such a way that the fleet can handle the material that needs to be moved. Of course this requires much more input data than the Material Movement option. Data for both the haulage and loading fleets needs to be put into the setup, as well as the haul roads that can be used and the different waste dumps that are available. An overview of the waste dumps and imported haulage network can be seen in figure 19 below.

The resulting schedule will contain data on grade and tonnes for each period but also provide data on trucking hours required, number of trucks that are needed, fuel consumption and total haulage costs. It does this both for the entire operation, but also split out by destination.

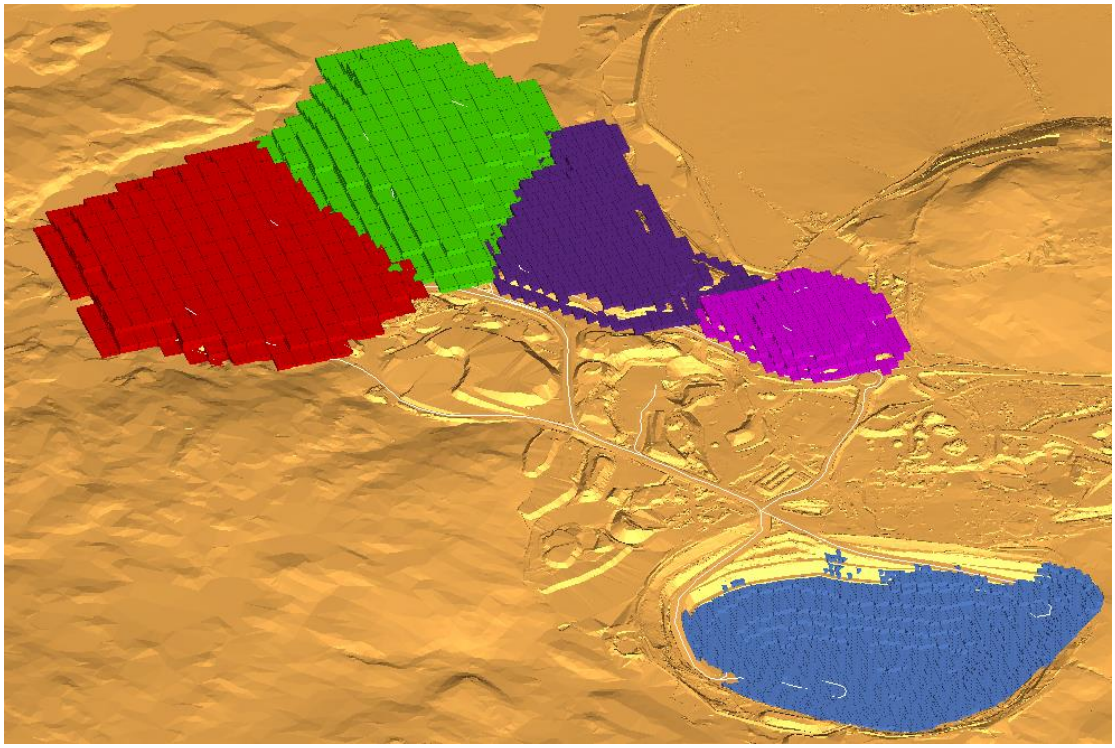

Figure 19 - Haulage setup, with the pit in blue, low grade dumps in pink & purple, waste dumps in red & green and the haulage network represented by white lines

## 11.2 Waste dump development

The optimization of the development of the waste dump goes more or less hand in hand with the optimization for haulage, since it is not possible for the software to determine the best way to fill the waste dump if it has no information on the routes the material can take to get there. (Craig, 2014)

To illustrate the impact just the waste dump development strategy can have three development scenario's will be evaluated. Five waste dumps were designed to test the haulage function of the scheduler and these will be used to illustrate the difference that can be made.

All scenario's will make use of the same 2 low grade waste dumps where all waste material with iron grades of 21% and higher will be sent, these dumps will be filled identically all the time and will therefore be left out of any further analysis.

