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Evaluation of methods for stope design in mining and potential of improvement by pre-investigations

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Abstract

The importance of stope design for mine planning is considerable. Therefore, stope design and its challenges have been in the focus of research for the past 50 years. Empirical, numerical and analytical methods for stope design have been developed over the past decades in order to improve this process. This thesis is assessing which areas for improvement there still are and which problems are still only unsatisfactorily solved.

After establishing background knowledge about the importance of stope design for mine planning and evaluating the factors influencing stope design, the focus is laid on the development of stope design methods in the past, as well as current research related to the topic, to create a comprehensive overview of recent and future developments. This is done by means of a literature review and research analysis. On the other side, the mining industry´s needs and challenges related to stope design are assessed, by means of survey, mine visit and interview. The insights gained in both parts are compared and checked for potential harmonies and disharmonies. Finally, from those conclusions practical recommendations for the GAGS-project are extracted and consecutively presented.

In stope design research the focus and dominance of empirical methods has slowly shifted towards more research being conducted in the area of numerical and analytical methods. It can also be concluded that numerical methods and personal expertise are far more important for stope design within industry than commonly assumed. It was identified that in order to improve stope design, it is desired to increase the amount of geotechnical data acquired, the software improved, and stope design integrated within the general mine planning process. Additionally, interesting insights were gained by an in-depth analysis of survey responses, for example, the outstanding importance of the cut-off grade for stope design within gold mining operations.

In order to allow for an optimal acceptance of novel geotechnical methods for stope design, the acquired data should be implementable into stope design within three days, preferably be compatible or implemented within a software and allow for stope design to be integrated into general mine planning. To promote the benefits a comprehensive scientific case-study demonstrating the realized benefits should be performed.

Keywords Stope Design, Literature Review, Survey, Underground Mining

Foreword

Dear reader,

I would like to hereby appreciate your time and effort put into reading this thesis, as I have also taken the time to create it over the course of the past 6 months.

First, I would like to thank my parents for their continuous support, over the course of my life, and without whom I would not be able to stand, where I am standing now. The same goes for FEMP, having this unique EMC-program, which allowed me to have so many unique and international experiences over the past 2 years.

To talk about the thesis itself, I would like to think back to the day when I received an email, that was talking about the opportunity to become part of the GAGS-project research team. It sounded like a journey I would like to embark on. So, I took the chance and can now say that it was the right decision.

I would like to thank Professor Mikael Rinne for giving me the chance to take part in this research project and also for his and Mateusz Janiszewski´s continuous support and feedback while creating this thesis. It helped me learn even more about scientific writing and gain an in-depth understanding of stope design.

For the survey part, I would like to thank all the amazing respondents, who made it possible to conduct this survey. The dedication identified within the responses, motivated me even more and made me understand the importance and relevance related to the topic of stope design, and how much struggle there still is.

I would like to thank Markus especially, who has dedicated most time out of all respondents and helped me out the most to get a practical in-depth understanding of the stope design process, its challenges and relevance for underground mining.

Finally, I would like to thank the Finnish government and Finnish society for giving me an insight into what an equal and developed country really feels like. Same goes for all the amazing people I got to spend time and share experiences with, especially Piia.

Espoo, 29th September 2019

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List of Abbreviations

WP	**W**ork **P**ackage
GAGS	**G**eochemical **A**nd **G**eophysical Methods for **S**tope Design
FEMP	**F**ederation of **E**uropean **M**ineral **P**rograms
LIBS	**L**aser-**I**nduced **B**reakdown **S**pectroscopy

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1. Introduction

At the moment, underground mining operations are progressing into deeper and increasingly more complex deposits, associated with more challenging geological conditions, while the demand for minerals and metals keeps growing rapidly. Additionally, ore grades are decreasing, and thus, valuable metals will more likely occur as refractory or trace minerals in future mining operations.

Following the goal to transform the mining industry into a more sustainable one, the necessity to invent and implement new technologies and approaches to improve ore recovery and reduce ore dilution arises. Additionally, increasingly challenging geological conditions can potentially result in more hazardous working environments. To prevent this, adequate considerations in the mine planning and design are deemed necessary.

1.1. Surface vs. Underground Mining

Mining has long been separated in surface and underground mining. The rise in mining equipment scale along with the less restrictive regulations towards the implementation of new technologies in surface mines has led to a considerable divergence in the mining industry and mining science, between surface and underground mining (Nikbin, 2018). A very widespread form of surface mining is open-pit mining. The characteristics of open pit and underground mining operations can be seen in Table 1 below.

Underground mine planning and design optimization received little attention due to their complexity and variability of problems inherent in underground mining operations. Still, there is a lack of studies for optimization of ultimate stope boundaries. This should take into optimizing the layout, considering operational, technical, and physical constraints (Erdogan, 2017).

However, the dominance of surface mines in terms of mined material by mass and value over underground mines keeps on decreasing (Atlas Copco, 2014). With depleting deposits and as former open pits are being transformed into underground mines when they reach depths where mining from the surface is no longer feasible, research for underground mines has picked up pace in order to keep up with the challenges associated with the ever-increasing demand for mineral resources, while resources decrease in grade and thus increases in mining efficiency become more and more essential (Nhleko 2018).

Table 1: Characteristics of Open-Pit vs Underground Mining (O´Sullivan & Newman 2015; Sotoudeh et. al 2017)

Attribute	Open Pit Mining	Underground Mining
Complexity	Less Complex	More Complex
Waste mining	High	Low
Stockpiling ore	Possible	Possible
Environmental Disruption	Large Footprint	Small Footprint
Safety	Relatively Safe	Relatively high Risk
Extraction Costs	Low	High
Reclamation Costs	High	Relatively Low
Investment Volume	Relatively low	Relatively high
Automation	Fully implemented	Depending on the Mining Method but less widespread
Associated Risks	Low	High

In general, it can be concluded that the implementation of new technology in underground mining is not keeping pace with surface-based mining (Bootsma, 2018).

Additionally, the public opposition to mining operations keeps on increasing globally. The general public prefers mining with a limited environmental impact (Moffat, 2014); thus, underground mining with its low degree of visible impact should be considered a possible beneficiary of this trend.

The relevance of stoping based mining methods for the future of the mining industry cannot be overestimated. As environmental concerns become more and more relevant and are turning into an essential aspect of obtaining and maintaining the social license to operate mining endeavors, the feasibility of utilizing open pit and caving underground methods, with their visible environmental impact will further decrease. (Zhang, 2015)

1.2. Developments in Underground Mining

In the versatile world of mining, underground stoping has proven itself efficient and reliable, allowing for high productivity, safety, and efficiency at comparably low production costs. Due to its benefits, it plays an important role in the mining industry nowadays, and its importance tends to increase in the near future (Villaescusa, 2014).

