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Ore Pass Design and Placement

Master's Thesis
European Mining, Minerals and Environmental Program

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Abstract

A current trend in mining is towards lower grade deposits when easy to access mineral deposits are depleted in the world. Therefore, to make the current deposits accessible, a cost of mining need to be economic. Costs can be decreased in equipment and mine planning to maximize the availability and utilization of equipment for example by decreasing travelling and hauling distances in daily production. Ore passes are one of the possibilities to decrease hauling costs when mine is evolving the greater depths.

Ore pass design and placement is conducted using modified Bieniawski's design strategy for rock structures. Thesis studies in detail all parameters affecting to the ore pass design and placement. With the strategy and data available from mine and literature, a case study for Kittilä Mine had been carried out.

Data collection from literature review and data acquired from the mine site was made and applied in the Bieniawski's design strategy. Production related factors were weighted more in the design process in order of mining to assess the ore pass design and placement. The location and design of the ore pass were optimized using a state-of-the-art technology and best practices in combination with mathematically optimized location.

Via strategy it was possible to identify the project risks, technical viability and feasibility of the ore pass project. Case study shows that via applying the design strategy it is possible to show that mine can benefit from using ore passes in its operations and that ore passes are financially viable solution if ore passes can be operated the way presented in this study.

Preface

The topic of ore pass design and placement was given to me after having practical internship in Kittilä mine in the spring of 2016 and later discussions in the fall of 2016. This topic was an interesting combination of optimization and design. It has given a great insight to mine production statistics and how to apply this data in daily mine management and planning.

I would like to thank my university supervisor Prof. Mikael Rinne for enabling the chance to cooperate with Kittilä Mine. Big thanks goes also to Andre van Wageningen, Manager of Technology and Development who was the original author to define the Master Thesis topic.

Great thanks goes to my thesis supervisors Elen Toodu and Kyösti Huttu who allowed me to acquire all the mine data I was willing to use in my thesis and put me to work in daily operation of the mine – giving me many practical ideas concerning ore pass operation.

I would like to thank other staff in Kittilä Mine as well. During my works, I got a lot of help in rock mechanics from Rock Mechanics Engineer Antti Pyy and Marc-Antoine Bealieau from Agnico Eagle Technical Services who came all the way from Canada to teach me HaulSIM software.

The thesis was able to define the ore pass design and location for the ore pass(es) to Kittilä mine and I hope it has given new ideas and help to Kittilä Mine to achieve its future development plans.

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Definitions

Capex = Capital expenditure
C.O.G = Center Of Gravity
DEM = Discrete Event Modelling
CMS = Cavity Monitoring System
LOM = Life of Mine
MSHA = Mine Safety and Health Administration (USA)
NPV = Net Present Value
Opex = Operating expenditure
Ore pass Longevity = Overall ore tons through the pass during its life time
PFC = Particle Flow Code
ROM Ore = Run Of Mine Ore
TKM = tonne-kilometer
TP1 = Footwall Drive 1, towards north (*In Finnish: Tasoperä 1*)
TP2 = Footwall Drive 2, towards south (*In Finnish: Tasoperä 2*)
Underground ore movement = Transportation process from blasted ore to surface

1 Introduction

1.1 Background for research

A current trend in mining is towards a lower grade deposit when the easy to access mineral deposit is depleted in the world. Therefore, to make the current deposits accessible, the cost of mining need to be at an economic level. Common ways to achieve lower costs of mining are increasing productivity by optimizing the mine planning, equipment and operations. This means in terms of equipment and mine planning to maximize the availability and utilization of equipment for example by decreasing travelling and hauling distances in daily production.

Ore passes are one of the possibilities to decrease hauling costs when mine is evolving to the greater depths. Via help of gravity, ore can be transported easily from production level to another. In addition to hauling costs, well designed ore passes can decrease operating costs and increase productivity. Ore passes ore often built in combination of a shaft to achieve the benefits of vertical ore transport. Selective sub-level longhole stoping mines have challenges due to relatively high mining cost and therefore one way drifts are used for access the ore body. Therefore, haulage ways in the underground mine are often a bottleneck of the production. To facilitate the productivity, this bottleneck can be avoided using ore passes.

Documentation of ore pass design and placement is poor and often the complexity of the ore pass system design is underestimated. That can be seen from many publications of ore pass failures and disappointment in meeting the design criteria. Also, new technology especially related to equipment automation and full autonomy increases the numerous ways of applying ore passes to mine production.

Kittilä mine has the previously mentioned characteristics and mine is willing to evaluate the potential of ore passes in future production. Mine has a production rate of 1.6 Mt/a and is advancing to depths nearly 1 km. Mine has future study on-going to evaluate the potential to increase the production to 2 Mt/a and is seeking new ways to be able to achieve the target. One part of the plan is to utilize ore passes.

1.2 Research problem

The research problem is defined as a multi criteria problem. Vast amount of design parameters is influencing to the design and placement of the ore pass. Part of this study is to identify these parameters and create a competent ore pass design and placement strategy for answering following question:

"*Can the growth of haulage costs be decreased in a mine while mining advances deeper in the orebody by optimizing the number, location and operation of the ore passes by using a state of art ore transportation technologies and practices?*"

1.3 Research target

The target of this thesis is to verify ore pass design using state-of-the-art technology. The target is to give recommendations about number and the type of ore passes Kittilä Mine can use in future. The thesis also collects the best practices to operate ore passes and highlights the benefits of ore passes. Benefits expected to have with competent ore pass design and placement are a decrease in haulage costs in terms of tonne-kilometers and higher productivity of the hauling system.

1.4 Limitations of research

The thesis is limited to underground ore transport from fragmented ore in the stope to the underground crusher. Research is done using various sources, academic papers and industry publications to create an overall picture of factors influencing ore pass design and placement. Further, data available in Kittilä Mine is used to assess this knowledge to create a case study where ore pass design and placement procedure is created. There is no practical data collection or laboratory analysis made. Only data available from the mine and geological or geotechnical assessment made by different authors is used in this thesis.

2 Literature Study

2.1 Underground ore movement technology

The underground ore movement technology plays a significant role in underground mining and has a great economic influence to the mining operation. Ore passes can be a part of this underground ore handling process. The ore pass being a part of this ore movement chain has an influence to the process and its influence on other steps is evident. Possible ore handling processes occurring in the thesis are broken ore hauling after a mine development and production blasting, tipping to the ore pass, crushing, hauling on haulage level and ore transport to the underground crusher. In addition to ore, also waste handling can be done through ore passes being transported within the same rock pass system or as a diversified system with a separate waste rock passes and ore passes.

For the performance of the mine, it is important to create an ore-handling strategy for stabilizing the production variability, reduce unexpected costs and increase the adaptability to changing operating conditions such as metal price fluctuation. An important simple concept of ore handling strategy is the value chain of the mining system. While the ore is moving forward in a handling process it turns to a new value state after every process step. Before every process step there can be an upstream buffer (i.e. stockpile) and after the process. a downstream buffer (i.e. storage bin). Purpose of the buffers is to provide surge capacity, limit the influence of the process on each other and therefore reduce variability in performance. Evident part of the strategy is to identify the bottleneck of the handling system and design the capacities of the process steps based on the bottleneck, being the step with the lowest rate of production. A simple rule of thumb for designing the bottleneck is to locate it to the process where the capital cost per ton of incremental ore is greatest. This rule must not be taken as a certainty because the limiting factor might be outside of the underground handling process and it also depends on the design of the whole mine. (Darling 2011, p. 1271)

2.2 Ore pass

Ore passes are inclined or vertical shafts between (sub-) levels in a mine. They provide a low-cost vertical ore transportation route where ore is transported with help of gravitational force. Therefore, the major cost of ore pass operation is the initial capital cost to excavate and build the ore pass system whereas operational cost stays at relatively low level. Ore passes are called rock passes, especially when a waste and ore is transported in the same pass. Dictating driving force towards ore pass systems is demand to increase the efficiency of the underground ore movement system. Thus, the main design and location principle is to minimize the operating cost of the system.

Ore passes are used in mines where it is considered that normal hauling truck operation has too high operating cost when long level distances are limiting the capacity or overall mine hauling capacity is not efficient enough. Ore passes are suitable for high tonnage underground mines which are creating significant, continuous ore flow or wide orebodies where level distance is high or when mining occurs in depths using hoisting shaft. The best suitable mining methods for ore passes are massive caving methods such as block caving or longwall mining, but also other mining methods become feasible in depths, especially if metal ore is extracted. Additionally, ore passes are often beneficial in mines where continuous or semi-continuous transportation system such as conveyors or hoisting shafts are used. This means that when the high capital cost, massive and fixed transportation system is used, it is convenient to maximize the utilization rate and have benefit on its low operating costs by directing all possible ore movement through a conveyor/hoisting shaft via ore passes. Ore passes bring benefits in reduction of hauling traffic and can be considered as a benefit, because the need for truck hauling related infrastructure decreases and less intensive jamming increases productivity. Also, shape of the orebody is always affecting whether proceed towards the ore pass system or not. Having a vertical connection between different mining levels, it is more feasible when the orebody is pipe shape or massive where all production areas are near the centerline of the orebody. In more dispersed orebody, shallow or tabular, the profitability of the ore pass system is lower when distances from production areas are too long and high throughput of the ore pass cannot be maintained.

2.3 Ore pass system

Ore passes can be built as one single long section or by building numerous vertical sections. Typically, multiple ore passes are built based on the development and timing of access to the mine. Especially where orebody geometry is irregular or horizontally wide, ore passes are typically constructed as a network of multiple sections which are interconnected. Interconnected ore passes forms an ore pass network system where the ore pass is built through multiple levels and from levels, a finger raise connects the level to the ore pass system (Figure 6). The flow in individual sections between levels can be controlled with gates, chutes or chains. In addition to finger raises, it is possible to connect separate ore pass systems with hauling equipment, conveyors or feeders.

Ore passes can come in different extents and different arrangements. The number of ore passes and ore pass arrangement is dependent on excavation method of the ore pass, orebody geometry, location of the infrastructure, hauling equipment and production rate of the mine. Multiple ore passes are increasing the production reliability thus increasing development costs. With placement of underground crushing system and haulage level, the adaptability of the ore pass system can be increased if the ore body is horizontally wide.

Lessard et al. have identified three typical ore pass configurations (Figure 1). An ore handling system can be located near a shaft, distance away from the shaft or close to the mining activities. Near the shaft, placement has the benefit in transportation distance between crusher and the loading pocket is short as possible, but distance to production area is longer. The major disadvantage is the risk to cause negative impact to the integrity of the surrounding host rock around the shaft. Locating the ore pass away from the shaft is decreasing hauling distance from the stopes to the ore pass. This configuration results in a long haulage distance between ore pass and loading pocket. This means that often ore is crushed after ore pass and hauled by horizontal transportation method such as conveyors. The greatest disadvantage of the arrangement is the increased infrastructure and maintenance due to transportation necessary between crusher and loading pocket. Last option is to excavate a hauling level to a fixed depth. It enables mine to operate multiple ore passes and extend the ore pass network in a horizontal direction. Option increases production adaptability and reliability but also development costs are higher. Haulage on the haulage level can be carried out with different methods such as hauling trucks, conveying or rail haulage. (Lessard, Hadjigeorgiou 2003)

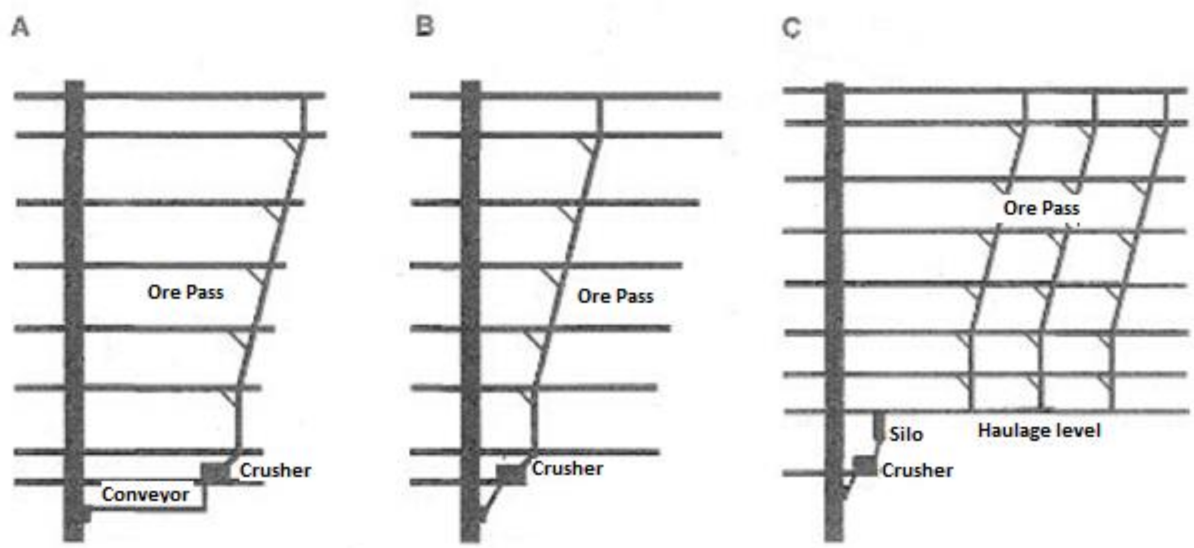

Figure 1 Ore pass system configuration with finger raises after Lessard (2003)

Ore passes can be dual systems as well. The usage of dual system means that mass flow of waste rock and ore is diversified. Therefore, separate passes are built for waste and ore, resulting in a higher capital cost and more complex operation but potential to reduce operational costs. That means a lower hoisting and transportation cost because only ore is transported to the surface. It also reduces the energy consumption when underground crushing is used because the feed to the crusher does not include waste rock which is neither crushed nor hoisted. Waste pass system often leads to the rock breaker whereas ore pass ends to a vicinity of crusher or haulage level. Waste passes can be also advantage when mine is willing to maximize the waste rock dumping to underground. The waste pass creates a surge capacity which can be used to delay the waste rock delivery to the stopes to be rock filled. Different material parameters between ore and waste must be considered in dual systems. To keep the production security, redundant ore passes can be built for production stability and making sure that the rock flow from blocked ore pass can be directed to the redundant pass and no production delay occurs.

2.4 Excavation of ore pass

A major categorization of excavation methods is to distinguish them into a continuous excavation method or method using conventional drill and blast cycle. Simply, continuous methods (i.e. raise boring) gives smooth walled, round cross sectional ore passes whereas other method’s result can be any shape but the wall surface is rough and fractured due to blast damage. In excavation advance, continuous method is superior.

Operational aspects influences the decision of the excavation method and equipment selection. Transportation of equipment, size of access and number of personnel influences the selection in the production areas of underground mine. In limited space, dimensions of equipment might become the limiting factor. Operational vice, equipment for ore pass excavations can be used alternatively for other construction works like construction of ventilation raises. Depending on the production rate, high capital costs of raise boring equipment cannot be justified if the utilization rate is too low. System capacity, such as maximum dimensions and penetration rates needs to be considered while choosing the best alternative. Data about ore pass construction methods is not widely collected or generally distributed but few studies about excavation methods and ore pass dimension in Canadian Mines have been made (Hadjigeorgiou et al. 2004b, p. 809).

Costs and safety aspects of rock pass excavation methodology have been researched by Sachse et al. Selection of excavation method is valuated amongst other things through safety, cost and risks. Excavation method can be also dictated by local expertise to specific method or to an equipment which is already available in the mine site. (Sachse, Westgate 2005, p. 759)

There are four major excavation methods of excavating a raise. These are:

1. Conventional raising
2. Drop raising
3. Alimak
4. Raise boring

Conventional raising refers to a conventional drill and blast method where specific cross sectional area is blasted sequentially, advancing downwards. Method is simple but in passes with small cross sectional area, mucking and charging becomes challenging. A tiny working site makes the method slow and mucked material need to be hoisted from the bottom of the pass. Because of the dimensional limitations, ore pass excavations using conventional raising is uncommon.

Drop raising is a method which need access to the top and bottom of the pass. In literature, it is often called long-hole method. First phase box-hole is drilled downwards to make a connection between top and bottom of the pass. Later, charging and blasting is done sequentially upwards from the bottom. Blasted rock drops naturally down from the pass. Inclination of the pass is limited to be at least around 45 degrees to guarantee the removal of blasted rock. The method is limited by the length of box-hole – increasing length decreases the accuracy of the method. Drop raising can be considered as a non-optimal one for an ore pass excavation due to absence of ground support and disturbance of the blasting (Lessard, Hadjigeorgiou 2003).

Alimak raising is using conventional drill and blast method with a lifting cage to construct an ore pass. In conventional drill and blast method, cross sectional shape and dimension can vary a lot, making method very adjustable. Compared with boring methods, working safety is relatively low. Raising technique in Alimak contains a cage which is driven in rail. A blaster makes full drill and blast cycle travelling along in the cage. The operator drives the cage from down to the face of the raise, drills and charges the overhead blasting holes and drives back down. After blasting operator drives back to the blasted face, scales and installs rock support. The cage has a roof to protect the operator from falling rocks. Advantages of Alimak method are the unlimited length of raise, low capital costs and adaptability to different cross sectional shapes. The greatest disadvantage of method is the influence of blasting. Blasting creates fractures to the intact rock and weakens the pass wall. In weak rock and high rock stress situations it results in increased wall degradation. Rough surfaces after blasting restrains the flow of ore in the pass and therefore decreases the efficiency and increases the risk for blockages.

Raise boring is continuous excavation method. It includes many different configurations to drive a shaft. It can be done in a full profile raising between levels like in the box-hole boring or by using blind boring the hole downwards between levels and if necessary reamed to a full profile or using normal raise boring with a pilot hole. In normal raise boring method, in the first phase, the pilot hole is drilled and later reamed to a full size. Boring methods are very efficient and create a smooth surface to the walls of the ore pass, creating better material flow conditions and wall stability. Greatest limitations in the boring equipment are the relatively high capital costs and equipment dimensions. The demand of site preparation for the equipment is extensive compared to blasting methods. (Heiniö M. 1999, p. 283)

A lot of ore pass projects are done by using empirical knowledge, but little documentation about design parameters, construction or excavations exists. Some data can be found from Canadian and South-African mines. Statistically Alimak method is the dictating method for ore pass excavations in Canadian Mines. In Quebec region, 63% of driven ore passes have been made with Alimak raising and only 3% were bored. Usage of Alimak had been chosen because of the reasonable level of safety, simultaneous installation of rock support and Alimak being one access method. It must be noted that influence of local expertise is hard to evaluate to the selection of raising method. (Hadjigeorgiou et al. 2004b, p. 809)

Depending on rock type and conditions, rock support is necessary in the construction phase and in the operation phase if rock stresses and the quality is not competent. In the excavation phase, ore passes might need support installation to keep the walls of the ore pass stable and in the blasting methods for maintaining personnel safety. Especially in Alimak method, simultaneous installation of rock support downsizes the overall construction time of ore pass because the same support can be used as a final support (Hadjigeorgiou et al. 2004b, p. 809). Common rock support types in the Alimak method are bolting and shotcreting. Boring methods, being low impact method to ore pass wall stability, enable the installation of rock support after raise boring. In the excavation phase, normally there is no need for rock support in the ore pass due to a small diameter of the ore pass. In deeper mines, stress state causes rapid development of “dog earing” after raise boring and simultaneous shotcreting have been proposed as a solution (Vieira, Durrheim 2005, p. 785). Occasionally, depending on the design criteria of the ore pass, the bored ore pass can be operated without significant rock support.

2.5 Location parameters of ore pass

Location of the ore pass is a compromise between the quality of the rock mass and operational parameters. Principal design criteria are the minimization of operating costs by minimizing hauling distances and maximizing the ore flow of a single ore pass. After selecting the optimum location, it is important to check that it fulfills the other parameters such as rock mechanics. There are multiple examples where logistically optimal location has led to production problems and very high maintenance costs due to bad design and rock mechanical issues. Parameters related to the rock mass quality are straight related to geology. While locating the pass, it must be noted that often long vertical passes are intersecting multiple geological zones or characters and therefore one optimum location cannot be found.

2.5.1 Geology

Geology of the deposit and mining area has influence to the ore pass design and placement. In the placement of the ore pass, local geological features should be considered. Major geological characteristics such as rock type, jointing, shape of the ore body, fault zones and possible foliating dip are important factors when locating the ore pass.

Rock type defines the overall strength of the surrounding rock and the basis for the design criteria. The ore pass should be placed in a location of competent rock. Jointing, foliation dip and fault zones influence on the longevity of the ore pass. Fault zones should be avoided completely, especially if the ore pass is desired to have longevity. Jointing and foliation dip should be considered in the orientation of the ore pass – it should be orientated close as possible to perpendicular to the foliation dip or the joint set direction, to prevent significant degradation. Often selection of location is dominated by production factors and support and lining materials can be used to compensate non-competent geological features. To limit the influence of geology, rock mechanical measures and core sampling data are good sources to log the potential area. For example, Stacey et al. claims that the quality of the rock mass has the most significant impact on the performance of the ore pass. (Stacey, Swart 1997, p. 13)

2.5.2 Rock mechanics

Rock stresses in combination with geological structures defines the design parameters and final placement of an ore pass. Stress state, rock strength and jointing are important rock mechanical factors to predict the stability of the ore pass. Higher stress state requires more rigid support to prevent harmful deformations and degradation of the walls. Mine works, including vibration, air blasts and deformation induced stresses have an adverse influence on the structure of the ore pass. Other factors influencing on the stability are water inflow and sometimes acidity and salinity of ground water promoting the corrosion of steel rebar and other type of bolt support. To define the rock type and the strength of the rock, drill core sampling and laboratory tests should be carried out to get an estimate for the rock mechanical behavior of the rock mass.

Rock stress causes deformation to the ore pass walls resulting in deformation of the ore pass. Deformation appears in dog earing phenomena (Figure 2) where the cross-sectional area begins to convergence in direction perpendicular to the principal stress. Deformation leads to spalling, a falling of free blocks and scaling of the ore pass wall. Therefore the stress-state is one of the factors defining the level of rock support.

Figure 2 Dog earing occurs in high stress conditions (Hadjigeorgiou, Mercier-Langevin 2008b) and (Hart 2006)

In literature, different rock mechanical parameters have been used for a design or analysis parameters for rock passes. Generally, rock stress, Q-system (Barton et al. 1974) and rock mass rating (*RMR*) (Bieniawski 1989) are probably the most common parameters which have been used for characterizing the rock mechanical state of the ore pass. Also, other raise and ore pass related factors have been used. For example, Esmaeli et al. (2010) have used Raise Stability Ratio (RSR) and McCracken et al. Q-rating (1989). Also, a study of deep mine rock passes by Joughin et al. used (2005) Rockwall Condition Factor (RCF) to characterize current rock mechanical situation in an ore pass.

Another parameter for ore pass rock mass analysis is the Bieniawski's RMR-rating. That is a generally known rating parameter to define rock mass quality in mining and tunnel engineering and there is a relation between Q-rating and RMR-index, but changing Q-values to RMR and vice versa, should be avoided because these values are not based on the same assumptions. (Bieniawski 1989) . Joughin et al. (2005) for example have evaluated rock pass degradation rates by using rock stress and RMR values. He found that RMR value lower than 80 seems to be threshold value for deterioration in the performance of the ore pass.

This research will assess the risks of ore passes and define other rock mechanical design parameters such as the longevity of the ore pass based on the most common rock mechanical parameters. Q-rating values are used in this study because these parameters are commonly used in mines and easy to acquire and compare with other studies and data sources. RMR- and Q-systems have been used in combination of both parameters in recent research of ore pass longevity (Hadjigeorgiou, Mercier-Langevin 2008b).

Few studies about effect of stresses have been carried out. These studies imply that in some specific rock conditions stresses have great influence on ore pass longevity. Studies have concluded stress analyses using linear-elastic and elastic-plastic models (Sjoberg et al. 2003). The studies imply that for wall degradation, induced tangential stress to the ore pass walls has influence on the stability. Martin et al. (1999) have found the same conclusion who found that fracturing in an underground opening occurs when maximum tangential stress exceeds 0.4 of the uniaxial compressive strength. Moreover, impact of stressing and destressing phenomena due to the extraction of ore is increasing the degradation in terms of falling destressed rock blocks and wedges.

To define the in-situ stress state, the magnitude of horizontal (σ_h) and vertical stress (σ_v) needs to be measured or modeled to calculate the direction and magnitude of principal stress (σ_1) in the location of the ore pass. Based on maximum stress (σ_{max}) and ratio of rock strength (σ_c) Hadjigeorgiou et al. (2008a) have created a design chart based on ore pass data collected by (Stacey, Swart 1997). Data from multiple countries including Canada, South Africa and Sweden, have been plotted in a rock stress vs. ore pass tonnage chart. Chart expresses the relation between ore pass support and stress state (Figure 3). This chart is also a basis for the Ore Pass Longevity Index, discussed in Chapter 2.6.1.

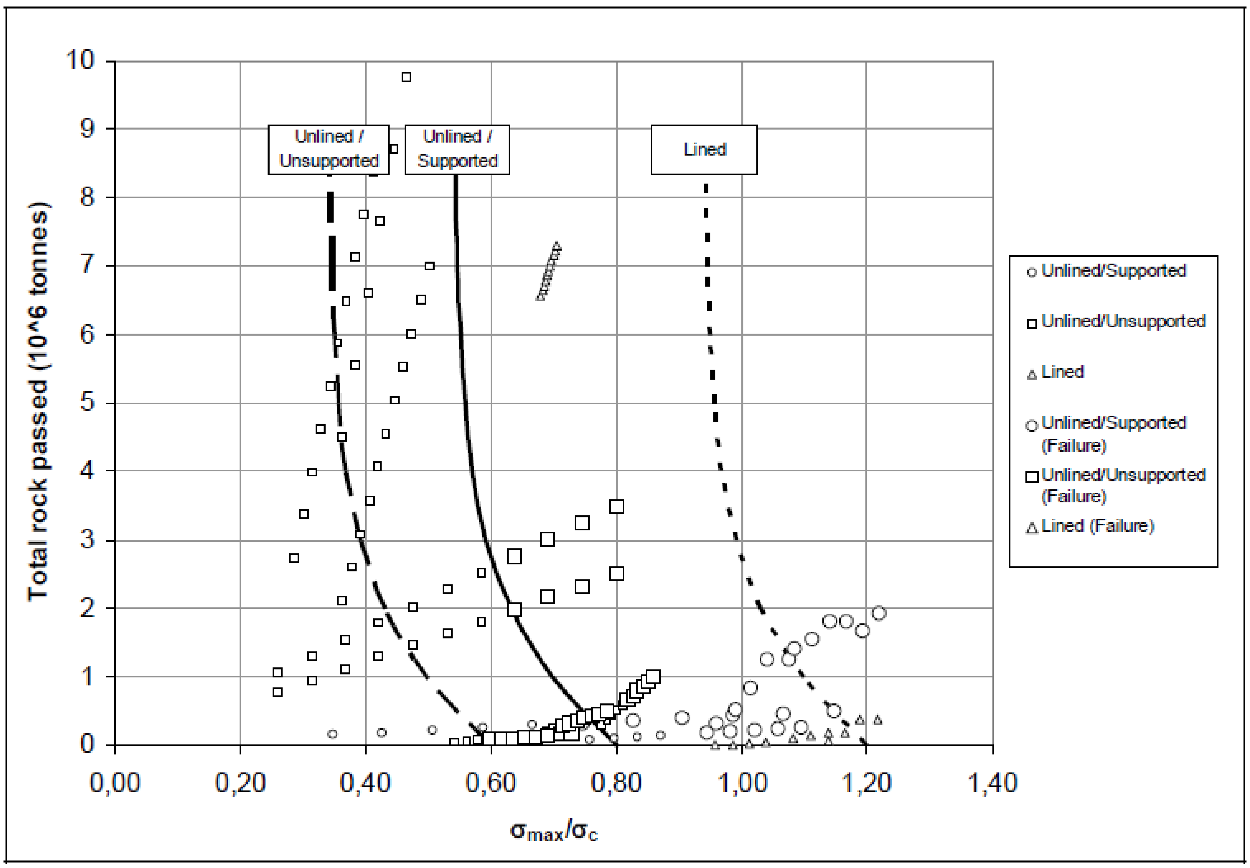

Figure 3 Ore pass stress state versus tonnage (Hadjigeorgiou, Mercier-Langevin 2008a, Stacey, Swart 1997)

Q-system and its Q-raise wall stability modification is commonly used to describe rock mass quality. It combines information from six different parameters which includes information about rock quality, jointing and stresses. In Q-system, Rock Mass Quality Q is defined:

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF}$$

Where,

RQD = Rock Quality Designation
J_n = Joint Set Number
J_r = Joint Roughness number
J_a = Joint alteration number
J_w = Joint water reduction factor
SRF = Stress Reduction Factor

The equation can be sub-divided further to three classes:

$\frac{RQD}{Jn}$ = Size of intact rock blocks
$\frac{Jr}{Ja}$ = Shear strength along the discontinuity planes
$\frac{Jw}{SRF}$ = Stress environment on the intact rock blocks

Multiplication of terms results in the Q-parameter. Value of Q-rating is in a logarithmic scale between 0.001 and 1000, greater value indicating better rock quality. Q-system characterizes the rock mass quality, combining information from multiple parameters. Not only Q-value is used, also support recommendations are made by using only the sub-terms which can be used for assessing wall stability for example when Qr value is calculated.

Values greater than five (Q > 5) has been identified to protect from uncontrolled ore pass failure in 10 underground mines studied by Hadjigeorgiou et al. (2003). In contrast, Smith et al. describes in a case study from East boulder Mine that three ore passes were excavated to a rock mass Q-rated below three. None of these ore passes were operation after two years, these ore passes failed due to kinematic wedge failures. (Smith et al. 2006)

For bored raises Qr-value is used to characterize the rock quality and can be applied for the ore passes. Qr value was developed by McCracken et al. (1989). It has been modified from Q-rating by using Kirsten's method to define SRF with additions of raise specific corrections like adverse sets of discontinuities and weathering. Basically, it is defined as a raise-bore rock quality in terms of block size and inter-block shear strength. For wall adjustment, Q_r value for walls is adjusted described in the Appendix in Figure 51.

For raise boring and ore pass stability in the construction phase it is possible to calculate Maximum Unsupported Span (MSUS) for circular bored raises by using Qr and RSR value:

$$2\ x\ RSR\ x\ Q_r^{0,4}$$

Where,

RSR = Raise Stability Ratio
Q_r = Raisebore rock mass quality index

For ore passes it is recommended to choose higher RSR value. For ventilation raises and shafts, 1.3 had been used but for ore passes 1.6 is suggested being more convenient (McCracken, Stacey 1989). Peck et al. have tested Qr value in practice in Australian and New Guinean Mines. Study showed that Q-system is not representative enough in cases of marginal stability. It gives contradictory results compared with RSR due to less robust structure of the ore pass. He suggests that emphasis should be focused on the other given parameters such as block size, inter-block shearing and rock strength/principal stress ratio, in cases of marginal stability. Practical results imply that Q-value is underestimating the need of support below depth of 900 meters. (Peck, Lee 2007)

2.5.3 Equipment and operational constraints

This chapter includes review in different equipment and their influence on the decision of ore pass placement. The chapter will concentrate more on the general aspects and actual equipment selection is discussed in the design and research phase.

Equipment and operational constrains are considered when location is being defined. Every specific equipment has its own specific efficient working range, travelling distance and/or capacity. Hauling equipment can be categorized based on hauling distances and capacities and similarly loading equipment and crushers have their own specific capacities. These are considered in the ore pass placement decision. These characters combined with operational constrains such as turning radius and energy supply of equipment results in a complex problem. In the ore pass placement problem, location of the ore pass should be defined first, based on production, geology, rock quality and hauling distances. After location is decided, operational constrains of equipment should be kept in mind as a final constraint making sure that the solution is practical and realizable.

Other issue to be considered is the simultaneous operations. Can the hauling and tipping run in different levels simultaneously to the same ore pass? Generally, it is forbidden, but using barriers for isolation it is possible to allow other mining activities near the ore pass. If situation is unavoidable, with proper online traffic management, the tipping process can be sequenced to allow multi-level tipping simultaneously. Also in drilling and blasting cycle, question arises about possibility to operate multiple stopes at the same time in the same sub-level. Challenges in simultaneous operations include overlapping operations in hauling and tipping, intersecting driving routes and in the blasting phase, the possibility to run simultaneous operations in the same sub-level. Also, the number of ore passes per sub-level has significant influence to the possible operational method and simultaneous operations.

2.5.4 Ore pass system and existing infrastructure

Besides equipment constrains, existing and other planned infrastructure defines the layout of the ore pass system. Existing infrastructure influencing on the locations are for example power supply, dewatering, roads, ventilation infrastructure, mining method and hauling level. Mining method and hauling level is designed based on the ore body geometry. These are the biggest restrictions for the location of the ore pass. Mining method defines the location and schedule of stoping sequence and production rate per stope and sub-level. Haulage level should be set to level where the hauling cost can be minimized, meaning that it should be placed in the deepest part of the ore body or current resources. In case of the shaft, hauling level is set close to a depth where underground crusher or loading pocket is planned.

Dewatering and ventilation infrastructure is not restricting the location of the pass system but it must be considered that increasing number of openings between sub-levels changes significantly the ventilation network. Dewatering networks has to be considered for a case of accidents where excessive water inflow forms flooding risks and new openings enable the water to flow through mining levels. New equipment might need a new high voltage infrastructure to be designed. For example, crusher and hydraulically operated chutes and gates needs electricity to work.

The ore pass itself needs new infrastructure as well. It needs high cost items such as underground crushers, conveyors, feeders, gates and chutes to create a continuous ore transport system. The need for these systems is dependent on the proposed ore transport system. Some of the items are necessary, some of them not, depending on the layout of the system. There are numerous different ore pass transportation layouts in the world. Layout depends significantly on whether there are underground crusher or hoisting shaft. If a shaft is present, most convenient is to crush the ore underground to decrease the hoisting cost by increasing the bulk density to decrease the volume of the hoisted ore. Without the hoisting shaft, it is more questionable to invest in an underground crushing plant. Underground crusher demands lot of space underground and often it is more affordable to crush the ore in the surface. Location of the underground crusher can be anywhere near the hauling level. Generally, to reduce infrastructure it should be in location near the ore passes or next to a hoisting shaft. To guarantee the constant utilization rate to the crusher, surge bins before and after crusher should be considered. In this study it is assumed that underground crusher is located close to the ore pass system.

In ore pass system conveyors and feeders can be used to transport and feed the ore in/between processes. To reduce costs, these should be designed to minimize transportation distance. In case of conveyors, underground space and operational needs like maintenance has to be considered while planning size of the drifts and infrastructure need. Combining existing infrastructure in design of new ore passes is a challenging procedure. Some infrastructure is left and some need to be renewed or replaced to fit the new mine layout. The task, in combination of the simultaneous run of mine is demanding.

2.6 Design parameters and structure of ore pass

2.6.1 Longevity of an ore pass

Useful life time or longevity of the ore pass is important to define in the design phase. It creates the framework for the whole design process. If the ore pass is utilized for short time period, none support or minimum support is used whereas if the ore pass is utilized for many years, it needs to be designed and supported carefully to guarantee the production reliability. In competent rock mechanical conditions even high longevity ore passes can be designed without support. Ore pass longevity selection is based on mine strategy. Simple ore passes can be excavated quickly, but failure of the ore pass often results in production disturbances. Alternatively, a well designed and constructed ore pass is reliable but capital investment is much higher.

Life time of an ore pass can be defined in multiple ways. Life time can be measured in terms of years in operation or in an ore flow through the pass in tonnes. Measuring the life time of pass in years is not kept very convenient to represent the actual longevity because the degradation rate of pass is highly correlated to the tonnage flowing through the pass. Higher tonnage results in significantly reduced operational life time. Ore pass longevity can be defined as a stand-up time how long the ore pass stays fully operational without extensive rehabilitation. The longevity of ore pass can be extended through rehabilitation works meaning that pass must be closed during a maintenance - that means alternative routes to ore movement must exist if production shall not stop.

Hadjigeorgiou et al. (2008b) have been investigating ore pass longevity. The study concludes the existing situation of ore pass design techniques and tools and proposes an empirical ore pass longevity estimation procedure. His result is an ore pass longevity index, which is defined based on rock quality and stresses, geological structures, ore pass orientation and layout, operating factors and throughput of the ore pass (Figure 3). The ore pass longevity index is a result of Longevity Reduction Factor (LRF) and Longevity Extension Factor (LEF):

$$\text{Ore Pass Longevity (million tons)} = 20\ (LRF)\ (LEF)$$

Where,

$$LRF = (A_1 \times A_2 \times A_3 \times A_4)\ (B_1 \times B_2)\ (C_1 \times C_2)$$
$$LEF = (F_1 \times F_2)$$

A_1 = Stress Regime
A_2 = Rock Mass Classification (Walls)
A_3 = Major Structure
A_4 = Orientation with respect to major joint set or bedding
B_1 = Material Size
B_2 = Fingers/knuckles
C_1 = Blasting to Restore Flow
C_2 = Cushion Guidelines

F_1 = Ground Support
F_2 = Liner

Factors are shown in the Appendix in Figure 53. Ore pass longevity index estimation varies between 15 000 tons to over 45 000 000 tons, depending on the input. Results have been good with an approximate error of 200 000 tons.

2.6.2 Material characteristics and fragmentation of blasted ore

An ore transport process begins from a stope, where blasted ore is hauled to the tipping point where the ore pass collar is located. To design the ore pass and possible screen dimensions, the fragmentation of the ore has to be determined. In combination of the screening also crusher type will influence on the maximum diameter of rock particles. The material flow is a very critical factor in the ore pass operation and malfunctioning or inefficient system have high economic consequences. Till the last decade, flow related problems in ore passes have not attracted engineers' interest to solve the problem in the design phase – engineering solution has concentrated only on solving failed ore pass systems (Hadjigeorgiou, Lessard 2007).