There will be two scenario's using 2 waste dumps for any other waste, both of which will be replaced in the third scenario by one big dump that was designed to build up the final slope permitted along the property boundary, so reclamation can start earlier. The 2 scenarios with identical dumps will use a different development strategy, while in one it will be completely up to evolution to determine development, the other scenario will be developed level by level. Properties where the scenarios differ are also displayed in table 3 below.

To make sure only the development strategy is evaluated the hour stamp feature is used, which means that the development in the pit is predetermined and therefore identical in all scenarios. This schedule is 24 months long, and therefore this will be the timespan evaluated. The haulage fleet consists of Caterpillar 793F trucks, at 70% availability and 70% utilization. Production was set at 1.6 Mton per month, of which 750 kton ore.

Table 3 - Waste dump development scenarios

| | Waste (Fe <21%) | Development |
|---|---|---|
| Scenario 1 | 2 dumps | Level by level |
| Scenario 2 | 2 dumps | Evolution |
| Scenario 3 | Boundary dump | Evolution |

As can be seen in table 4 and figures 20 & 21 on the next page there is quite a significant difference in the haulage hours and fuel consumption associated with each scenario. This same sort of effect has been seen in other operations as well (Craig, 2014).

Table 4 - Waste dump optimization results for 24 month run

| | Fuel burn (liter) | | Total haulage hours | |
|---|---|---|---|---|
| | Total | Waste | Total | Waste |
| Scenario 1 | 12,027,658 | 5,606,361 | 60,827 | 31,432 |
| Scenario 2 | 11,290,492 | 4,869,195 | 57,935 | 28,540 |
| Scenario 3 | 11,884,887 | 5,463,590 | 59,986 | 30,591 |