In the past, the design of underground stopes was mainly executed by individual approaches until the development of the so-called empirical methods, namely the Mathews stability graph method, and its numerous adaptations (Suorineni, 2012). Thus, this method has been subject to extensive research activity in order to achieve more adequate and reliable predictions for stope stability, allow for optimized stope design, and get rid of the flaws and problems inherent to this method (Villaescusa, 2014).

In respect to the aforementioned challenges, which the mining industry is facing today, the necessity arises to further advance in the process of designing and dimensioning stopes in varying geological conditions, in order to allow for more reliable stope design. This is to be executed by applying and implementing scientific advancements from other areas and research from mining-related areas in the stope design process. Additionally, this will allow for improved stability predictions, and decreased ore dilution and will thus allow exploiting given deposits with increased efficiency and recovery while lowering the production costs.

1.3. Theoretical Background

The thesis is part of the **G**eophysical **A**nd **G**eochemical Methods for **S**tope Design (**GAGS**) project. The project focuses on the improvement of mine planning by novel utilization of geophysical and geochemical methods to characterize rock properties for mine planning and geometallurgical assessment. The underlying question this research project is trying to answer is: How can the geophysical and geochemical methods be used best to improve mine design?

Thus, as part of the GAGS project, scientific tools for fast and reliable characterization of rock mass will be researched and developed to provide rock engineering properties for stope-scale mine planning.

The goal of GAGS is to increase the ore recovery and to minimize ore dilution with mine planning and stope design based on geophysical and geochemical methods. This main goal is reached through the specific objectives of three **W**ork **P**ackages (**WP**), each focused on one of three themes: spectral geometallurgic fingerprints (WP1), geophysical methods (WP2), and the integration of the methods for mine stope design (WP3).

As part of WP3 of the GAGS project, this thesis is aiming to identify the methods currently applied and research in stope design. Additionally, the needs of the industry related to it, and the most promising applications for the methods to be researched in the other work packages of the GAGS project, will be assessed.

1.3.1. Scope of Thesis:

The GAGS project is aiming to implement new geophysical and geochemical methods into the process of dimensioning and designing stopes. The inclusion of borehole-geophysics, laboratory geophysical measurements, and **L**aser-**I**nduced **B**reakdown **S**pectroscopy (**LIBS**) measurements to gather real-time in-situ data for the stope design process is relying on an in-depth understanding of the processes involved in the state-of-the-art stope design methods. The question of how these novel methods can be most adequately applied in this process also needs to be addressed to help guide the focus of the research activities within the GAGS project.

The mining industry is often affected by a considerable amount of disharmony or lag in relation to the research activity in the area. In order to minimize this disharmony, a mutual approach strategy should be considered desirable. This approach is based on the incorporation of the most recent inventions and advancements in research, as well as the research itself that needs to identify and adapt to the needs of and the state-of-the-art applied in the industry and identify what hinders the industry from implementing novel technology.

Therefore, while WP 1 and 2 follow the common research approach to deliver a solution to a known problem, this thesis as part of WP 3 aims to identify the recent research, how much of this research has reached the mining industry and assessing expert opinion on the biggest problems to be addressed in the area.

Research problem:

The currently and historically applied technologies and methods in the process of designing stopes are mainly based on empirical models. These models have been proven to be inadequate or unreliable, in relation to stope stability and ore dilution amongst others, in several cases (Suorineni, 2014). When stope design is addressed in current research, the focus lies on implementing numerical and heuristic models in the process of optimizing stope stability predictions, reducing ore dilution by optimizing stope design and finding more realistic models with the given data. While little changes and questions have been applied to the overall scheme of how the underlying data for the stope design process is acquired. This is where the GAGS project comes into play, by applying novel geophysical and geochemical methods into the process of acquiring geotechnical and geometallurgical in-situ data of the rock mass.

Proposed solution to the research problem:

In order to allow for substantial improvements in stope design, it is necessary to gather information about the exact procedures involved in the state-of-the-art methods applied in this process. The focus thereof should, therefore, be on methods applied by the mining industry and recent research related to underground stope design. This will help to understand how the industry has been dealing with the challenges associated with optimizing stope designs and where potential solutions can most likely be applied to improve the processes involved to design stopes.

Goal and Objectives of the Thesis:

The goal of this thesis is to create a general overview of the state-of-the-art of stope design methods applied in the mining industry, research activity in the area as well as the industry´s approach to the topic and to identify the potential for improvement. The findings from this are then to be utilized by creating a general guideline in the form of recommendations for the GAGS project.

1. The objective of this thesis is to describe the state-of-the-art of stope design methods in international underground hard rock (metal) mines.
2. The thesis aims to identify the needs and problems associated with the current stope design methods and how research has responded to these needs.
3. The thesis is to identify potential areas of implementation for new geophysical and geochemical methods and how these benefits could potentially be demonstrated to create a positive response to the industry.

Research Questions:

The following list gives an overview of the research questions associated with the objectives:

Identification of common practice in industry and desired areas of improvement:

1. What are the current methods for stope design used in mines?
2. How can the stope performance of new designing methods be measured, and improvements be demonstrated?
3. What are the needs of the industry concerning stope design?

Reviewing, summarizing and analyzing recent research in the area:

4. Which methods for stope design have been researched and what are their limitations?
5. What is the focus of recent research activity related to underground stoping?

6. How has the stope design research developed and changed focus with time?

Correlation between research and industry needs:

7. How can research meet the needs of the industry?
8. How can the results of the GAGS project be promoted towards implementation by the industry?
9. How can the benefits of the novel methods over currently applied stope design methods be measured and evaluated?

1.3.2. Research Methods

The research methods used in this thesis are: Literature Research, using industry contacts, using survey science by means of a questionnaire, mine visits and interviews with industry professionals, research evaluation and contextualization. This subchapter only displays a short summary of the research methods applied in the thesis; a more detailed description of the applied methods is given in the subsequent chapters.

Research method description:

- Literature Research:

Accessing and analyzing historic and current literature and research to gather knowledge about the state-of-the-art stope design process and the focus of recent research in the area. Therefore, research papers, publications, books, master and doctoral theses are reviewed.

- Industry contact:

This method is based on creating correspondence with mine sites to gather actual industry knowledge about their stope design processes and involved methods. Additionally, this serves to find responsible people on the mine site in order to get more relatable responses for the survey, these can then be used during the GAGS project in order to enter into project discussions with an elaborated level of background knowledge about the mine specific stope design procedures. Additionally, the mine sites should be considered for potential involvements in the process of implementing the novel stope design procedures, this is the process of finding a partner mine for GAGS.