Fragmentation of the rock/ore is the result of the production blasting in the stope. It can be controlled by using well designed and optimized drilling patterns, openings and specific charge. To limit and modify the diameter of the particles, screening or rock breakers are used before tipping material to the ore pass. Compromise between screening methods and material flow should be done while considering material flow issues before the ore pass.

Gravity flow in the ore pass is influenced by material properties of the fragmented ore and configuration of the ore pass. In the past, design recommendations for material flow in the ore pass were studied on small scale models in a laboratory using empirical experience. Recent years, computer based numerical simulations and calculation methods have been used to simulate material flow. Methods such as Distinct Element Methods (DEM) with Particle Flow Code (PFC) have been used to simulate interlocking hang-up phenomena (Hadjigeorgiou, Lessard 2007, p. 820).

In a study of ore passes, Hadjigeourgiou et al. have identified that mass flow in the ore pass system can be divided into three stages with specific mass flow characteristics: Into the ore pass, in the ore pass and out of the ore pass. This characterization helps to identify the important factors of mass flow in different flow phases. In the ore pass system, there are a lot of technologies and equipment influencing on the mass flow. In the first phase, mass flow begins from tipping the ore to the opening of the ore pass. Second phase, ore moves through screen into the ore pass where material properties plays a significant role. The sizing of the broken ore can be done by different screening methods at the tipping point. Oversize boulders increases the wall impact and number of blockages in the ore pass and are harming the production. Mass flow is controlled using different technologies and systems such as chutes and gates. Finally, in third phase, the ore is discharged from the ore pass using chutes and transported to the next process, for instance crushing.

A blockage is defined as an impediment in the discharge area and whereas a hang-up is occurring in the transit zone of the ore pass. Typically, the blockage occurs in the discharge area where different discharge infrastructure is built. The infrastructure limits the diameter of the ore pass, like chutes and gates, and therefore creates a potential place for a blockage. These blockages are typically wedged blocks. Alternative source for formation of blockages are fine or sticky material which accumulates to the walls of chute or ore pass walls. This is also called a rat holing phenomena. Hang-ups occur often in form of arching due to interlocking coarse particles or as cohesive arching when a significant proportion of fines exists. Different estimates for the proportion of fines in a grain size distribution are presented to indicate potential cohesive arching. In case of ore passes, fines are defined to be particles having a diameter less than 0.07 mm. Suggestions for the limits of fines indicating risk for cohesive arching ranges between 10 % and 20 %. Rule of thumb for cohesive arching is that if material contains fines (< 4 mm) more than 10% of its weight - potential for blockages exists. Hadjigeorgiou et al. have noted that some mines have come across with flow related problems even though grain size is favorable. Their interpretation is that material handling system is whether producing greater amount of fine material or the material is segregating while tipped to the ore pass. Paste fill can be a source of cohesive fine particles also and therefore might impact to the material flow while excavating secondary stopes. (Hadjigeorgiou, Lessard 2007) and (Hadjigeorgiou, Lessard 2003).

Material flow is dependent on fragmentation and shape related factors such as grain size distribution, an angle of repose, and a shape factor. Also, finely graded material results in a cohesion and higher moisture hold capacity. Grain size has simple physical limitations - ratio of the maximum particle size (d) to the diameter of the ore pass (D) must be large enough to prevent material flow problems such as blockages. Similarly the angle of repose and the grain shape factor has influence to the ore flow and formation of blockages. Naturally, cube-shaped particles have a higher angle of repose than spherical ones. Literature claims that a density of the ore has a great impact on the degradation level. Hadjigeorgiou et al. (2004b, p. 813) discovered that enlargement of the ore pass versus the design volume is significantly higher if the unit weight of ore is higher than 30 kN/m3. (Lessard, Hadjigeorgiou 2003) and (Hadjigeorgiou, Lessard 2010).

2.6.3 Dimension of ore pass

Ore pass dimension including length, maximum diameter and volume are important factors in selection of design and ore flow. Length of an ore pass is based on operational needs and technical limitations. It is dependent on mine layout, distance between mining levels and operational needs such as hauling infrastructure. Also, stability is an issue of length – longer pass is traversing more geologically different areas. For example, the average length in Canadian mines is 87 meters. Often mines with stability problems reduces ore pass length when new passes are built. (Lessard, Hadjigeorgiou 2003, p. 516)

Numerous guidelines and studies about the dimensioning of the ore pass and fragment size of ROM ore exists in literature (Figure 4). These tests have been made in small laboratory scale model or computer simulations. A ratio between the ore pass diameter (D) and the largest rock block size (d) is an important factor to predict development of inter-locking arch hang-ups. The diameter is always a compromise of D/d – ratio and the size of excavation. A smaller diameter in an ore pass is more stable, cheaper and creates less disturbance to the surrounding host rock whereas a large diameter is more expensive to excavate and increases the demand for rock support.

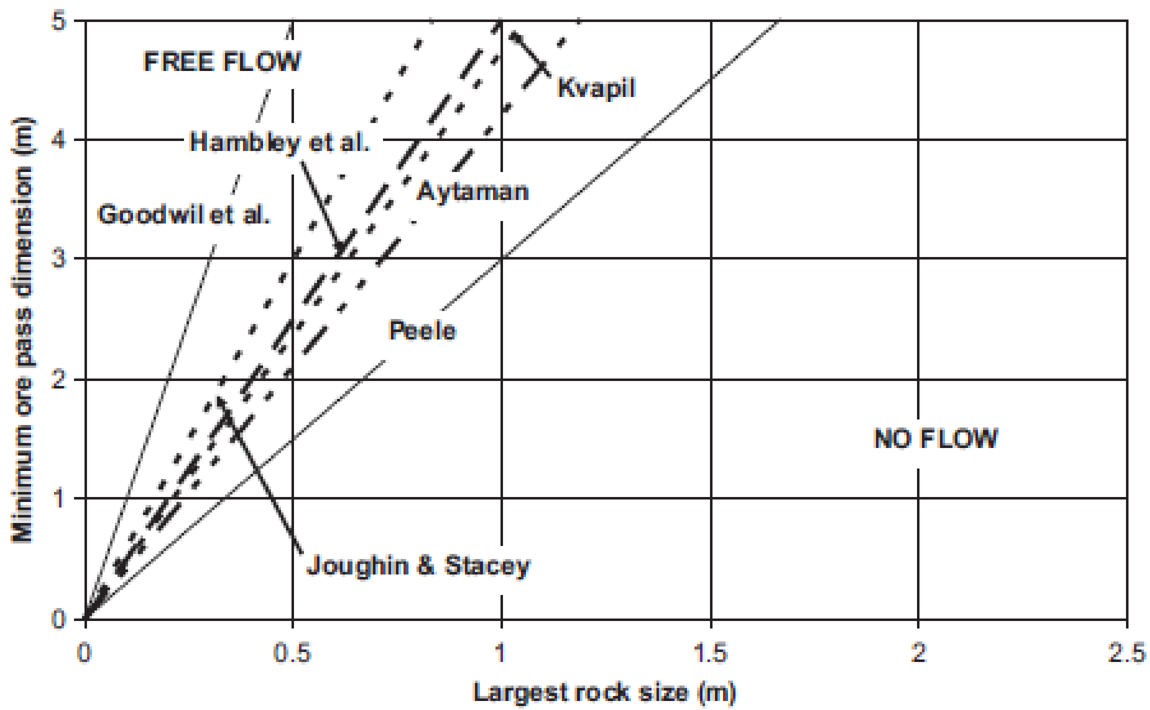

Figure 4 Maximum rock size (d) versus minimum ore pass diiameter (D) after various authors to define the material flow (Hadjigeorgiou, Lessard 2007, p. 823)

D/d - ratio of free flow in the Figure 4 is ranging between three and ten. Deviation in proposed ratios is so wide that if cross sectional area is calculated on different proposals, difference in area grows as great as tenfold between authors. Therefore, definition of the ratio is complicated and other factors and assumptions creates a big variance to the material flow. Older studies about bulk solids were made by Jenike (1961) who recommended the ratio of two between the ore pass diameter and average dimension of particle size. Jenike’s theory was based on assumption that slab-shaped rocks tend to orient long axis parallel to an ore pass and therefore smaller ratio can be used. Recently computer simulation analysis of material flow parameters and dimensions have been done using Particle Flow Code (PFC) in order to define the ratio. Computer simulation results have been relatively similar compared with the small-scale laboratory tests. Thus, models claims that sufficient ratio would be in the range of three to five. Generally, simulation models are giving more conservative results because in small scale laboratory tests, tested material is uniform in terms of the shape and diameter. (Hadjigeorgiou, Lessard 2007, p. 832 - 833)

Fine particles forms cohesive hang-ups and blockages. These occur when fine material builds up in a walls of the ore pass and cumulates to a hang-up. Formation of these hang-ups is based on “sticky” adhering particles induced by cohesion and suction. Mechanical analysis of cohesive and suction induced hang-ups in vertical and inclined passes have been studied by Vo et al. He found that in cohesive materials, for a prevention of potential formation of hang up, ore pass diameter (D) should be greater than 6.3 meters. To fully prevent hang-ups when moisture content is greater than 2.5%, diameter of the pass should be high as 12.9 meters! For wet conditions, the diameter of the ore pass should be more than doubled from the case of dry material. These large diameters are not technically or economic viable to excavate and therefore focus on, safe operation, decreasing water inflow and moisture content is a more convenient way to mitigate the problem. In addition, a significant increase in hang-ups occurrence were found in the analysis of passes with greater than 30 degrees inclination. Releasing methods in cohesive hang-ups are more difficult to dislodge due to problematic blasting set up and mud rushes. Therefore, the potential for cohesive and suction induced hang-ups should be considered in the design face if conditions for cohesive hang-ups occur. (Vo et al. 2016)

Figure 5 Blockage of large boulder (Hart 2006)

Influence of the ore pass shape to ore flow is studied by Hadjigeorgiou (2007). Commonly used cross sectional shapes are round and square. Boring method creates round cross sections but with blasting methods it is possible to create round, spherical or square ore passes. Simulation models claimed that square shape cross section have better material flow characteristics and reduces risks for hang-ups (Table 1). This is contradictory to the empirical data gained from another empirical study from Canadian underground mines (Lessard, Hadjigeorgiou 2006).

Table 1 Influence of inclination, shape, rock fragments and D/d - ratio in PFC simulation model. (Hadjigeorgiou, Lessard 2007)

Ore pass inclination (⁰)	Ore pass Shape	Rock fragment shape	D/d ration for free flow	Section area required for free flow (for d = 1.0m)(m^2)
90	Circular	Spherical	2,8	6,2
90	Circular	Cubical	4	12,6
90	Square	Spherical	2,6	6,8
90	Square	Cubical	3,8	14,4
65	Square	Spherical	3,4	11,6
65	Square	Cubical	4,6	21,2

Altogether, D/d –ratio is a dictating factor in the ore pass dimension selection. Shape of the ore pass and fragmented rock are less critical factors. Shape of the pass is closely related to the construction method and equipment selection. When deciding the dimension also volume of the ore pass should be considered because the ore pass can offer a potential surge capacity. Numbi et al. (2014) for example, have showed in simulation analysis of utilization rate of underground crushing plants that energy consumption can be reduced by optimizing the switching control of crusher and increasing surge capacity of ore passes.

2.6.4 Inclination of ore pass and finger raise

Inclination of the ore pass has direct effect on the material flow. Steep inclination increases material flow velocity, degradation rate and impact loading in the bottom of the ore pass. In addition to a velocity, steep inclination angle increases risk for blockages and hang-ups. Vice versa, shallow inclination does not facilitate required material flow.

More complex ore pass systems, consisting of finger raises connecting sub-levels, have more significant importance in selection of inclination. Angle between finger raise and the ore pass should be designed to minimize the impact loading to the ore pass walls (Figure 6). This area is defined as an impact zone (Figure 7). Experience and simulation models have been demonstrated that finger raise and ore pass intersection is the most vulnerable location to face severe degradation. (Esmaieli, Hadjigeorgiou 2011).

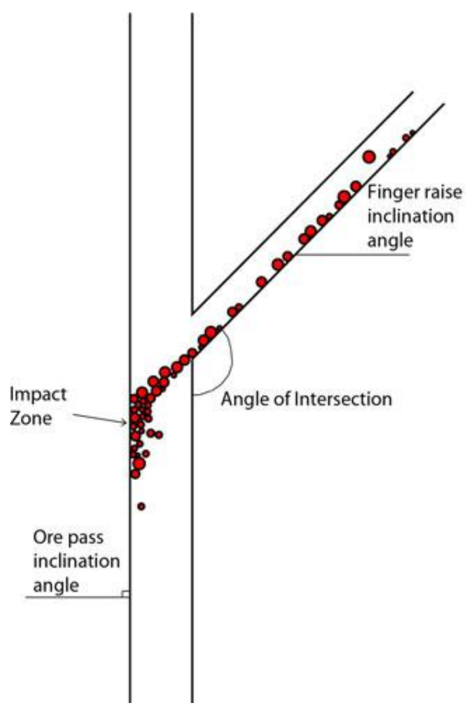

Figure 6 Finger raise configuration (Esmaieli, Hadjigeorgiou 2011)

Esmaieli et al. have given recommendations for the ore pass and finger raise inclinations by simulating material flow using PFC simulation. Results showed that highest impact loads are occurring when an intersection angle is between 140 and 145 degrees. Empirical observations proved that degradation rate in the ore passes with intersection of 140 to 145 degrees were facing the highest degradation rate. These results can be used for a recommendation for selecting the ore pass and finger raise configuration. Table 2 lists the results of the simulations (Esmaieli, Hadjigeorgiou 2011).

Table 2 Orientation recommendation for finger raise configuration after Esmaieli et al. (2011)

Ore pass inclination (°)	Finger raise inclinations (°)		
	Best	Acceptable	Problematic
90	75, 80	60, 65, 70	
80	80	65, 70, 75	60
70		60, 65, 80	70, 75

2.6.5 Screening

Ore passes can be operated with or without screening infrastructure. Purpose of the infrastructure is to restrict the maximum particle size entering to an ore pass. Oversized boulders creates a risk to blockages, hang-ups and damage to the ore pass or crushing system. The screening device is also spreading the impact force of the ore when tipped to the ore pass. The infrastructure can be used just before the crusher as well, but then big boulders entering the ore pass cannot be sorted, causing higher degradation in the ore pass. If screening devices are not utilized, alternative methods can be used to sort oversize boulders. For instance, mucking crew can use rock breakers and hammers before feeding the ore in to the ore pass. Control of oversized boulders must be done visually by mucking crew or the rock breaker operator. In Canada for example the statistics implies that 55% of reported ore pass systems were using size controlling infrastructure (Hadjigeorgiou et al. 2004b, p. 811).

Even though in sub-level caving mine in Sweden, Sjöberg et al. (2003, p. 44) recommends screening as a method for increasing the ore pass stability. It seems that usage of screening in the industry is polarized when productivity conflicts with production security. Screening increases reliability, but reduces productivity in terms of reduced material flow (Hadjigeorgiou, Stacey 2013, p. 797). Therefore many mines reports that grizzlies have been abandoned due to reducing effect on productivity in the ore pass (Stewart et al. 1999) and (Costello, Knights 2013).

Three typical screening techniques are used to limit the access of the broken ore. These are a scalper, grizzly and mantle (Figure 49). A scalper is a screening device with parallel bars. Experience from scalpers is that they are relatively expensive to operate and a problem associated with the scalper is the wedging of blocks between the bars. Consequence of wedging is a clogging of scalper which can be fixed whether forcing the block through or mucking it away. Forcing blocks through the scalper causes damage such as broken and missing bars which might cause harm in later stages of the ore transport process. Second screening technique, a grizzly, is more rigid to restrain big blocks. It is kept as the best technique to retain large boulders. Grizzlies are more durable and demand less maintenance. Important design parameter for grizzlies is the grid size because wrong sizing limits the material flow and inhibits mucking. The grizzly limits the boulder size more than scalper and therefore more focus on ore fragmentation should be made. A mantle is the third option to prevent oversized rock blocks. It is rigid, easy to manufacture and compatible with a rock breaker. Its screening accuracy is lower than grizzlies and therefore larger rock blocks entering to the ore pass system can have impact on the ore pass degradation.

A screening device can be installed horizontally or ab inclined surface. The inclined surface is kept more efficient placement for higher throughput, because material slides down on the surface of screen. In the design phase, must be remembered that inclined grizzly has less effective aperture size. In a mine, every time oversized block is present on the ore pass grizzly, it needs to be removed and crushed elsewhere meaning that each time LHD needs to wait for tipping a next load to the grizzly. Optimization of the grizzly grid is important to reduce the down time of ore pass system. Costello et al. increased productivity significantly by optimizing the grid and shape of the bars by reducing the downtime of LHD during a clogged grizzly. Kumar et al. for instance, mentions that in Kiiruna mine, ore pass boulder control costs few million euro per year. (Kumar 1997) (Costello et al. 2013)

2.6.6 Wall degradation

Ore pass walls are impacted by wall degradation during its usable life time. Degradation is inevitable in the ore pass and therefore it is hard to avoid completely, but with technical solutions and material characterization it is possible to control and forecast the degradation rate and progress. Identifying the degradation methods is important part of the ore pass design. Failure development is highly progressive phenomena and without knowledge, it is hard to prevent after commencing. Extensive degradation leads into problems in mine production for example by increasing the occurrence of hang-ups (Hadjigeorgiou et al. 2004b, p. 815).

Wall degradation can be categorized into five different phenomena after Morrison et al. (1995) and based on this categorization, a percentage of the occurrence in Canadian mines is listed after Hadjigeorgiou et al. (2004b):

1. Structural failures facilitated by material flow (53%)
2. Scaling of walls due to stresses (11%)
3. Wear due to impact loading (23%)
4. Wear due to abrasion (27%)
5. Blast damage and hang-up cleaning (1%)

First two of the degradation methods are mainly related to the location of the ore pass. These can be mitigated by selecting a location where geological structures and rock mechanical properties are favorable to mitigate the degradation of the walls. Last three degradation categories are more related to a design of the single ore pass. Limiting material size and selecting appropriate dimensions, inclination and technologies are powerful tools to reduce wearing of the walls.

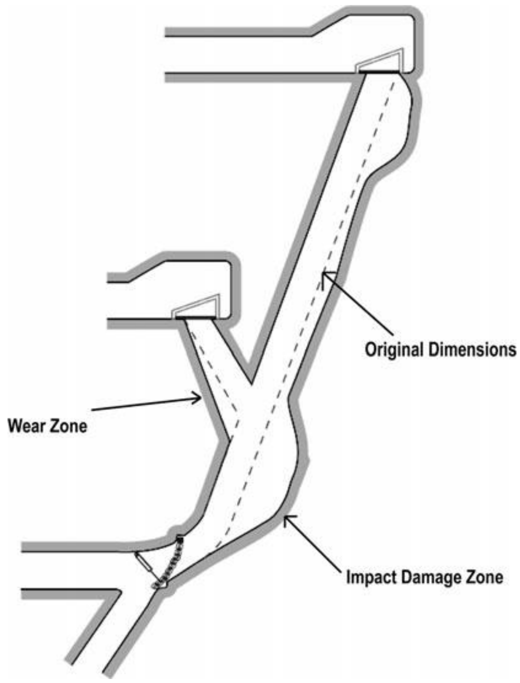

Figure 7 Schematic picture of ore pass with damage and wearing zones, Esmaieli et al. (2011).

Structural failure, facilitated by material flow, is the major cause of degradation. Due to the impact of the material flow to weak walls, the degradation of the walls propagates quickly and expansion of the ore pass can be large as tenfold. If the ore pass is situated in a geological weakness zone or parallel to the foliation dip it is more than probable that ore pass will fail eventually (Hadjigeorgiou et al. 2004b, Stacey, Swart 1997). Another degradation method is the scaling of the walls in high stress areas. This can occur even in competent rock conditions. High stress state and especially high K-value exposes ore pass to deformations. K-value, the ratio of principal stress and rock strength should be less than 0.3 to avoid stress damage in competent rock (Brummer 1998) and (Hadjigeorgiou, Mercier-Langevin 2008a). A common way to observe the phenomena is a spalling or dog earing where the cross section of the pass flattens and eventually destroys the ore pass if significant support is not installed. Influence of stress can be reduced by choosing correct location and orientation for the ore pass. The pass should be orientated parallel to a principal stress and far enough from production areas to decrease the impact of induced stresses (Brenchley 2006) and (Stacey et al. 2005, p. 803).

Material flow degrades the ore pass walls due to abrasion and impact forces. Impact loading creates damage to the walls being highest in the finger raise intersections and in the end of the ore pass, causing major damage to the chute headframe for example. The same way the abrasion causes degradation but is more likely to occur in the footwall of the pass where grooving effect can be identified. Stability analysis of ore passes in Kiirunavaara Mine showed in Sjöberg’s (2003) computer modelling that formation of groove increases the extents of shear failure. The groove in the ore pass floor act as a kerf for shear failure and around the groove it propagates a tensile failure (Figure 54). Material flow related degradation can be prevented by decreasing material flow and grain size, using liners and reducing material flow speed by making the ore pass inclined or excavating dog legs to the end of the ore pass (Figure 47). Last degrading method - blasting, for hang up releasing has considerably small impact on overall degrading. Blast damage is based on vibrations, shockwave and air blast creating fracturing and scaling to the ore pass structure. In literature it is found that it has relatively little impact on the ore pass degradation and hang-ups can be released also by other alternative methods (Hadjigeorgiou, Mercier-Langevin 2008b). Weathering and oxidation is not listed in the Morrison et al. categorization of degradation methods, but Brenchley et al. (2006) reminds that it has an impact on a quality of rock in the ore pass walls as well.

Wall degradation can be prevented by using special liners or structures in the walls. These structures are for example wear plates (Figure 47) and wearing blocks (Figure 50). The wear plates can be installed in the intersection of the finger raise to the impact zone and blocks to the ore pass walls to reduce the wearing. Wearing block's operational principle is to reduce flow speed of the ore and create broken ore pockets which function as a natural cushion and wearing protection. Placement of wearing blocks is defined by inclination and dimension of ore pass and material characteristics such as angle of repose. In a low-tonnage mine with high grade valuable ore, the block system might not be feasible due to stacked ore in the pockets which is hard to recover. The lost value of stacked ore might overcome the benefits of reduced degradation.

2.6.7 Support and liners

Ore passes can stand without support in good rock conditions and low stress environments. Weak rock conditions, high stresses and long ore pass lifetime demands rock support. Ore pass support depends on excavation method a lot, with raise boring method, the ore pass can be very stable whereas blasted raises need more support due to blast damage. Pass support includes normal conventional rock support methods such as bolting and shotcreting. Generally, low stress and good rock conditions (Q>5), extensive support and lining is not particularly necessary if tonnage of material flowing through an ore pass is moderate. Mobile and sectional liners, such as steel wear plates, are more practical solution for these cases. These can be installed to a high wear zones like the intersection of finger raises and ore pass or to a footwall of an ore pass to reduce grooving effect due to material flow. Later on, the wearing plates can be replaceable if ore flow has significant wearing impact.

Due to material flow, also liners can be considered as a support method giving support and protection of degradation for the ore pass walls. Through the useful life time, ore passes can be rehabilitated by renewing liners. Remedial support has very limited capacity and therefore design of a competent support system is very important in the design phase. Installation of rock support to ore passes is challenging because of small, nearly confined space.

Historical perspective, old passes consistently neither had rock support nor liners. Old degraded ore passes have been abandoned and replaced with new ones. For last couple of decades, ore passes are often supported because the rehabilitation of the ore pass is found to be very expensive (Joughin, Stacey 2005, p. 798). The major cost of a malfunctioning ore pass is related to the production delays. Alternatives for rock support in an ore pass are rock bolts of various kind, mainly grouted rebar, cable bolts and steel rails. Also fabric support like meshes, lacing and shotcrete can be used. Steel liners, cast concrete or shotcrete with additives is used for lining a pass if considerable degradation may occur. Failed cast concrete protection is very hard to rehabilitate.

For instance, Hadjigeorgiou et al. (2003) reports that in Quebec mines, only 8% is unsupported whereas in South Africa it is 50%.

Bolting is the most popular reinforcement type for ore passes. Earlier most common support method were the usage of resin-grouted rebar, but nowadays cable bolting with resin grouting is becoming more and more popular. Earlier, high tensile support was installed already in the excavation phase which worked as permanent support after commissioning. High tensile support has been found to be problematic because stiff tendons are transmitting the shockwaves induced by impact of falling ore and cracking the binding of grout (Brenchley 2006). Nowadays, cable bolting is preferred being more flexible method. In cable bolting, the diameter of the pass is not limiting the maximum length of the bolt. Some applications included usage of fiberglass rebar but these have been found expensive and ineffective reinforcement for passes, even though some mines are reporting it to be a better option than grouted rebar (Hadjigeorgiou et al. 2004a). Bolts or cables are installed in an overhead angle from the perpendicular axis of the wall to prevent degradation and spalling of the side walls. Also, it is important to combine the tendon support with a wire mesh or strong liner to prevent wearing. Otherwise rock between tendons gets worn out and eventually destroys support capacity of bolts (Figure 8). Other possible, tendon like, support are a different kind of hoist ropes, steel bars and rails which can be mounted to the ore pass walls. (Hadjigeorgiou et al. 2004b) and (Vieira, Durrheim 2005, p. 786-787)

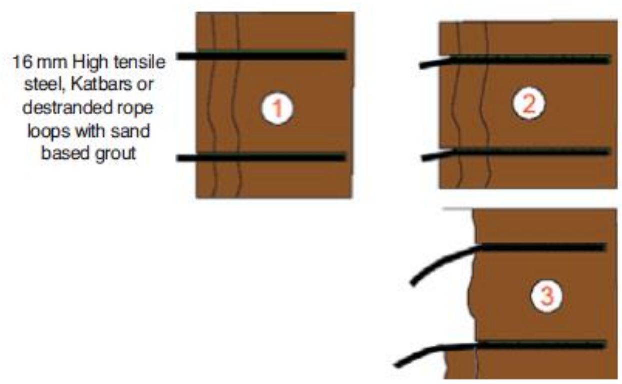

Figure 8 Adverse effect of high-tensile support tendons in the ore pass (Brenchley 2006)

Ore passes can be supported or lined with fabric type support like meshing, lacing and shotcrete with fibers. More than just considering liners as a support it has important function to protect other rock support (Hadjigeorgiou et al. 2004a, p. 495). Fiber type support might cause problems because it can decrease material flow properties of the ore pass walls. Liner material can be part of the supportive structure in the ore pass or it can be designed to prevent degradation. Generally, the concrete lining is not sufficient if the abrasion is not allowed but it can function as a wearing material. Concrete can be shotcreted to the walls or use casting. Cast concrete has been reported beeing difficult to replace after the degradation have advanced to a state where the concrete rings has to be replaced or renewed (Hart 2006, p. 4). Concrete is significantly softer material than volcanic rocks and therefore the ore is degrading the concrete liners and therefore it cannot be kept as primary support. To prevent degradation, the liner should have a hardness rating of 5 Mohs or higher to resist the abrasion. Andesite (5.5 Mohs) and corundum (9 Mohs) have been used in the ore pass liner applications to increase the hardness of concrete. Corundum is significantly harder than andesite, but polished and smooth nature makes it hard to use, it bonds weak to a concrete and support and fragments had been reported dislodging from softer wetcrete. Despite the andesite have been found to be too soft material against abrasion, due to its higher bonding capacity, it is preferred alternative for example in South African Moab Khotsong Mine. (Brenchley 2006, p. 13 - 15)

2.6.8 Material flow control

Material flow is gravity movement of rock particles in the ore pass. The flow in the pass can be a free flow without any additional flow control infrastructure but often it is necessary to control the flow by cutting the flow or reduce particle velocity. Gravity movement of material includes rolling, sliding and inter fragment collision. The flow can be modified by changing inclination, limiting cross sectional area or closing the pass completely. These changes can be made using chains, gates or chutes (Table 3). Also with feeders, material flow can be first stopped and then continued. Flow control is important especially when multiple ore passes or finger raises are operated. It helps to control material flow and manage surge capacity of the system because blasted material from different mining areas can be whether diversified or blended. Also regular draw control reduces risk for hang-ups.

Table 3 Material flow infrastructure and combinations

Material flow infrastructure	
1. Dog leg	5. Chutes + Control gates
2. Chute	6. Chutes + Crash gates
3. Control chain	7. Chutes + Control chains + Gates
4. Gate	8. Chain feeder(s)

Free flow without any material flow is the simplest way of operating the ore pass. Without any flow control devices velocity of material, impact forces and discharging cannot be controlled. The easiest way to limit material flow and velocity is to build dog legs (Figure 47). Dog legs are tilted endings of the ore pass and therefore material does not fall in free fall speed into the bottom of the ore pass. These are used to limit impact force of the broken ore and helping the hauling of material if the ore pass is operated open i.e. the ore pass is not filled with rock. Dog legs can be applied in combination with gates and chutes as well.

Chutes can be used to control material flow (Figure 9). They are made of inclined steel plates enabling good material flow out of the chute. Chutes are often operated with hydraulic cylinders. The same as defining ore pass dimension also capacity and the maximum diameter of the chute has to be defined when selecting a one. Occurrence of blockages in chute area are often common and releasing with explosives is difficult due to blast damage. Chutes are improving the safety compared to a free flow ore pass, but also chutes are recreating other serious safety problems. If chutes are used, it is impossible to indicate the mucking level of the ore pass from the bottom of the ore pass with eye sight. Therefore, it is important that a safety procedure is created to maintain the safety when the chute is opened. Experiences in mining industry have shown that mud rushes are common in case with chutes. Also monitoring of the mucking level is important that ore pass is not operated empty and therefore creating serious impact forces to the chute framework. Greatest benefit with chutes is the adjustable hydraulic system which enables the dozing of the rock flow. Therefore it can be used for direct discharging to trucks. The chute can be installed with weighting unit or measuring box to make it accurate. There are two kinds of chutes available, some can be mounted permanently to create a permanent loading station or then it is possible to use mobile chutes which can be moved to different parts of the mine. Depending on production rate, selection between fixed or mobile of chutes must be made. Generally, in combination of horizontally wide deposit and small production rates mobile chutes can be a more feasible alternative.

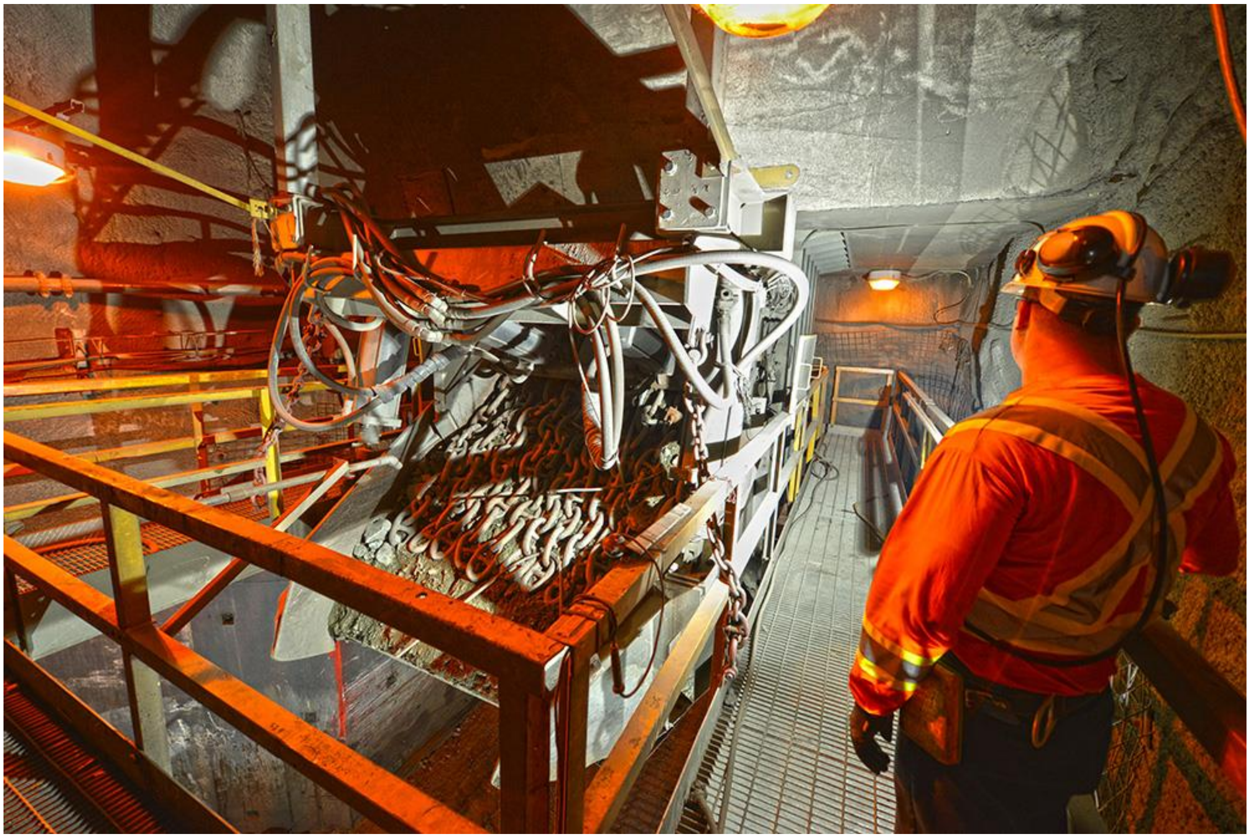

Figure 9 Chute loading station where truck is loaded below the steel frame. Chute is equipped with chains and water spray to smooth material flow and decrease dust emissions. (Variant Mining)

Control chains are used for slowing down and limiting material flow (Figure 9). The operational principle of the chains is based on the weight of the hanging chains form the head block or hanging wall of the ore pass. Chains are limiting the speed of the material flow by reducing the flow area and absorbing the kinetic energy of the falling rock. Even more, hanging chains are a good device to absorb impact forces before chutes inside the ore pass. The chains can be made maneuverable by adjusting the hanging length of chains with a hydraulic height adjusting system.

A more rigid and adjustable alternative for material flow control are gates (Figure 10). Those are operated hydraulically and the bottom of the ore pass can be sealed completely with the gates. The gates are useful if there is a need of limiting material flow in a long ore pass, for example in the junction of different production levels and finger raises (Figure 47). Heavy duty gates can face high impact forces and therefore these can be used as a crash gates before chutes. Gates has limitation in its strength and for extreme impact loading installation of protecting chains can be used.

Also apron feeders or chain feeders can be used for discharge and material control. These feeders are chutes which are inclined more than the angle of repose. The flow of the material is created by using rotating chains in the chute. Rotating chains makes the material slide along the chute.

Figure 10 Press gates controlling the material flow in the bottom of the ore pass

2.7 Mine operation with ore passes

2.7.1 Ore pass discharge methods

Material flow discharge in the ore pass can be done several different ways. It includes different operation principles and material discharge infrastructure. Ore passes can be operated with two different methods, whether open "flow through method" or by keeping the ore passes full. In literature, also cushion guideline or storage method is used as a name for operating full ore passes. Difference is that in a flow through system the ore pass is kept open from the bottom and in the full operating method specific amount of broken ore is stored in the bottom of the ore pass all the time. Sometimes ore passes are operated against its design principles using flow through regime, because there has been unexpected hang-ups while using full ore passes (Lessard, Hadjigeorgiou 2003).

In full operating method, broken ore works as a cushion layer at the bottom of the ore pass reducing impact forces of the falling particles. Direct impact forces to the infrastructure such as chutes ore gates are reported being one fourth in case of full ore pass, spreading the impact force to the ore pass walls and chute assembly (Beus et al. 1998, p. 5). Broken ore layer functions also as a static rock support creating perpendicular force towards the ore pass walls. Full ore pass operation method is considered as an important factor for the ore pass longevity (Hadjigeorgiou et al. 2010). Furthermore, the filled ore pass prevents air blasts and dust impact from falling rock to the ore pass. It also benefits the control of ventilation because the filled ore pass is almost air tight, keeping the mine ventilation network as simple as possible. The fill operation can be kept as a desired method for ore pass operation and it is beneficial because it offers surge capacity, balancing the material flow. Major challenges in operating ore passes full is the monitoring of the ore pass filling rate and creation of hang-ups in the ore pass. Using monitor system such as lasers, radars or cameras, rock level should be kept between minimum and maximum level (Figure 13). Too low ore level increases the impact forces to the ore pass infrastructure, risk for unexpected mud rush and enables air flow through the ore pass while dumping (air blasts). In contrast, high level creates increased static loads and risk for hang ups. Strict guidelines must be designed to operate with full ore pass method.

Open ore pass method is robust operating method for an ore pass system. Especially safety, air blasts and the usable lifetime of ore pass is worse in open method than in previous method. Open method is simple and cheap to operate but should be considered only if small tonnage is expected to flow through and for exceptional or temporary situations. Higher free fall distance and no cushion results in a higher velocities and impact forces. High impact forces does not facilitate installations of infrastructure like chutes and gates making the open method simpler and cheaper. Air blasts and the open ore pass creates dust and ventilation challenges. Meaning that tipping and mucking of the ore pass cannot be done simultaneously due to safety.

Ore passes can be discharged different ways (Figure 11). Common ways are pile, gate and feeder options discussed in the previous chapter. These options are different in operating costs, demand for infrastructure, material flow continuity and equipment need. Simplest method is the pile option which doesn’t include any additional infrastructure like a discharging aperture. Tipped ore gets piled to the bottom of the ore pass where the ore is mucked with LHD. To prevent structural damage, air blasts and maintain air seal, ore pass should be kept partly filled. The method is cost effective but comes with a cost of monitoring systems and lower productivity. Ore pass fill level should be monitored to guarantee that no sudden rock flow or mud rush occur while loading. This needs good information about amount of tipped material in the ore pass. It is recommended that only remote controlled or automated LHD is used to muck ore.