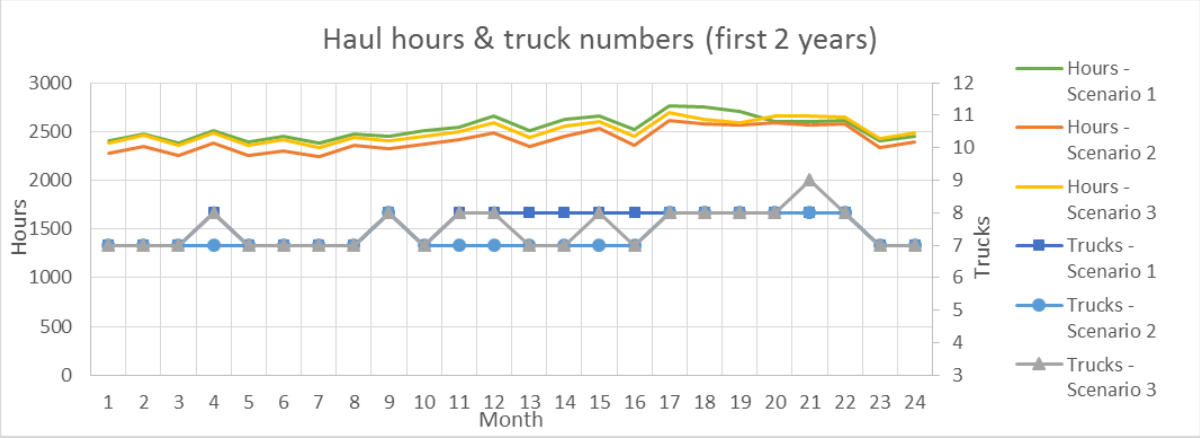


Figure 20 - Trucks numbers and Haul hours per scenario

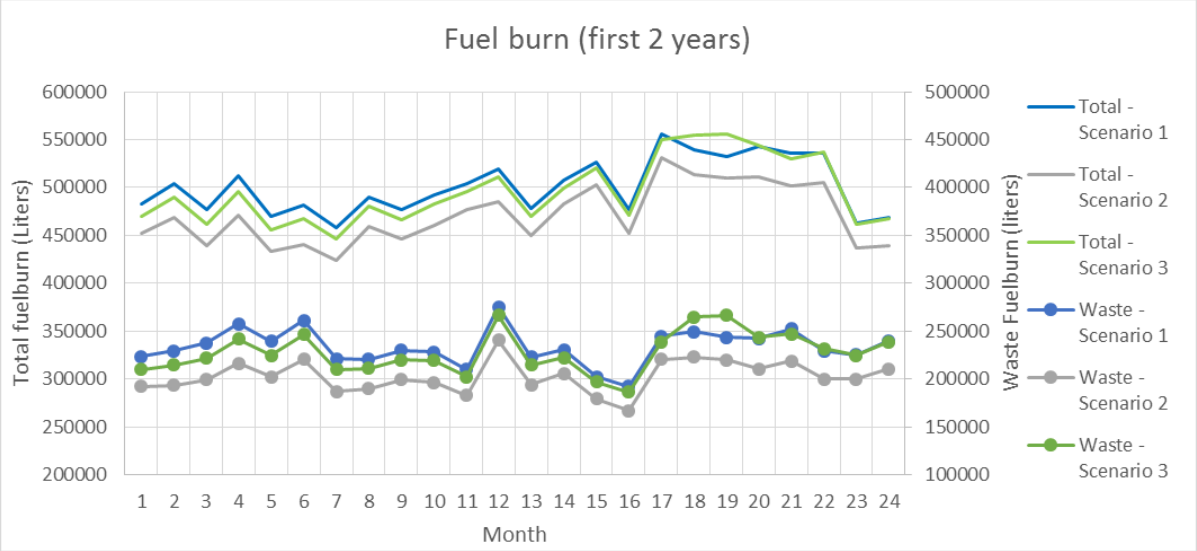


Figure 21 - Fuel burn in total and for waste only for each scenario

This of course is all well and good but needs to be verified against some measured data, this can be seen in figure 22. At the start of the Leveäniemi project, when the current trucks were bought a fuel burn estimate was made by Pon, who would supply the machines. This predicted an average fuel burn of 180 liters per operating hour for the Caterpillar 793F.

Data gathered by the maintenance department from refueling from the first half of 2017 suggests that fuel consumption is 123 liters per operating hour respectively, this is averaged and rounded to 130. These numbers are based on total fuel burn and 400 operating hours per month for the nine trucks that are present. In order to compare this with the data from Evolution it is necessary to account for this by dividing the total fuel burn not by the Evolution operating hours, but by the 3600 assumed by maintenance instead.

For the data from Evolution the setup from scenario 1 (level-by-level development) was altered to resemble production during the time that fuel data was collected (1330 kton/month total, 450 kton ore). The comparison is shown in figure 22 below, where it can be seen that Evolutions estimate is very close to the estimate made by Pon when the project started. Comparing against fuel data from maintenance resulted in a lower fuel consumption predicted by Evolution when recalculating to 9 trucks, this can be explained by the fact that the trucks in reality are also used to carry screening waste from the crushing station to the waste dump, which is not modelled. Accounting for this by instead recalculating to an 8 truck fleet results in a pretty accurate prediction, however before significant stock is put into these numbers a detailed validation should be carried out.