- Survey:

The survey conduction relies on sending a questionnaire to numerous mining industry professionals preferably working in mine sites applying stoping methods in order to gather knowledge about the variety of applied methods and the potential dominance of certain ones, their needs and potentially promising areas for the GAGS-project research. The results are then to be analyzed and evaluated.

- Mine Visits and Interviews:

Mine visits serve to gather more in-depth on-site insights that cannot be covered by remote contact or the questionnaire and identify potential issues in need and prone to improvements. This allows for gathering knowledge about potentially critical details in relation to stope design, which could be overlooked by industry professionals. As part of this contact, an ever greater in-depth knowledge is to be achieved by means of interviews. Also, for finding a partner mine for the project these visits are to be considered crucially necessary.

- Research analysis (evaluation and contextualization):

The findings of the thesis need to be consecutively evaluated. This will allow to establish a correlation between the research and the identified industrial needs. Finally, this allows identifying potential harmonies and a profoundly appealing necessity for the GAGS project.

1.3.3. Thesis Structure

The thesis is structured in a way to allow for cohesive understanding. In the first chapter, the topic and the general outline of the thesis are presented. Then in the second chapter, the stoping based mining methods, and background information about underground stoping are presented. These include stope design and factors of influence, which are introduced and elaborated. Consecutively in the third chapter, the existing methods for stope design are reviewed and presented comprehensively, before the recent developments in the area are depicted, and finally evaluated. The fourth chapter is then focusing on the industry´s point of view, by presenting expert opinion in the form of the results of the questionnaire, the insights from the mine visit, and individual interviews, the results are then discussed and summarized. In the fifth chapter, the results from chapters three and four are brought into context and their correlation is discussed. This allows correlating the identified problems to the offered solutions. Before the value of the investigation is presented. Additionally, the value of the investigation is quantified.

The second last chapter represents a conclusion of the thesis and gives an idea of possible implications for the GAGS-project.

The last chapter of the thesis is concluding the thesis as a whole and presenting the results of the investigation in a compressed form. Therefore, the initially formulated research questions are answered again based on the results of the investigation.

2. Underground Stoping

As the name “**G**eophysical **A**nd **G**eochemical Methods for **S**tope Design” (**GAGS**) already states the focus of the research project lies in the implementation of geophysical and geochemical methods into the stope design process. Thus, the necessity arises to establish in-depth knowledge about the involved processes and discuss the limitations of stope design. This chapter delivers this background knowledge in a compacted form.

The basic definition of a stope describes it as an “underground excavation made by removing ore from surrounding rock” (Hamrin, 1982). There are however more elaborated definitions of stopes, which more adequately account for the inherent complexity of stoping and the related processes, e.g.: “A stope is a large, three-dimensional, mineable volume whose maximum size is correlated with the geotechnical properties of the host rock and is the basic unit for stoping methods. The void left by an extracted stope is sometimes filled with an aggregate to provide structural stability, a process referred to as backfilling. Most underground stoping mines are separated into vertically spaced levels based on the maximum stope height, creating a near-regular grid of possible stope positions” (King, 2017).

2.1. Stoping-based Mining Methods

The necessity to utilize mining methods with limited impact on the surface is becoming ever more urgent. To satisfy this necessity the application of non-caving underground mining methods demonstrates a convenient solution and thus gives a promising outlook towards increasing importance of these mining methods for the mining industry as a whole. Thus, the pillar and artificially supported, so-called stoping-based, mining methods, with no or very limited subsidence are the solutions of choice for the future challenges of the mining industry (Villaescusa, 2014). The lack of visible environmental damage from these mines will possibly also allow for a more positive public perception of the mining industry.

These stoping based mining methods rely on stopes within an orebody for ore production and have already become amongst the most common methods in modern underground mining. This is due to their inherent operational safety, reliable design and relative cost efficiency (Dzimunya et al., 2018). The reliable usage of large-scale blasting turns the most stoping methods to one of the lowest-cost underground mining methods (Hartman, 1992).

There are several general issues with the division of mining methods in categories. Initially, there are several different parameters commonly applied to separate the mining methods in different categories. This results in fundamentally differing mining method categories.

The division chosen in this thesis is illustrated in Figure 1. Additionally, mining methods commonly have different names due to their seemingly limitless minor adaptations. Sometimes these names lack scientific definition and are used interchangeably which results in a considerable amount of confusion.

Figure 1 limits itself on naming the main underground mining methods and dividing them into three categories: Pillar supported, artificially supported, and unsupported mining methods. Following this definition, the main interest for geotechnical assessment of the rock mass is limited to the pillar and artificially supported mining methods.

The mining methods in Figure 2 illustrate the operations involved in and the general layout of four stoping-based mining methods, namely Sublevel Open Stoping, Cut & Fill, Vertical Crater Retreat and Room & Pillar. This is a small but adequate selection of the main stoping methods, that require in-depth geotechnical knowledge about the deposit, in order to allow for their application. To apply stoping-based mining methods the stability of the rock mass has to be accurately estimated in order to allow for stope and mine stability, safe and economic operations, conditions that are essential to mining nowadays. These mining methods are thus prone to the potential utilization of novel geophysical and geochemical methods for their stope and mine design.

Stoping-based mining methods are prone to dangers related to instability of the surrounding rock mass. This creates a considerable danger to both people and equipment (Vallejos et al., 2015). Thus, stoping-based mining methods are relying on adequate estimations of the stability of the rock mass in which they are applied, to allow their own application. This condition results in considerable efforts being put forward in order to allow for reliable estimations, predictions and dimensioning of the stopes to be mined.