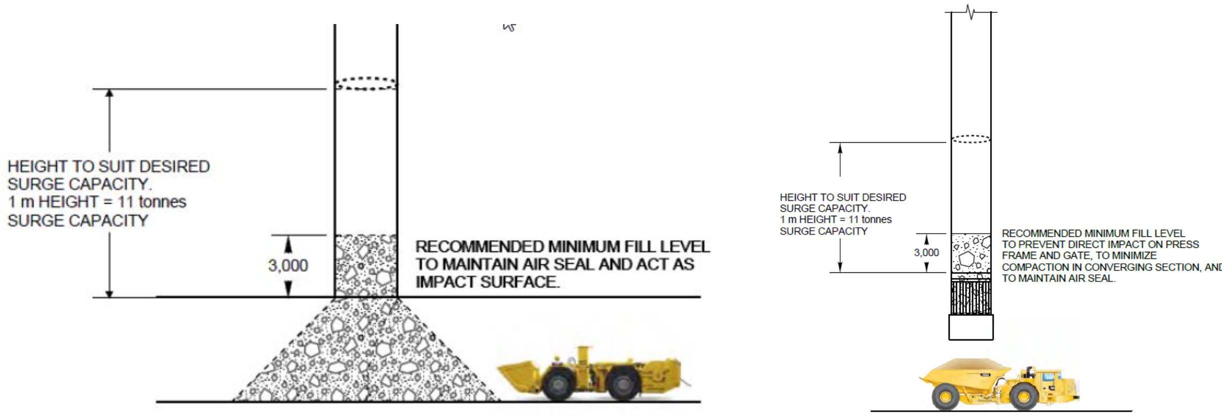

Figure 11 Ore pass discharge with pile or gate/chute option after Jenike & Johanson (2011)

Second, more sophisticated method is to use a gate in the bottom of the ore pass. In gate method, a hydraulically operated gate is controlling the material flow. The gate is opened every time the hauling truck is under the gate and specific amount of ore can be released to the truck. This method requires that ore pass is all the time partly filled due to impact forces. Benefit of the method is the controllability of the ore flow and the rate of automation which can be utilized in this method (Figure 12). Gate method is efficient but compared to last method, spillage is higher and accuracy of the loading process is less accurate.

In third option, gates are replaced with feeders. There are many different kind of feeders in the market, but apron feeder or Ross chain feeder are possible alternatives. The ross chain feeder can be used especially in case where material is transported continuously to the next phase i.e. conveyors because the chain feeder creates smooth continuous material flow. The apron feeder is more suitable for truck hauling: the feeder feeds the hauling truck fast and accurate by conveying exact amount of material to the bed of the truck. The loading process is gentler to the mining truck compared with chutes, accuracy reduces amount of spillage and therefore need for maintenance and cleaning decreases.

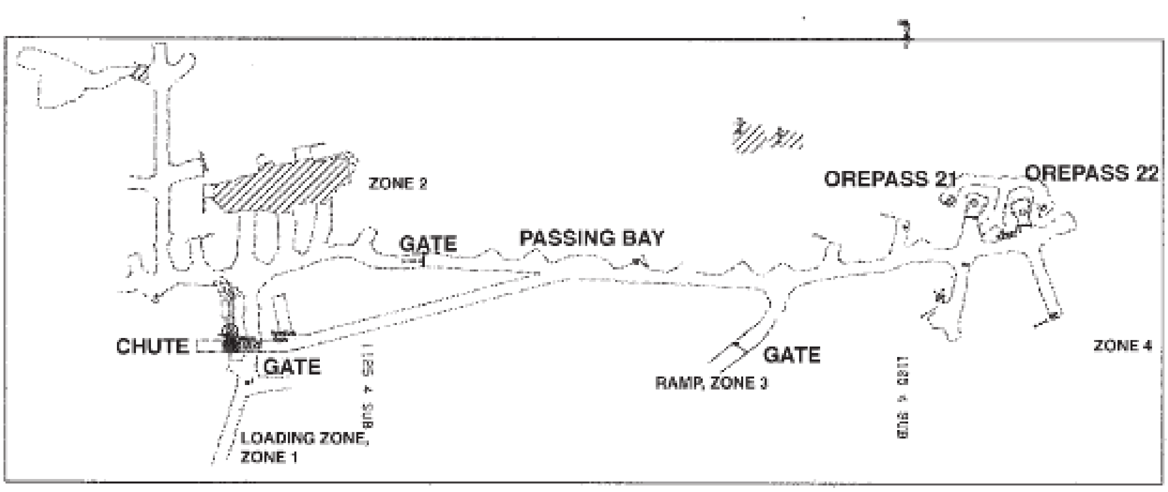

Figure 12 Chute discharge in combination with automated hauling enables ore passes to be connected to each other (Swart et al. 2002)

2.7.2 Equipment selection

Equipment selection for the mine is dependent on the mining method and mine layout. Ore passes changes the equipment need, depending on the principles how hauling is organized. When the equipment need is calculated, the degree of flexibility in production is decided. Full transform to the ore pass system means less trucks, but in case of production problems in the underground ore flow, it means that there is no flexibility to change hauling capacity back towards truck hauling. Therefore, it is recommended that partly capability to traditional truck hauling is maintained.

General mine layout with ore passes includes investments in LHD's and dumping trucks. Capacity of the equipment is calculated by using a normal cycle time approach with a manufacturer supplied statistics including consideration in equipment dimensions and maneuverability. Additionally, depending on production method other ore movement equipment is used. These methods are capital investment intensive systems like rail transport, conveyors and feeders. Systems are increasing productivity thus reducing flexibility. Recent development in robotics and automation has improved the productivity of traditional rubber tired hauling equipment and has been studied as a potential alternative in operating the ore passes.

Ore movement begins from blasted ore in the stope which is mucked using LHD. For this journey there are no other alternative method to be used. It is specialized to load, haul and dump material in short distances (<250 m). Productivity, but also safety and ergonomics of an operator can be increased by applying automated LHD's. Therefore LHD can haul and dump material whether fully autonomously or partly remoter controlled. Based on literature and experience autonomous and remote controlled LHD's productivity is contradictory. Some mines report higher productivity whereas some are reporting an increase in cycle times due to slow mucking and overall productivity loss because of time consuming preparations. Biggest production benefit in automation is the possibility operate automated equipment also right after blasting during shift change. Operational limitation in the LHD is the economic hauling length. It is shown that hauling costs per ton starts increasing significantly when 250 meters is exceeded. The inverse relation of productivity versus distance is almost squared to the distance in short distances. Longer distances are more economic to transport using a dumper or truck.

After LHD tips the ore to the ore pass, there exist multiple options how the hauling can be further on organized. One option is to interconnect the ore pass to another one and no equipment is necessary. When the ore is in the ore pass it can be stored to the pass or it can be drawn immediately. Depending on discharge method, the bottom of the ore pass can be open or equipped with a chute, gate or feeder. If the ore pass is operated open or with gates, it means that LHD is taking care of drawing the ore pass. Depending on the distance to the next location it can be whether loaded to a dumping truck or hauled directly to its destination. When chutes or feeders are deployed, straight dumping to a truck is possible. Chutes and feeders enable the precise filling of the truck bed, which can be also fully automated. Automation gives full new opportunity for automated trucks to be operated in sub-levels as a counter option to rail carriage. Autonomous and automated dumping and hauling truck is a considerable option in the haulage level where initial investment in rigid infrastructure can be kept minimal compared to rail haulage. Other applications with autonomous or man driven LHDs are the interconnecting paths between ore passes. Ore passes traversing sublevels in different paths of the mine can be connected using LHD hauling between the end of the ore pass and tipping point of the new pass (Figure 12).

The production rate of the mine is limiting the size of investment. Higher production rate justifies higher initial investment to enable an option of rail transportation, conveyors and feeders to be deployed in wider scale. In stoping methods, production rate in a single level does not justify the usage of conveyors or rails, but recent development of conveyors for hard rock applications is making them more technically viable solutions. Where production rates are higher and distance longer, conveyor transportation becomes more feasible. Conveyor method in a bottom of the production area i.e. in the hauling level could be a feasible system also in sub-level stoping mine. That would consist of a conveyor fed by feeders or chutes, collecting the ore from other parts of the mine through an ore pass network. Benefit in conveyor transport is the energy consumption, a smaller need of space and a constant ore flow (for example to crushing station). Further surge capacity of a conveyor would enable the mine to reduce the surge capacity of the underground ore movement system. The conveyor's downsides are the high initial capital investment, limitations in particle size and rigidness of the overall system. In conveyor system, the particle size is important factor, big particle size causes spills, blockages and significant wear to the conveyor. For example, Finsch Diamond Mine have used sizers to make the particle size suitable for a belt conveying before hoisting it. In case where mine life is long and ore body delineation is known far to the future, conveyor belt is a strong option. The conveyor system can be either mounted to a floor or it can hang from the roof. Smaller conveyor applications and feeders can be used along the path of ore movement process. That means locations where ore passes connect to each other or between haulage level, surge storages or crusher feeders or conveyor can be applied for transport. A big cost factor with larger conveying systems is the maintenance drive way for vehicle access. That has to be designed for a conveyor thus increasing excavations and costs of a conveyance system.

Besides hauling equipment, other necessary equipment for ore pass operations are necessary. The ore pass tipping- and drawing points has to be cleared out to make sure undisturbed operation. Especially in the tipping point boulder control is important. Boulder control is done by using excavator or LHD to clear out the tipping point to guarantee continuous operation. When autonomous LHD's, are utilized, the operator has to make sure that no oversized boulders are hauled to the tipping point because an automated system can't handle the exception that boulder is blocking the way. Before an ore pass or underground crusher, oversized boulders should be sorted in a separate bay where these can be blasted or broken using a rock hammer. Best option is to prevent the occurrence of oversize boulders by optimizing the stope blast.

2.7.3 Operational needs for equipment

There are many operational needs which need to be considered to create functioning underground ore movement system with ore passes. Typical set up in an underground sub-level stoping mines contains multiple operations which are on-going simultaneously in the same sub-level. For a fluent functioning of working groups, careful planning and scheduling in allocation of work force must be done. Often production targets are not met because tiny working areas does not allow a proper allocation of working phases which leads to logistical problems and tasks occur same time at the same place. Ore passes can be considered as a contributive factor, because the primary impact of the ore pass network is the reduction of hauling equipment travelling along the sub-levels. Therefore a well-functioning ore pass system is making the local logistics in a single sub-level less intensive. To make this happen, next paragraphs will analyze the operational requirements of the ore pass system. In Figure 47, layout with necessary operational equipment is presented.

The most critical location for ore pass operations is the tipping point, also referred as a tipple, which connects the production level to the ore pass. That is an excavated place where the loader is carrying the ore from a stope. It is often built on a short drift to make sure that it does not cause any disturbance to other activities. Placement into a drift is also advantageous because it can be sealed from other mining area when it is not used. Therefore ventilation, dust and safety issues can be mitigated. For an optimum loading cycle, the direction of the drift should be chosen to be as shallow as possible to minimize the cycle time and extra loading in loader's wheels and frame while making tight turns. For automated equipment, the direction of the ore pass drift strike is irrelevant in terms of productivity, because it can drive backwards as fast as forward. Man-driven LHD is always faster to go forward and therefore for fluent operation a consideration for reversing bays should be taken into account.

A tipping point should be excavated with overhand dip to make sure that water inflow is away from the tipping point to reduce risks for mud rushes and cohesive blockages. Ditching is done at a tipping point to improve dewatering towards sub-level and pumping stations. The tipple should be equipped with proper lighting and an indicator system which indicates whether it is safe and allowed to tip the ore to the pass. Lighting system enables the operator to make visual inspection that big boulders or foreign objects are not entering the ore pass system. Particle size analysis through video can be applicable to boulder size tracking as well. These have become common in many industrial processes to monitor the particle size distribution online. Despite the problems with dust and moist, this might be potential method in future. This would enable a mine to increase tipping efficiency, by taking screening devices away, blocking the ore pass throughput. Above the ore pass, to the roof, readiness for pulley or winch installation could be prepared to facilitate for future needs for rehabilitation, blockage releasing and inspections. The actual tipple drift should be made fully sealed using wind doors or optionally installed grizzly boxes, which are lifted from the ground and equipped with lids to isolate air blast, dust- and noise emissions.

Sometimes disturbance such as blockage or mining activity in the same or another level does not allow haul the material to the tipping point. Alternative dumping location, a stock pile bay should be designed to every level. Location should be as close as possible to the actual location of the ore pass from where it is easy to load, carry and dump when access to the ore pass is recovered. It should be also easy to access that no harmful loading and maximum frame/wheel turning occur while operating. If the disturbance of the ore pass system is taking time, the stockpile bay area should be designed to enable truck hauling in exceptional situations. For the case of disturbances and malfunctioning of the ore pass system, preparedness for such cases should be considered in the design phase. For example, locations for inspection accesses (Stacey, Swart 1997, p .21) to the ore pass should be preliminary analyzed, to maintain access and a fast response, if critical disruption of material flow occur during the life time of the ore pass.

In the hauling level, the layout of the discharging area is dependent on the ore pass network. Operational wise, chute and feeder loading does not differ from each other, they need similar infrastructure. In a chute or feeder operated ore pass loading, the area consists of a steel frame of the chute or feeder system which is often operated remote or autonomously. A haulage truck is loaded by driving it underneath the frame. The frame is normally mounted in a concrete structure and bolted to the walls of the haulage drift. Also for keeping the loading area flat and smooth, a poured concrete slab in the floor increases the durability of the area, securing fixed loading height and minimum maintenance of drive way. For safe operation, chute area should be equipped with a guiding system which indicates that the truck is in an optimal place to successful chute loading.

Designing excavations of the actual hauling level and drifts, consideration whether one lane or two lane drift is necessary for operations should be done. Especially, in an autonomous truck loading option, it should be remembered the ability to fully operate in one lane. Human cannot go underneath a chute and therefore passing bays should be placed at least in locations where it is necessary to go by a chute. Other infrastructure to be considered in hauling level are truck loops and reversing bays for hauling equipment. Truck loops are mainly necessary if truck hauling is not automated.

A critical link of the ore pass system is the end point of the underground ore movement chain - the crusher. Crusher is the bottleneck of the underground ore transportation. The main purpose of the ore pass system is to feed the ore in a level that utilization rate of crusher stays as high as possible. Therefore during crusher switch offs, ore has to be whether stored in an ore pass system, in silos or underground stockpile bays. In case of silos, the tipping area has relatively similar requirements as the tipple of ore pass. Crushers has limited intake dimension for boulders and therefore before a crusher there should be a screening device. Screening in the crusher is necessary even if the ore pass system is equipped with grizzlies, because in exceptional situations the crusher might be necessary to be fed by direct hauling from production stopes.

2.7.4 Ventilation and dust control

In wide perspective, ore pass systems should not have significant influence on the mine ventilation, but has impact on local conditions of mine air. Extensive ore pass systems are often equipped with gates and chutes disabling that ore pass network is an airway. Locally, openings between sub-levels create new paths for the air to enter and exit. Therefore the main impact is to a local mine workings and people working in the vicinity of an ore pass. Another issue is the impact of pressure change during the material is tipped and falls down in the ore pass.

While ore is falling, more fines is created due to grinding action occurring when material is hitting to ore pass walls. Air blast from "piston effect" makes the fine particles airborne and creates a dust problem. Piston effect could be reduced by connecting the ore pass to other opening or another rock pass, thus relieving the pressure (Kissell 2003). Air blast is unavoidable in ore pass operation, but in the design phase it is possible to reduce the falling speed of the material and therefore reduce the air blast. Ventilation and dust mitigation techniques such as water sprays and booster fans can be used to control the dusty air. Kissel et al. also mentions a recommendation that dusty air should be discharged to an exhaust airway, isolating the area by using airtight doors or locating the tipping point to a short dead end with a local dust collection system. Chutes and gates are good ways to reduce material speed and shielding the path to prevent a movement of dusty air from opening to another. Dust creates health issues to working personnel but also reduces ability to detect ore pass mucking level and disturbs the operator, equipment and sensors in the ore pass area. Similar actions should be thought when selecting other ore pass equipment like feeders and conveyors which can be a significant source of dust emissions.

2.8 Maintenance and management of ore passes

2.8.1 Management of ore pass system

Modern mining operations demands a lot of in-situ and online data from mine production to reach high productivity. These include location data of current active mining locations, the ore grade and concentration of other substitutes in the ore and waste rock. These are for example, gold grade and Sulphur content which has impact on the ore refining process. This data is important for the run of mine and for processing plant. Constant feed to a processing plant can be done via grade control and blending applications. For an optimum process, feed going in to a crusher and further to a processing plant has to be tracked, measured and reported to the plant, in advance, before the ore enters to the crusher. Ore pass systems are therefore problematic because they are blending the ore and waste rock from different locations. Making the problem more complex, the ore is not transported immediately to a surface stockpile but is kept in an ore pass. Therefore tracking the ore flow content, location and time are very important if these parameters are changing a lot. Generally, ore passes are easier to manage if extracted material is a bulk mineral such as iron ore, but high value ore is more complex because its occurrence is more dispersed and the grade has more variability.

To successful ore pass operation location and tonnage of the ore must be tracked one way or another. The easiest way to track the state of the ore in a pass system is reconciliation. With reconciliation it is possible to estimate the tonnage and grade of the ore based on a block model. It gives a good estimate for the expected material flow in an ore pass. Nevertheless, the block model cannot be the only source of information. Estimated block values and grades must be verified before feeding it in to a processing plant. Tonnage can be easily tracked by LHD's, equipped with an automatic weighting bucket. The grade is harder to measure and therefore procedure for ROM sampling must take place before the ore enters the plant. Without accurate information, the grade control procedure, blending low grade material with high grade to make constant mill feed to the plant is impossible. Another option is to sample before tipping the ore to an ore pass or right after the pass. If sampling is done after tipping the ore to the ore pass, dilution and blending due to scaling and mixing ore from different stopes must be considered. Dilution and blending can be estimated by calculating the blend of different ore grades from the block model, but reliability of the blending calculation and block model should be verified and checked regularly to guarantee a realistic outcome. Ore flow can be tracked with ore flow tags which are commonly used in block caving mine, but can be also applied to the ore pass situation. It could enable to attach a time dependency to the ore tracking data.

More complex ore pass system can have significant surge capacity. Management of the ore pass should therefore include a system, monitoring the amount and location of ore which is stored in an ore pass or silos. That would also enable possibility to blend material like in a normal stockpile management procedure. For ore pass systems, gates or chutes should be used to enable accurate blending. Similar to block caving mine, if multiple ore passes are used, draw control at the bottom of the ore pass has to be managed and planned. Whether ore passes are discharging to a truck or conveyor, multiple sources makes the tracking more complex. Ore should be drawn in regular intervals from all sources for constant feed to an underground crusher, but also for following best-practices in ore pass operation.

Dilution in an ore pass system should be minimal. If the ore pass is built a correct way and significant scaling and degradation does not occur, the dilution of the ore due to material dilution from walls should be negligible. When the ore pass is used for the first time it should be noted that dilution can be higher for the first buckets of ore. This is because after excavation, loose rock blocks and slabs might fall down and dilute the ore. Later, dilution in the ore pass should stabilize and later begin diluting again when the ore pass reaches its designed life time. Previously described phenomena is easily controllable via ore grade sampling which reveals if a diluting ore pass degradation is taking place.

2.8.2 Ore pass inspections and monitoring

During the lifetime of the ore pass, its structural integrity needs to be inspected and monitored in a regular basis. Monitoring is carried out to ensure undisturbed material flow and production reliability by inspecting the integrity of the ore pass and its liners. Unexpected degradation might lead to severe failures or mud rushes and therefore it is important to keep the ore pass condition status up to date. Frequency and the need for monitoring and inspections are highly dependent on rock quality, production rate and operational method of the ore pass.

Based on operational needs the ore pass can be equipped with a continuous, online monitoring system (Figure 13). For example in the full ore pass operating method, filling rate should be monitored continuously to guarantee that the muck level stays in predefined constrains to maintain safety and stable production. In the free flow system, muck level monitoring is not necessary, but some kind of monitoring or procedure must be implemented that ore tipping to the pass and mucking from the bottom can be executed safely. For example, the tipping point can be equipped with a monitoring system sensing the state of the ore pass that it is safe to tip the broken ore into the pass. Permission can be signaled to the operator by traffic lights.

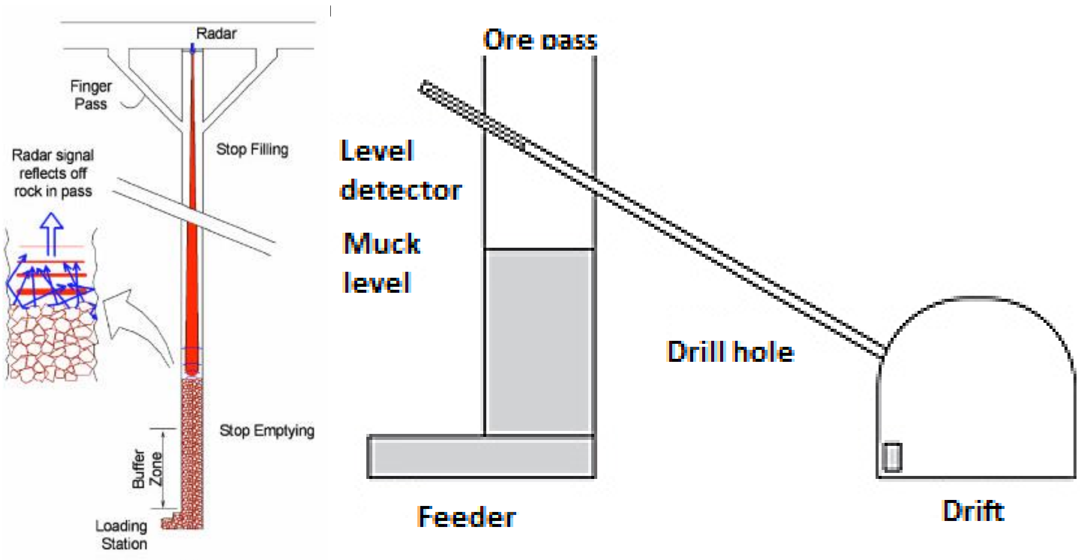

Figure 13 Radar based ore pass monitoring system (Brooker et al. 2007) and electromagnetic induction sensor layout in Pyhäsalmi Mine (GTK).

There are four types of methods for muck level monitoring: Visual, measuring tape, laser and reconciliation. Visual inspection is the cheapest and simplest but in practice, it is complicated and unreliable. In dark, dusty and wet conditions it is often hard to make reliable visual observations. Also visual observation requires a lot of manpower and it is difficult to gather-up any quantitative data. Measuring tape has similar problems to visual observation: it is difficult due to mining environment, labor intensity, unreliable results and lack of continuous measurement even though it could be measured through a video connection. Laser and radar sensors are promising technologies to define the muck level, but there have been problems with radars in shallow passes and in case of lasers, the dust have been reported disturbing the measurement (Brooker et al. 2007, p. 548).

No matter which one used from previous three methods, reconciliation should be used to back calculate the expected muck level. Reconciliation has limited accuracy, but it gives a good overview of material flow and the information can be further used in the ore movement process. Nowadays there an ore flow tracking tags available in the market, which can be used to map a location and the muck level in the ore pass. In addition to the muck level monitoring and inspections this data gives valuable information about the ore pass material flow, blockages and degradation rate. Pyhäsalmi Mine has also used a device based on electromagnetic induction. The device is defining the muck level based on electric conductivity of the ore (Figure 13).

Other necessary monitoring activity for an ore pass is the degradation monitoring. During the lifetime of an ore pass, it is common that the cross sectional area in different sections of the pass faces significant degradation. It is more than common that the area is more than doubled during its life time. Even more than tenfold enlargement to an original dimension have been reported. Degradation monitoring can be made using multiple methods: Visual-, drilling-, camera-, cavity monitoring systems or by reconciliation. Visual inspections are relatively similar to muck level monitoring, except that for degradation observation it is more than necessary to go into the pass to make reliable observations. This naturally requires substantial safety arrangements. To map the degradation rate it is possible to do drilling so that the location of deformed wall can be calculated from the length and direction of the drill hole and use the core for geotechnical analysis.

Cameras have been used widely in the industry to track ore pass condition. These can be mounted on a winch or buggy which is driven to the ore pass (Sjoberg et al. 2003) and (Jarosz 2008). Recently, CMS (*Cavity Monitoring System*) have become more and more common due to the reduced price of technology and can be used for mapping the ore pass walls and especially changes in the volume and shape of the ore pass. In degradation monitoring, reconciliation should not be forgotten – it is a powerful tool to calculate tonnage and grade changes in the ore pass system and therefore gives a comparative estimate for ore pass material flow and reliability for the other measures. A state of the liners can be monitored using wear nails in the liner material or analyzing mill feed where degraded liner material can be distinguished. (Hadjigeorgiou et al. 2004b)

2.8.3 Rehabilitation

Necessity of ore pass rehabilitation can be detected from an obvious increase in dimension of the ore pass, irregular ore flow or large blocking of waste rocks (Garner 2006). Ore passes are relatively cheap to build but rehabilitation is expensive. The actual cost of rehabilitation works have not been studied, but experience is indicating that unplanned rehabilitation is very expensive and its effectiveness is limited if the degradation of the ore pass has already started (Hadjigeorgiou et al. 2004a, Hadjigeorgiou, Mercier-Langevin 2008a). Expensiveness of ore pass rehabilitation is related to a production delays, special techniques used in construction and massive safety arrangements (Hadjigeorgiou, Stacey 2013). The special techniques are necessary in an ore pass rehabilitation due to small working space, unstable wall stability and very dangerous set up for mine personnel. Often abundant ore passes or excavation of a new pass is more feasible than rehabilitation of the existing one. Aspects leading to the decision to rehabilitate an existing ore pass is often made in situation when the pass is indispensable and without rehabilitation works mine production is threatened.

Generally, ore passes can be rehabilitated whether renewing liner material or adding additional support. Depending on the pass design, liner material can be replaced with a new one like in case of wear plates and chutes. Other liner material, such as concrete casts or layer of shotcrete can be renewed after significant degrading. Also in case when walls are badly damaged, backfilling can be used to make the pass stable. Backfilled ore passes are redeveloped through fill by boring it to operational dimension after curing or a “tube/pipe” is installed before pouring the backfill to the pass. Backfill is soft material and therefore a tube or other liner should be installed. Sometimes, if the damage of the ore pass is limited to a one specific area, bolting (mainly cable bolts) can be used to prevent propagation of damage. Similarly, Swellex bolts have been used in some mines (Hadjigeorgiou et al. 2004a). Installation of tendon support is normally installed via additional access raise and drilling crosscuts. Steel rings can be used to support walls as well. (Stacey, Erasmus 2005)

However, experience have shown that damage in an ore pass is often propagating and getting only worse after the first signs of degradation is observed. Rehabilitation is often only method to slow down the deterioration. Severe degradation can be referred to a self-mining of the ore pass, meaning that the pass is degrading due to instability. In extreme cases, self-mining is so extensive that it becomes a risk to the local mine stability in surrounding area. For example in South-African Kloof Mine, self-mining extended to a haulage level below and for rehabilitation area had to be filled with 30 000 tons of waste rock. (Hart 2006, p. 2)

2.8.4 Material flow releasing methods

A careful design of the ore pass is the best method of avoiding material flow related problems in an ore pass. Still, due to degradation and changing material properties, ore passes tend to block or hang-up. To guarantee stable mine production and minimize production losses due to flow problems, it is important to consider and design a procedure how to prepare in case of a blocked ore pass. Because of the vertical structure of the pass, releasing a blockage is a difficult and very dangerous. A direct line of sight is hard to achieve without going under the ore pass which exposes to a great risk of direct hit of unexpectedly released hang-up.

Releasing methods can be categorized based on the type of blockage material or location of the blockage or hang-up. Blockage near the end of the ore pass or in a chute is easier to release than a hang-up which is 20 meters high in a pass. Actual releasing can be done via applying mechanical force to a blockage, water or using blasting. Mechanically, the blockage can be released using rock hammers, drilling, water or high air pressure. With water and high air pressure it is possible to release obstacles up to 20 meter height. A reachable blockage in the chute area can be removed whether mechanically or by blasting. The drilling needs always a redundant connection to an ore pass, because under the hang-up it is dangerous and forbidden to work.

A common way to release a hang-up is to use explosives. The limiting factor is the installation of the explosive charge. In case of heights, special methods are applied to reach the blockage. That means using for example extendable arms in LHD to locate the charge, a buggy which can be driven to the blockage, shooting a ballistic charge (slug shot) or using special compressed air propelled device “Spoutnik” which can be flown to the target and detonated. Methods with explosives are likely to cause degradation and geometry changes to the walls and sometimes damage to the chutes. Another downside with explosives is the blasting fumes – blasting has to be scheduled related to other mine operations.

Before choosing a suitable releasing method, it is important to recognize the type of the blockage whether it is a hang-up formed because of interlocking particles or a cohesive hang-up. Cohesive hang-ups are difficult to dislodge using blasting, because it is hard to aim the specific spot and the actual blasting effect is not effective in cohesive material. Blasting might compact the cohesive material and making dislodging even harder. Therefore other methods needs to be considered. Applying water from below is the most common and the first method to apply in most mining applications. Water is efficient to release cohesive hang-ups, but it also creates risk for a mud rush. If water is introduced above the blockage, amount of water has to be evaluated to prevent excessive mud rush and flooding when the blockage is released. Experiences in South-African, Canadian and Australian mines have shown that only ore passes equipped with chutes can be released safely by introducing water (Hadjigeorgiou, Lessard 2010, p. 271).

2.8.5 Ore pass hazards

Ore pass hazards are related to risk of scaling and falling rocks, mud rushes and air blasts. Accidents, production delays and damage to a personnel and equipment happens often when these hazards occur unexpectedly. To reduce the occurrence of these hazards it is important to understand the background conditions which have influence on the formation of these hazard. Vertical and relatively narrow structure of the pass makes direct visual observation of the hazard almost impossible and often chutes or gates are blocking the direct visual sight to the pass. Therefore, other safety measures and protocols must be used to avoid unexpected hazards. For example, MSHA data implies that shaft and ore pass-related accidents are common in the United States and in South-Africa. Portion of the ore pass accident is significant in overall accident statistics (Stacey, Erasmus 2005). Researchers have identified from the incident reports that especially people working in areas related to mucking, material loading and unloading were susceptible to death or injury. Injuries and fatalities were often caused by problems in ore pass chutes and gates in situation where muck is released from the blockage or due to a structural failure of the ore pass gates and chutes. Reason to these hazards is the lack of ore pass design capabilities and standards. (Beus, MJ., Ruff, TM. 1997)

Hazards related to hang-ups and blockages are often unexpected and create a very high risk for injury or fatality. These are situation where the hang-up is released spontaneously. Falling rock creates threat for the personnel working underneath ore pass or in the vicinity. Cumulating broken material to the top of a hang-up might lead to significant impact loading while released causing extensive impact loading to the chute framework and air blast damage and dust problems to surroundings. Hazards described previously are often hard to handle when the problem already exists, but these can be minimized with careful analysis of design parameters to prevent blockage occurrence and developing a monitoring system to alert for disrupted material flow.

Formation of cohesive or a normal hang-up can be reduced by operating ore passes carefully. Sometimes foreign material such as steel support, timber or grout flows are causing the actual hang-up phenomena. Despite the preventative measures, sometimes the hang-up formation is unavoidable, then only mitigating action to be done is to identify it early enough to prevent the incident. Therefore monitoring and inspections are important. For chutes and gates, it is possible to install strain-gage measurement systems to measure loading of the frame and make regular inspections to a chute system. Structural failure is often related to a formation of hang-ups and blockages in the ore pass. Scaling walls results in falling slabs, which might fall against discharging infrastructure or temporary block the ore pass system. Passes with piling option falling objects might cause injury risk for personnel working nearby the ore pass, even though accessing to the end of the ore pass should be forbidden. Rare but more serious degradation can lead to a bigger structural instability to surrounding mining area. Sometimes unexpected degradation leads to situation described previously. In Kiiruna Mine for example, unexpected enlargement of ore pass could have been the initiating cause of a fatal rock burst. (Sjöberg et al. 2011).

Air blast and dust are both results from falling ore and rock material. Dust comes from preceding phases such as blasting and loading but when material in the ore pass is grinded while falling, the piston effect in the ore pass with air blast makes the dust spread all over the surrounding area. Generally, the dust problem can be controlled with traditional dust mitigating techniques and correct operation disciplines. While making design, should be remembered that the air blast is very powerful. It is found in a vertical ore passes that the tipped ore to a pass compresses a column of air ahead of it towards the bottom of the ore pass. This air blast creates lateral impact forces hitting the pass walls with a full momentum of falling ore. It create threat to all mine workers in the vicinity of an ore pass. Phenomena has significant impact on degradation and support selection. (Brenchley 2006, p. 13)

Mud rushes can occur as an independent hazard but can be also caused by other factor such as disturbance from seismic activity or air blast. Normally, these rushes are that fast that it is almost impossible to escape when it is about to occur. Mud rushes are formed when following 4 elements are present: Mud forming material, water, disturbance of the mud and route where mud can discharge. As an example, a severe accident happened in Maroelabult Mine in 2004, where insufficient drainage and management lead to a mud rush. The blockage of the rock pass was observed before the accident, but people were not aware of risks related to an observation they had made. Shortly after, the mud rush led to seven fatalities and five injuries. (Butcher et al. 2005)

3 Research Methods

3.1 Strategy for ore pass design and placement

For ore pass design and placement study, Kittilä Mine is used as an example. The case study will be carried out by using a modified approach of design strategy for rock structures by Bieniawski (1992). Using the methodology for ore pass design and placement was proposed by Hadjigeorgiou et al. (2013). For this thesis, the strategy had been modified by changing the order of steps to meet the targets of Kittilä mine production. More weight is given to production constraints such as hauling distances in the design process. Design process and steps are clarified in Figure 14.

Case study will proceed step by step using following order of modified methodology:

1. Clarity of design objectives and functional requirements
2. Optimization
3. Minimum uncertainty of geological conditions
4. State-of-the-art practice
5. Simplicity of design components
6. Constructability

Clarity of design objectives and functional requirements

Kittilä Mine is an underground gold mine with production of 1.6 Mt per year. In future, the mine is studying the feasibility to increase its production to 2 Mt per year. Therefore, the mine is looking for new ways to increase productivity and especially decrease hauling distances while mine is getting deeper and deeper. Methods includes possible investment in hoisting shaft and ore passes. Ore passes as an option to increase productivity is demanded to guarantee stable underground material flow: production stability with minimal disruption. The pass system is expected to decrease level haulage distance hence helping mine to cope with jamming truck haulage and high tonne-kilometers. The ore passes with automation also enable the mine to increase its productivity during smoke hours. Twice per day, the mine production is stopped for 2 hours due to blasting and ventilation of the blasting fumes. If these hours could be utilized for loading and hauling, it would result in approximately 20% higher productivity.

Optimization

Optimization of the ore pass system is crucial to gain the economic benefits which are expected to have via objective and functional requirements of the system. This means as a fixed long-term investment, that location and design parameters are carefully designed and analyzed. In this study, scenarios for potential locations are defined and optimized using all available data sources and recommendations for design and location is given. Impact to tonne-kilometers, hauling distances and productivity increase is due diligence study to find the optimum solution.

Minimum uncertainty of geological conditions

Ore passes will traverse through different geological zones which are analyzed to get a better estimate for the ore pass stability, longevity and design. This is carried out by ensuring that the geological conditions does not oppose the selection of the ore pass location. To some extent, adverse geological conditions can be compensated using heavier rock support scheme, but sometimes the only option to create a successful ore pass system is to move the ore pass section further away from the weakness zones. For example major water inflow to the ore pass can support the decision of moving the location of the ore pass.

State-of-the-art practice

Kittilä mine is a modern mine with enthusiasm towards a production automation and safe operation. The mine has succeeded in a testing of autonomous hauling and loading equipment and holds a strong mind towards utilizing the system in wider perspective. The ore pass system must be designed to host automated hauling and loading equipment. For ore pass design, it means a potential for usage of automated chutes and dozing techniques to load a mining truck. The utilization of chutes and other infrastructure for automation means higher initial capital investments which must be justified by using state-of-the-art design practices – a malfunctioning ore pass cannot host chutes or other sensor technology necessary to automation.

Simplicity of design components

Mining environment is a rough place for engineered objects. Meaning that design object must bear a lot of abrasion, corrosion and mechanical shocks. The ore pass is one of the most extreme structures in an underground mine. It gets a constant hit from falling rock, mass of thousands of kilos and therefore facing remarkable degrading impact. Dust and moisture are making the operating environment mechanically robust and abrasive. Therefore it is more than important to design the system in a way that it is resistant to these latter impacts and if necessary is easy to maintain and replace if necessary. Ore passes can be kept also as a significant safety risk for a mine and therefore simplicity of system and procedures must fulfill the safety requirements.

Constructability

Constructability is a mixture of technology and culture of the mine. Kittilä mine hosts a competitive environment for ore pass excavation and therefore the question is more dependent on design and company culture. Construction as in its simplicity is a selection between raise boring techniques and drilling and blasting. This is more often a company culture preference: which one is kept financially more justified and is there presence of know-how in the surrounding region to get raise boring equipment. Kittilä mine have succeeded in full face raise boring in diameter of 4 meters ventilation raises and therefore raise boring could be an option for traditional drill and blast.

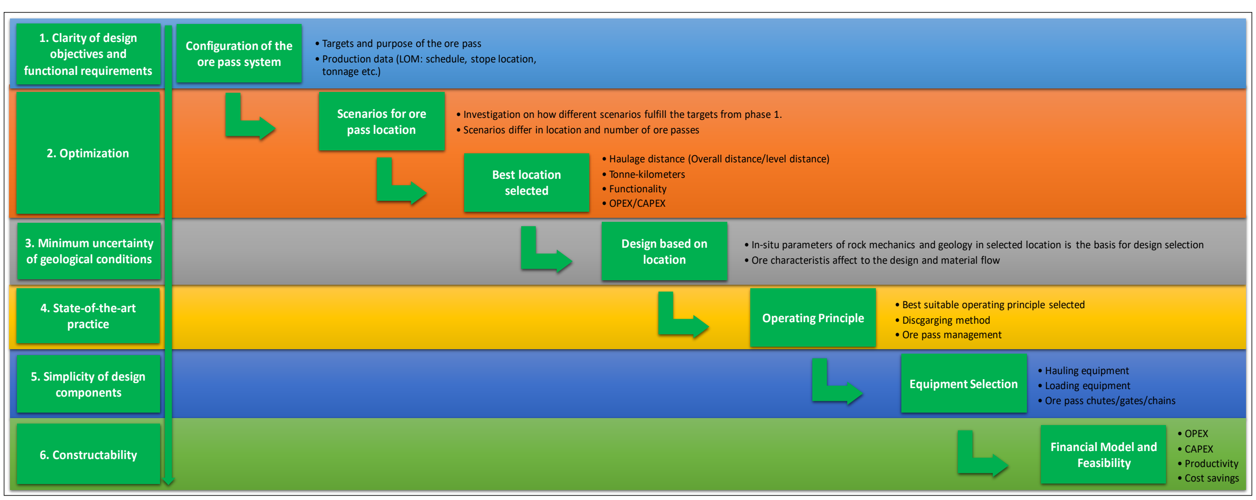

Figure 14 Strategy for design and placement of ore passes.