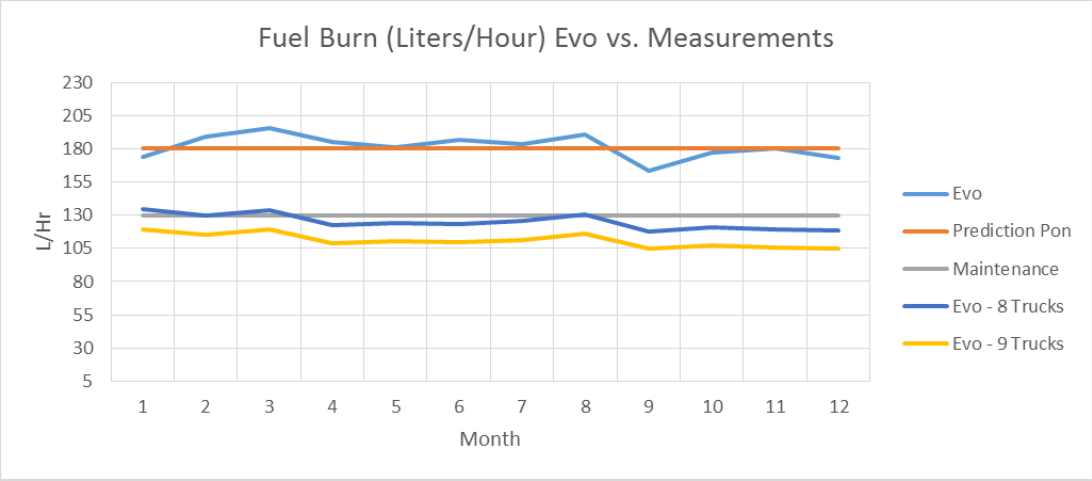


Figure 22 - Simulated fuel burn from Evolution plotted against initial estimate and measured data

### 11.3 Haulage network optimization

When considering possible layouts, or changes to the layout, of the haul road network, these alternatives can be put in to an Origin-Setup, much like the different waste dump options in chapter 11.2.

If this is combined with a cost estimation for constructing the different alternatives it will give a good basis to judge the alternatives on a cost-benefit basis.

### 11.4 NPV optimization

It is possible to input cost data associated with the mining project, which will lead Evolution to rank the schedules it makes on Net Present Value as well. This option can be applied in combination with any other objectives that may be set.

With the detailed planning horizon for Chronos on about 3 months and the project already up and running, the opportunities of this feature were not explored any further. It is however important to note that it is possible to make use of this function, which could be useful for schedules looking further ahead, more towards the long term side of things.

# 12 Conclusion

First objective of this thesis work was to verify that it was possible to use it to produce a schedule for LKAB Svappavaara which not only delivered acceptable tonnes and grade for each schedule period, but was also possible to mine. From the side by side comparison it can be concluded that this is indeed possible to do this and obtain a schedule with a similar quality to the current method.

Secondly, after comparing both methods it can be concluded that although there are certain drawbacks to using Evolution, these are quite minor and manageable in comparison to the benefits that can be gained by using it, most notably the ability to plan further ahead with little to no extra work. This makes it possible to achieve a better integration between the long term and medium term plan.

The major secondary benefit is that the amount of repetitive manual work, the cutting and re-cutting of blocks, is greatly reduced. Even if blocks are cut at the end of the process in order to aid the short term planning the number of iterations for cutting is reduced down to one, since the area's that need to be planned are taken from the Evolution schedule.

Besides replacing Chronos it was demonstrated that there are also some things that can be done using Evolution that are not possible using the Chronos module. These include optimization on haulage and net present value, as well as scheduling the development of waste dumps. From what has been demonstrated it can be concluded that there is a possibility to achieve significant benefit using these extra functions.

# 13 Discussion

## 13.1 Limitations

This research is limited to the investigation of only on alternative to the current process. This was inherent to the setup of this project, since it was meant to investigate the potential of a readily available but currently unused alternative.

## 13.2 Recommendations

For Leveäniemi a trial phase is recommended, where the medium term planning will be done in Evolution, the solid triangulations cut for short term planning, after which they are verified by Chronos or the Vulcan Advanced Reserves module, to make sure that the planning criteria have been satisfied.

## 13.3 Opportunities for further research

### *13.3.1 Evaluating other software*

In this research we only examined one alternative, since it was readily available. In order to be sure this is the best alternatives, alternative products will also have to be looked in to. As stated previously there are other scheduling software packages on the market. Comparing some of these could provide valuable information on their relative performance.

### *13.3.2 Exploring other features in more detail*

In this research we have identified a number of features in Evolution, which have the potential to be very beneficial. These include optimization on haulage and net present value, as well as scheduling the development of waste dumps. Because of time and focus considerations theses have not been explored in great detail.

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