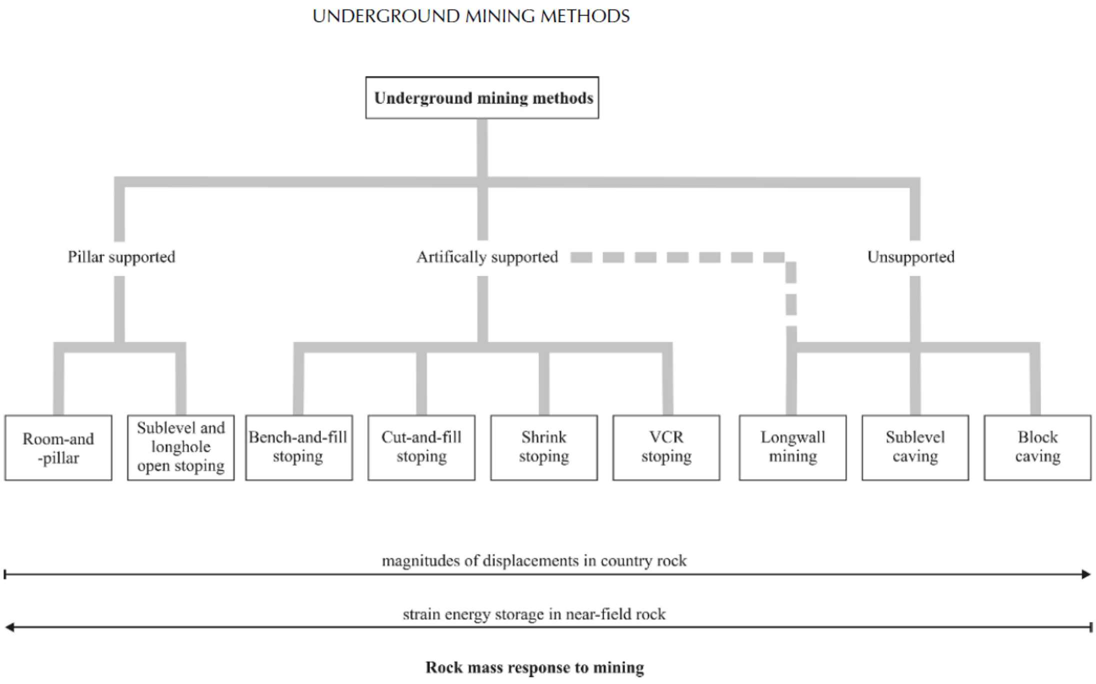


Figure 1: Hierarchy of Underground Mining Methods (Brady, 2013)

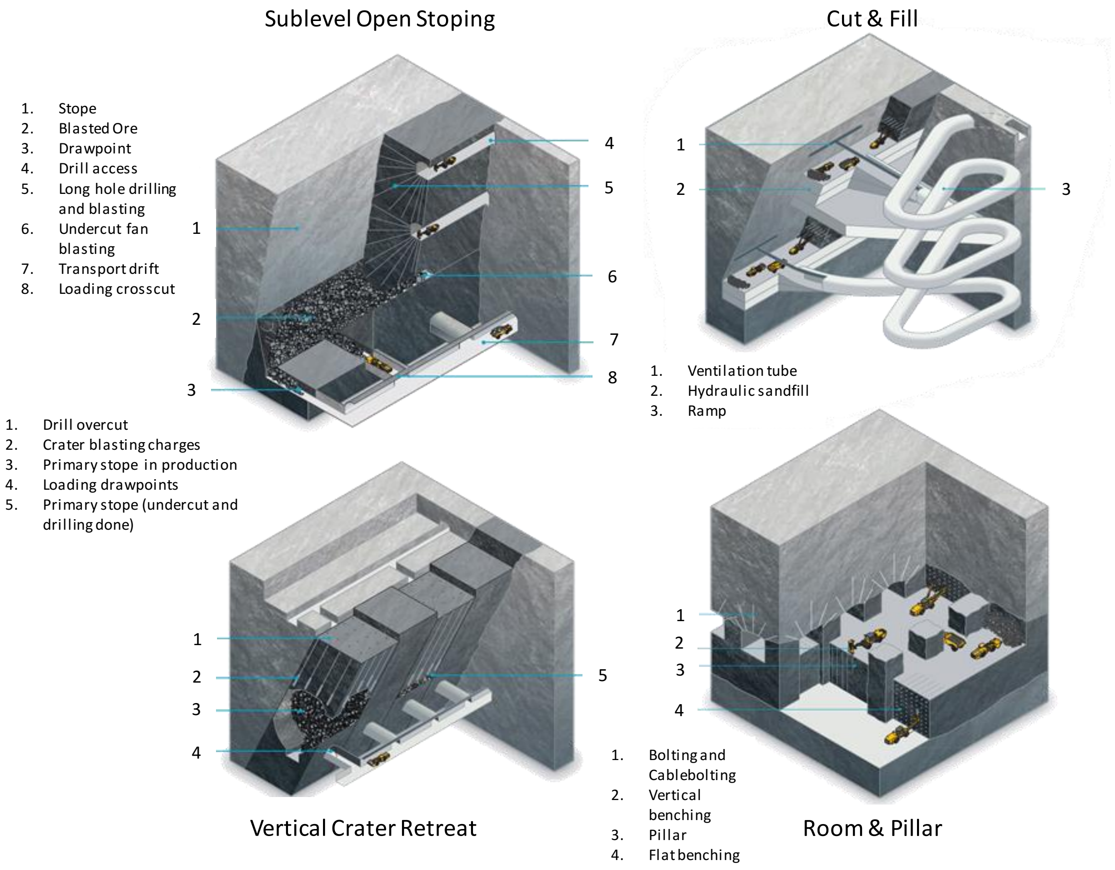


Figure 2: Overview of Mining Methods (Atlas Copco, 2014)

2.2. Mine Design vs. Stope Design

Underground mine planning can be divided into three phases: the development of layouts and stope envelopes, production scheduling, and the selection of equipment and utilization (Musingwini, 2016). Stope Design represents only a small part of the overall process of mine planning but is impacted and impacting all phases on different levels of intensity. Figure 3 illustrates the complexity of the stope design process. There are several interdependencies and loops within this process, meaning that there are several factors influencing other factors and eventually themselves. This looping dynamic results in an increased complexity and limits the achievability of truly optimal solutions, since additional information about the deposit naturally becomes available during the progression of a mining operation but is not available initially. This problem is to be considered a limited data problem which is to be most adequately solved by utilizing an iterative solution approach. However certain decisions need to be taken initially in order to start the mining operation (Nhleko, 2018).

Dividing this process into steps allows for the creation of rudimentary initial solutions. Initially, the orebody and its extent are estimated, then the rock mass characteristics are incorporated within this model before the global mine planning is performed based on this framework. Consecutively a more detailed design is established, which takes into account additional factors. Usually, the results are grouped and performed based on different scenarios, which are then evaluated based on different parameters, the most common one being the NPV estimation.

Stope Design is only a small but essential part of mine design. The overall layout of the mine and its overall feasibility strongly depend on the stope size, location, orientation, and extraction sequencing. In order to allow for the creation of a near-optimal stope design, it is necessary to gather a maximum of geotechnical information. In general stope, design optimization improves the economic potential of any underground mining operation and maximizes overall mine profitability (Sotoudeh, 2017).

To perform a stope design usually, the general rock mechanical conditions are evaluated, considering these conditions the access infrastructure is planned, then the stope and pillar sizes and locations are defined preliminarily before the resulting influence on the rock mass is simulated and checked for adequacy. If the design is applicable the layout is used for scenario analysis. In order to allow for a better understanding of the difficulties resulting from the interdependencies, a possible loop, similar to the mine design loop (Villaescusa, 2008) is explained in detail here:

The most efficient infrastructure and stope layouts depend on the production sequencing, as the rock mass response affects ease of production and use of rock support, additionally the time value of money impacts earnings and expenditures. By gathering additional geotechnical information fundamental changes to stope and mine design can become necessary. To adequately address this complexity and uncertainty in planning it needs to be adequately evaluated and integrated within the planning process.