3.2 Analysis and selection of suitable ore pass placement(s

Due to the dominating influence of location of the ore pass to the lifetime costs of ore passes, location scenarios are defined in the first phase. Afterwards, locations are verified by checking other parameters influencing to the ore pass design and placement. For the mine, suitable ore pass locations are based on mine layout, hauling distances, safety and geological/rock mechanical parameters.

For the scenario analysis, a sufficient number of basic scenarios are defined to analyze the influence of location (in terms of coordinates and inclination) to overall ore pass performance. Greatest cost reduction in ore pass operation comes from minimizing the hauling distances. This can be evaluated by studying the block model and extraction sequences of the mine. More than the block model, LOM is more suitable for design analysis, because the block model does not take into account the time dependency of the grade and tonnage. Ore passes should be located close to the center of gravity (C.O.G). Therefore C.O.G is defined to mining levels to define the location of the ore pass. Generally, ore pass location is a linear optimization problem, where the target is to minimize the hauling distance between production stopes and the ore pass. This is done using Least Square Method to minimize the distance. The optimized model using Least Square method with design constraints of maximum inclination is applied to find the optimal location. Other constraint for ore pass operation is the number of ore passes per level. This can be studied by inspecting the schedule of stoping from LOM. Through analysis it is simple to find the production targets that ore pass needs to meet. From LOM it is important to find the overall tonnage flow through ore pass and its distribution in time and location.

Production capacities and cycle times are easy to calculate for equipment but in an underground mine that is not enough to find the competent solution. To verify the location and practicality of the solution, discrete event simulation of hauling is made. HaulSIM software is used to inspect the phenomena of jamming, benefits of chutes and surge capacity and overall productivity of the ore pass system. With discrete-event simulation it is possible to find the bottlenecks and solve the actual maximum amount of trucks which can be utilized for ore haulage. Difference between operation with ore pass chutes and without chutes is also simulated in HaulSim. In pile discharging method the truck is assumed to be loaded in 180 seconds, whereas in the chute loading, time is set up to 30 seconds. Chutes enable to store the ore in the ore pass and impact of surge capacity with chutes is simulated using surge capacities 427, 641 and 854 tonnes. Impact of automated and autonomous equipment is taken into account running all scenario also with automated equipment, meaning that lunch and shift changes are discarded. Every scenario was replicated five times and average of these were calculated. HaulSim parameters are listed in Table 4.

Table 4 Parameters in HaulSim simulation

Parameter	Value
Truck capacity	27t
Mechanical availability	85 %
Maximum speed on the level	15 km/h
Maximum speed on the ramp	25 km/h
Lunch	30 min
Shift change + smoke hours	220 min
Simulation time	4000 min
Ore pass discharge time	30s or 180s
Surge capacity	427t, 641t or 854t
Normally distributed random variability in loading and dumping time	Right skew 4%
Random stop interval (min)	normal(2000,10,1)
Random stop time (min)	normal(400,10,1)
Equipment specs set to the manufacturer default	

To evaluate the benefits of ore passes, simulation of haulage routes from stopes S700L151_1, S775L171_1 and S875L163_1 were done to identify the truck need if ore passes are not utilized. For calculating the number of trucks, maximum congestion time was 30% and loader utilization was kept as high as possible. Simulation resulted in need of 5, 6 and 8 trucks in same order as previously mentioned stopes. The result implies that there are a threshold number of trucks after the increased number of trucks does not increase the productivity due to jamming and waiting induced congestion. The congestion can be explained with critical distance. That is, overall length of hauling cycle divided by the number of trucks. If the distance is lower than the average speed of truck multiplied by loader's cycle time - congestion occurs.

$$\frac{l_{cycle}}{n} > \frac{t_{loader}}{v_{truck}}$$

Where,

l_{cycle} = length of the hauling cycle (m)
n = number of trucks
t_{laoder} = cycle time to fill one truck
v_{truck} = average speed of a truck

Simply, if the loader cannot load the hauling truck fast enough, truck coming after, using average speed, needs to wait in a loading area resulting in queuing and jamming on the footwall drive. Results can be found in Appendix (Figure 56).

3.3 Analysis and selection of suitable design(s)

Suitable design is defined based on the location and in-situ parameters of the hosting rock. In the Kittilä Case study, data from geology, rock mechanics and other relevant sources is used to make a competitive design. The data is analyzed and a best fit design is defined in order of optimum location and operation constraints. Geological-, rock mechanical and material flow parameters play a big role in the design selection and these are defined from available data on the mine site.

For evaluation of rock stresses impacting on the ore pass structure, an elastic model is set up and using measured rock and stress data it is possible to evaluate the rock mechanical stress state of the ore pass in single two-dimensional analysis. Also, operation method has influence on the selection of ore pass design in terms of infrastructure items such as monitoring and chute systems.

3.4 Cost-Benefit and Sensitivity Analysis

For the optimum scenario, a financial model is set up to estimate the feasibility of investment in the ore passes. The analysis contains estimation of capital and operation costs of ore passes. Benefits of the ore passes can be calculated in terms of reduced annual tonne-kilometers and savings in capital which is valuated using the opportunity cost of capital. The ore passes brings benefits also which are hard to valuate, such as decreased traffic jams, accidents and simpler maintenance management. Also infrastructure costs are lower due to smaller road degradation and from cost of building remucks and loading bays for trucks.

Due to economic characters of mining industry it is important to look at the costs and benefits in terms of changes in the project costs. This means analyzing the scenarios in terms of change in LOM or change of commodity prices and how it will impact on the feasibility of the ore pass system. Feasibility in terms of changing Opex and Capex and mine plan is introduced. Also development in technology reduces the need for ore passes. Fully autonomous hauling and loading decreases itself the need to cut down haulage equipment, because traffic jams in underground is often results of human error. Safety and risks are having impact as well to the feasibility of the system. How to make sure that ore pass system is functioning through its' planned life time and what is the effect of a failing system on the overall mine production?

4 Research Material

4.1 Production rates, targets and development of the mine

Production rates, targets and future development of mine is an important factor for selection of suitable ore pass designs and placements. Often ore passes are being built when other infrastructure is existing already. For example, the main ramp and majority of mining levels in the areas of the new mining zone might already exist and therefore these must be taken into account in the study. Generally, shape of the orebody is limiting the location of the ore pass to the footwall of the orebody in Kittilä. That is, because otherwise steeply dipping ore body might traverse the ore pass network in the future and the degradation zone would form towards footwall drive. Ore pass location in the footwall is defined by existing infrastructure, simulation and analysis of hauling distances and by considering stability and safety parameters such as rock mechanics.

The extraction of stopes is disseminated to a large area meaning that also the stoping sequence and timing needs to be taken into account. Life of Mine (LOM) data and other necessary production data is gathered for evaluating their influence to the design and location of the ore pass. Following LOM data were used for analyzing production:

- Stope ID
- Level ID
- Ore Tonnes
- Level Haulage Distance
- Ramp Haulage Distance (To crusher or stockpile)
- Coordinates (x,y,z)
- Exctraction start date

Also financial parameters are collected to calculate the feasibility of the project. The following Table 5 comprises the data which have been gathered for Kittilä Mine Ore Pass project:

Table 5 Production data of Kittilä Mine

Parameter	Description
Ore	Gold 4,6 g/t LOM: 1.6Mt/a Looking for expansion to 2 Mt/a
Waste	approximately same as ore production
Drifting	12 km/a
Stoping	100 - 200 per year Stopes 4000 - 15000 t
Backfilling	Pastefill Rock Fill Cemented Rock Fill 32-65% of waste placed underground annually.

4.2 Geological and rock mechanical data

Geological description of Kittilä Mine gives a good basis for evaluating the suitability of ore passes. Kittilä mine rock is relatively competent and hard with a precaution of jointing and water inflow in places. Generally, Mafic Pillow Lava (MPL) is dominating lithology with minor intersections of Massive Mafic Lava (MML) and Faults. Geological parameters are listed in the Table 6.

Engineering geological description is "Very strong grey with white calcific veining fine grained jointed MAFIC PILLOW LAVA. The texture of the rock contains rounded pillow structures and the intensity of the calcite veins are variable and are mainly closed/cemented. The Rock Quality Designation (RQD) is generally classified as excellent with moderately spaced joints. There are 2 joint sets present with some minor random sets. The joint surfaces are either rough irregular and planar with calcite or chlorite infill or planar polished with graphite infill."

Table 6 Geological parameters of Kittilä Mine

Parameter	Description
Orebody	Major rock units strikes north/north-east, narrow shear zones (breccia)
Dip	Steeply dipping
Direction	North-South (0^o)
Host rock	Mafic Pillow Lava (MPL)
Shear/Fracture zone	Shear zones in 740m and 966m

Kittilä mine has carried various borehole studies to assess the rock quality for different investment projects such as underground crusher and new main level. Data collection and parameters from these studies have been used in the ore pass analysis. These studies have been conducted by SRK (2017), Geovista (2015), Hakala et al. (2009) and Drillcon (2012). These borehole studies included for example geophysical logging pilot holes where following techniques have been used:

- Optic Televiewer (OTV)
- Acoustic Televiewer (ABI)
- Natural gamma radiation
- Full waveform sonic (FWS)
- Fluid temperature and conductivity (FTC)
- Bi-direction spinner flowmeter (SFM)
- Compensated density (DEN)

Also recently bored ventilation raises have been videoed and can be used to support other rock mechanical observations. These raises have a diameter of 4 meters, developed using a full face back reaming. Table 7 and Table 8 summarizes the study results of various geological and rock mechanical parameters which have been used for analyzing the suitable ore pass location and design.

Table 7 Rock mechanical parameters of Kittilä Mine

Rock Mechanical parameter	**Description**
UCS	180
SRF (*Stress Reduction Factor)*	1 – 12,5
In-situ stress after Hakala et al.:	
$\sigma 1$	2,8 x $\sigma 3$
$\sigma 2$	$\sigma 1$ / 1.7
$\sigma 3$	γH
Jointing	
Joint Set Number	Two major joint sets J1, J2. Minor J4.
Joint Filling	Rough irregular and planar joint surfaces with calcite or chlorite infill or planar olished graphite infill.
Direction	J1: Moderately to Steeply dipping to the East J2: Steeply dipping to South-South-East J4: Moderately dipping subhorizontal joint set similar to the vein set
RQD	Excellent
RQD/J_n	10 - 20, several zones < 8
J_r/J_n	> 0,4 Stabile Blocks, not conclusive
Q_r	> 0,3 localized intervals below
MSUS	RSR 1.6 for ore passes is used.
Water Inflow	Estimated max. 59,2 liters
Parameters for Elastic Model	Hoek-Brown
GSI	60
m_i	17
Disturbance factor (D)	0
Intact modulus (E)	60000 MPa
m_b	4.074
s	0.0117
a	0.503

Table 8 Material flow parameters of Kittilä Mine

Material flow parameters	
Mineralogy	Arseno-Pyrite, FeAsS
Density	2.9
Swelling	1.6
Maximum Diameter (D)	1m
Hardness (Arseno-Pyrite. FeAsS)	5,5 – 6 Mohs (Mindat)

5 Selection of Location

5.1 Configuration of the ore pass system

In this chapter, scenarios of different ore pass networks are defined and analyzed. First phase, production data and LOM is analyzed to define the functional requirements of the ore pass in terms of mine production. Location is defined using research material acquired from the mine. Due to the long life of mine and multiple big ore lenses simulations are done only for Suuri Deep Zone. Deeper parts of the zone are kept favorable for ore pass operation due to uniform orebody and close location to a potential underground crusher location and scenario for the hoisting shaft. Scenarios are based on LOM and its production statistics for years 2018 – 2035.

Decision of ore pass locations and number must be based on production rates. The mine has already made up a decision that all stopes above level 675 are hauled to the surface using rubber tired trucks. Below 675 investigations for an alternative to haul the ore to the underground crusher located underground has been made. Possible haulage level, ore silos and underground crusher could be located at the approximate level of 900 meters. In deeper parts, decision whether connect the levels top of each other using ore passes is dominated by a potential tonnage of ore from upper level which can be fed to the ore pass. In Kittilä mine, tonnage per level is varying between 21 600 – 631 600 tonnes. Using number of stopes per level, the number is varying between 2 – 77 stopes. In this study decision to build an ore pass between levels 675 and 900 was selected. Selection was made by considering the number and tonnage of stopes per level and it was found infeasible to conclude levels 625 and 650 due to low tonnage.

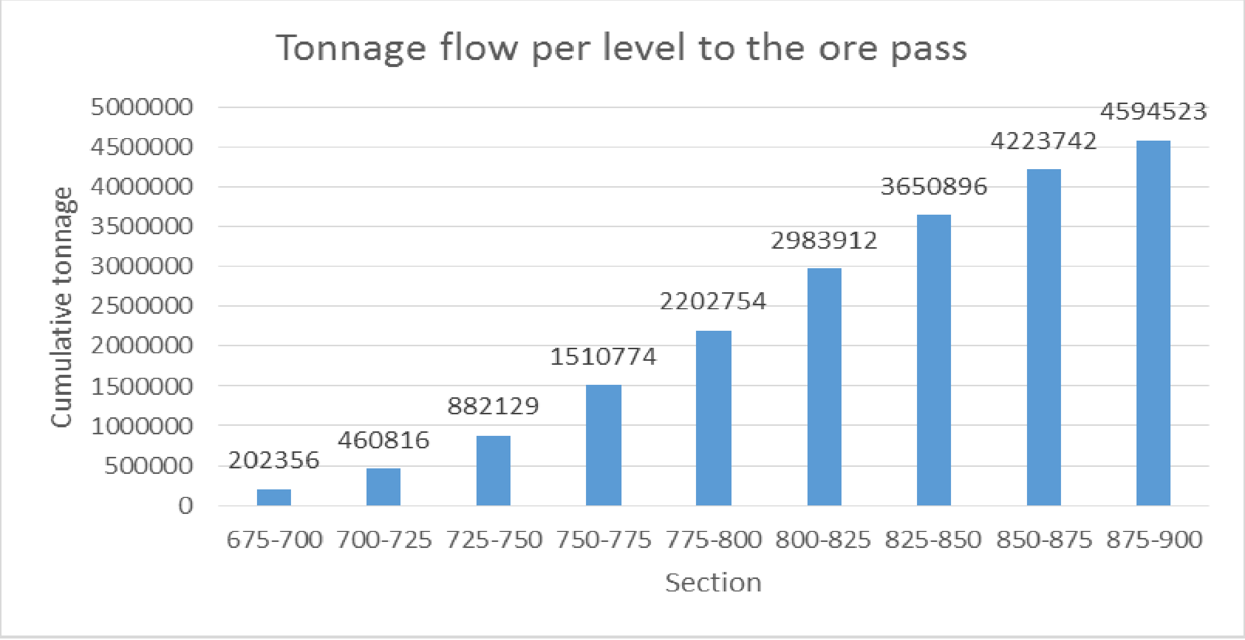

Figure 15 Cumulative sum of ore tonnage flowing through every ore pass section.

Majority of the ore will flow through the ore pass during the years 2020 – 2026 (81%) which can be seen from Figure 16. Therefore more focus on the years 2020 - 2026 should be made. Also Figure 17 depicts that only few percent of ore is located in between levels 675-725 and majority is located below it. Therefore, the deeper levels are significantly more important for mine production. Long periods are challenging to predict due to uncertainties in mine development and especially the longevity of the ore pass is hard to forecast due to high tonnage which can be seen from Figure 15 where the cumulative sum of ore flow reaches nearly 4 Mt. For location perspective waste rock is not considered in the configuration of the ore pass system because mining method has relatively high selectivity and therefore separate waste passes are considered unfeasible in a large scale. Mine is using in addition to paste filling also cemented rock fill and therefore waste rock is used locally in underground and sometimes ore passes could be utilized for waste transport.

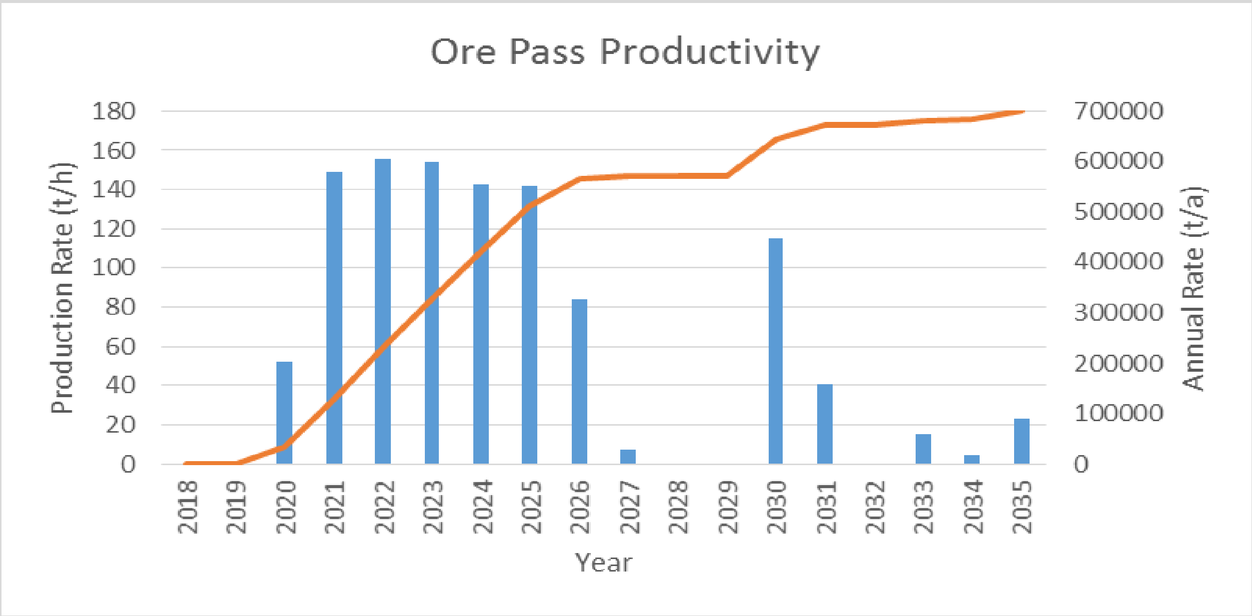

Figure 16 Percentage of tonnage per level which is assumed to flow through the ore pass

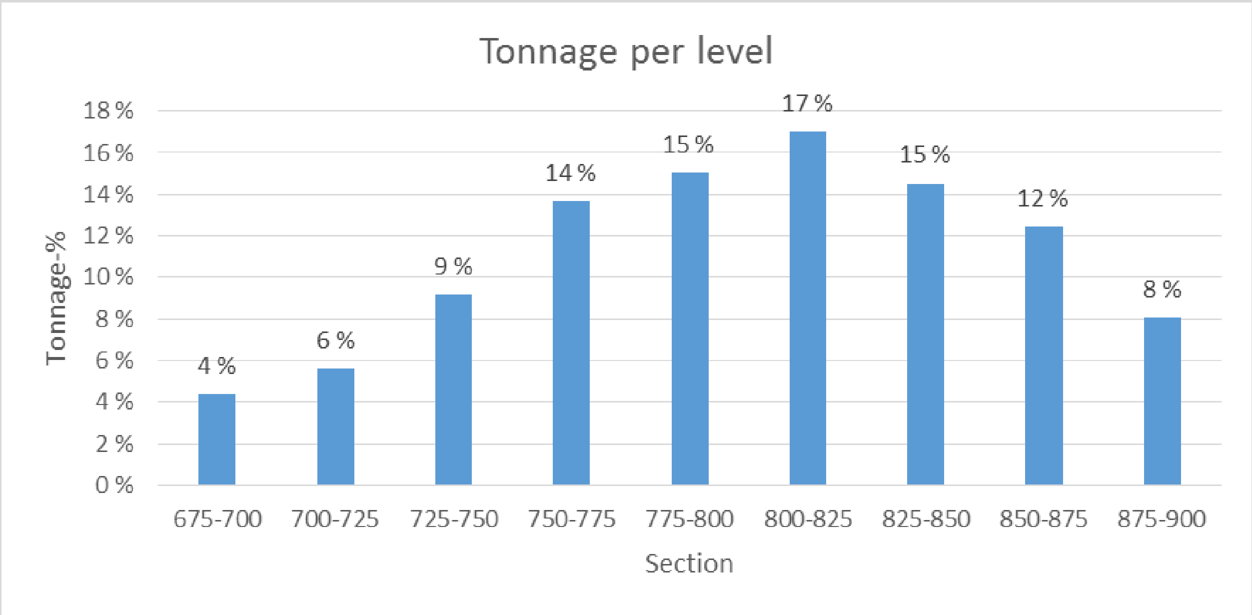

Figure 17 Spread of tonnage through mining levels.

5.2 Scenario Definition

Scenarios were defined to study the influence of ore pass location on mine production. Scenarios were defined by using production statistics of the mine and selecting the scenarios in a way to represent clearly different advantages of different locations selection.

The location problem is constrained by hauling distance, inclination of the ore pass, the maximum length of single ore pass and location related to other mine infrastructure. Scenarios 1 and 2 are optimized and inclined within orebody whereas scenarios 3, 4 and 5 were defined to find the limits within orebody and location of the ore pass. In Scenario 6 ore passes are used locally between levels neither leading to haulage level nor close to the underground crusher area.

- Scenario 1: Ore pass aligned through C.O.G's
- Scenario 2: Two Ore Passes aligned through COG's both Footwall Drives
- Scenario 3: Ore Pass in the Southern Edge of the Suuri Deep Zone
- Scenario 4: Ore Pass in the Northern Edge of the Suuri Deep Zone
- Scenario 5: Ore Pass in the Edges of the Suuri Deep Zone (Scenario 3 + 4)
- Scenario 6: Ore Pass usage locally (Partial trucking)

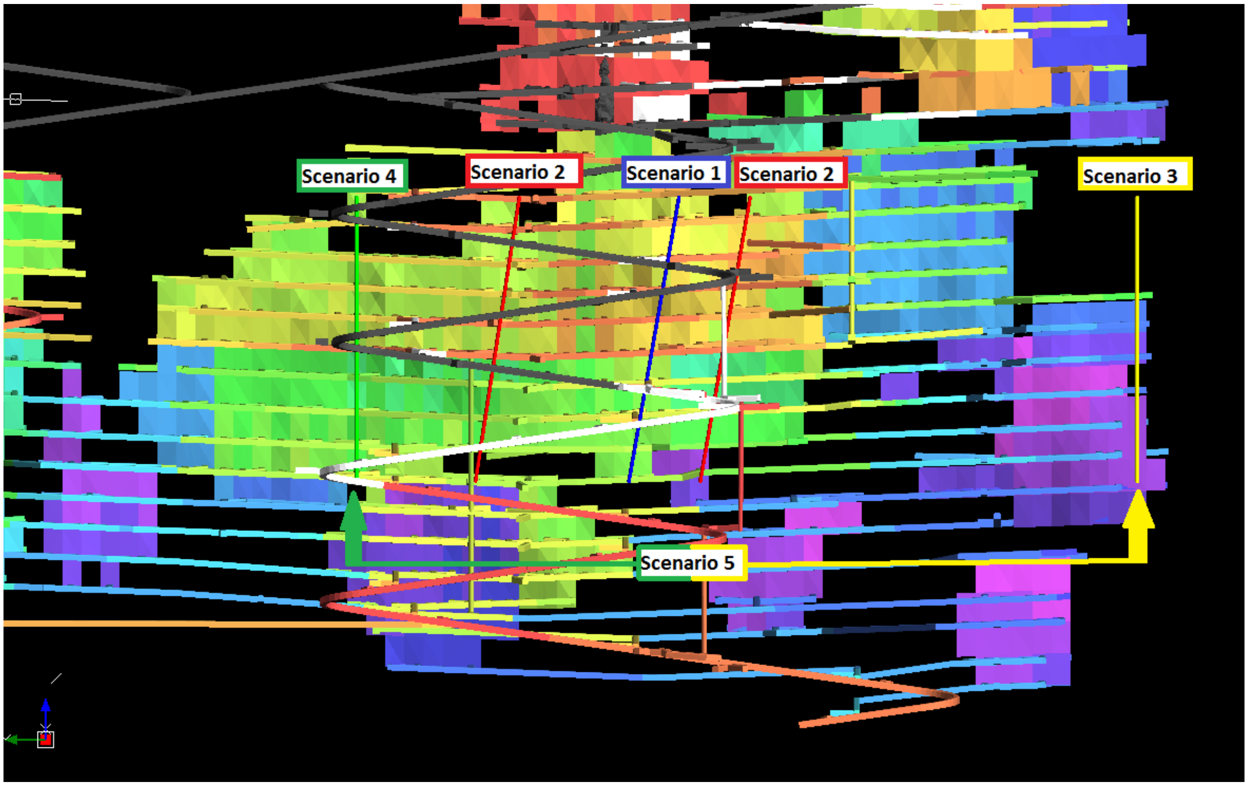

Figure 18 Ore pass location scenarios 1 - 5. Color of stope represent the extraction year of the stope.

Optimization model was done using an ore pass length from 675 level to 900 level, which was identified to be the most suitable based on production statistics. The length is far lengthier than normal suitable ore passes, but an option for sectioning the ore pass to smaller sections is recommended. The ideal optimal solution between levels 675 and 900 is a line traversing mining levels in location where hauling distances in the level is minimized within other constraint and possibly by splitting the ore pass system to shorter sections along the optimum line.

Least square method was applied to Scenarios 1 and 2 where optimal location for one pass in Scenario 1 and two passes in Scenario 2 were necessary to be calculated. In scenario 2, two ore passes have been optimized separately by splitting the level into southern and northern mining area, using coordinates of the footwall drive which intersects north and south footwall drive in the middle of the ore lens. Other scenarios are not optimum in terms of level haulage distance, but are independent of other infrastructure because these are located in the edge of the orebody.

Weighting factors of level tonnage were to decrease the effect of over-representation of levels where tonnage is low. Optimization was done by using MATLAB's Curve Fitting Tools. In Kittilä, the orebody is delineated along north-south axis (i.e. y-axis) and therefore the problem was simplified to a 2D problem, where horizontal hauling distances (d) along y-axis is being minimized (Figure 19). In the direction of the x-axis the hauling distance difference was negligible and therefore was not included in the optimization. Along the x-axis (west-east) ore pass system should follow the near vertical orebody in safe distance apart from the orebody and other mine infrastructure.

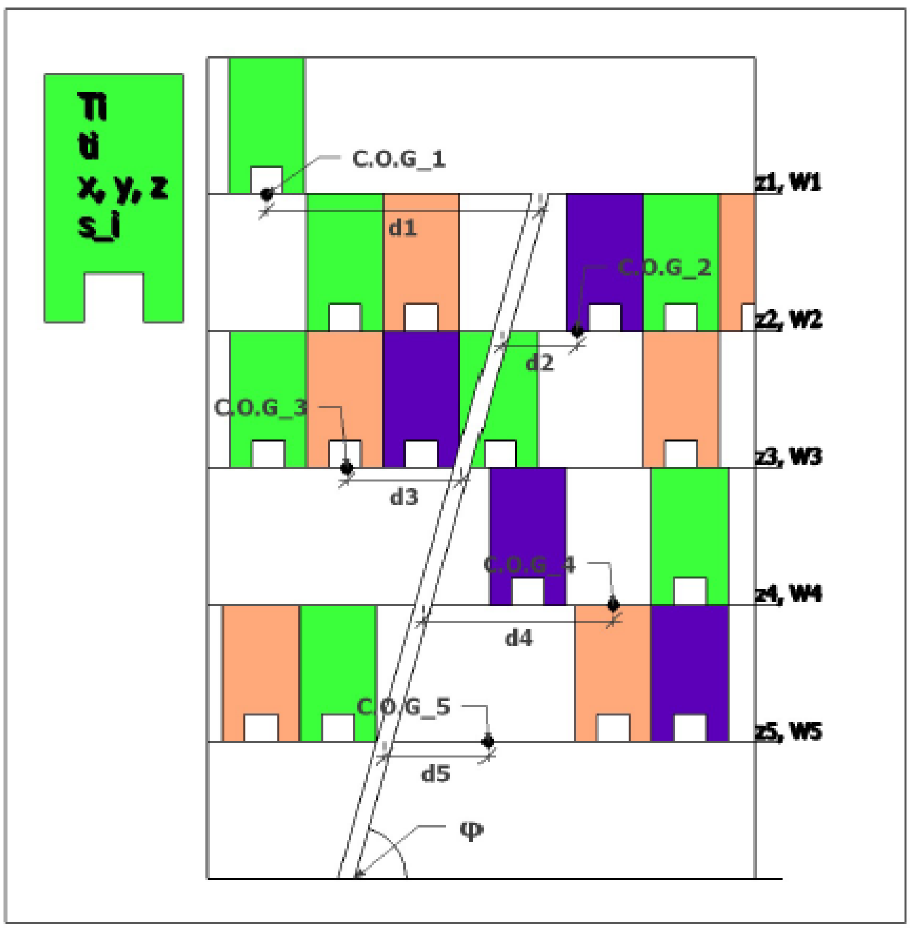

Figure 19 Schematic picture of ore pass location optimization. Using tonnage, extraction date, coordinates and hauling distance, distance d_i = (yi-ŷi) were mimimized.

For optimization of scenario 1 and 2, two parameters were calculated from LOM Data to minimize the error estimate s; a level specific C.O.G (y_i) and tonnage per level were used as a weighting factor (w_i). For MATLAB, these parameters were defined as a vector. Using weighted least-squares it was possible to minimize the error estimate (d), which represents the hauling distance between stope and ore pass:

$$d = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2$$

Where,

d = estimation error (distance between ore pass and c.o.g's of mining levels)
n = number of level
w_i = level tonnage
y_i = y-coordinate of C.O.G in level i
$\hat{y}_i$ = y-coordinate of estimated ore pass in the intersection of level i

A constraint of minimum inclination of 80 degrees for the ore pass alignment was applied. Without using constraint, ore pass inclination would have fallen below 70 degrees which does not guarantee material flow. Using line fitting functions the optimal solution was found thus level distances were minimized. This optimal solution was later applied to a real case by considering other design parameters and constraints. Figure 20 shows the optimization result of ore pass lineation in y-direction. There are four lines in the figure representing the c.o.g of the mining level, an ore pass fitted using least squares, an ore pass using least squares with slope constraint and ore pass with weighted least squares and slope constraint.

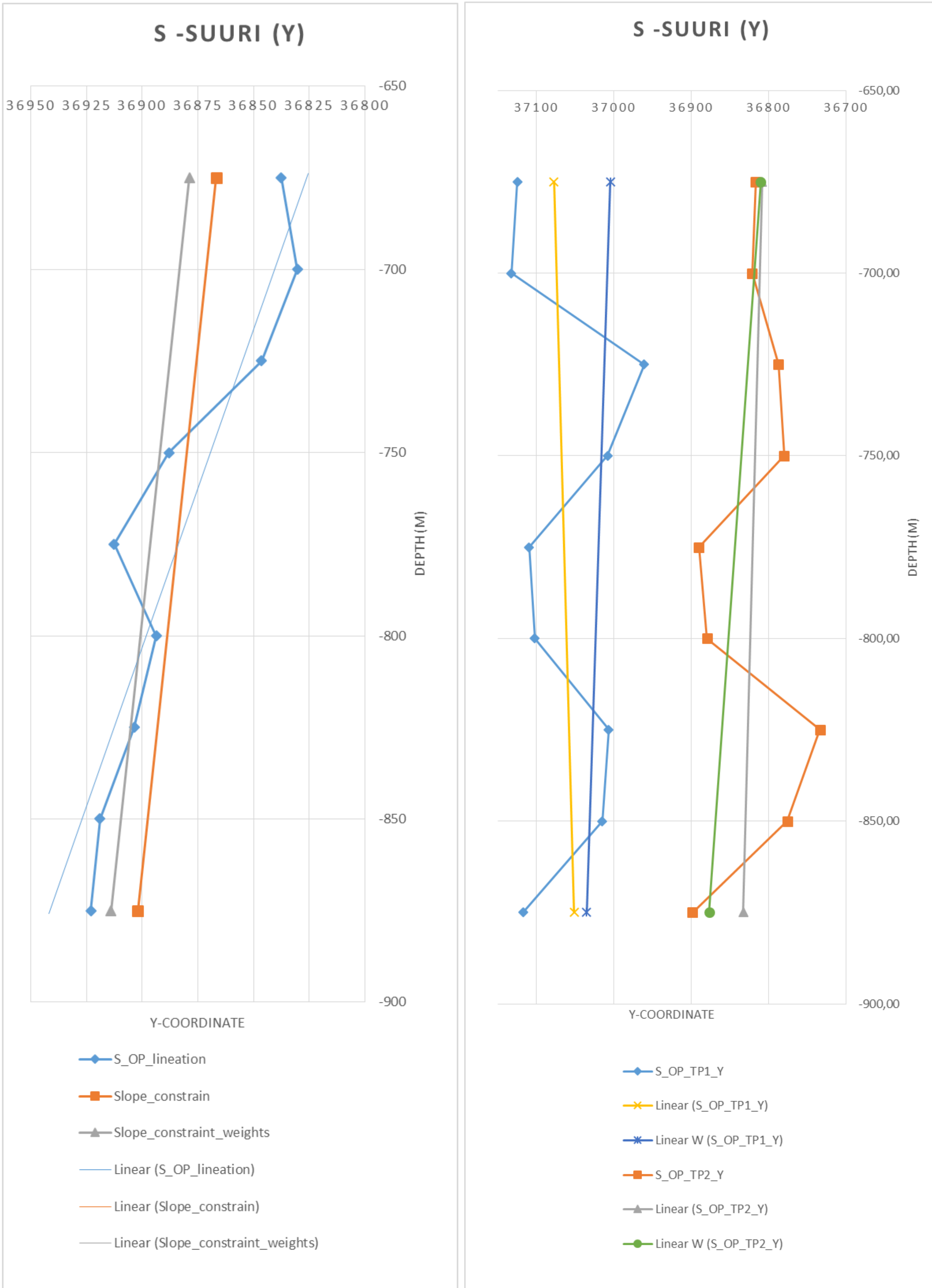

Figure 20 Ore pass lineation of Scenario 1 and Scenario 2. Lineation is shown in function of depth and y-coordinate

Optimization gives an optimal line traversing the orebody thus minimizing the level haulage distance (i.e. distance between stope and ore pass). This optimal solution must be fitted to existing mine layout and also guarantee that location is practical for ore pass operation. In addition, for traversing other mining infrastructure, ore pass degradation might cause, unexpected growth of volume and cross sectional areas which must be considered as a safety distance between ore pass and other infrastructure. The degradation zone (i.e. footwall of the ore pass and intersection of finger raise) should be placed outbound direction from other infrastructure. Also, the ore pass should not cross other infrastructure if an inclined pass is built. Therefore, the ore pass cannot follow the optimal line, but must be deviated slightly from the optimum case.

In addition to optimized scenarios 1 and 2 and vertical scenarios 3-5 also scenario 6 was created to find the feasibility of constructing only short sections of ore passes. Scenario 6 was fully simulated by using HaulSIM. The scenario has an assumption that location can be selected freely to fit the current production scheme, but the location should be selected in order the guidance in the literature review. Scenario is modelled by selecting location for ore pass discharge points in levels 700, 775 and 875. The haulage distances are calculated and simulated in HaulSIM and special emphasis is directed towards the jamming phenomena of footwall drive and what is the maximum amount of haulage trucks which can be used to meet the production targets (Figure 21).

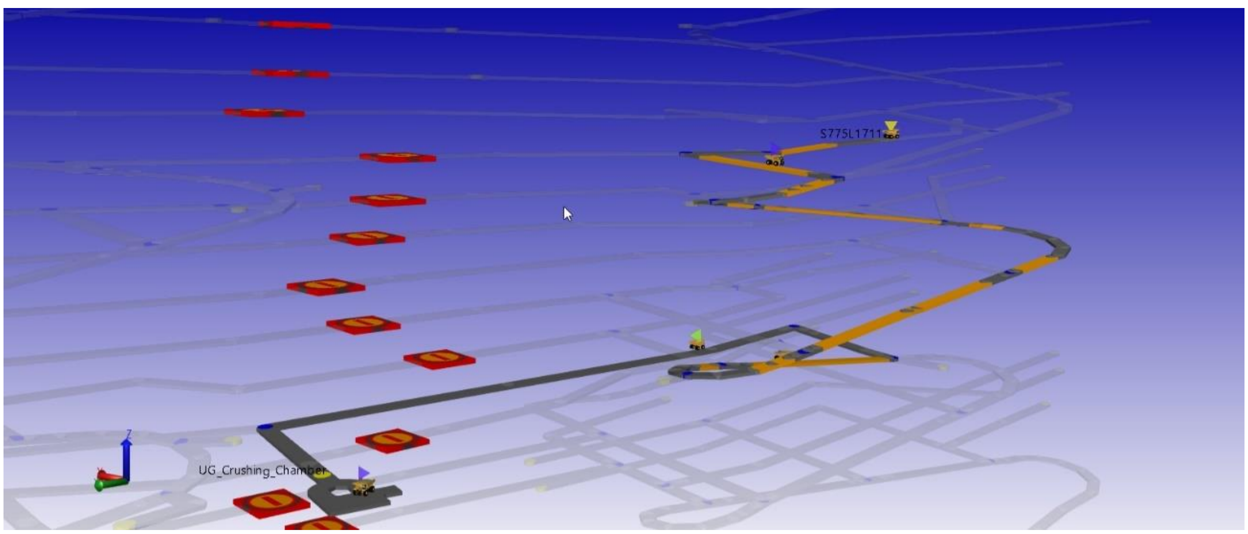

Figure 21 HaulSIM simulation for Scenario 6. Ore is hauled from level 775 using trucks to the underground crusher.

Results of different scenarios were evaluated using selection tables. In the evaluation of scenarios characteristics of individual scenario were rated to 7 categories: *Distance/TKM*, *Level Distance*, *OPEX*, *CAPEX*, *Productivity*, *Rock Mechanics* and *Technological Risk*. (Figure 22)

Distance / TKM	Level Distance	OPEX	CAPEX	Productivity	Rock Mechanics	Technological risk
Overall haulage distance from stope to UG Crusher, which is directly proportional to tonne-kilometers	Level Distance is indicating the distance between stope and ore pass. Level distance is important because long hauling distances in a one way access drift impacts significantly to the equipment selection and productivity.	OPEX includes need of equipment and devices, personnel and maintenance of the ore pass. This is greatly dependent on number of sections in the ore pass. More ore passes or sections means more ore pass related infrastructure.	CAPEX are mainly costs from excavation and equipment. Ore pass number and equipment selection has great influence to CAPEX.	Productivity is higher for ore pass systems having two ore passes, but also when level haulage distance is kept low and operation of LHD is facilitated.	Rock mechanics are concidered in terms of safety. Centered location of the ore pass is riskier location due to proximity to other infrastructure and activites.	Risk is based on number of failure sources and the complexity of the ore flow process. Ore pass systems are complex systems where blockages, hang-ups, tehcnical failures or design errors might lead to malfunctioning system.

Figure 22 Definition of rating parameters for scenario selection.

The scenarios were graded giving points 1 – 4, one being the most suitable option. First five categories have been graded simply by giving the best grade to scenarios having smallest value. *Productivity* is graded using the assumption that low level distance increases productivity in terms of using loading equipment instead of trucks for material movement and since multiple ore passes increases productivity compared to a single ore pass per level. *Rock mechanics* and *Technological Risk* have been mainly assessed by considering production security. Multiple ore passes are decreasing impact of temporarily blocked or ore passes under maintenance by securing material flow in these exceptional situations. Additionally, location in the center of orebody creates risks when unplanned degradation occurs if the ore pass is located near important mine infrastructure. For technological perspective, multiple ore passes have challenges in the ore pass management system thus making the system more complicated and expensive. Chapters 5.1 – 5.6 contains all the scenarios analyzed and following results are shown for every scenario:

- Average haulage distance from Stope to Ore pass
- Histogram where number of stopes is given in function of hauling distance between stope and ore pass. Histogram uses a category interval of 0,05km.
- Decision table of the scenario

5.3 Scenario 1: Ore pass aligned through C.O.G

Scenario 1 is an effective way to align the ore pass. The pass is located near the center of gravity in every mining level. Thus, the haulage distances are minimized as can be seen from Figure 23 - 24. The scenario holds a high productivity and low tonne-kilometers. Especially, the level haulage distance is beneficial, because 91% of all stopes in the Suuri deposit are less than 250 meters apart from the ore pass, thus can be assumed that all the ore can be transported using LHD's. By contrast, one ore pass is creating higher production risk if reason or another the ore pass is temporarily not available. Central location is also making some concern in terms of rock mechanics and safety. Close location to the other infrastructure creates rock mechanical risks, air blast and dust problems. Selecting only one ore pass is cost effective decision, but might follow with a risk in production security.

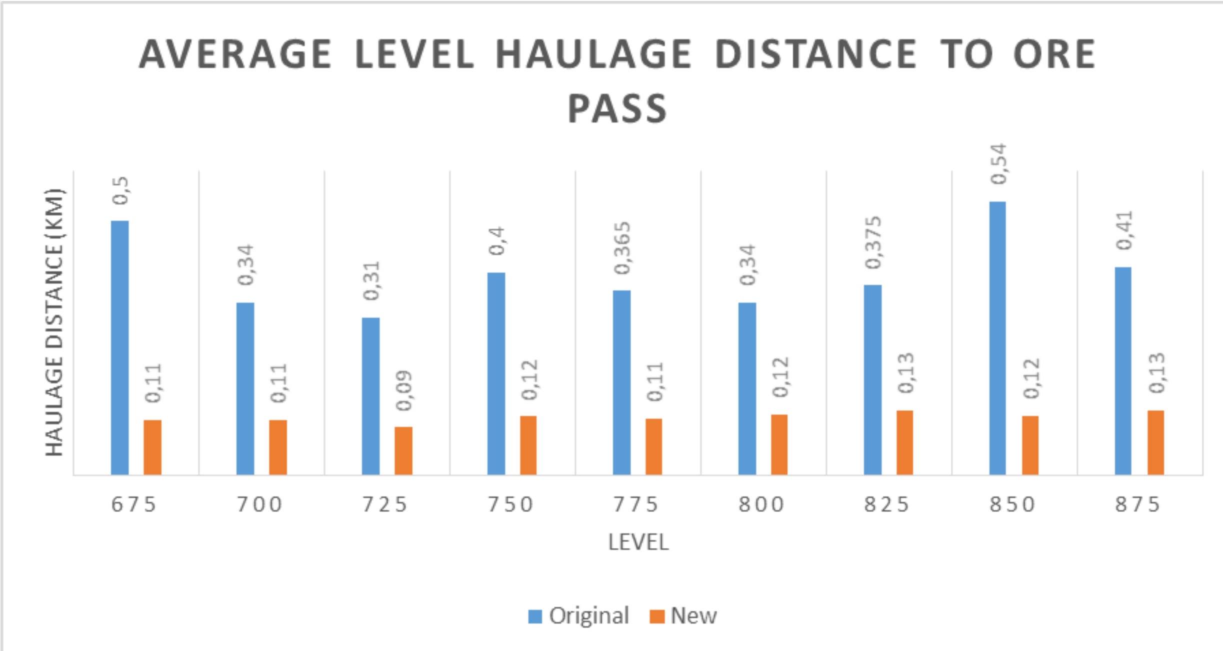

Figure 23 Scenario 1, Average level haulage distance per level.

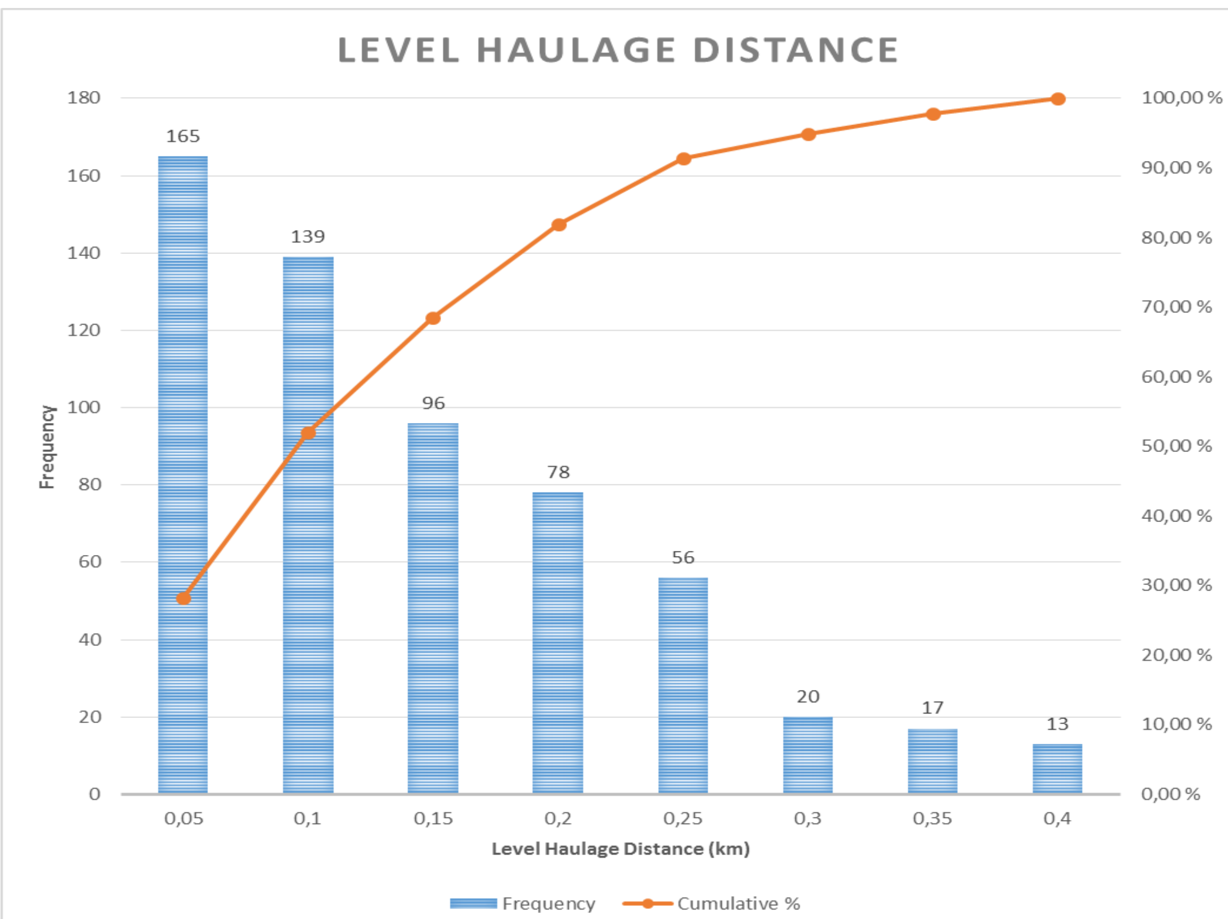

Figure 24 Scenario 1, Number of stopes within haulage distance categorized to 0,05km intervals (n=584)

Scenario 1	Rating	Description
Distance / TKM	2	Distances are relatively low, but higher than in OP North option.
Level Distance	1	Level distance distribution is very good. 91.4% of stopes are less than 250m apart from ore pass.
OPEX	1	Simple one pass serving whole Suuri area decreases operation costs.
CAPEX	1	Simple one pass decreases capital expenditures
Productivity	2	One pass makes system more rigid and hauling distance per level is higher than in 2 pass system.
Rock Mechanics	3	Single pass and its location in the center of ore lens makes rock mechanics important because pass is traversing other structures close by.
Technological risk	2	Greatest risks are associated to the chute system, degradation and material flow.
Result	**12**	*"Optimal solution with decreased OPEX and CAPEX"*

Figure 25 Decision table of Scenario 1. Single ore pass traversing the C.O.G and therefore level distance is minimized.

5.4 *Scenario 2: Two Ore Passes aligned through COG's of both Footwall Drives*

Scenario 2 has the same benefits as the Scenario 1 as being an optimized scenario. In combination with two ore passes per level, this scenario gives very short level haulage distance. This mean that the ore pass operation has high productivity. Scenario 2 is more secure hence there are two passes per level. Unexpected unavailability of the ore pass does not have significant influence on the production because a redundant one can be used. Also the degradation rate of ore pass is lower when material flow is divided into two passes. Two ore passes enable to operate simultaneously two ore passes or shield another ore pass area and have other drill and blast activities in the region of the other ore pass. Results of scenario 2 are in Figure 26 – 30.

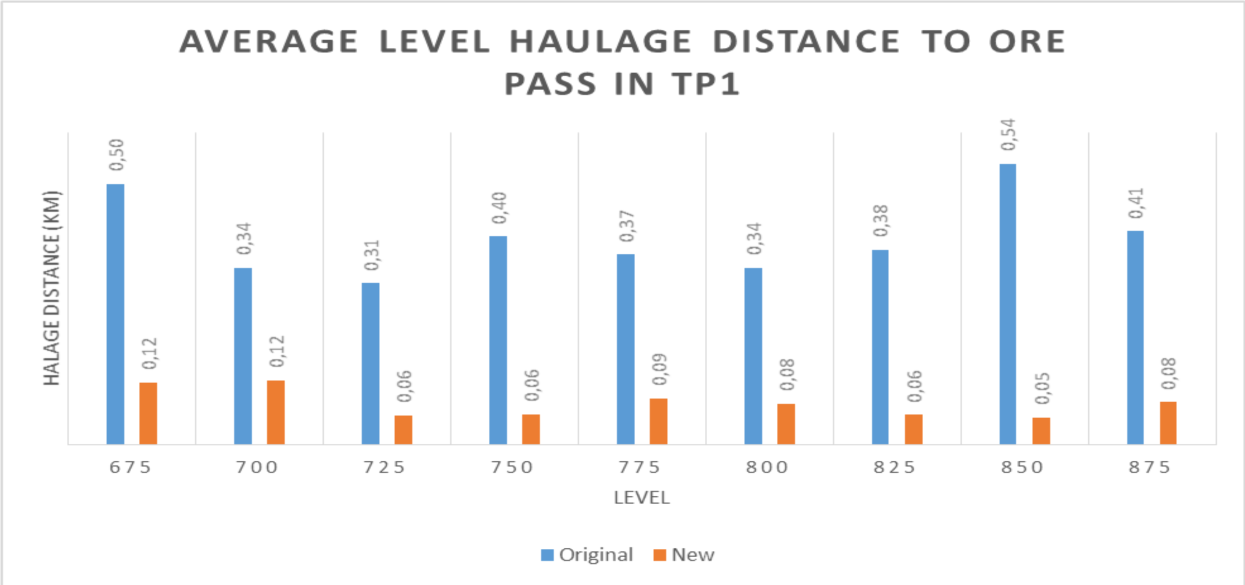

Figure 26 Scenario 2, Average level haulage distance per level in TP1

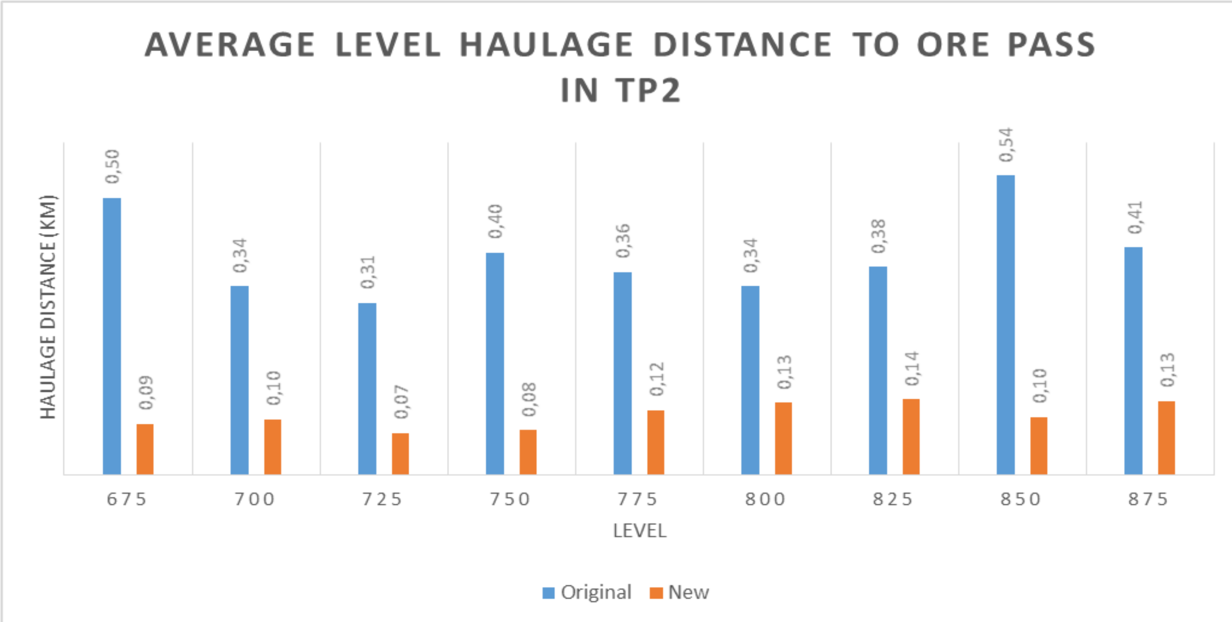

Figure 27 Scenario 2, Average level haulage distance per level in TP2

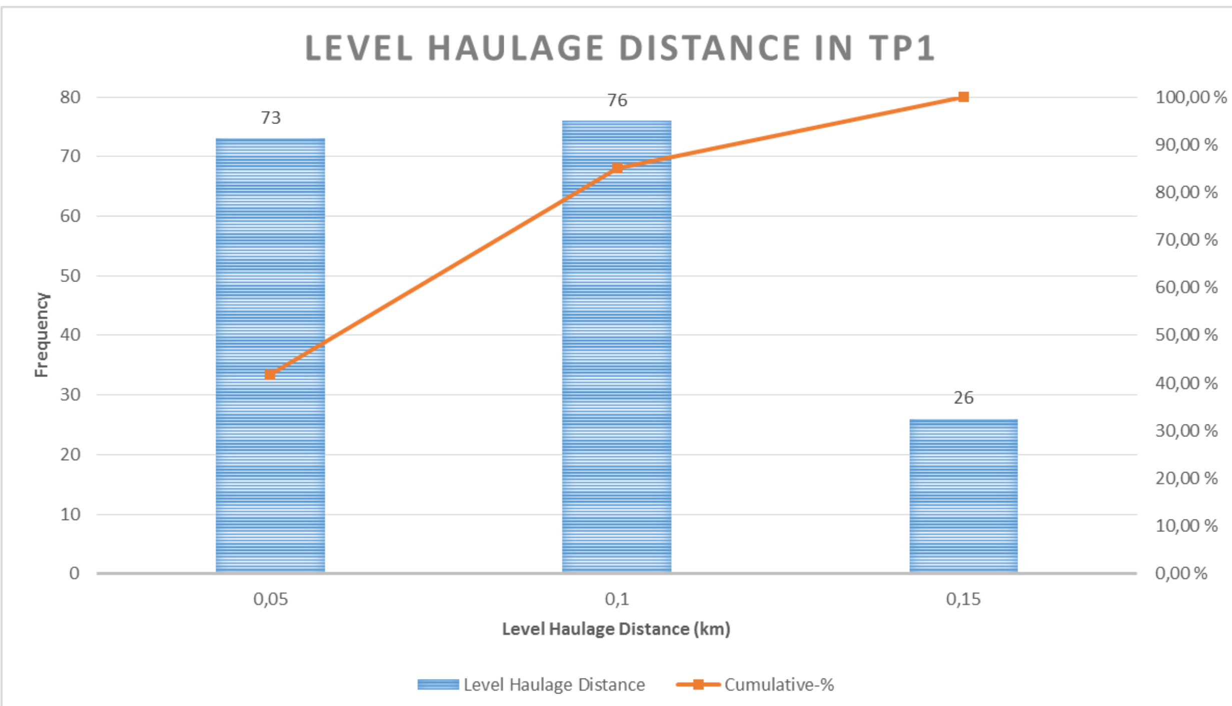

Figure 28 Scenario 2, Number of stopes within haulage distance categorized to 0,05km intervals in TP1 (n=175)

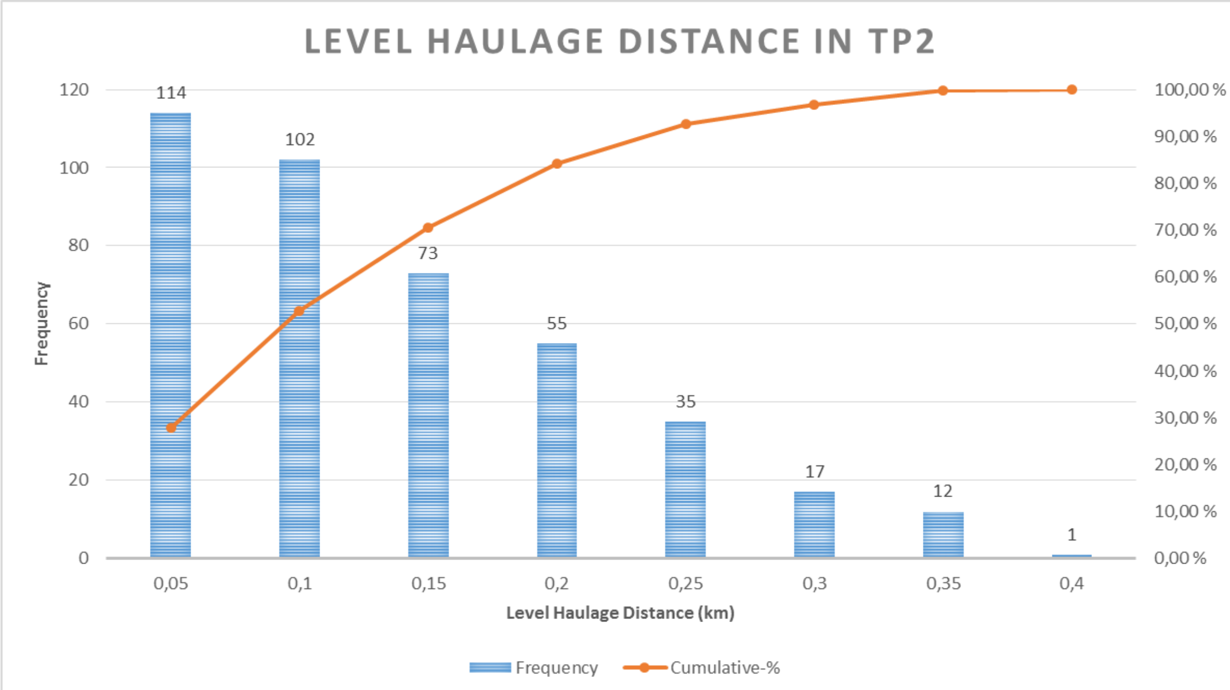

Figure 29 Scenario 2, Number of stopes within haulage distance categorized to 0,05km intervals in TP2 (n=409)

Scenario 2	Rating	Description
Distance / TKM	1	Distances are relatively low, but average higher than in Scenario 4 option.
Level Distance	1	Level distance distribution is superb. 94.9% of stopes are less than 250m apart from ore pass.
OPEX	3	Two ore passes serving Suuri area increases operational costs.
CAPEX	2	Two ore passes increases capital expenditures.
Productivity	1	Hauling distance per level is less than single pass system and gives flexibility in case of ore pass failure or maintenance. TP1 and TP1 can be operated separately.
Rock Mechanics	2	Center location in Suuri makes rock mechanics important because pass is traversing other structures close by. Wall degradation lower than in single system.
Technological risk	3	Greatest risks are associated to the chute system, degradation and material flow. Material control and management important when operating with two passes.
Result	**13**	*"Increasing CAPEX results in a high productivity with lowest level distances"*

Figure 30 Decision Table of Scenario 2. Two ore passes, each pass is traversing the C.O.G of either norhern or southern footwall drive.

5.5 Scenario 3: Ore Pass in the Southern Edge of the Suuri Deep Zone

In means of location, scenario 3 is a very safe option. It lies in the edge of the Suuri Deep Zone and locates easily without any conflicts with intersecting other mine infrastructure. Therefore, the scenario does not contain any risk related to severe degradation causing safety risk to mine stability and therefore abandonment of the ore pass. Placement of the ore pass related infrastructure is easy for this scenario. On the other hand, distant location results in a long level haulage distance, potential traffic jams and high operating costs. Results are in Figure 31- 33.

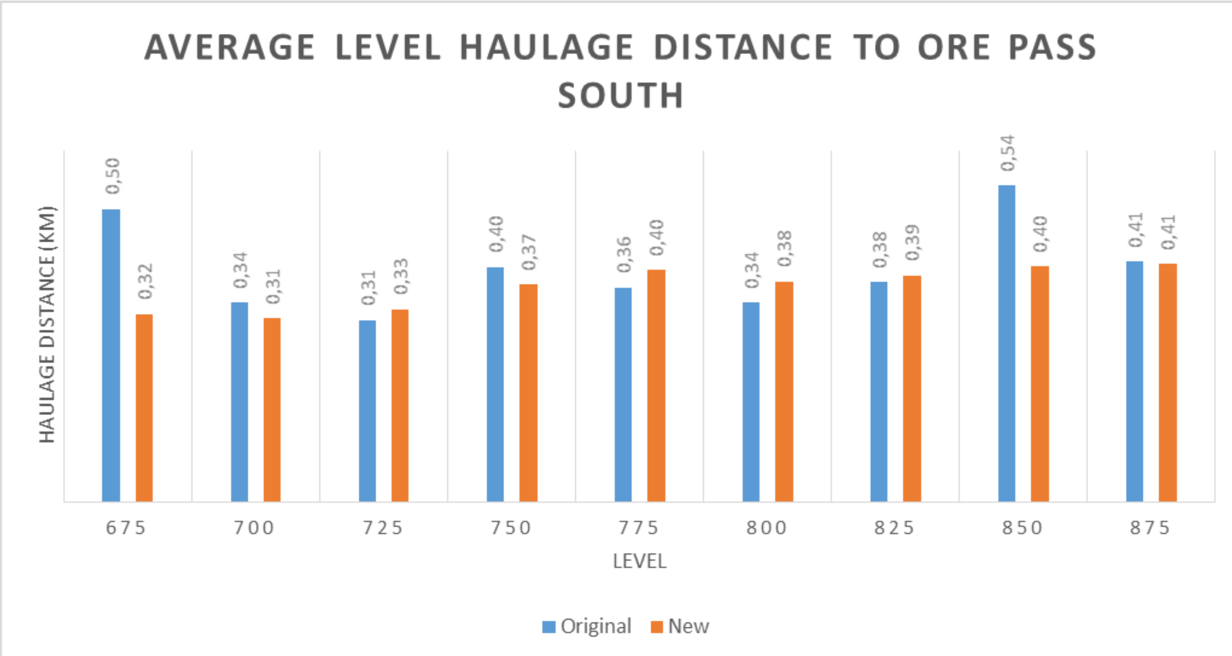

Figure 31 Scenario 3, Average level haulage distance per level

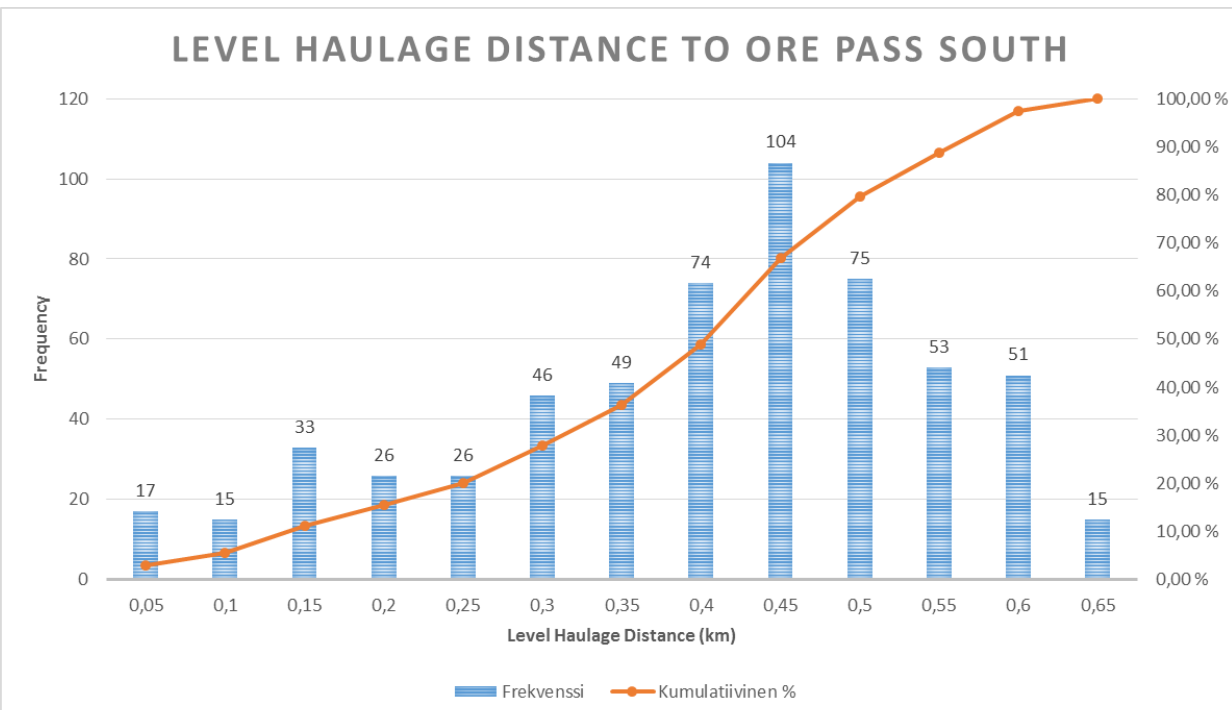

Figure 32 Scenario 3, Number of stopes within haulage distance categorized to 0,05km intervals (n=584)

Scenario 3	Rating	Description
Distance / TKM	3	Overall distance is highest of all excluding except trucking option.
Level Distance	4	Level distance distribution is poor. 20,0% of stopes are less than 250m apart from ore pass. Haulage truck transport in levels is necessary.
OPEX	2	Simple one pass serving whole Suuri area decreases operation costs.
CAPEX	3	Simple one pass decreases capital expenditures
Productivity	3	Long level haulage distance creates jamming in one way drift. System is also more rigid than 2 pass system.
Rock Mechanics	1	Single pass located outside the mining area holds only minor risk of degradation.
Technological risk	1	Greatest risks are associated to the chute system, degradation and material flow. Degradation risk is lower than other scenarios due to distant location.
Result	**17**	*"Safe option with low productivity for ore pass system"*

Figure 33 Decision Table of Scenario 3. Ore pass in the southernmost point of Suuri Deep Zone.

5.6 Scenario 4: Ore Pass in the Northern Edge of the Suuri Deep Zone

Scenario 4 is the most optimum scenario in terms of overall hauling distance, it is leading directly into the vicinity of an underground crushing station. Therefore, it results in a low tonne-kilometers but comes with a cost. Average level haulage distance is longer and especially the spread of the distances between stope and the ore pass is such long that additional trucks/dumpers must be used to haul the ore in the mining level. Like the Scenario 3, locating the ore pass to the edge gives the benefit that it is not close to any other mining infrastructure. Results are in the Figure 34 – 36.

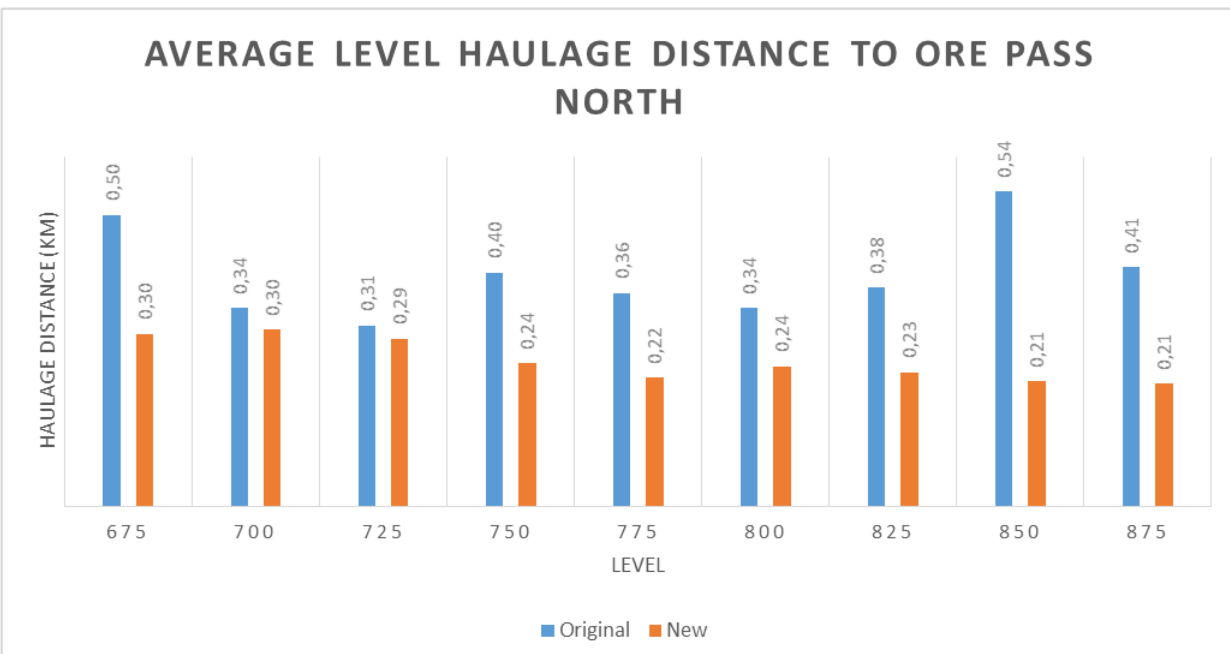

Figure 34 Scenario 4, Average level haulage distance per level

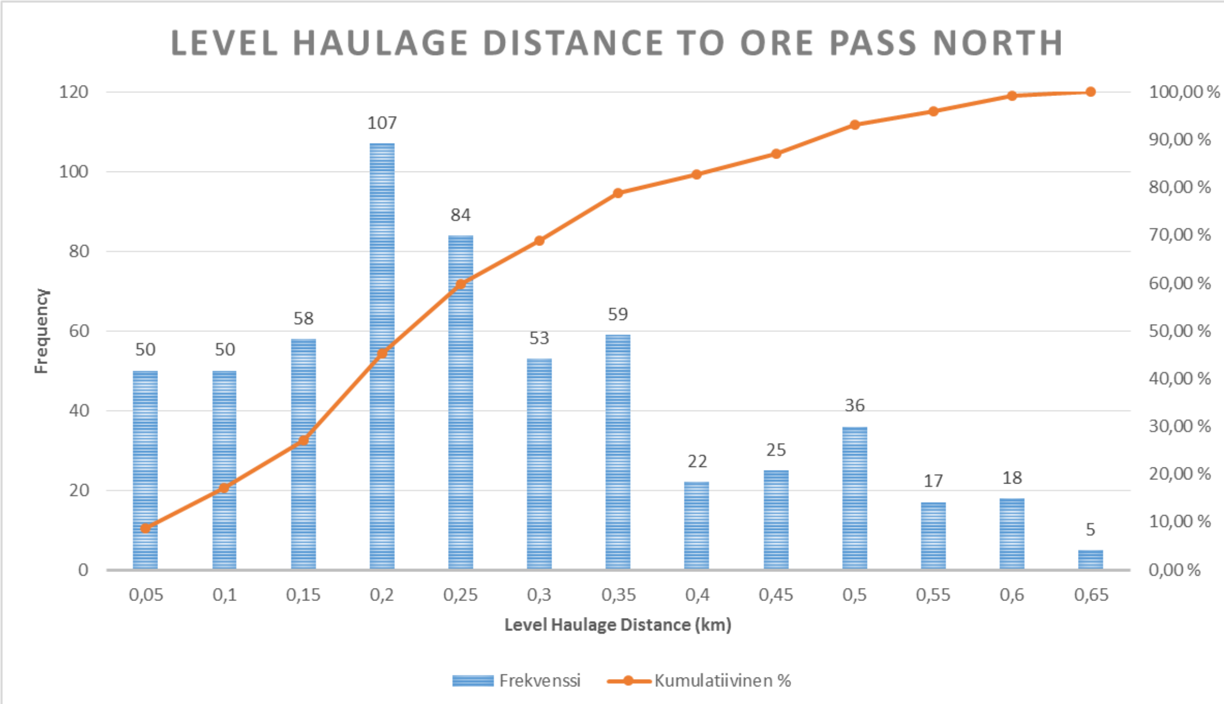

Figure 35 Scenario 4, Number of stopes within haulage distance categorized to 0,05km intervals (n=584)

Scenario 4	Rating	Description
Distance / TKM	1	Overall distance is lowest of all.
Level Distance	3	Level distance distribution is moderate. 59,8% of stopes are less than 250m apart from ore pass. Haulage truck transport in levels is necessary occasionally.
OPEX	2	Simple one pass serving whole Suuri area decreases operation costs.
CAPEX	2	Simple one pass decreases capital expenditures
Productivity	2	Long level haulage distance creates jamming in one way drift. System is also more rigid than 2 pass system.
Rock Mechanics	2	Single pass located outside the very center of mining area holds only minor risk of degradation.
Technological risk	2	Greatest risks are associated to the chute system, degradation and material flow. Degradation risk is lower than other scenarios, but higher than Scenario 3.
Result	**14**	*"Distance minimized solution with a large spread of level distance and high CAPEX"*

Figure 36 Decision Table of Scenario 4. Ore pass in the northernmost point of Suuri Deep Zone.

5.7 Scenario 5: Ore Pass in the Edges of the Suuri Deep Zone

Scenario 5 is a combination of Scenarios 3 and 4. It comes with all benefits in two previous scenarios and has benefit related to the usage of two ore passes. Productivity is higher, degradation impact of ore is lower due to less material is moved through single ore pass and production security when unexpected unavailability of a single pass occurs. Naturally, two ore pass system increases the capital and operating costs of the ore pass system. Results are in Figure 37 – 39.