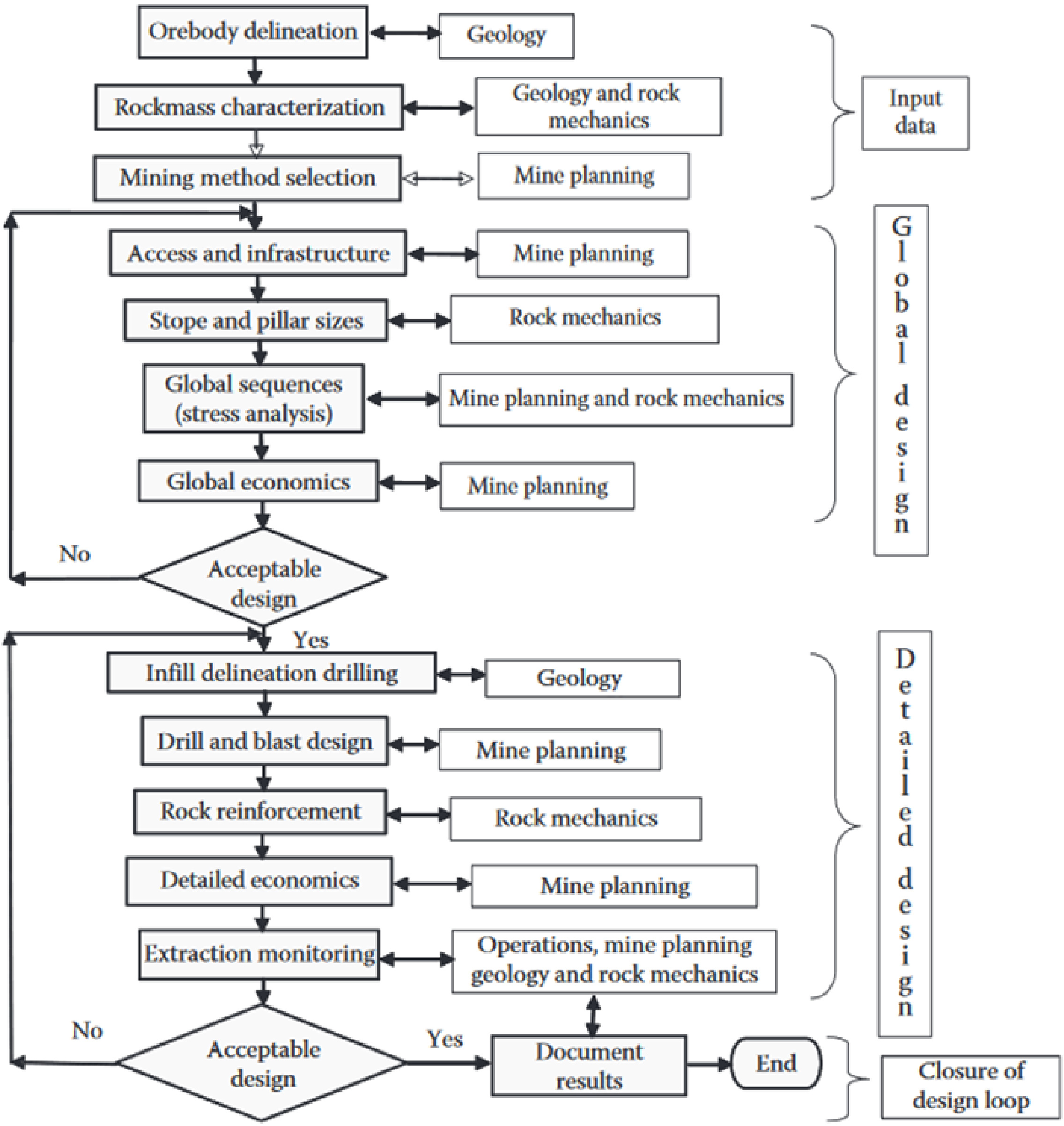


Figure 3: Flowchart: Stope Design Process (Villaescusa, 2014)

2.3. Stope Design Stages

The stope design process is commonly divided into several separate stages depending on the advance of the mining project as a whole and the level of detail used for the stope design.

The main stages for stope design according to the state of the mining operation are commonly: geotechnical evaluation, economic estimation, sequencing, exact production planning, blast pattern design. These stages are fundamentally different in their purpose, level of detail and reliability of estimation (Erdogan, 2017).

Typically, a detailed modeling of the stopes straight from the initial planning of a mining operation is neither possible nor beneficial, since it bears the potential to generate misleading interpretations. Thus, the incorporation of uncertainty into the planning process is a considerable improvement (Grieco, 2009).

In the early days of a mining operation, (e.g. the feasibility-study-stage) the geological and geomechanical data, as well as their reliability and level of certainty, is very limited, despite these unfavorable conditions, initial decisions about the mining method to be chosen need to be established early on already. When the decision to mine or not is taken and a mining method is chosen, thus certain mining-related parameters need to be assumed. These parameters include but are not limited to for example production rate, stope size, equipment dimensions, mining cost, dilution, recovery.

An approach for a comprehensive division of the stope design process into stages is illustrated in Figure 4. Within this approach, the process is divided into three fundamental parts, namely: basic input parameters, design stage, and reconciliation. The basic input parameters herein consist of the orebody delineation, rock mass characterization, and mining method selection. This is followed by the design stage, where the general mine design and detailed stope design is created. Finally, in the reconciliation phase, the stope is monitored, and a back-analysis is performed. The data from this process is then used to refine the stope designs, by utilizing more detailed input information.

In order to establish estimations as reliable as possible, it is important to adequately assess the influence of the rock quality, though the availability of detailed data commonly prohibits the use of numerical modeling here. Commonly, rough estimates based on empirical methods serve this purpose. When more geotechnical data becomes available during the progression of the mining operation a higher accuracy and detail stope design process is typically executed.