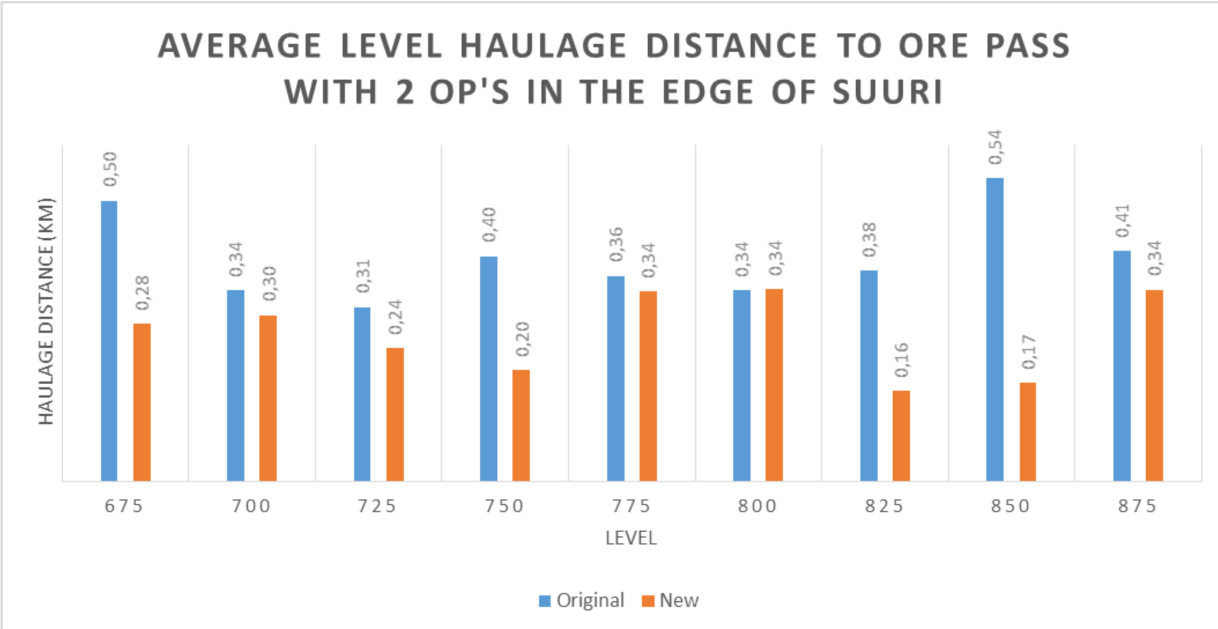

Figure 37 Scenario 5, Average level haulage distance per level

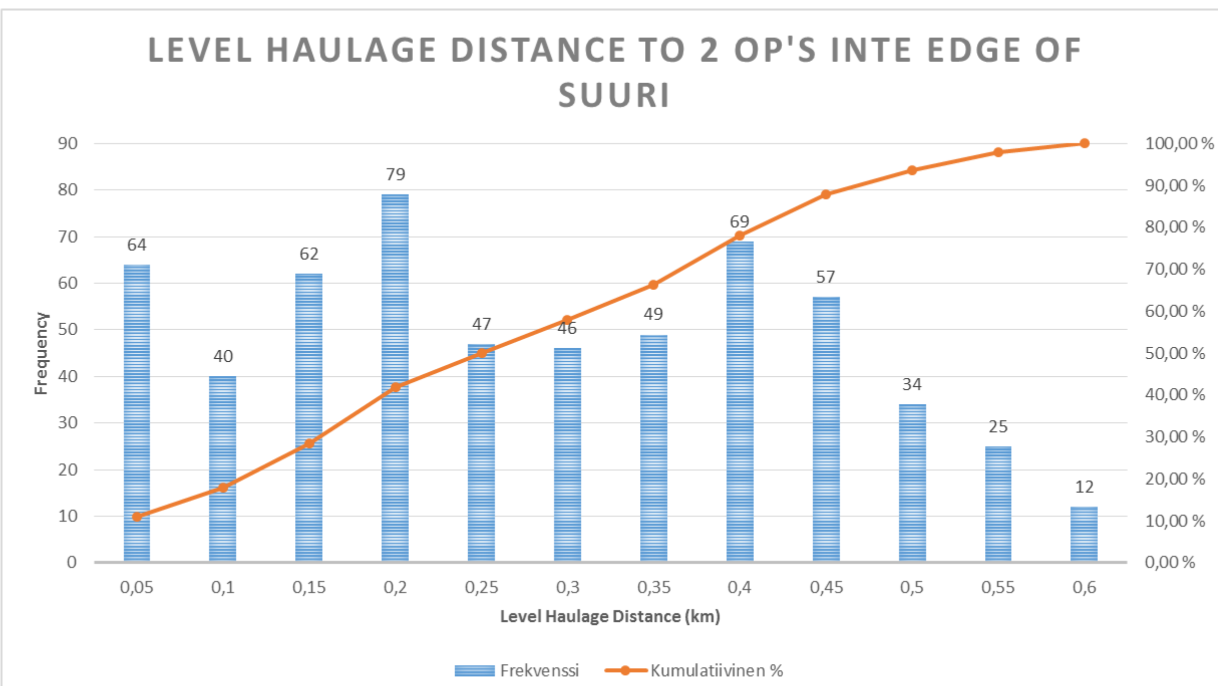

Figure 38 Scenario 5, Number of stopes within haulage distance categorized to 0,05km intervals (n=584)

Scenario 5	Rating	Description
Distance / TKM	2	Average distances are really low, but the spread of distance per stope is high.
Level Distance	3	Level distance distribution is moderate. 50,0% of stopes are less than 250m apart from ore pass. Trucking is necessary occasionally.
OPEX	3	Two ore passes serving Suuri area increases operational costs.
CAPEX	3	Two ore passes increases capital expenditures.
Productivity	2	Hauling distance per level is less than single pass system and gives flexibility in case of ore pass failure or maintenance. TP1 and TP2 can be operated separately.
Rock Mechanics	2	Location in the edge of Suuri makes pass system more stablet because pass is not traversing other structures close by. Wall degradation lower than in single system.
Technological risk	2	Greatest risks are associated to the chute system, degradation and material flow. Material control and management important when operating with two passes.
Result	**17**	*"Non optimal location increases CAPEX, but reduces risks"*

Figure 39 Decision Table of Scenario 5. Two ore passes, one located in the northernmost and one in southernmost point of Suuri Deep Zone.

5.8 Scenario 6: Ore Pass usage locally

Local option uses the ore passes only locally. Meaning that ore passes are not leading straight to either haulage level or an underground crusher. Therefore, the ore is tipped to the ore pass, loaded in trucks from lower level's discharge area and afterwards hauled to the final destination whether surface or underground crusher.

Benefit of this scenario is the great adaptability to different mining schemes. It does not need much rigid infrastructure and the haulage routes and methods can be modified also after commissioning. Greatest downside in the scenario is its limited ability to decrease the effect of jamming – the bottle neck of Kittilä Mine. Neither this method is decreasing the tonne-kilometers effectively. Mainly, jamming can be reduced if the discharge area is in a two-way drift, or in a loop, that truck can be loaded immediately after another. Simulations showed that when ore handling time in the ore pass is too high, the ore pass is decreasing productivity. This can be improved installing a chute loading system which reduces truck loading time. Installation of chutes, and facilitating load and haul automation, it is possible to dump the ore pass full, right before blasting and therefore operate ore passes by emptying ore pass during blasting and shift change.

Partial trucking with construction of new passing bays and partly two lane mine drifts will help to increase the productivity of the haulage fleet, but the excavation costs for these improvements are high. This can be seen as a partial solution and transitions phase towards higher utilization of ore passes, but have limited capabilities to reduce the jamming effect in the mining level. The rating of the scenario 6 is in Figure 40.

Scenario 6	Rating	Description
Distance / TKM	4	Trucking has the highest distances and tonne-kilometers due to vertical travelling in ramp.
Level Distance	3	Level distance is very high and causes jamming in the level thus decreasing the productivity.
OPEX	4	Operational costs in truck hauling is high when level and vertical distances increases certain level.
CAPEX	3	Capital expenditures are high due to need of numerous new trucks.
Productivity	4	Overall productivity is low. Trucking enables flexibility and fast response to different production schemes. TP1 and TP2 can be operated separately.
Rock Mechanics	1	There is no risk in terms of rock mechanics, wall degradation or ore pass failure.
Technological risk	1	There is no technological risk, but amount of trucks to be fitted underground is limited. Fleet management has potential to increase productivity.
Result	**20**	*"No risks, no productivity increase, no savings"*

Figure 40 Decision Table of Scenario 6. Ore passes are used locally and partly trucked with trucks.

5.9 Summary of Scenarios

Decision between locations is highly based on company policies and how much they are willing to take risk. Scenarios overall grading is presented in Figure 41. Every scenario previously presented are possible to exercise but the costs, savings and other benefits differ in every scenario. Reduction in tonne-kilometers is varying significantly in different scenarios (Figure 42). Therefore, it is hard to distinguish especially between Scenarios 1, 2 and 4 which all have clear, scenario specific benefits. For this case study, selection is to be done to continue to the selection of the ore pass design.

Closer look at scenarios reveals that Scenario 1 is superior in terms of productivity and construction costs if its risks can be managed. The scenario has higher than average rating in rock mechanics which can be controlled using due to diligence actions and monitoring processes while commencing and operating the ore pass. Therefore, in Chapter 6, design analysis is based on Scenario 1.

Summary	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Distance / TKM	2	1	3	1	2	4
Level Distance	1	1	4	3	3	3
OPEX	1	3	2	2	3	4
CAPEX	1	2	3	2	3	3
Productivity	2	1	3	2	2	4
Rock Mechanics	3	2	1	2	2	1
Technological risk	2	3	1	2	2	1
Result	**12**	**13**	**17**	**14**	**17**	**20**

Figure 41 Summary of Decision Tables. Lower overall rating is kept as a better selection.

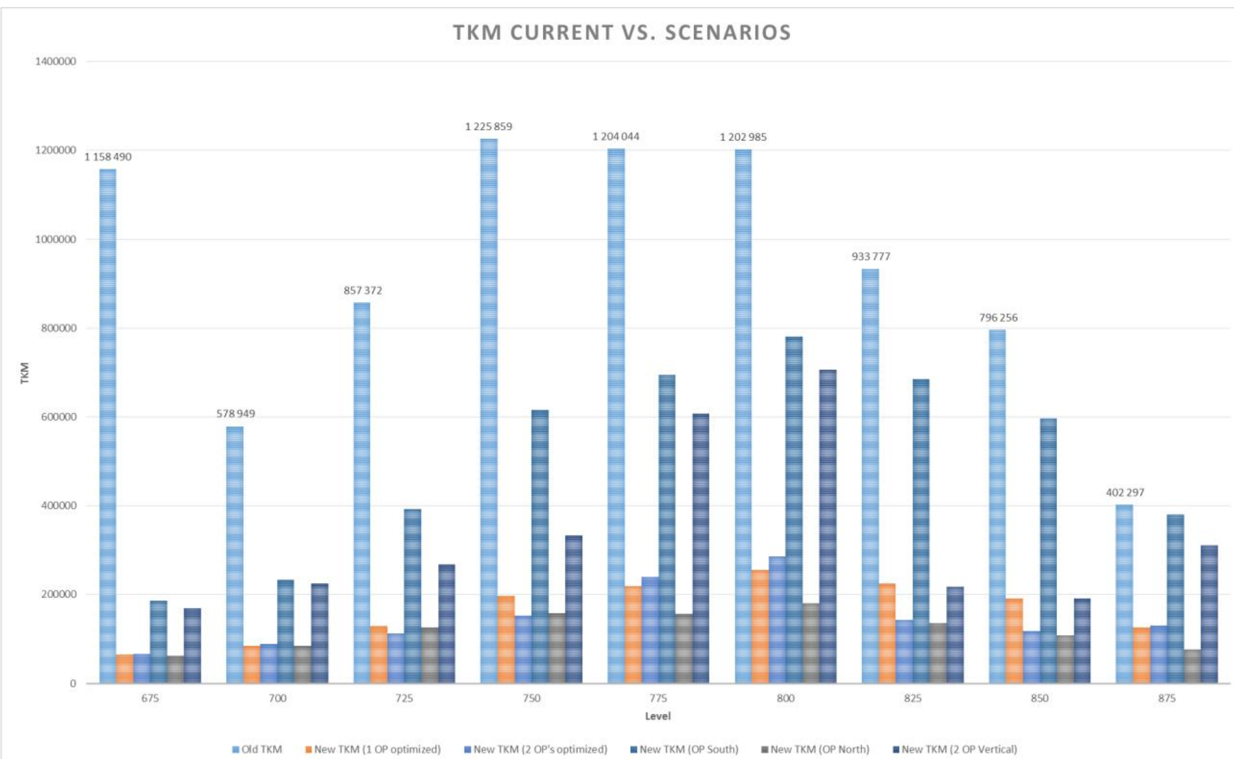

Figure 42 Overall summary of tonne-kilometers per level including all scenarios and current situation.

6 Selection of Design

Actual detailed design and the financial model is studied for Scenario 1 which was chosen to be the most optimum. Generally, design parameters can be applied to multiple ore zones and ore passes in Kittilä Mine. There are many other areas which can be identified as a potential location to increase mine productivity using ore passes. Parameters used for defining the design is listed in Table 6 - Table 8. Design recommendation is given for Kittilä Mine in the following order:

- Length, Inclination and dimensions
- Rock mechanics and degradation
- Operation principle
- Equipment Selection
- Ore pass management and safety

6.1 Length, Inclination and dimension

Design of the ore pass for Kittilä is significantly influenced by the production rate of the production areas. The whole feasibility of the pass and longevity are dependent on the flow through rate. Length of the ore pass is therefore dependent on the number of levels which are decided to connect to each other. Rock mechanical perspective, actual length does not have significant influence on the stability but longer raises are more difficult to construct and carry out maintenance work. Section length should be less than 100 meters to guarantee the stability of the pass and enable maintenance of the ore pass as well. Occurrence of blockages or degradation is hard to stop and rehab in a longer ore pass section. Sections can be isolated from each other using chutes or gates.

Scenario 1 consist of a system which is 200 meters long and therefore it is recommended to be split at least two sections which can be independent of each other by installing gates or chutes. Also the shape of the ore pass and its vertical uniformity is supporting the selection i.e. orebody has uniform and relatively same production rates through every level. Number of levels operated annually supports this scheme. The annual number of levels under production is varying between 3 – 14 levels per year per lens, average being 4. Having this as a maximum length it can be said that every section of the ore pass is being used every year.

Grain size of fragmented ore has the most significant influence on the diameter and the length recommendation is based on the empirical experience from other mines, particle flow code results and production rates of the mine. For scenarios, diameter of 3 meters was used. Which means that maximum diameter of ore should be 600mm or less to keep the D/d – ratio above 5. This can be kept as an optimum diameter of the ore pass, but for current situation without grizzlies, risk for hang-ups arises. Therefore it is recommended to carry out a fragmentation study to identify the amount of oversized boulders and whether the fragmentation of blasting can be decreased in more detailed planning in drill and blast engineering. If fragmentation is not sufficient enough, compromise between the ore pass diameter, grizzlies and boulder handling must be made so that smooth and cost-effective ore pass operation can be maintained. Shape of the ore pass is not important when the cross section of the ore pass is large enough and it is more question of company culture and local knowledge in excavation methods. For a stability point of view, the raise bored ore pass is slightly more stable and easier to support, especially if liners are used. Kittilä mine has good experience in raise boring of 4 meter ventilation raises and therefore raise boring can be recommended.

Finger raises and its number are depending on the length of the ore pass. Inclination of finger raise versus the actual ore pass should be fitted to the guidelines mentioned in Chapter 2.6.4 to minimize the wear in the intersection of finger raise and the pass. If finger raises are used, it is common to equip them with lids to prevent air blast, under pressure due to piston effect and dust emission. Finger raises have shallower inclination than the actual ore pass and therefore ore flow might be weak in the finger raises. Therefore, lining the finger raises with steel plates could enable better productivity and lower risk for blockages. Before commissioning the ore pass system, it is recommended to inspect the degradation rate of the intersection of ore pass and finger raise which is identified to be the impact zone of falling rock. A schematic finger raise configuration for Kittilä mine is showed in Figure 47.

Inclination of the ore pass is following the orebody but keeping a safe distance to the orebody, other mining infrastructure and footwall drives. There are 3 main join sets and also fourth joint set J3, but it is assumed to be an overturned dip direction, being the same as J1 identified in the geotechnical study (Figure 52). Locating ore pass parallel in a direction of these joint sets should be avoided. Joint Set J1is dipping steeply towards east and might cause risk for wall degradation, because the angle between ore pass walls are less than 45 degrees in places. To mitigate the adverse wall degradation, the ore pass should be aligned within following guidelines:

- Dip: 75 - 90^{o}
- Dip Direction: 0 – 45^{o} (North or North-East)

Fracture zones and jointing should not impact much to the selected lineation of the pass, but should be kept in mind when deciding the orientation and especially if some unexpected degradation will occur in the future. From perspective of material flow, inclination should be kept within the guidelines mentioned in the literature study, memorizing the fact that shallow dip is beneficial for decreasing degradation and flow velocity. This is important especially if gates or chutes are applied.

6.2 Rock mechanics and degradation

Recommendation for rock support is made based on the stress regime, the Ore Pass Longevity Index, geotechnical logging and other rock mechanical parameters. Generally, rock is competent, even though being fractured and rock stress is at a moderate level. Generally, this means that ore pass sized structures should be stable in these conditions. There are recently raise bored 4-meter diameter ventilation raises in the Kittilä Mine where minor dog earing effect can be seen. In-situ stress-states are not considered having major influence on the ore pass stability.

The knowledge of Kittilä mine stress regime is limited. The stress regime is based on Finnish Stress Test Database and its lower bound stress testing data which had been used as a basis of other studies for Kittilä mine. Rock strength in possible ore pass area is between 160 – 200 MPa. Rock stresses in level 675 and 900 varies between 50-98 MPa indicating that there is possibility to dog earing. Dog earing occurs when the ratio $\sigma_{max}/\sigma_{UCS}$ is higher than 0.4. A simple elastic model of the ore pass cross section was created in Map3D software to form an idea of the in-situ stresses around the circumference of the ore pass (Figure 43). The elastic model claimed that there can be significant stress concentration in the ore pass walls. Therefore ore passes are expected to be exposed to rock mass deformations.

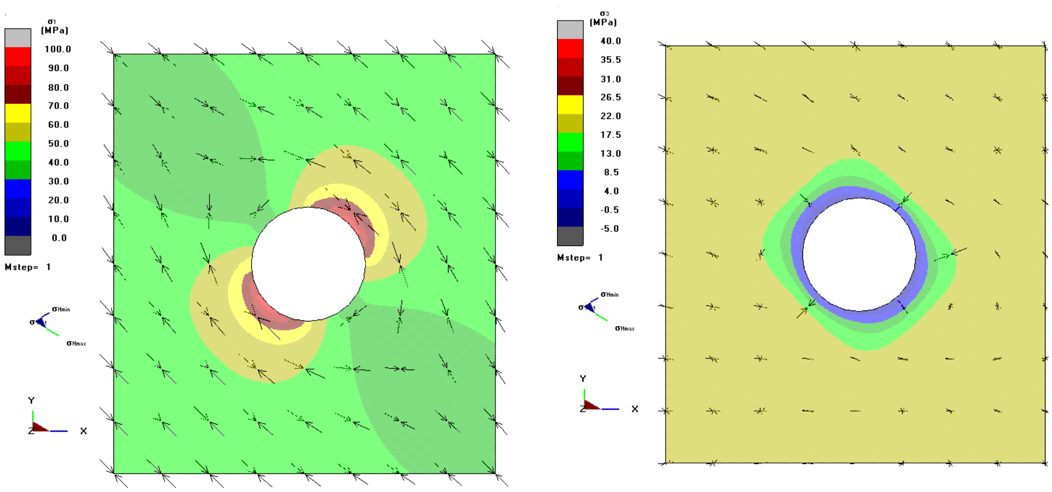

Figure 43 Induced stresses around the horizontal cross section of an ore pass (D=3m) in depth of 690m

Tangential stress was calculated from the elastic model, giving relatively high values, exceeding 100MPa (Figure 69). High value in tangential stress would mean that that the rock deformation would exceed the limits of elastic rock deformation and would result in irreversible plastic deformation. Therefore tangential stress value was kept slightly too high value, which is possibly due to limitations in the elastic model, despite that Sjöberg et al. (2003) found no difference between elastic and plastic models in their stability analysis of ore passes in Kiiruna. Therefore a plastic model should be applied to define the tangential stress. There are some stress related dog earing effects in the ventilation raises bored to 4 meters in diameter in Kittilä Mine, confirming that there are stress related deformations in relatively small diameter raises. The dog earing effect might impact to the overall ore pass longevity if the major principal stress has direction perpendicular to the direction of the foot wall. Dog earing and grooving effect is described in the appendix in Figure 54.

For assessing the rock mass stability, RQD and Q-rating were used. Mainly, RQD-index is excellent and therefore the rock mass has good characteristics to host ore passes. There are some local areas where value of blockiness (RQD/Jn) drops below 8. Small value in blockiness might cause a higher degradation rate for the ore pass due to a higher number of free blocks which might scale down in an ore pass due to abrasive rock flow. Jr/Ja –ratio (0.4) indicates that the resistance to prevent mobilization of free blocks is relatively low but it is hard to evaluate how much more susceptible the blocks are to be mobilized in the ore pass due to impact forces of falling ore. McCracken et al. (1989) have defined ratios RQD/Jn and Jr/Jn to be *"poor"* and *"very poor"* in terms for how suitable the rock mass is for raise boring. Also in places, Q-value is indicating minor stability problems which might have adverse influence on the ore pass longevity.

A maximum unsupported span was calculated in function of depth for every 25 meters section of ore pass from level 675 to 875 (Table 9). RSR value of 1.6 was used for ore passes. The maximum unsupported span was varying between 0 – 7.7 meters. Zero value is from depth 762.5 where core-logging data was not recovered due to fractured rock and significant water inflow (Table 9).

Table 9 Maximum unsupported span (MSUM)

Depth (m)	MSUS (m)
687,5	7,71
712,5	7,71
737,5	7,35
762,5	0,00
787,5	2,93
812,5	3,20
837,5	6,09
862,5	1,10
887,5	6,97

The ore pass is as good as its weakest section and therefore extensive system should not be located traversing weakness zones Based on the drill hole logging, few weak zones were identified. Earlier geotechnical study has identified weakness zone in level 900 which should be avoided to maintain the stability of the ore pass (SRK, 2017). As far as possible, these areas should be avoided by locating the pass away from intersecting the weak zone. The actual weakness zone might not degrade more than the competent zone, but especially the geological transition zone might cause problems because ore will hit and bounces in the edge.

Water inflow is expected to be significant in certain areas and therefore these areas should be avoided if possible. Otherwise, the ore pass should be isolated from the collar that no extensive amount of water can access the pass or by using grouting to seal the fractures despite grouting might not be effective way to mitigate water inflow due to degrading effect of ore flow.

The Ore Pass Longevity Index was calculated to clarify the impact of different support and lining selection. Three different variations for ore pass support scheme were done to describe the influence of ore pass support and operation method to the overall ore pass longevity. First option was calculated without rock support or liners, second was with using cable bolting and 150mm liner and third option without liners and support, in combination with bad operation principles.

Results predict that ore passes and a chute system might need rock support, wear protection or replaceable liners to prevent degradation. In scenario 1, where the Suuri Deep Zone have a full ore pass system from 675 level to a level in 900 meters, flow to the bottom of the ore pass rises close to 4 Mt in the years 2020-2035 (Figure 44). Results indicate that there are sections between level 750 and 825 where predicted ore flow based on LOM is exceeding the value of Longevity Index (Figure 45). If cable bolts and 150mm or thicker concrete liner is used, only one section falls below the Longevity Index. Therefore utilization of support and liners in certain sections of ore passes should be evaluated. The result is important to take into account in the number of ore passes. Splitting ore flow to two section decreases the effect of degradation significantly.

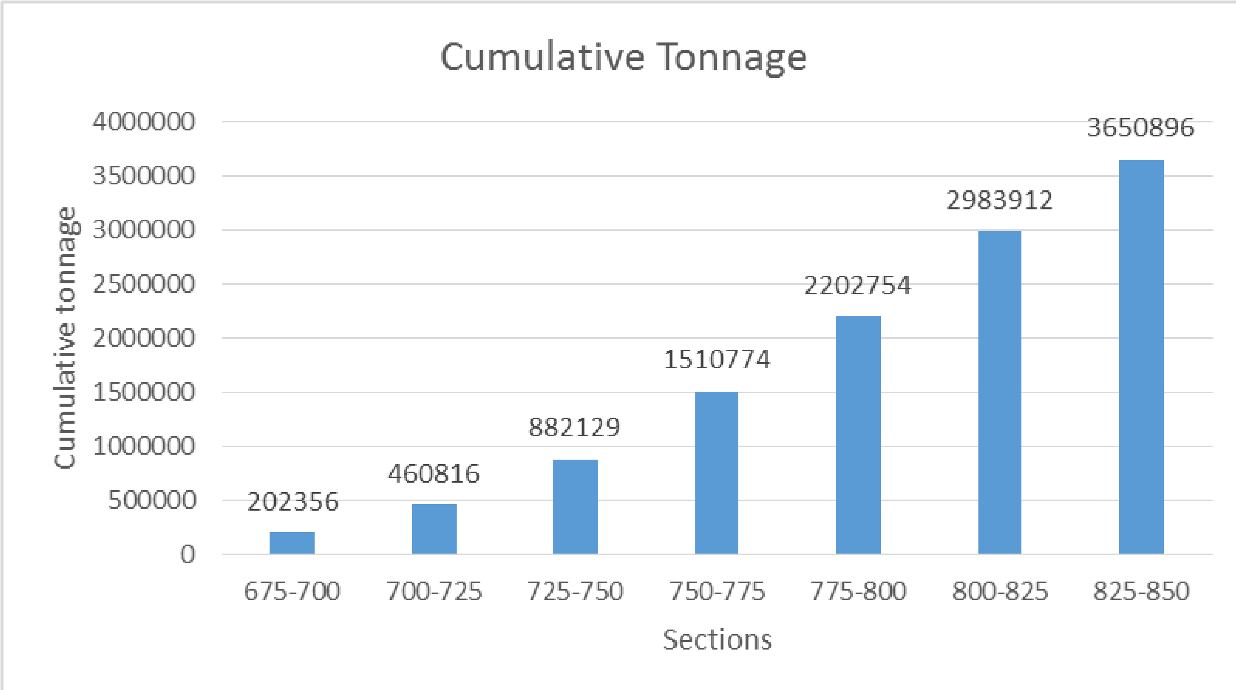

Figure 44 Tonnage through the sections of ore pass during years 2020-2035

No Support

Pass	Avg-Depth	$\sigma_{1\ (Mpa)}$	$\sigma_{c\ (Mpa)}$	k	Q_r	A1	A2	A3	A4	B1	B2	C1	C2	LRF	F1	F2	LEF	Longevity Index		Ore Flow 1OP	Ore Flow 2OP
675	687,5	42	180	0,24	9	1	0,6	1	1	0,9	0,8	1	1	0,43	1	1	1	**8,64**	**Mt**	0,20	0,10
700	712,5	44	180	0,24	9	1	0,6	1	1	0,9	0,8	1	1	0,43	1	1	1	**8,64**	**Mt**	0,46	0,23
725	737,5	46	180	0,25	8	1	0,6	0,5	1	0,9	0,8	1	1	0,22	1	1	1	**4,32**	**Mt**	0,88	0,44
750	762,5	47	180	0,26	0	1	0,05	1	1	0,9	0,8	1	1	0,04	1	1	1	**0,72**	**Mt**	1,51	0,76
775	787,5	49	180	0,27	0,8	1	0,05	1	1	0,9	0,8	1	1	0,04	1	1	1	**0,72**	**Mt**	2,20	1,10
800	812,5	50	180	0,28	1	1	0,05	1	1	0,9	0,8	1	1	0,04	1	1	1	**0,72**	**Mt**	2,98	1,49
825	837,5	52	180	0,29	5	1	0,6	1	1	0,9	0,8	1	1	0,43	1	1	1	**8,64**	**Mt**	3,65	1,83
850	862,5	53	180	0,30	0,07	0,7	0,05	1	1	0,9	0,8	1	1	0,03	1	1	1	**0,50**	**Mt**	4,22	2,11
875	887,5	55	180	0,30	7	0,7	0,6	1	1	0,9	0,8	1	1	0,30	1	1	1	**6,05**	**Mt**	4,59	2,30

Support + Liner

Pass	Avg-Depth	$\sigma_{1\ (Mpa)}$	$\sigma_{c\ (Mpa)}$	k	Q_r	A1	A2	A3	A4	B1	B2	C1	C2	LRF	F1	F2	LEF	Longevity Index		Ore Flow	Ore Flow 2OP
675	687,5	42	180	0,24	9	1	0,6	1	1	0,9	0,8	1	1	0,43	1,4	1,7	2,38	**20,56**	**Mt**	0,20	0,10
700	712,5	44	180	0,24	9	1	0,6	1	1	0,9	0,8	1	1	0,43	1,4	1,7	2,38	**20,56**	**Mt**	0,46	0,23
725	737,5	46	180	0,25	8	1	0,6	0,5	1	0,9	0,8	1	1	0,22	1,4	1,7	2,38	**10,28**	**Mt**	0,88	0,44
750	762,5	47	180	0,26	0	1	0,05	1	1	0,9	0,8	1	1	0,04	1,4	1,7	2,38	**1,71**	**Mt**	1,51	0,76
775	787,5	49	180	0,27	0,8	1	0,05	1	1	0,9	0,8	1	1	0,04	1,4	1,7	2,38	**1,71**	**Mt**	2,20	1,10
800	812,5	50	180	0,28	1	1	0,05	1	1	0,9	0,8	1	1	0,04	1,4	1,7	2,38	**1,71**	**Mt**	2,98	1,49
825	837,5	52	180	0,29	5	1	0,6	1	1	0,9	0,8	1	1	0,43	1,4	1,7	2,38	**20,56**	**Mt**	3,65	1,83
850	862,5	53	180	0,30	0,07	0,7	0,05	1	1	0,9	0,8	1	1	0,03	1,4	1,7	2,38	**1,20**	**Mt**	4,22	2,11
875	887,5	55	180	0,30	7	0,7	0,6	1	1	0,9	0,8	1	1	0,30	1,4	1,7	2,38	**14,39**	**Mt**	4,59	2,30

Worst case with no grizzlies + bad operation

Pass	Avg-Depth	$\sigma_{1\ (Mpa)}$	$\sigma_{c\ (Mpa)}$	k	Q_r	A1	A2	A3	A4	B1	B2	C1	C2	LRF	F1	F2	LEF	Longevity Index		Ore Flow	Ore Flow 2OP
675	687,5	42	180	0,24	9	1	0,6	1	1	0,9	0,8	0,9	0,5	0,19	1	1	1	**3,89**	**Mt**	0,20	0,10
700	712,5	44	180	0,24	9	1	0,6	1	1	0,9	0,8	0,9	0,5	0,19	1	1	1	**3,89**	**Mt**	0,46	0,23
725	737,5	46	180	0,25	8	1	0,6	0,5	1	0,9	0,8	0,9	0,5	0,10	1	1	1	**1,94**	**Mt**	0,88	0,44
750	762,5	47	180	0,26	0	1	0,05	1	1	0,9	0,8	0,9	0,5	0,02	1	1	1	**0,32**	**Mt**	1,51	0,76
775	787,5	49	180	0,27	0,8	1	0,05	1	1	0,9	0,8	0,9	0,5	0,02	1	1	1	**0,32**	**Mt**	2,20	1,10
800	812,5	50	180	0,28	1	1	0,05	1	1	0,9	0,8	0,9	0,5	0,02	1	1	1	**0,32**	**Mt**	2,98	1,49
825	837,5	52	180	0,29	5	1	0,6	1	1	0,9	0,8	0,9	0,5	0,19	1	1	1	**3,89**	**Mt**	3,65	1,83
850	862,5	53	180	0,30	0,07	0,7	0,05	1	1	0,9	0,8	0,9	0,5	0,01	1	1	1	**0,23**	**Mt**	4,22	2,11
875	887,5	55	180	0,30	7	0,7	0,6	1	1	0,9	0,8	0,9	0,5	0,14	1	1	1	**2,72**	**Mt**	4,59	2,30

Figure 45 Calculated Ore Pass Longevity Index for 3 variations for one or two ore passes. Red color indicates that ore flow is higher than calculated ore pass longevity.

6.3 Operation principle

Most significant decision in the ore pass operation is the discharge method. Literature study was concluding different methods but only one is applicable to full scale utilization of the ore pass system. Ore passes must be operated using continuous ore flow with chute/feeder discharge. The pile option cannot reach the productivity level which is necessary during the years 2021-2025. The problem is that in the pile option, it takes too much time to dump into the ore pass and then to be mucked again from discharge area. Only change to facilitate the pile option is the autonomous loaders using simultaneous loading and mucking of ore passes. Otherwise, load and discharge mucking cycle of an ore pass is decreasing the productivity of the ore pass system by nearly 50%. Results of the simulations can be found in Appendix in Table 10 and Table 11.

Benefits of chutes were simulated separately to find out the benefits of chutes. HaulSIM simulation for Scenario 6 was run with different parameters to simulate chute loading. This was made by using ore pass discharge dumping time of 30 seconds instead of truck loading with LHD and loading time of 180s. Simulations revealed that chute loading is decreasing the number of trucks from 3 trucks to 1 trucks when ore passes were discharged directly to the truck using chutes from level 775. If automation is used, gates and chutes are necessary to control the material flow. If automated/autonomous equipment is used, simulations showed that ore pass operation with chutes is nearly doubling the productivity of the ore pass system, up to 220t/h, when it is assumed that equipment can work during shift change and ventilation of blasting fumes.

Gates and chutes must be protected from straight impact force of falling ore. Therefore the ore pass should be built slightly inclined position and excavate a dog leg to the end of the ore pass. Dog leg's purpose is to mitigate the impact force of the rock to the gate/chute frame. These can be built in combination of heavy chains to further decrease the impact force. If gates and chutes are used to host automatic loading and hauling equipment, it is necessary to consider other safety and monitoring related technology as well. This means sensors to monitor and manage the filling rate of the ore pass, chute operation and flow disruptions. Technologies for monitoring are listed in the Chapter 2.8.2 and it is highly recommended that these sensors would be connected online to facilitate an ore pass monitoring system which could be managed from mine control room (Figure 55). The data of ore pass system status (i.e. tonnage, grade, level in operation, chute loading etc.) is important to mine operation but also for geologists and processing plant to forecast blending and grade of the mill feed. These sensors should be also used for safety management like identifying blockages, mud rushes and inhibit simultaneous loading from different levels.

Ore passes are also chancing the mine layout in the mining level. Infrastructure for the ore pass and its other facilitating infrastructure is taking place. Access to the ore pass is built on every level. The access is located based on optimum location of the ore pass, but also by taking into account safety and other operative aspects (Figure 46). It should be located in an area where it is easy to access. Therefore the access can be turned in contrast to the level access drift making the intersection easier for loader to access the ore pass. It is recommended that the access is turned to a minimum angle between footwall drive. This is, because intensive short hauling creates significant abrasion to the loader tires and frame which comes with a cost of increased operating costs. The direction of the pass should be in a direction where the center of mass or expected higher number of stopes exists. The access is excavated slightly upwards to mitigate the risk of water flow inside the pass. For economic analysis average of 15 meters of drifting for ore pass access to every level were evaluated.

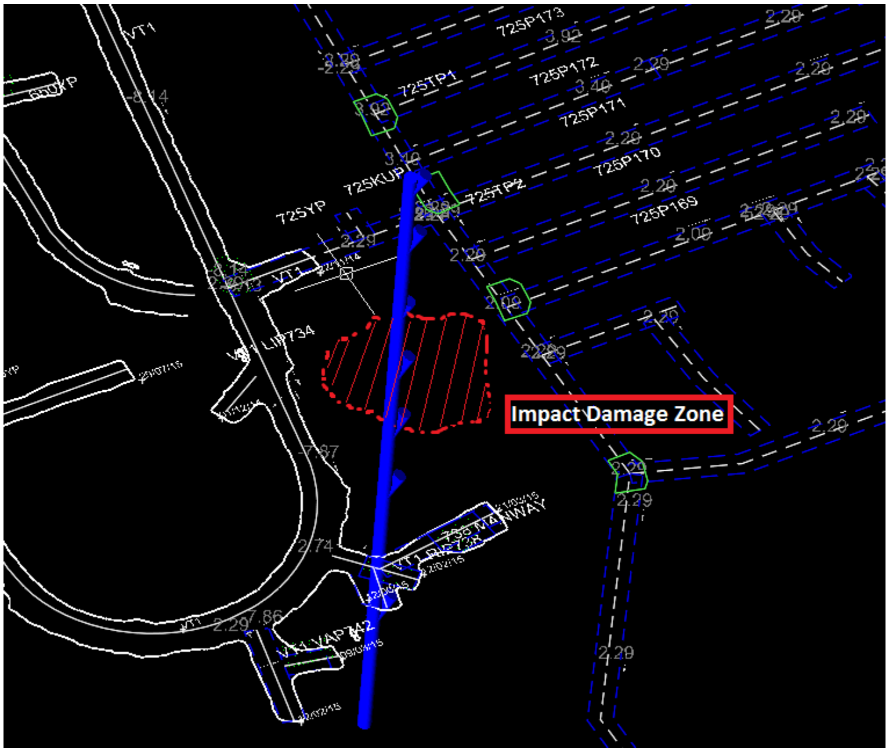

Figure 46 Ore pass location in respect to mine layout in Level 725.

Ore passes should be marked clearly and equipped with falling protection and lids if the ore pass has finger raises. Lids are reducing the dust and air blast impact from piston effect of falling ore. For automation, it is recommended to build loading boxes with an inclined face grizzly to the ore pass so that the actual tipping collar is raised from the floor of the drift. Otherwise the remote controlled autonomous loader might not be able to separate or re-muck oversized boulders, leading stoppages every time when the grizzly is blocked.

Separation of the tipping point from the footwall drive is important to decrease dust mitigations and air blast. This can be done by using wind doors, curtains or a gate. For ore pass management it is recommended that lids are equipped with sensors which signals the control room when the lid is open and the pass is under operation. The tipping point can be equipped with system signaling to the operator when tipping is allowed to the pass, for example using light signals. In an autonomous loading and tipping, mining level must be isolated from other mining areas, and tunnels can be equipped with WLAN connection. In two ore pass scenarios, it is possible to shield only other side of the mining level. Depending on the fragmentation, areas for boulder handling should be considered preventing the oversized rocks from entering the ore pass system.

Kittilä mine has relatively spread, almost vertically dipping thin but wide orebody with parallel lenses. Mine is using sub-level long-hole stoping with backfill to extract the ore. Depending on the thickness of ore body, transverse and longitudinal stopes are used. Therefore, actual tonnage is relatively small compared to bulk mining methods thus making the ore pass investment less feasible. The production stopes are often far away from each other and so are the need for infrastructure. Therefore it is important to consider options where the number and costs of fixed infrastructure is minimized. Equipment like chutes and other infrastructure such as WLAN/Radio network including radio transmitter base stations, should be mobile and be able to be replaced easily from production area to another. Summary of ore pass layout is showed in Figure 47.

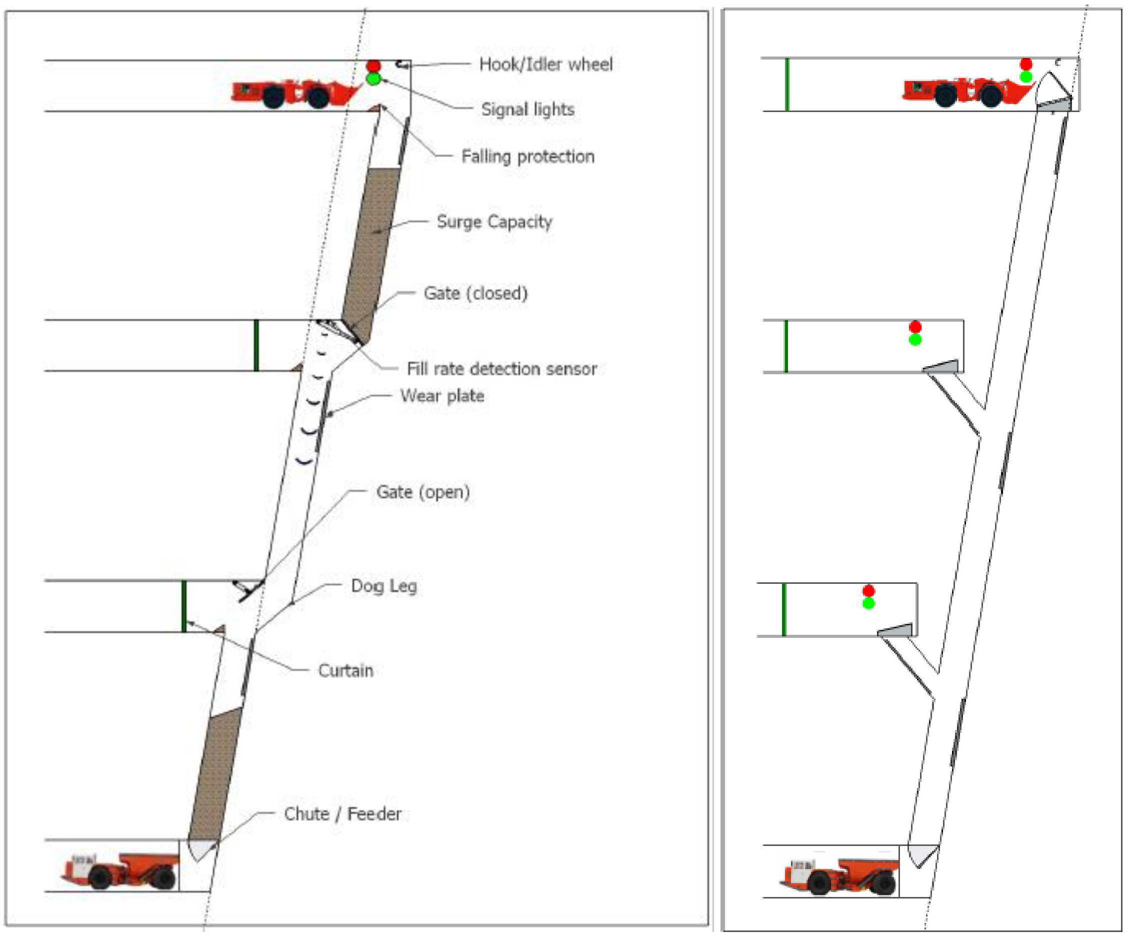

Figure 47 Two layout options for Kittilä Mine. Option with dog leg (left) and finger raise configuration (right).

6.4 Equipment

For the operation of the ore pass, equipment are selected based on hauling distances and the production rate. In Kittilä mine, this means that in Suuri Deep Zone with a C.O.G optimized pass system (Scenario1), it is possible to operate fully with LHD's in terms of hauling distances. This results in significant cost reductions especially in capital expenses when trucks are no longer needed. Other significant benefit is the highly decreased underground traffic which means less production delays and traffic jams in a crowded mine roads. The full ore pass system can still be a major risk factor, because it makes the underground mine ore transport system very rigid. Therefore it cannot adjust to quick productions stoppages like jammed access to the ore pass system. Therefore, small reserve capacity for hauling trucks to Suuri Deep Zone must be maintained one way or another.

Chutes have significant impact on haulage truck productivity decreasing the need for trucks from 3 to 1 if chutes are used for ore pass discharging. Chutes enable the ore pass to function as an intermediate storage and to reduce the cycle time of trucks. This impact can be seen in all scenarios

(Table 10). The chutes also enables the ore pass to have significant surge capacity up to 1000 t when chutes are used. Surge capacity is calculated for an ore pass equipped with chutes, 2/3 fill rate per section and using 3 meter ore pass diameter. Surge capacity gives flexibility for ore flow by enabling short disturbances without impact on ore transport. This impact can be seen from Table 10 in Appendix where overall productivity increases 10% when surge capacity exists. Instead of chutes also feeders can be used, but its ability to handle coarse ore is limited.

Using automation in Kittilä mine is highly desired character. It makes important to make the design of the system to host automated autonomous trucks and/or LHD's. Generally, study has shown that majority of the Suuri stopes can be operated via one pass, but in future from longer distances considerations for making the access large enough for trucks should be considered. Then it is possible to utilize autonomous trucks if distant stopes are hauled to the ore pass. For automation, a chute system is especially recommended for well-functioning ore pass discharge. Simulations have shown that the chute loading is increasing maximum productivity approximately 10%. Full automation with autonomous loading and hauling during shift change is increasing the productivity almost 100% compared with the convenient ore pass operation with a pile option. This is due to long travelling distance of mine staff from surface to the production area. The productivity increase in the chute loading is based on faster truck loading which was assumed to be approximately 30 seconds in chute loading thus decreasing waiting and idle time of trucks while approaching the ore pass discharge area.

Excavation of haulage level enables mine to further decrease the number of trucks. Haulage is recommended to be built from ore pass discharge area to the underground crusher. Suuri area lies in the southern side of the crushing plant but if the crushing chamber would be equipped with two bays, one in the north and one in the south, haulage level could be reached to the northern part of the mine to facilitate also ore passes in Sisar, Roura and Rimpi area. Simulations pointed out that one truck is able to transport up to 220t/h in haulage level having the length of 460 meters (Figure 60). That can be reached because there is no other traffic disturbing the hauling in haulage level. With sufficient surge capacity it is possible to reach continuous ore flow even when there are no on-going loading into the ore pass. This is a great advantage allowing short unexpected failures to the production equipment without having impact on overall underground ore transportation. Conveyor and rail haulage systems were found to be infeasible for Suuri Deep Zone due to the low annual production rate. In wider perspective, if ore passes would be utilized in the other zones of Kittilä Mine, possibilities to invest in a conveyor or rail system could be justified. These systems have high capital costs and to get full benefits, a higher production rate would keep the transportation process continuous and feasible. Mining Engineering Handbook suggests rail hauling for mines having production >5Mt/a (Darling 2011, p. 1275).

The design procedure of the whole system must take into account the mutual functions of the automatic loader, ore pass and the chute. The system must be able to work out in one package, where failure of any aspect gets signaled to the whole system, making it safe to operate. For the future global trend can go towards a battery driven equipment. That means for more autonomous independent loading equipment which can be left fully independently to operate in the level, making the productivity of an ore pass system even higher. Kittilä mine has long distances for example when equipment has to be refueled and therefore local charging option for electric equipment would increase the availability of the equipment.

6.5 Ore pass management and safety

To facilitate the ore pass system, mine has to create procedures for ore pass operation, maintenance and safety. Ore passes should be monitored and operated in regular intervals to guarantee sufficient functionality. Kittilä mine has well-functioning CMS systems for stope scanning and reconciliation which can be used to analyze the ore pass degradation rate. Also for regular maintenance, mainly a monitoring procedure should be designed to identify ore pass failure or significant damage in an early phase before a self-mining of the ore pass. Ore passes, and generally all underground open voids, creates a major safety risk if left unused for a long time. It creates a risk for unexpected hang-ups, mud rushes, collapses and air blasts. Therefore the unused ore pass sections should be whether regularly monitored or sealed and backfilled after terminating the operation of the pass.

Small raises are very complicated and dangerous to rehabilitate after major failure. The ore passes also requires education to miner, because passes create safety risks for all mine personnel in the vicinity. Normally operating level and the chute area should be closed when ore is being tipped to the pass. If there are no significant air blast and dust impacts, it is possible to allow miners to work in the vicinity of the chute system. Then it is important to close the possibility to an unexpected mud rush or inundation while opening the chute. For safety reasons, mine should create a capability to deal with hang-up or blockages situations by acquiring the knowledge and equipment to the mine site.

6.6 Financial Model

The financial model was calculated using discounted cash-flow model and Net Present Value (NPV). Feasibility of the ore pass system was calculated through potential savings in tonne-kilometers in different scenarios and considering the opportunity cost of capital using the reduced number of trucks. Cash flows of saved costs were discounted using a discounting factor of 15%. With the cash flow model and sensitivity analysis it is easy to analyze the feasibility of the ore pass network in terms of changing Opex, Capex and tonne-kilometers. Financial Model can be found in Appendix in Table 14 and Table 15.

Capex and Opex are estimated using expected costs of ore pass operation. Capital costs and operating costs of the ore pass are highly dependent on the selected configuration, operating principle and infrastructure costs such as excavation of haulage level and therefore costs are only rough estimates. Costs are not Kittilä Mine's own production data and result should be handled with care. Therefore the model is adjusted with sensitivity analysis which helps to evaluate the influence of real costs to the NPV. The unit costs used in financial model were evaluated using general estimates and might differ from real Kittilä Mine production costs. Used unit costs can be found in Appendix in Table 13.

Especially costs of ore pass operation are highly variable and investment into a haulage level is decreasing the NPV significantly. Thus investment in the haulage level is producing other benefits elsewhere. Haulage level is in the vicinity of the potential new main level and other production areas hence decreasing haulage distances, traffic and equipment need elsewhere. For the financial comparison of other scenarios, it is important to point out that one ore pass presented in the Scenario 1 is operating within the limits in terms of productivity and degradation. If the mine have a target to transport all extracted ore in Suuri Deep Zone through ore pass, the feasibility of two ore passes should be evaluated.

Result of the financial model indicates that ore pass system can bring significant cost savings in terms of reduced tonne-kilometers. In Kittilä mine, annual savings in tonne-kilometers are up to 1.2 million euro per year in 2022. Haulage level has significant impact on Capex and therefore two NPV's are given. With haulage level, NPV of the ore pass system is evaluated to be approximately 0.9 million euro and IRR 26% (Discount rate 15%) and without haulage level 2.2 million euro and IRR 82%.

The financial model was made using general estimates of hauling costs and should be kept in mind. NPV of the scenario should be handled with care and more emphasis should be put towards the sensitivity of the investment. A sensitivity analysis were carried out to identify the impact of chancing parameters which have impact on the ore pass project. Sensitivity is analyzed by chancing; *CAPEX*, *OPEX*, *Tonnage/Distance* and *tonne-kilometers*. To realize the cost savings, the ore pass project is highly sensitive to the tonnage which will be transported via the ore pass (i.e. utilization rate of the ore pass) (Figure 48). Without haulage level, initial capital investment is small and therefore has no significant financial risk to achieve positive NPV, approximately 60% of stopes in Suuri Deep Zone should be transported via ore pass. By contrast, investment to haulage level is capital intensive and if reason or another ore will not be transported via ore passes (less than 85%), it is hard to recover the costs of excavation of the haulage level.

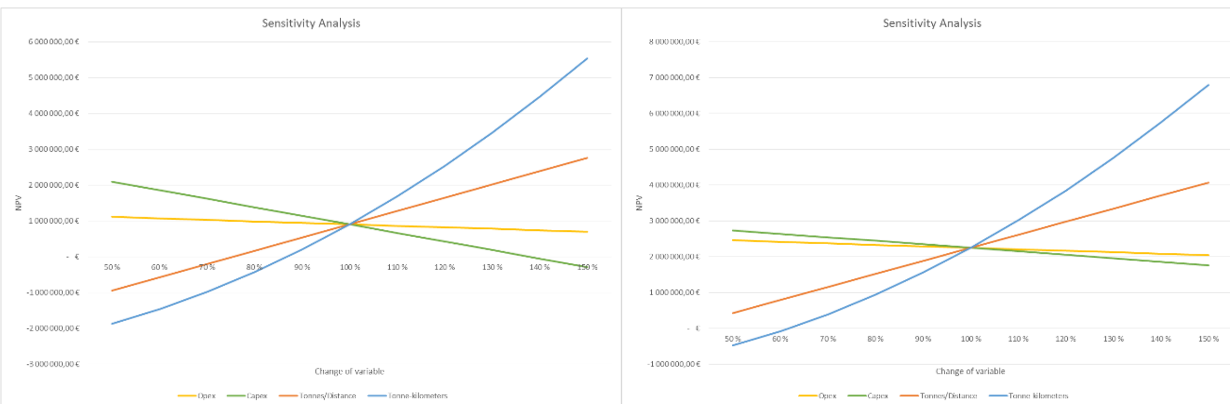

Figure 48 Sensitivity of investment of scenario 1 with haulage level (left) and without haulage level (right).

7 Reliability Analysis

The data for this study have been obtained from LOM Data from May 2017. The data consists of all mine parameters from stope dimension and characteristics to the scheduled extraction date. Data which the LOM plan includes is from January 2017 to the last day of year 2035. The data had been exported from Deswik Sched. -software to a text file which had been analyzed using Excel and simulated using discrete-event simulation software HaulSIM. Due to a time-dependent nature of mining, some issues should be highlighted.

The center of gravity and location of the stopes are only valid using current extraction scheme and commodity prices. Changing economic parameters changes the resource estimation leading to changes in cut-off grade, and further changes in the LOM and stoping sequence. Therefore, the center of gravity, stope locations and extraction dates might change in future. However, if the assumption of geostatistics is considered, minerals being distributed to a normal distribution, the center of gravity should not change much, despite the change in the cut-off grade. The decrease in tonnage will impact on the feasibility of the ore pass system but not its location. Moreover it is hard to predict the ore pass longevity and the time that ore pass is being used and therefore it is not convenient to evaluate the costs and benefits of ore passes for the long period of time. For example in Kittilä Mine the high peak in ore pass usage in the design area will be only from the year 2021 – 2026. That can be seen from the financial model where 75% of NPV is created during these years (Figure 70).

8 Conclusion

In this study modified Bieniawski's design strategy for rock structures were successfully applied in a study of ore pass design and placement. It was showed how changing the order of the methodology it is possible to define the problem and to apply it to mining environment. Using this strategy a Case study for Kittilä Mine had been carried out.

Scenario 1 were found to be a viable solution to utilize ore passes in Kittilä Mine. The mine can benefit from using ore passes in its operations and it showed that ore passes are financially viable solution if ore passes can be operated the way presented in this study. Ore passes are decreasing hauling distances significantly and removes the jamming problems completely resulting in a higher productivity and decreased hauling costs.

Chutes or gates should be applied in Kittilä mine to reach the productivity targets. Discrete event simulation showed that need for hauling trucks can be significantly decreased. On average, 5 trucks less are necessary to transport the ore in Suuri Deep Zone. Chutes as a discharging option enable the mine to utilize full autonomous equipment in mine production and results in significant increase in hauling and loading productivity. With help of chutes, autonomous equipment can be used also during shift change and blasting window. Productivity is almost doubled when autonomous equipment is used in an ore pass operation. In combination with haulage level, it is possible to operate the Suuri Deep zone with LHDs and one autonomous truck in haulage level.

Ore pass simulations showed that ore passes are decreasing the hauling distances and tonne-kilometers but it is not evident that actual productivity increases. That is, because ore pass is one "intermediate stockpile" more in the underground ore transportation chain. If dumping time and ore pass discharging times cannot be kept low, ore passes are actually decreasing the productivity. This was identified in the simulations in combination with chutes or without chutes.

9 Recommendation

Kittilä mine has competitive environment to exercise the ore pass project. There are no limitations in terms of geology, rock mechanics or production system which would inhibit the project. All risks of this project can be controlled. There are many other locations, in addition to Suuri Deep Zone, where ore passes can be deployed. Sisar and Rimpi areas are having high potential for ore pass operation. These areas could be combined to the same underground ore transport by combining the ore flows in a haulage level located near the underground crusher and new main level. For future operations on Sisar deposit, located below 1000 meters, it is important that mine can gather experience in ore pass operations in moderate depths before advancing deeper.

For obtaining a proper functioning ore pass system, Kittilä mine should look forward to verify the parameters analyzed in this study and gather empirical experience for operating ore passes. This means testing ore passes locally and gather its own specific data how the ore passes are functioning in its mining environment and what kind of impacts it has for underground ore movement. Mine should also study in detail the ore pass operation with shaft hoisting. Extensive ore pass systems come also with surge capacity and has an influence on the overall ore movement process. If in future, there are a hoisting shaft, surge capacity potential should be studied together with the hoisting shaft. It is recommended to make the following actions before exercising the ore pass project:

- Assessment of ROM Ore fragmentation and moisture content
- Mass flow analysis in the ore pass
- CMS survey of test ore passes in terms of longevity
- Assessment to create ore pass management and reconciliation procedure
- Implementation of automated loading and hauling equipment
- Simulation to estimate and verify the material flow in the underground ore transportation from stopes to the shaft.
- Detailed analysis of the cost items of the project

10 Summary

Ore pass design and placement were conducted using modified Bieniawski's design strategy for rock structures. Thesis studies in detail all parameters affecting to the ore pass design and placement. With the strategy and data available from the mine and literature, a case study for Kittilä Mine had been carried out.

Data collection from literature review and data acquired from a mine was made and applied in the Bieniawski's design strategy. More production related factor was weighted in the design process in the following order of the design strategy to assess the ore pass design and placement:

1. Clarity of design objectives and functional requirements
2. Optimization
3. Minimum uncertainty of geological conditions
4. State-of-the-art practice
5. Simplicity of design components
6. Constructability

Location and design of ore pass were optimized using state-of-the-art technology and best practices in combination with mathematically optimized location.

Via strategy it was possible to identify the project risks, technical viability and feasibility of the ore pass project. Case study showed that via applying the design strategy it is possible to show that mine can benefit from using ore passes in its operations and that ore passes are financially viable solution if ore passes can be operated the way presented in this study. The mine has competitive environment to exercise the project. There are no limitations in terms of geology, rock mechanics or production system which would inhibit this project. All the risks of this project can be controlled.

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12 Appendices

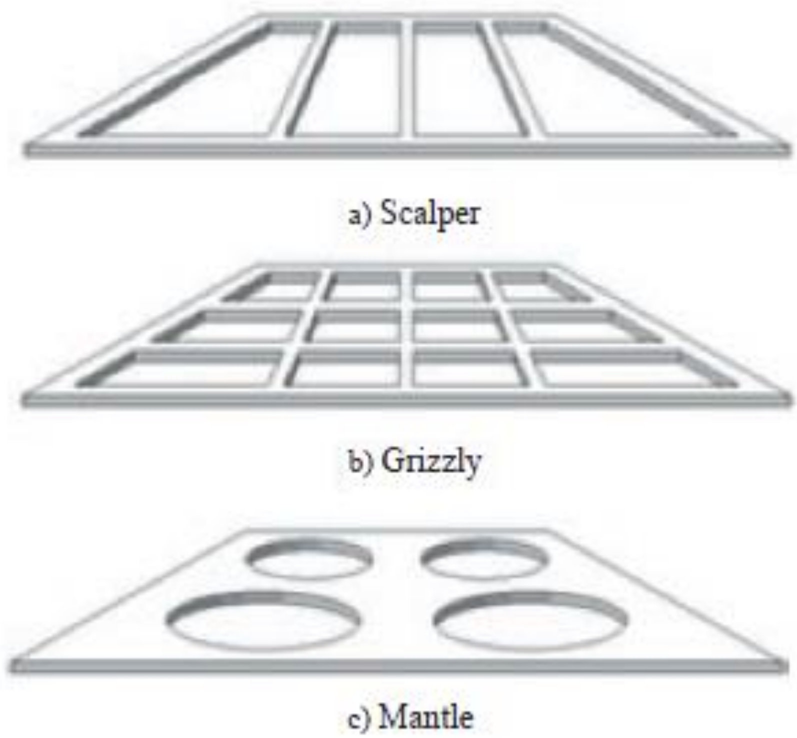


Figure 49 Screening infrastructure after (Hadjigeorgiou et al. 2004b)

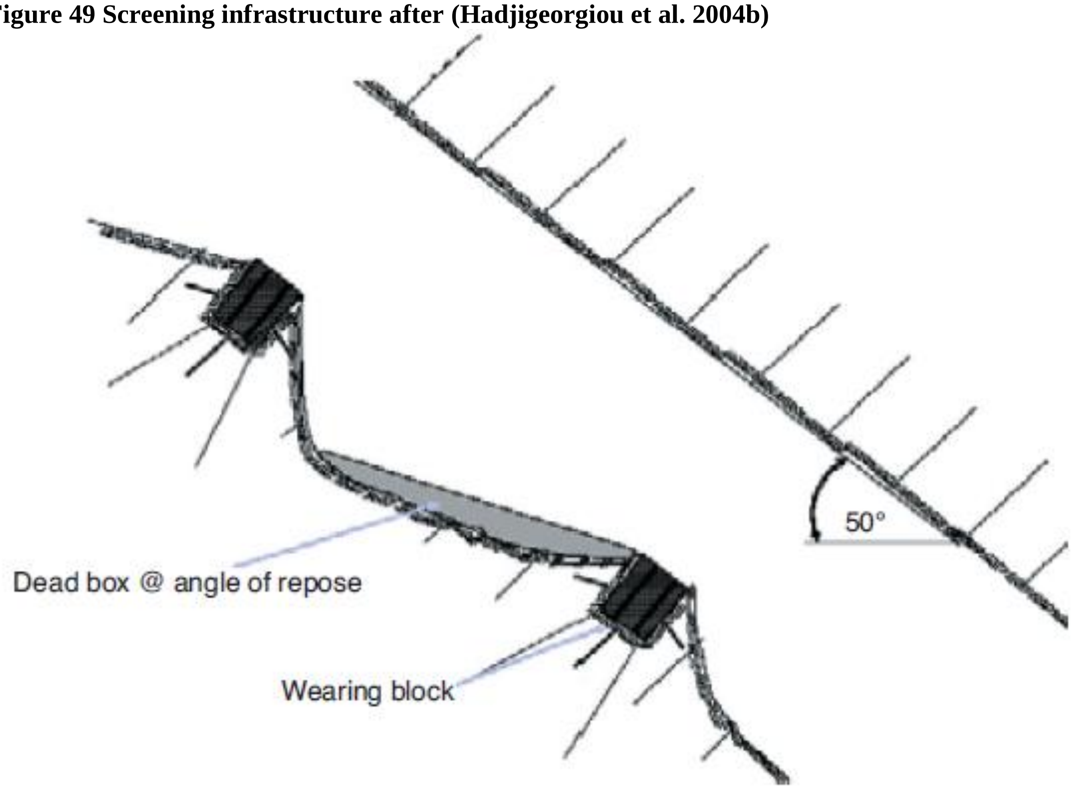


Figure 50 Wearing blocks can be used as a natural wearing protection in shallow inclined ore pass (Brenchley 2006)

Q_r

WALL ADJUSTMENT			
Q Sidewall	2.5Q	where	Q>1
Q sidewall	Q	where	Q<1
FACE ORIENTATION ADJUSTMENT			
Number of flat dipping (0 -30 degrees)	**1**	**2**	**3**
Major joint sets Adjustment of Q	0.85Q	0.75Q	0.60Q
WALL ORIENTATION ADJUSTMENT			
Number of steep dipping (60 - 90 degrees)	**1**	**2**	**3**
Major joint sets adjustment of Q	0.85Q	075Q	0.60Q
WEATHERING ADJUSTMENT			
Weathering Index	slight	moderate	severe
Adjustment of Q	0.9Q	0.75Q	0.5Q
Q_r = Cumulative sum of adjustments			

Raisebore class		VERY POOR	POOR	FAIR	GOOD	VERY GOOD
RQD/Jn	2	4	8	15	25	50
Jr/Ja	0,25	0,5	0,75	2	3	4

Figure 51 Adjustments for Qr and raise boring classification.

			Vein		Joint Set 1		Joint Set J1a		Joint Set J2		Joint Set J2a		Joint Set J3		Joint Set J4	
Logging	Depth From	Depth To	Dip	Dip Direction	Dip	Dip Direction	Dip	Dip Direction	Dip	Dip Direction	Dip	Dip Direction	Dip Direction	Dip	Dip	Dip Direction
Drill Con	550	600	47	349	50	92			67	143						
Drill Con	600	650	44	1	49	84			72	141						
Drill Con	650	700	37	2	57	107			78	139						
Drill Con	700	750	41	11	55	79			76	138						
Geovista	550	600	35	337	65	90			72	139						
Geovista	600	650	38	355	64	72			76	130						
Geovista	650	700	30	339					45	143						
Geovista	700	750	35	1					87	143						
SRK	750	800	32	21	69	73							71	260		
SRK	800	850	32	21	69	73							71	260		
SRK	850	900	57	342	74	136			59	82			49	249		
SRK	900	950	59	353	39	89							70	260	40	209
SRK	950	1000	45	355	47	78							36	267		
SRK	1000	1050	57	350	73	62	44	94							35	197
SRK	1050	1100	59	346	50	72							74	252		

Figure 52 Logging data from drill core logging STEC12009 and STEC16003

Table, Selection criteria for parameters (A1, A2, A3, A4, B1, B2, C1, C2, F1, F2).		
A_1. Stress Regime		A. GROUND CONDITION
$\sigma_1/\sigma_c > 0.5$	x 0.5	
$0.3 < \sigma_1/\sigma_c < 0.5$	x 0.7	
$\sigma_1/\sigma_c < 0.3$	x 1.0	
A_2. Rock Mass Classification (Walls)		
Q < 5 or RMR < 60	x 0.05	
5 < Q < 10 or 60 < RMR < 80	x 0.6	
Q > 10 or RMR > 80	x 1.0	
A_3. Major Structure		
Major fault/shearing zone (thickness in excess of 30 cm, continuity in excess of 3 times ore pass dimension, intercepting or less than 2 times ore pass dimension away)	x 0.5	
Ore contact (intercepting or less than 2 times ore pass dimension away)	x 0.9	
No major structure	x 1.0	
A_4. Orientation with respect to major joint set or bedding		
Interception angle < 45°	x 0.4	
Interception angle > 45° or no bedding	x 1.0	
B_1. Material Size		B. WALL IMPACT
$d_{95} > 1$ m	x 0.6	
$0.6 < d_{95} < 1$ m	x 0.9	
$d_{95} < 0.6$ m	x 1.0	
B_2. Fingers/knuckles		
Multiple fingers/knuckles	x 0.8	
One finger/knuckle	x 0.9	
No fingers/knuckles	x 1.0	
C_1. Blasting to Restore Flow		C. OPERATION
More than once per day	x 0.6	
Between once a day and once a week	x 0.8	
Less than once a week	x 0.9	
Occasional blasting (less than once a month)	x 1.0	
C_2. Cushion Guidelines		
Ore pass operated empty	x 0.5	
Ore pass operated full	x 1.0	
F_1. Ground Support		F. LONGEVITY EXTENSION
- No support	x 1.0	
- Rigid bolt support (rebars, rockbolts)	x 1.0	
- Cable bolt support	x 1.4	
F_2. Liner		
- No liner	x 1.0	
- Thin abrasion-resistant liner (6" or less)	x 1.4	
- Thick abrasion-resistant liner (6" to 12")	x 1.7	

Figure 53 Factors for calculation of Ore Pass Longevity Index

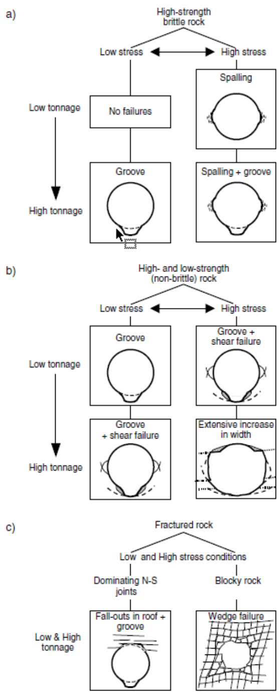


Figure 54 Ore pass failure categorization after Sjöberg et al. (2003)

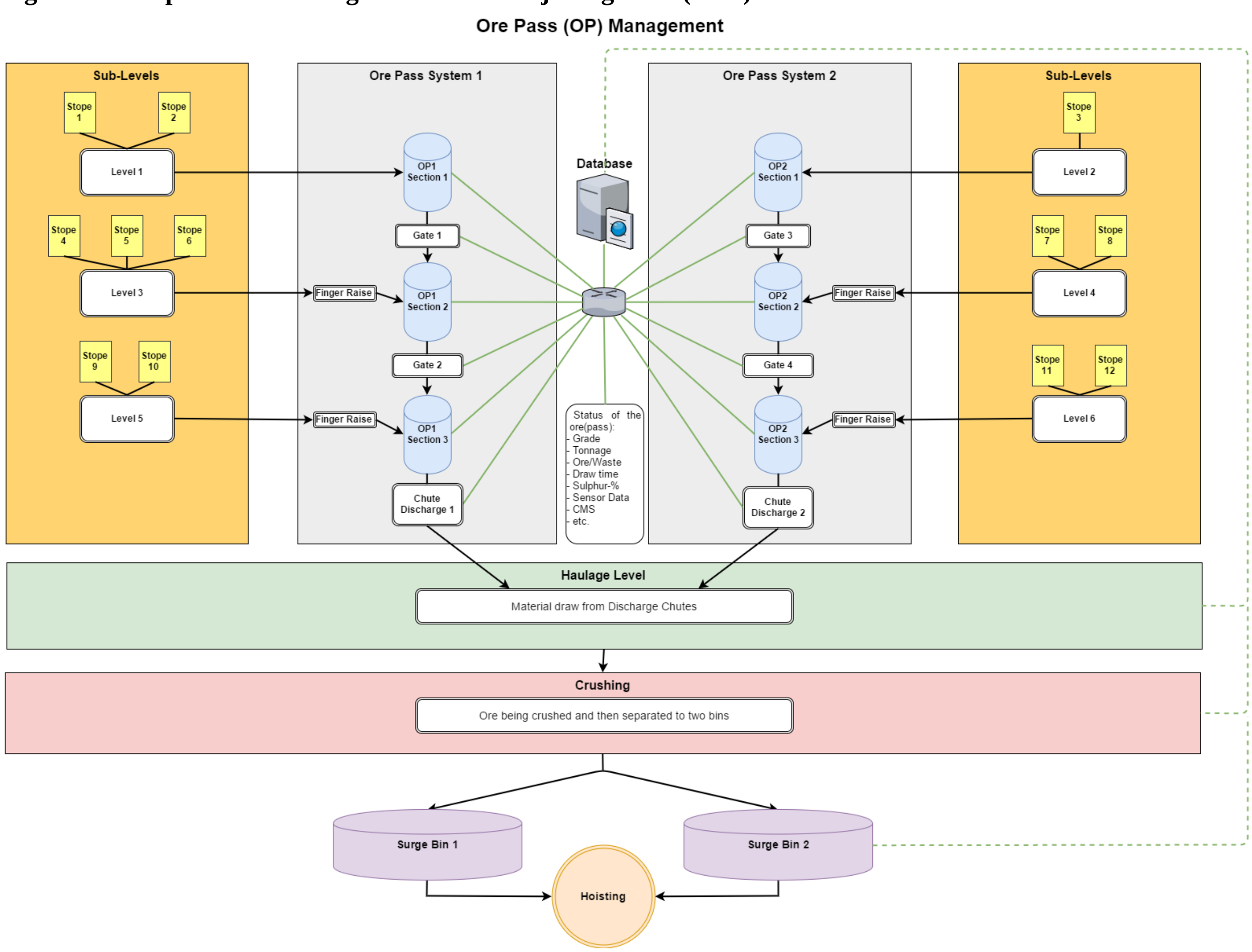


Figure 55 Schematic picture of ore pass management

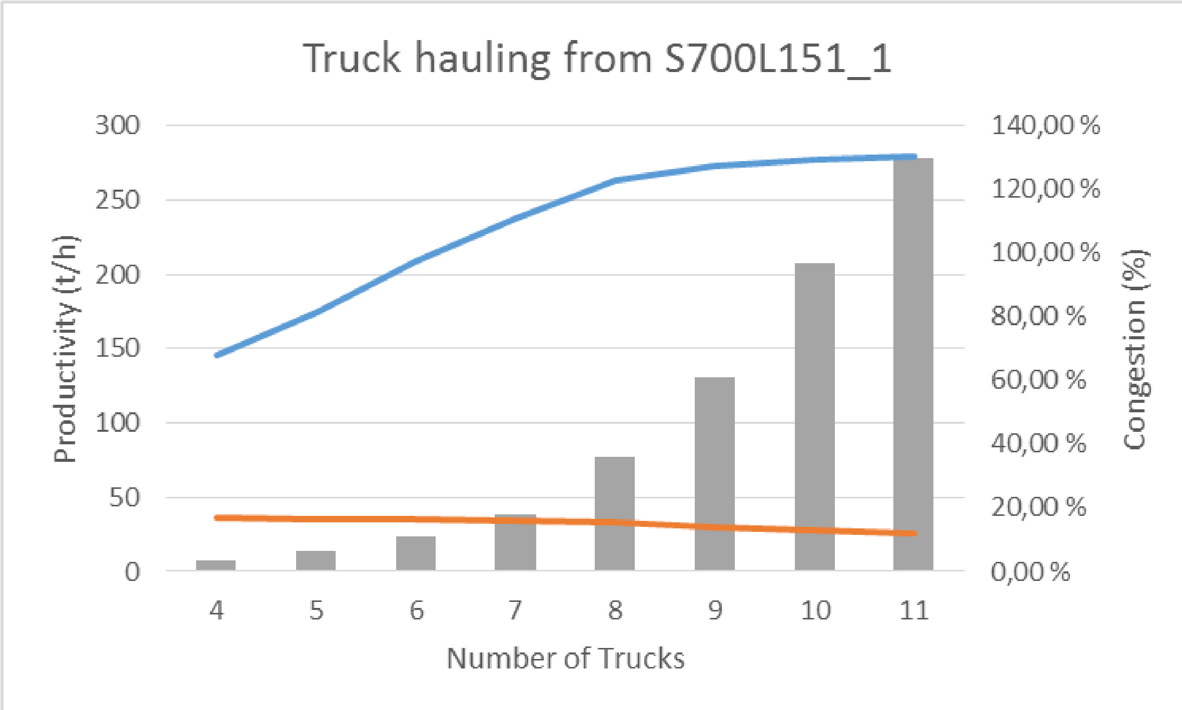


Figure 56 Haulage from S700L151_1 to underground crusher. Productivity in function of trucks.

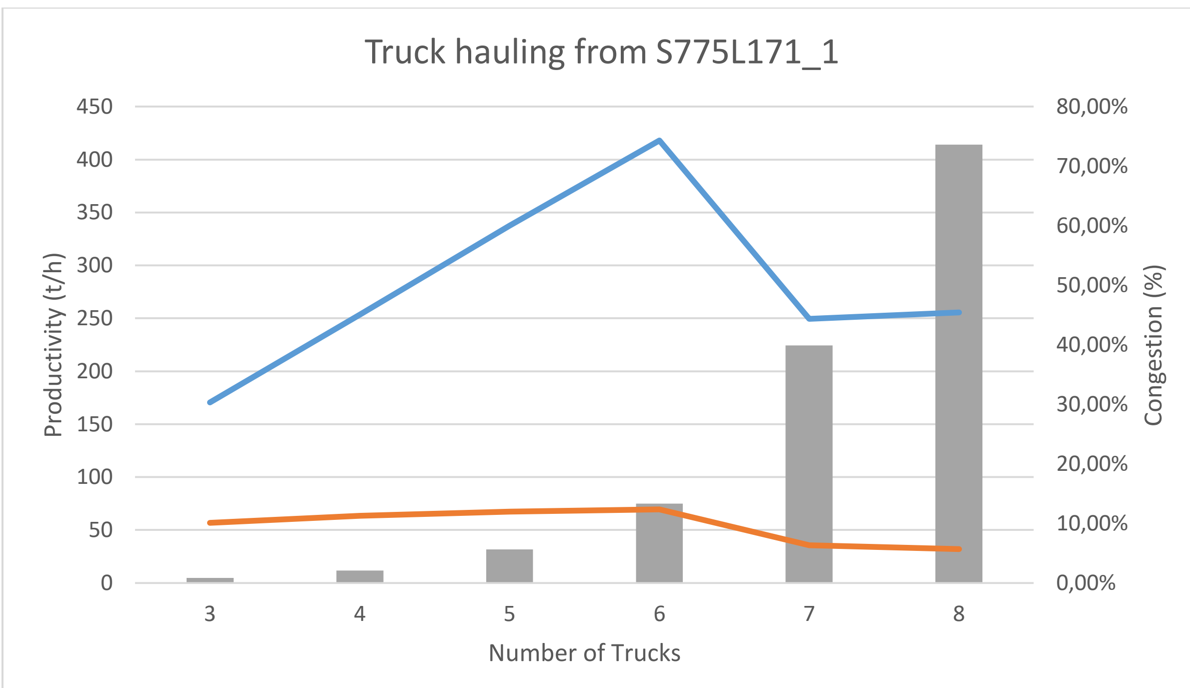


Figure 57 Haulage from S775L171_1 to underground crusher. Productivity in function of trucks.