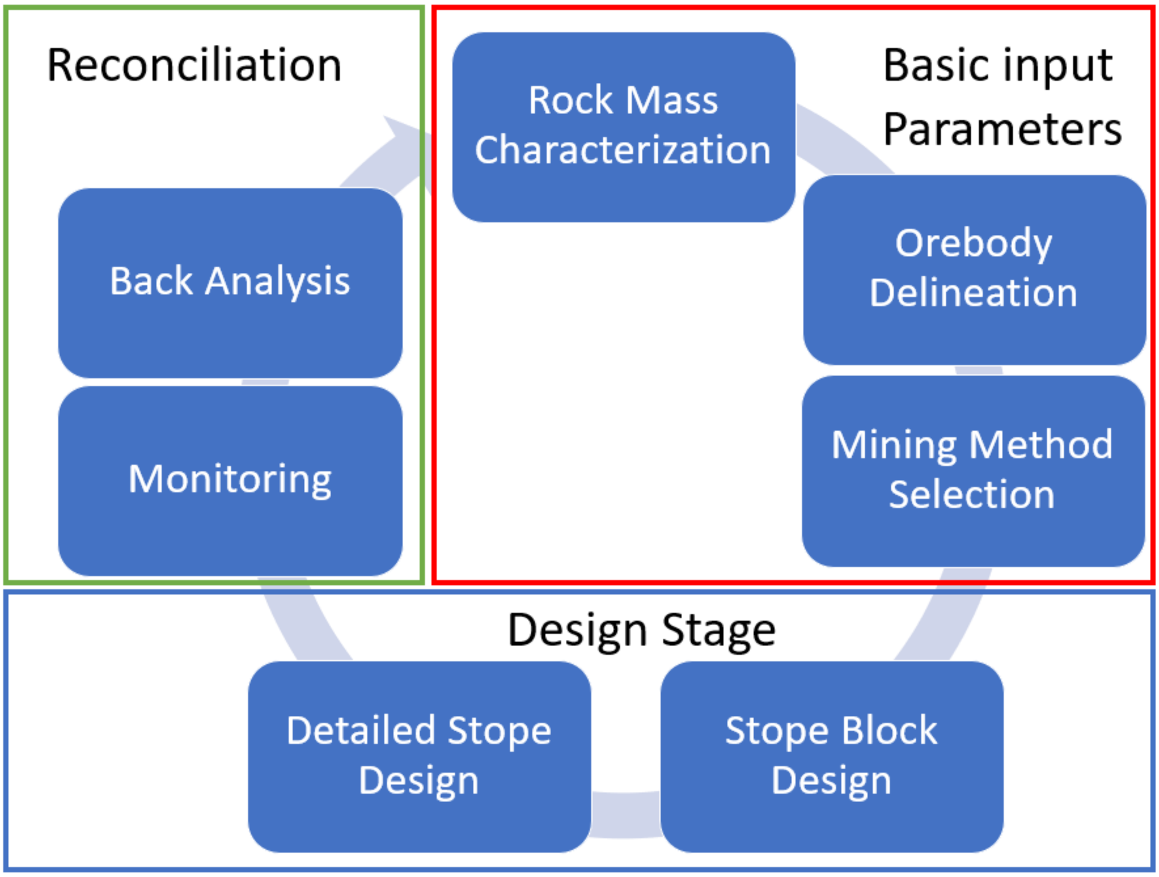


Figure 4: The Stope Design Loop (Based on Villaescusa, 2014)

2.4. Stope Design Factors

After the fundamentals of stope design have been discussed, the next logical step is to review the factors influencing stope design itself. As a result of the variety of influencing factors the discipline of stope design is considerably complex and has been in the focus of research for a considerable time.

Since stope design is mainly executed based on economical as well as safety evaluations, as mentioned previously, it is commonly based on stability and dilution, two factors that are strongly correlated for stope design (Feng, 2017). Several of the factors influencing stope stability and dilution can be seen in Figure 5. The diversity of parameters influencing only two stope design factors gives an impression of the inherent complexity of creating an adequate stope design.

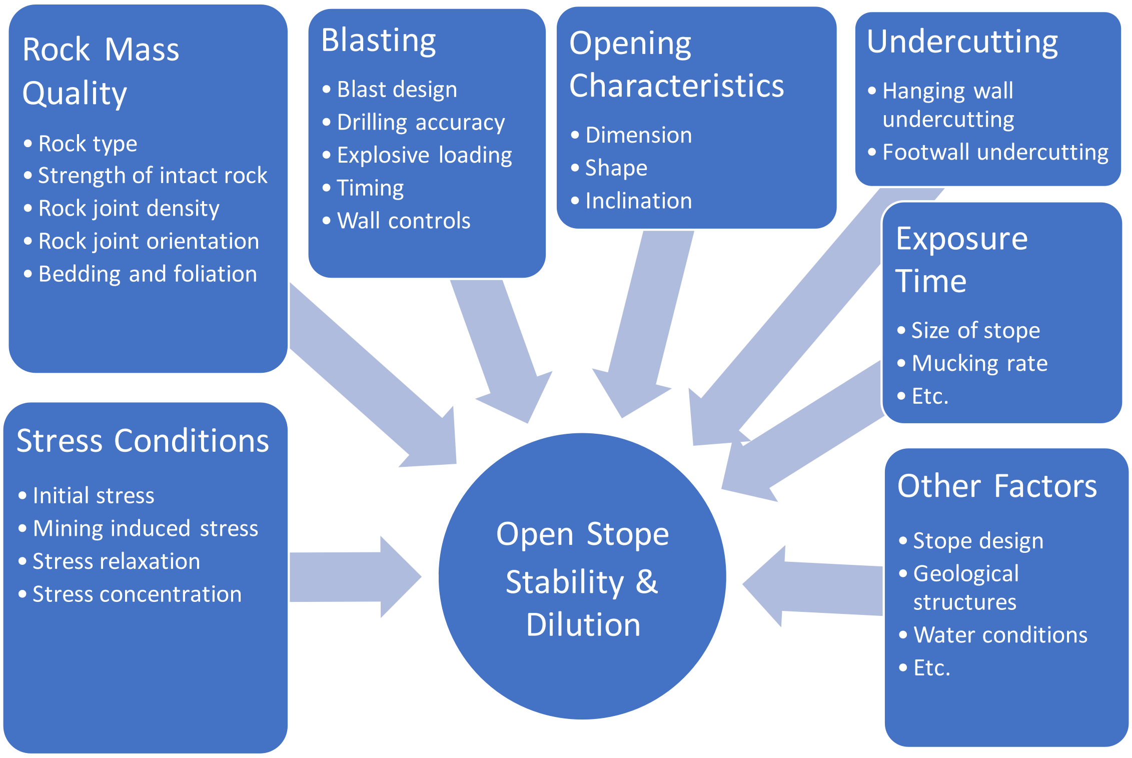


Figure 5: Process and Factors for Stope Design (Modified after Wang, 2004)

One of the difficulties of stope design lies within adequately evaluating the importance of the different factors influencing stope design. Additionally, it must be assessed how the various information that is collected in mining operations can be used most efficiently. The information commonly collected includes but is not limited to grades, extracted tonnages, fragmentation, lithology, geotechnical information, overbreak progression and seismicity. The collected information is commonly used for preliminary as well as back-analysis of stope designs (Vallejos, 2015).

It should always be kept in mind that all stope design factors are potentially bearing contradicting influences on stope designs. Thus, only by considering all different factors with a specific factor valueation can an adequate stope design be achieved.

2.4.1. Ore Grade

The ore grade is to be considered the fundamental moving factor determining stope design. As mining is mainly seeking to maximize profit, optimally only ore and no waste rock is to be mined, even though this is hardly ever possible. Typically, a fixed or variable cut-off grade is determined for a mining operation, this is then used in combination with the economic block model in order to identify the most promising stope locations (Will, 2018). Typically, the stope design resulting from this approach follows the orebody delineation.

The issue with the ore grade and cut-off grade is that they are based on variable factors themselves. The value of the mined ore is varying according to the mining cost, processing cost, and recovery and commodity prices amongst other factors. Bigger stopes usually have a lower specific mining cost which then again results in a lower cut-off grade, thus a certain degree of qualified guessing and assuming values based on experience and benchmarking is common practice to avoid this potentially unsolvable task (King, 2018).

2.4.2. Stability

Stability should be considered a factor of crucial importance for stope design. It impacts not only the feasibility and work-safety of a mining operation but also allows for the general realization of the project. As previously illustrated in Figure 5 several factors influence the stability of a stope and thus its design.

The influencing factors include, but are not limited to:

- Stope geometry and dimension
- Rock mass strength
- Geological structures
- Induced stress
- Rock support
- Blast damage
- Mine drift layout
- Exposure time

In order to adequately utilize the stoping based mining methods, it is necessary to estimate the stability of the rock mass. This is in order to minimize dilution, enhance recovery and facilitate production while minimizing the necessity for artificial support, with which stability is strongly correlated (Wang, 2004).

Stope dimensions, geometry, exposure time, rock mass and geological structures should be considered the factors primarily impacting stope stability. Smaller stope dimensions, an adequate geometry, low exposure time, and avoiding unfavorable geological structures have thus a positive effect on stope stability, without being strongly correlated with scaling costs. Whereas increasing the amount of rock support is strongly associated with scaling costs. In general stope stability is a factor that is prone to economic equilibration. Within the boundaries which allow for an adequate level of operational safety, the stability can be varied and optimized for maximzing economic profit (Papaionou, 2016).

For example, stope stability influences overbreak, thus selecting the right stope dimension can be considered a trade-off between tolerable overbreak and cost of mining more stable smaller stopes (Amedjoe, 2015).

2.4.3. Dilution / Recovery

Dilution and recovery are interdependent factors influencing stope design. As mentioned previously dilution and recovery are strongly correlated to stope stability. A lower degree of stope stability will consequently result in increasing dilution but also allow for higher recovery. The dilution and recovery can be used as an indicator for the quality of the stope design and applied mining practice, where a good stope design minimizes dilution and maximizes recovery (Clark, 1998).

Among the numerous ways to define and calculate dilution the most comprehensive definition is that dilution is the contamination of ore by waste material as part of the mining process (Wright, 1983).

Due to its inherent importance for mining operations dilution itself is a considerably well-researched topic and has been extensively defined. The different kinds of mine dilution are illustrated in Figure 6. Dilution is commonly divided into external and internal, additionally, ore loss as the opposite of dilution is commonly included in the definition of dilution. The different types of dilution can be planned, unplanned or geological. Planned dilution is commonly related to the form of mineralization zones or the applied mining method. Unplanned dilution, however, is related to stope stability or the lack of it, contamination and the applied mining methods. Dilution originating from geological conditions usually results from insufficient exploration and thus inadequate orebody delineation.

In order to allow for a better understanding of the different types of dilution, they are visualized in Figure 7. It shows the geological extent of the orebody, the limitation due to the necessary mining extraction and the extent of the actual mining extraction. This allows to understand the difference between planned and unplanned dilution in relation to the orebody. Commonly the term overbreak is used synonymously to unplanned wall dilution, while underbreak is to be considered equal to ore-loss.

An issue related to the process of quantifying the amount of dilution lies within the various slightly different definitions of the term. This is where the **E**quivalent **L**inear **O**verbreak **S**lough (**ELOS**) provides a convenient solution as an indirect measure for dilution, that is clearly defined. The benefit in its application is that it comes along with a unique and exact scientific definition, allowing for comparability (Suorineni, 2016).

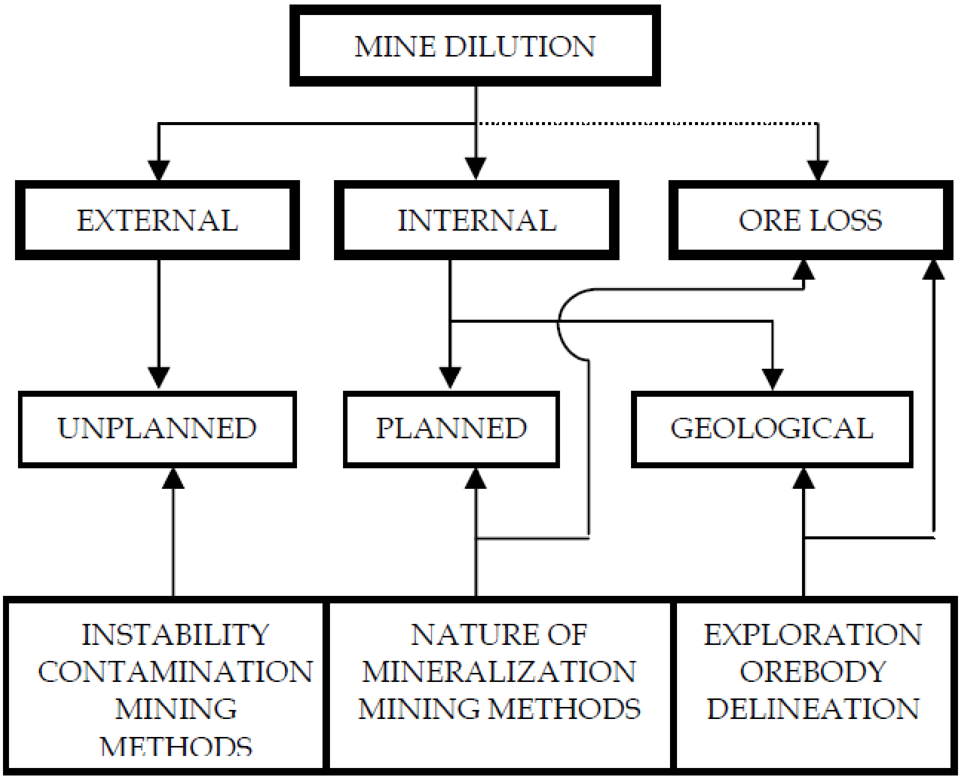


Figure 6 Classification of Dilution (Villaescusa, 1998)