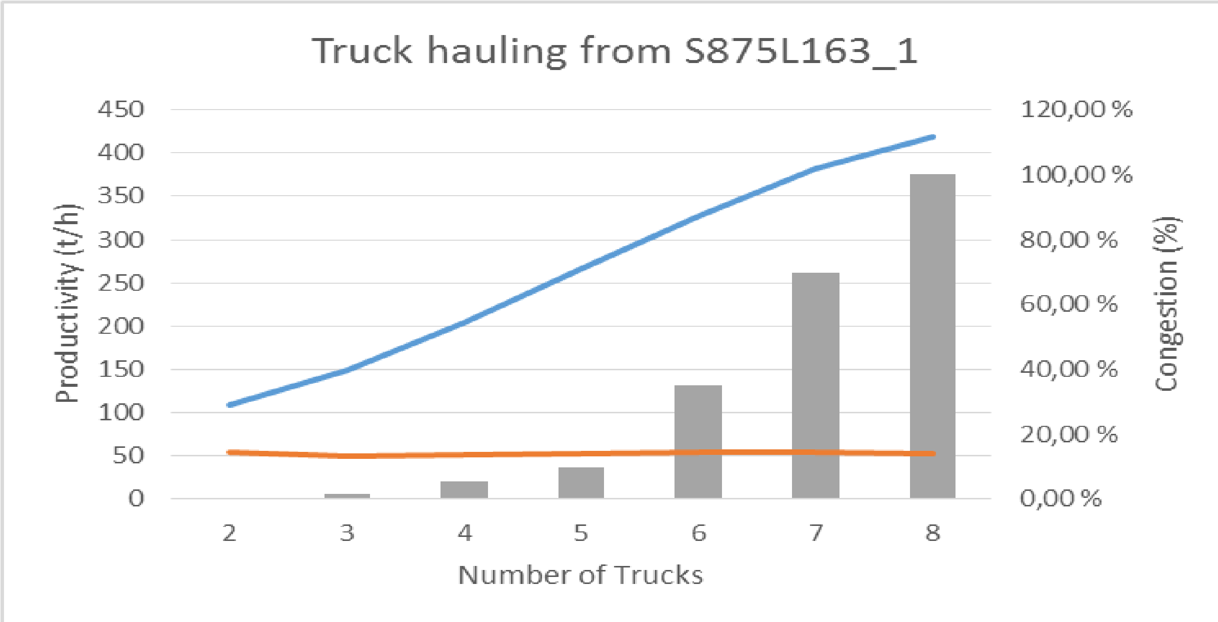


Figure 58 Haulage from S875L163_1 to underground crusher. Productivity in function of trucks.

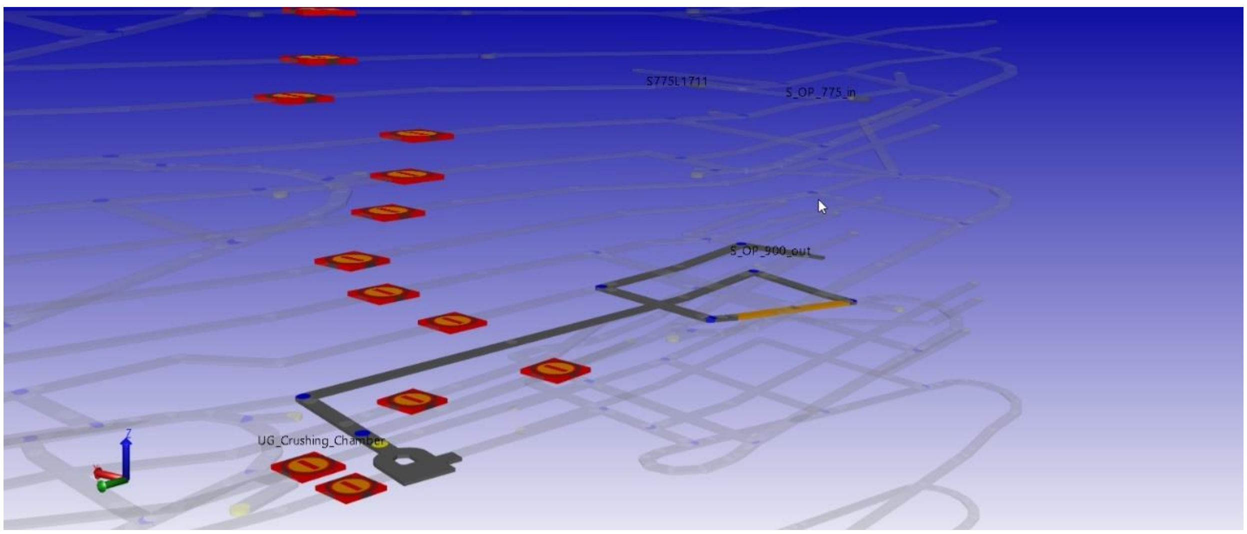


Figure 59 Ore pass from level 700 to 900. From level 900 ore is hauled to crusher using trucks.

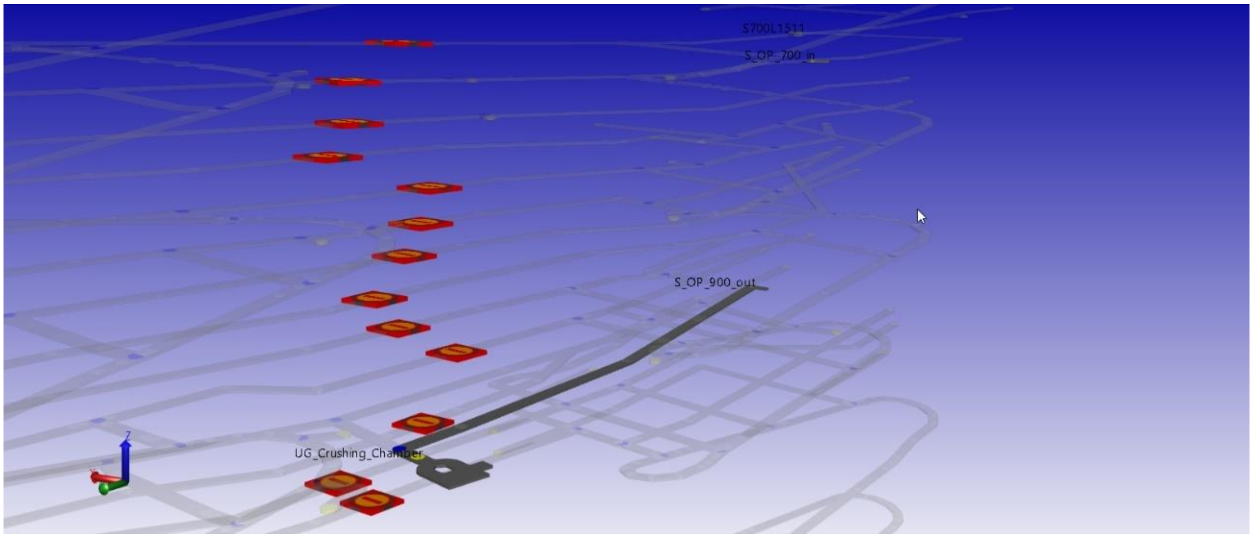


Figure 60 Ore pass from level 700 to 900. Haulage level is decreasing haulage distance significantly.

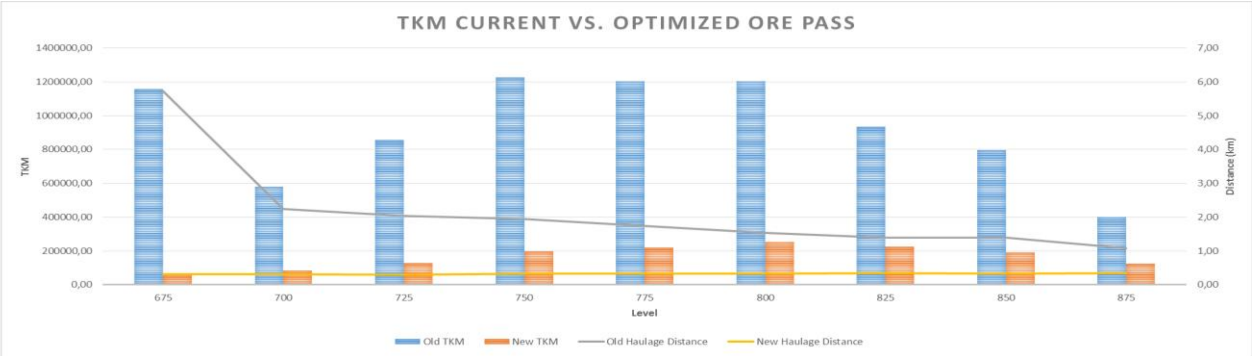


Figure 61 Scenario 1, summary of haulage distances per level compared to the current situation

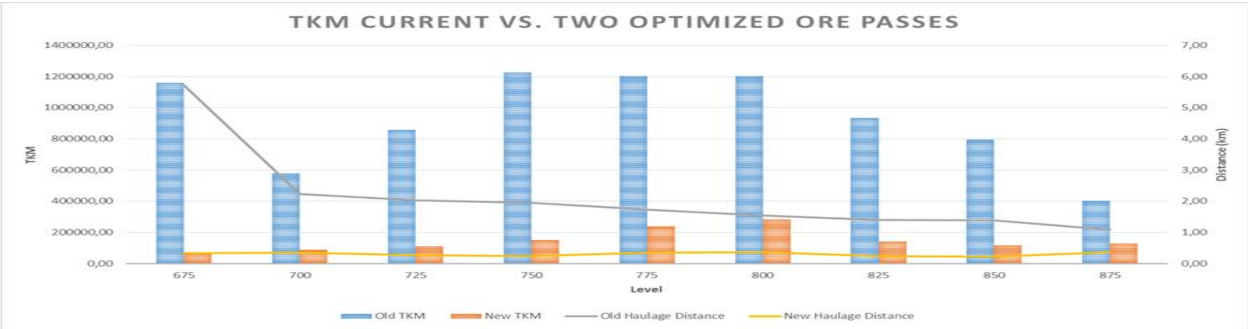


Figure 62 Scenario 2, summary of haulage distances per level compared to the current situation

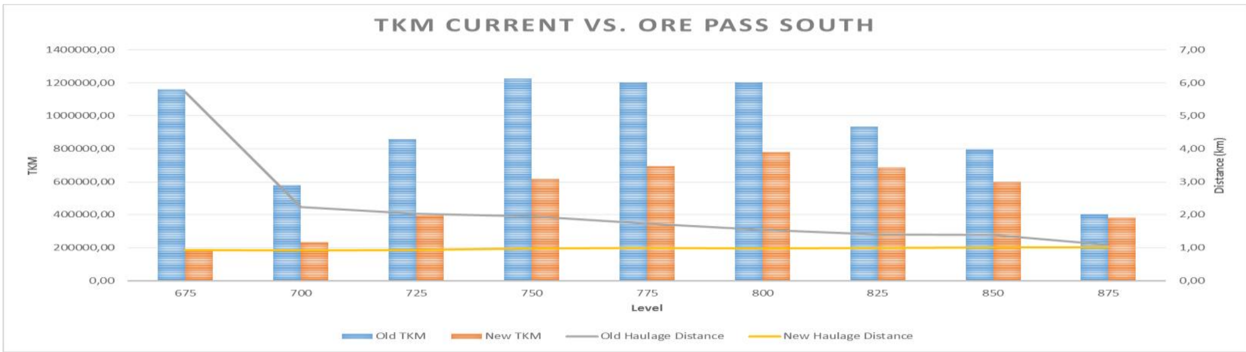


Figure 63 Scenario 3, summary of haulage distances per level compared to the current situation

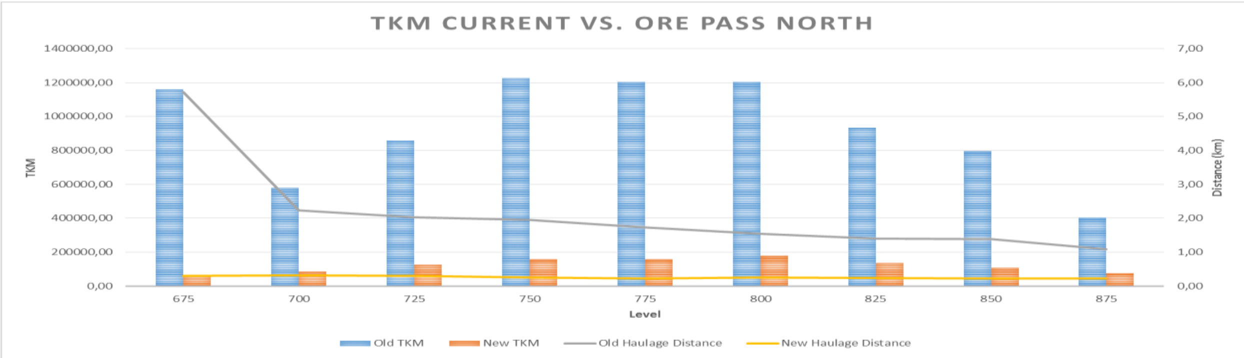


Figure 64 Scenario 4, summary of haulage distances per level compared to the current situation

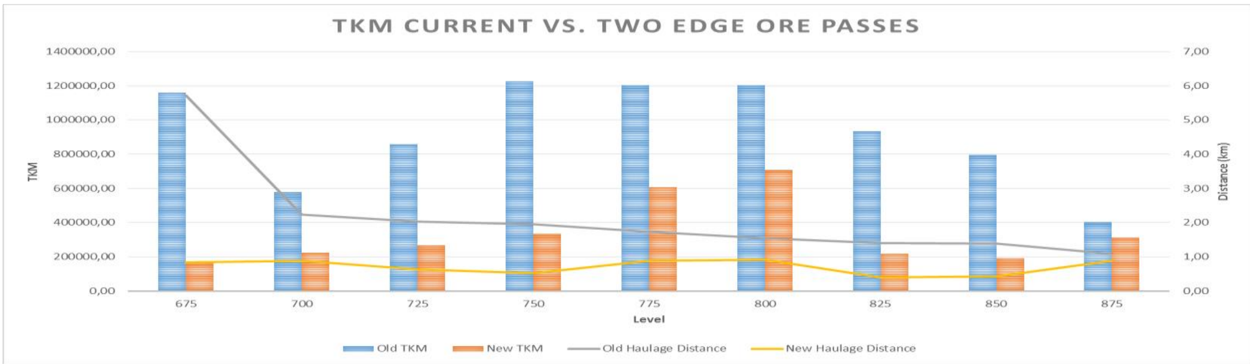


Figure 65 Scenario 5, summary of haulage distances per level compared to the current situation

Table 10 Simulations summary. Stope, utilization of chutes, surge capacity and number of trucks had been changed.

Human driven

Stope	No Chutes	Chutes	Haulage Level	Surge capacity			Trucks	Productivity	Congestion	Idle	Comment
				427	641	854					
S700L151_1	x			x			1	45	1,59 %	3 %	LHD limits productivity
	x				x		1	48	0,19 %	2 %	LHD limits productivity
	x					x	1	45	0,16 %	3 %	LHD limits productivity
No ore passes							4	146	3,72 %	-	
Stope	No Chutes	Chutes	Haulage Level	427	641	854	Trucks	Productivity	Congestion	Idle	Comment
S775L171_1	x			x			3	120	2,27 %	22 %	
	x				x		3	120	1,79 %	22 %	
	x					x	3	121	1,93 %	23 %	
		x		x			3	125	1,13 %	38 %	
		x			x		3	117	1,45 %	41 %	
		x				x	3	127	0,97 %	39 %	
	x		x	x			1	98	2,20 %	24 %	
	x		x		x		1	107	1,88 %	19 %	
	x		x			x	1	109	1,02 %	19 %	
		x	x	x			1	109	1,98 %	35 %	
		x	x		x		1	112	1,95 %	33 %	
		x	x			x	1	111	0,76 %	33 %	
No ore passes							3	171	0,87 %	-	

Table 11 Simulation where autonomous equipment can operate during shift change (i.e higher availability)

Automation

Stope	No Chutes	Chutes	Haulage Level	Surge capacity			Trucks	Productivity	Congestion	Idle	Comment
				427	641	854					
S700L151_1		x	x			x	1	92	0,12 %	3 %	LHD limits productivity
No ore passes							4	146	3,72 %	-	
Stope	No Chutes	Chutes	Haulage Level	427	641	854	Trucks	Productivity	Congestion	Idle	Comment
S775L171_1		x	x			x	1	220	0,10 %	1 %	

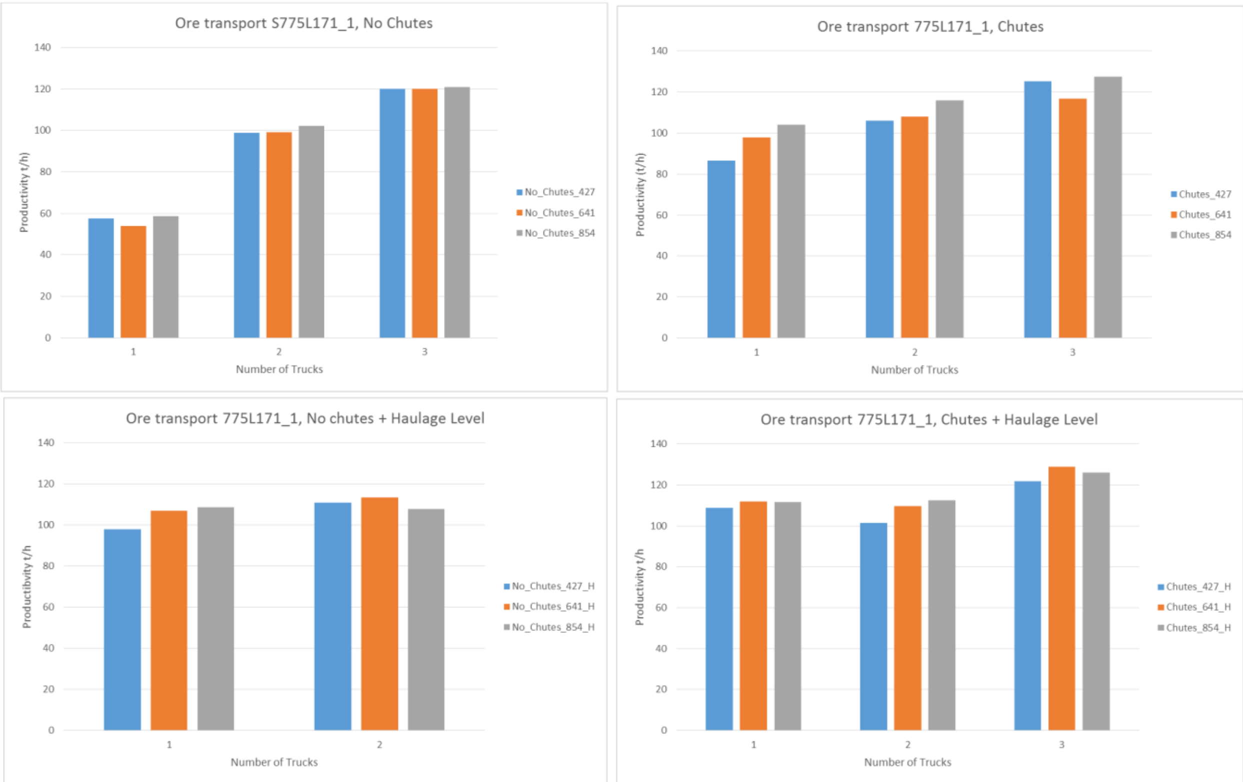


Table 12 Simulation results for ore pass operation from stope S775L171_1. Number of trucks, haulage level and surge capacities changes the productivity.

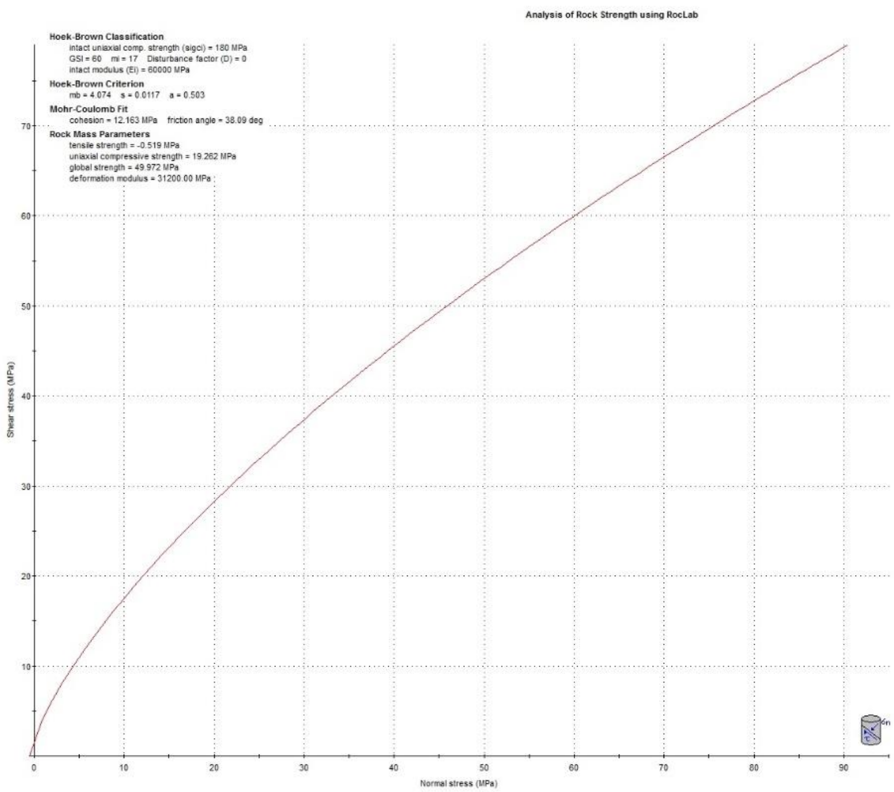


Figure 66 Input for Map3D elastic model

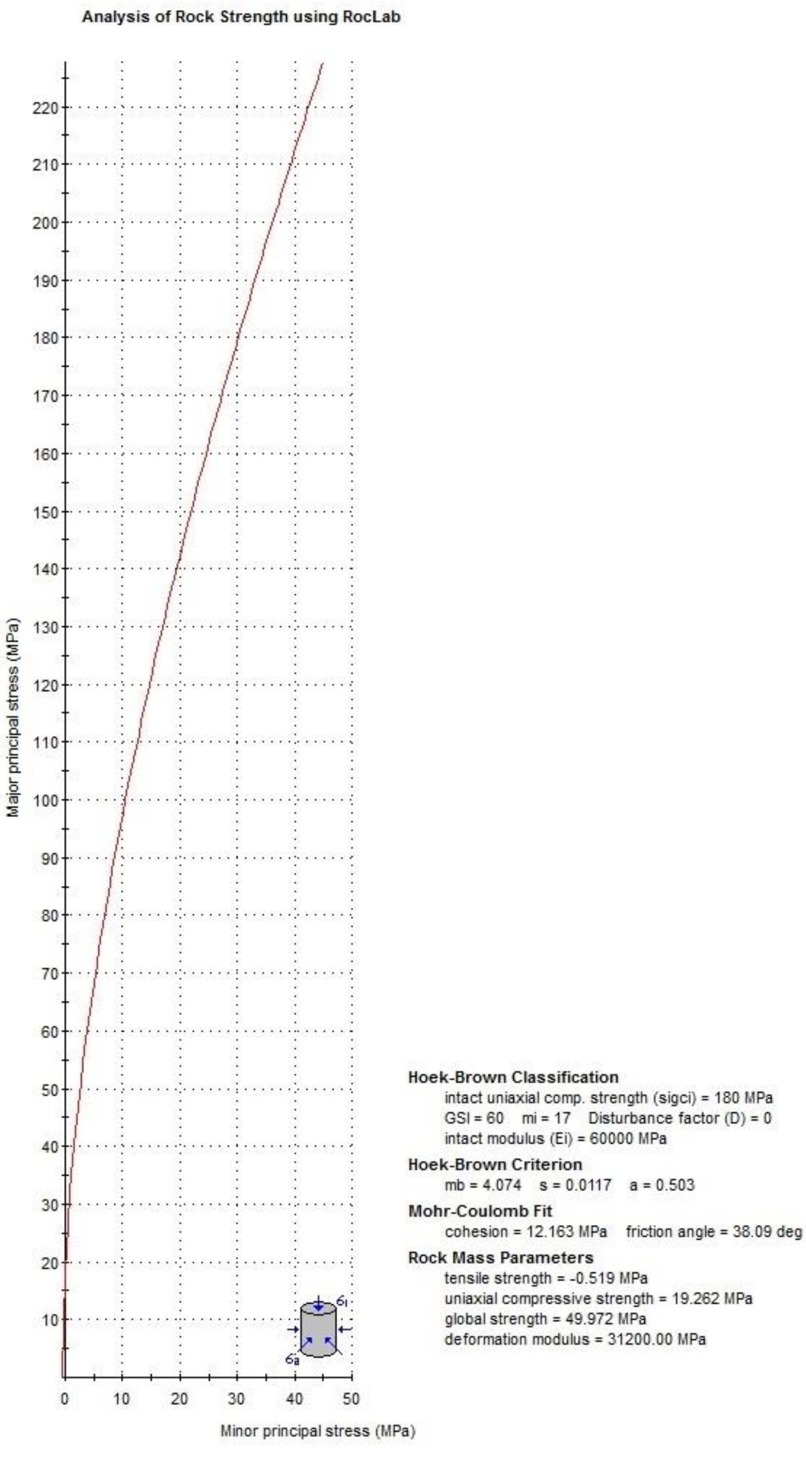


Figure 67 Input for the Map3D elastic model.

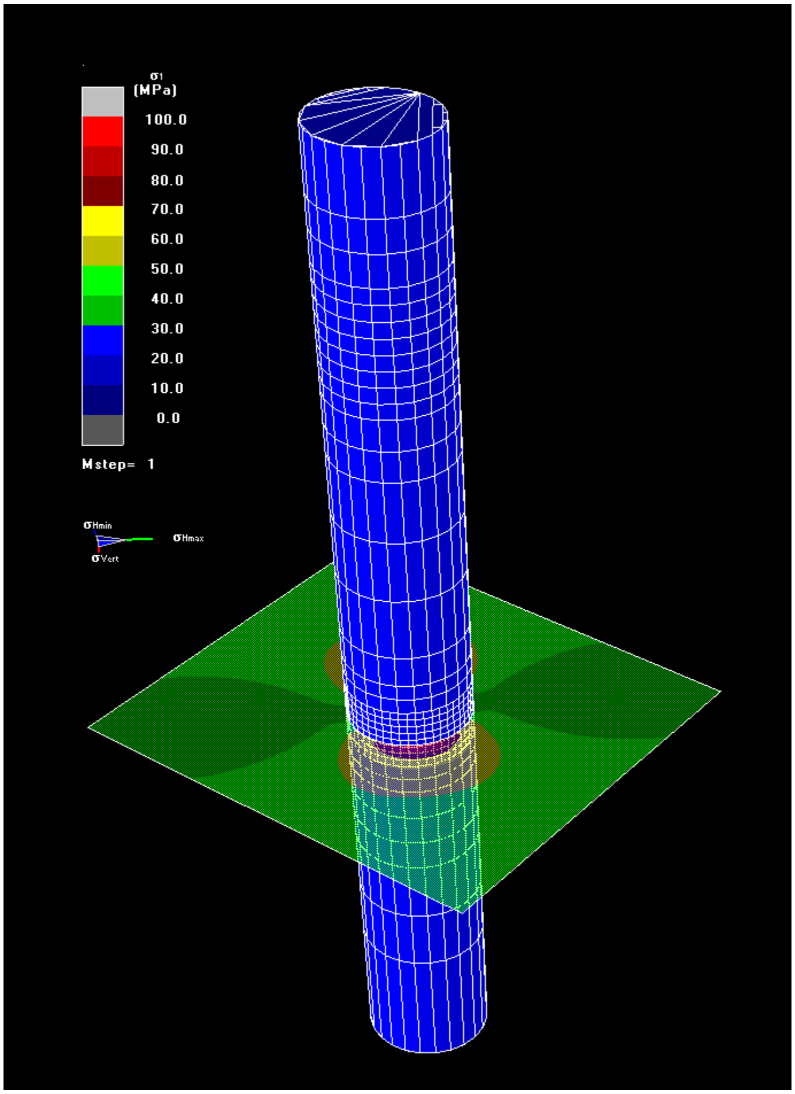


Figure 68 General picture of elastic model in Map3D

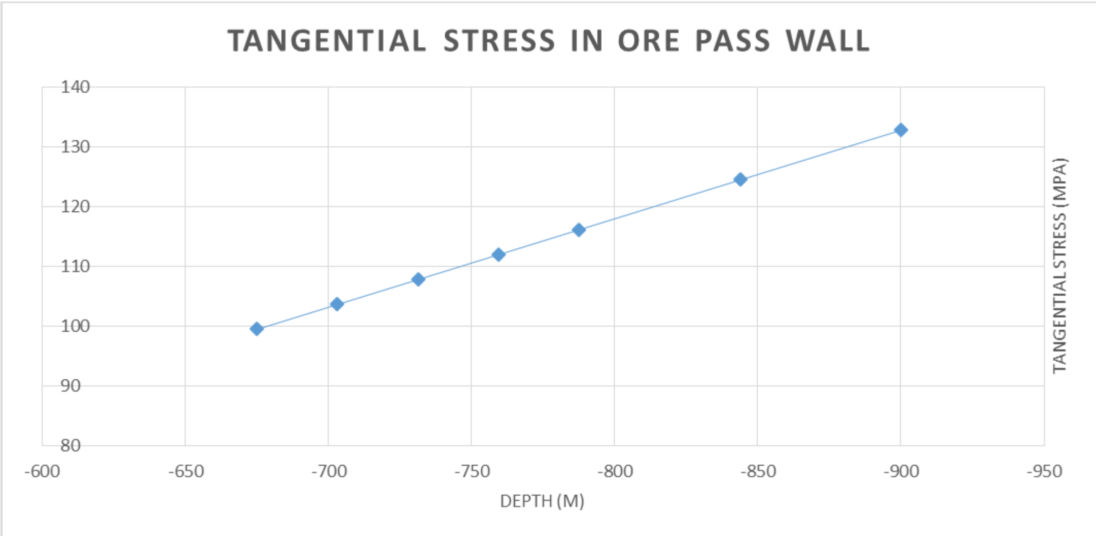
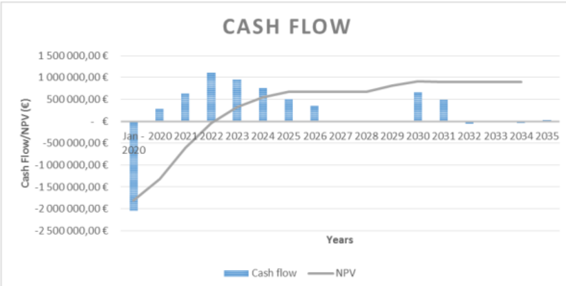


Figure 69 Tangential stress in the ore pass wall in function of depth. Elastic model.



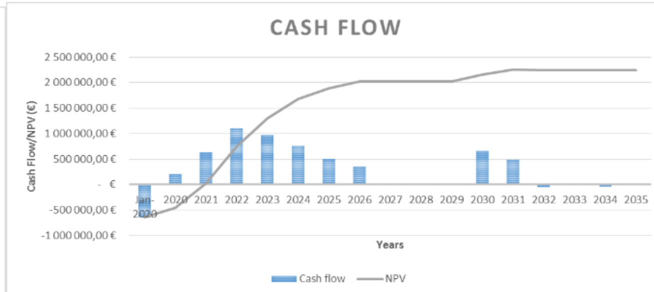


Figure 70 NPV and cash flow over years in Scenario 1 with haulage level (left) and without haulage Level (right)

Table 13 Estimated cost items on investment for ore pass

Cost Items																		
Revenue		from 6/1/2020																
Year	2020start	2020end	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
TKM_decrease		346845,80	957215,05	1202934,45	1062158,71	854913,40	606399,91	399366,05	41316,59	0,00	0,00	711095,82	543580,75	0,00	58414,87	8867,98	76193,16	tkm
TKM savings		346845,80	957215,05	1202934,45	1062158,71	854913,40	606399,91	399366,05	41316,59	0,00	0,00	711095,82	543580,75	0,00	58414,87	8867,98	76193,16	€
Opportunity cost of capital		187500,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Sum		534345,80	957215,05	1202934,45	1062158,71	854913,40	606399,91	399366,05	41316,59	0,00	0,00	711095,82	543580,75	0,00	58414,87	8867,98	76193,16	€
CAPEX																		
Raise Boring	200000,00	0,00	100000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	€
Excavations (15x8+H)	1650000,00	0,00	120000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	€
Chutes	200000,00	200000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	€
SUM	2050000,00	200000,00	220000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	€
OPEX		50000,00	100000,00	100000,00	100000,00	100000,00	100000,00	50000,00	50000,00	0,00	0,00	50000,00	50000,00	50000,00	50000,00	50000,00	50000,00	€
Opportunity cost of capital																		
Chute		200000	€/pcs															
Cost of truck		250000	€/pcs															
Less trucks		5	pcs															
Cost of drifting		3000	€/m															
Length of Haulage drift		470	m															
Length of development per level		15																
Number of levels		8																

Table 14 Financial Model with haulage level.

FINANCIAL MODEL OP One																	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Jan-2020	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
+Revenue	- €	459 345,80 €	957 215,05 €	1 202 934,45 €	1 062 158,71 €	854 913,40 €	606 399,91 €	399 366,05 €	41 316,59 €	- €	- €	711 095,82 €	543 580,75 €	- €	58 414,87 €	8 867,98 €	76 193,16 €
-Opex	- €	- 50 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 50 000,00 €	- 50 000,00 €	- €	- €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €
Gross income	- €	409 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
Depreciation (lin.)	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Net income before tax	- €	409 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
-Tax (0%)	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Profit after tax	- €	409 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
-Capex	- 640 000,00 €	- 200 000,00 €	- 220 000,00 €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Cash flow	- 640 000,00 €	209 345,80 €	637 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
Cumuative Cash Flow	- 640 000,00 €	- 430 654,20 €	206 560,85 €	1 309 495,29 €	2 271 654,00 €	3 026 567,40 €	3 532 967,32 €	3 882 333,36 €	3 873 649,96 €	3 873 649,96 €	3 873 649,96 €	4 534 745,78 €	5 028 326,53 €	4 978 326,53 €	4 986 741,40 €	4 945 609,38 €	4 971 802,55 €
Discount Factor	1,00	0,87	0,76	0,66	0,57	0,50	0,43	0,38	0,33	0,28	0,25	0,21	0,19	0,16	0,14	0,12	0,11
net present value	- 640 000,00 €	182 039,83 €	481 826,12 €	725 197,30 €	550 117,36 €	375 325,38 €	218 930,66 €	131 339,64 €	- 2 838,62 €	- €	- €	142 098,07 €	92 253,77 €	- 8 126,40 €	1 189,26 €	- 5 054,90 €	2 799,13 €
Cumulative NPV	- 640 000,00 €	- 457 960,17 €	23 865,95 €	749 063,25 €	1 299 180,61 €	1 674 505,99 €	1 893 436,65 €	2 024 776,29 €	2 021 937,67 €	2 021 937,67 €	2 021 937,67 €	2 164 035,73 €	2 256 289,51 €	2 248 163,11 €	2 249 352,37 €	2 244 297,47 €	2 247 096,60 €
NPV	2 247 096,60 €		NPV	2 247 096,60 €													
IRR	82 %																
Payback period	2																

Table 15 Financial Model without haulage level

FINANCIAL MODEL OP One																	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Jan - 2020	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
+Revenue	- €	534 345,80 €	957 215,05 €	1 202 934,45 €	1 062 158,71 €	854 913,40 €	606 399,91 €	399 366,05 €	41 316,59 €	- €	- €	711 095,82 €	543 580,75 €	- €	58 414,87 €	8 867,98 €	76 193,16 €
-Opex	- €	- 50 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 100 000,00 €	- 50 000,00 €	- 50 000,00 €	- €	- €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €	- 50 000,00 €
Gross income	- €	484 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
Depreciation (lin.)	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Net income before tax	- €	484 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
-Tax (0%)	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Profit after tax	- €	484 345,80 €	857 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
-Capex	- 2 050 000,00 €	- 200 000,00 €	- 220 000,00 €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Cash flow	- 2 050 000,00 €	284 345,80 €	637 215,05 €	1 102 934,45 €	962 158,71 €	754 913,40 €	506 399,91 €	349 366,05 €	- 8 683,41 €	- €	- €	661 095,82 €	493 580,75 €	- 50 000,00 €	8 414,87 €	- 41 132,02 €	26 193,16 €
Cumuative Cash Flow	- 2 050 000,00 €	- 1 765 654,20 €	- 1 128 439,15 €	- 25 504,71 €	936 654,00 €	1 691 567,40 €	2 197 967,32 €	2 547 333,36 €	2 538 649,96 €	2 538 649,96 €	2 538 649,96 €	3 199 745,78 €	3 693 326,53 €	3 643 326,53 €	3 651 741,40 €	3 610 609,38 €	3 636 802,55 €
Discount Factor	1,00	0,87	0,76	0,66	0,57	0,50	0,43	0,38	0,33	0,28	0,25	0,21	0,19	0,16	0,14	0,12	0,11
net present value	- 2 050 000,00 €	247 257,22 €	481 826,12 €	725 197,30 €	550 117,36 €	375 325,38 €	218 930,66 €	131 339,64 €	- 2 838,62 €	- €	- €	142 098,07 €	92 253,77 €	- 8 126,40 €	1 189,26 €	- 5 054,90 €	2 799,13 €
Cumulative NPV	- 2 050 000,00 €	- 1 802 742,78 €	- 1 320 916,66 €	- 595 719,36 €	- 45 601,99 €	329 723,38 €	548 654,04 €	679 993,68 €	677 155,06 €	677 155,06 €	677 155,06 €	819 253,13 €	911 506,90 €	903 380,50 €	904 569,76 €	899 514,86 €	902 313,99 €
NPV	902 313,99 €		NPV	902 313,99 €													
IRR	26 %																
Payback period	4																