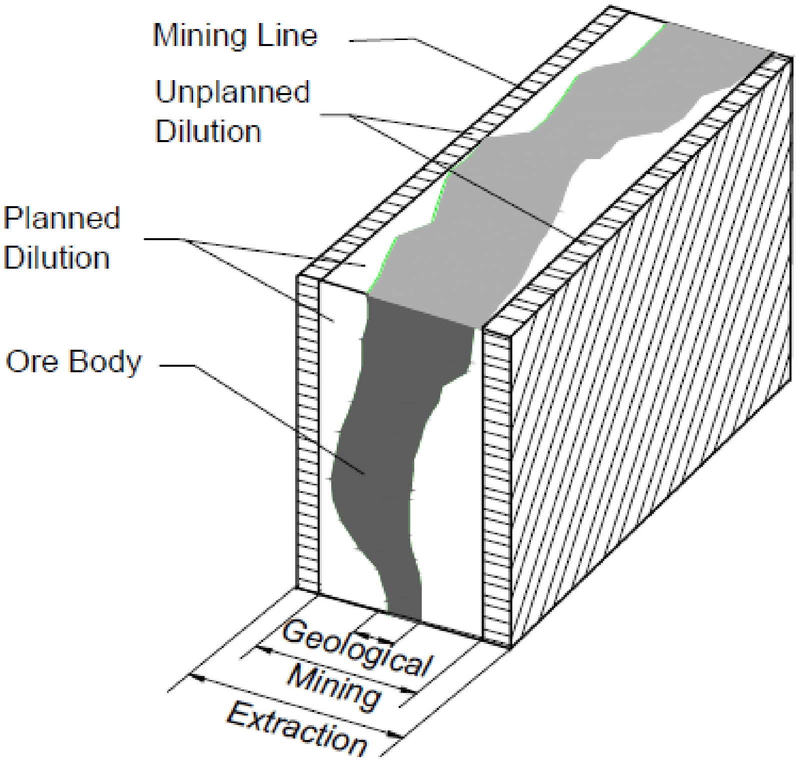


Figure 7: Dilution in Mining (Wang, 2004)

Considering the aspect of scale, it is common knowledge that smaller size machines for ore mucking in stopes with wall failure obtain better ore recovery and smaller dilution than bigger unmanned machines, due to lack of possibility to visually differentiate between ore and waste (Milne, 1998). This relation can be extended to most aspects of stope design, where an increase in stope size will most likely results in an increase in dilution but eventually allow for better recovery, due to economy of scale and thus lower specific mining costs.

2.4.4. Sequencing / Development Cost

An important aspect that needs to be considered while designing stopes for stoping based mining methods, is the development cost of stope infrastructure in relation to the sequencing of the stope extraction, even though it is only partly related to the stope design itself (Bouzeran, 2019).

The impact of sequencing on the stope design reaches up to the general mine design. The influence stretches from the time value of money related to the development cost up to the impact on rock stress levels, which can limit the dimensions of stopes to be mined in the future. Stress concentration in pillars due to unsatisfyingly performed sequencing can result in rock bursts, pillar failures, and stope collapses (Machuca, 2015).

The economic impact of sequencing on the development cost is mainly due to the impact of stope extraction sequencing on the point in time when specific access infrastructure development has to be performed, by taking into account the time value of money. Since, the stress distribution resulting from stopes mined previously, significantly impacts the stress environment. Thus, it should be considered beneficial to postpone the development of the stoping infrastructure and thus the spending of money as long as possible while it is most beneficial to generate revenues as fast as possible. The negative impact of specific stoping sequences on the rock stress, for example, and the resulting additional spending on rock support and decrease stope stability need to be taken into account, however. In order to allow for adequate stope design the financial expenditures for creating the access infrastructure to a stope need to be taken into account when calculating the stope specific cut-off grade (Villaescusa, 2014).

2.4.5. Equipment Size

A factor that is impacting stope design but might seem of minor importance and is thus commonly overlooked, is the equipment size of mining equipment available in a mine. Since the majority of the mining equipment to be utilized in a mine is usually determined during the planning, stage prior to the start of a mining operation and the transport of new mining equipment to an underground mine is associated with extensive difficulties the equipment should be considered a rather constant than flexible limitation.

Small mining equipment will allow for more selective mining operations in drilling and mucking but will limit stope size and increase the mining cost by unit. The impact of the equipment size is hard to measure, but this factor should not be neglected in planning and designing stages (Amedjoe, 2015).

2.4.6. Back-Analysis

Back-analysis is not a stope design factor that is preliminarily available for creating stope design. However, it delivers the possibility to initiate a reconciliation process as part of the stope design loop. Due to the limited-data problem inherent to the creation of stope designs, initially a suboptimal stope design is to be assumed and thus the reliability of initial stope designs should be considered as quite low, an issue that can be addressed by performing a back-analysis. This serves in order to check the initially implemented stope designs for adequacy and allows us to refine and adapt future stope designs (Qi, 2018).

2.5. Challenges of Stope Design

This subchapter delivers a more elaborate insight into the difficulties and challenges of stope design. The reason why stope design and finding optimal solutions for it is such a challenging discipline lies mainly in the various interdependencies that need to be addressed simultaneously as well as the limited data available for it.

Assuming that the optimization of stope design can be achieved by economically optimizing stopes and thus mines, even a truly optimal solution is hard to find considering the uncertainty associated with the ore grade estimation, the highly volatile commodity prices, unexpected dilution or ore loss. Additionally, the mining sequence can and will influence the rock mechanical conditions of stopes to be mined in its proximity, which will impact stope sequencing. Additionally, faults and fractures within the rock mass will only be discovered with the continuation of the mining operation (Dowd, 2016).

The rock stress which is increasing with the mine depth results in a highly complex and individual task to solve for individual mining levels. The economic pressure along with the time value of money along with the limited data problem results in the necessity to limit the planning to a certain extent. The development, backfill and artificial support cost need to be considered as variables, depending on the specific conditions. Thus, only if all these factors are considered a truly optimal solution can be considered achievable. But even if achieved can only be adequate for a certain point in time, resulting from the relation of the cut-off grade to commodity price (Dimitrakopoulos, 2018).

Considering these limitations finding at least a near-optimal solution seems to be achievable only with a fully integrated iterative approach that is producing a solution that is constantly optimized (Wagner, 2019). This addresses the issue of the ever-changing parameters and the delay in gathering information, even though it is still constrained by limited information and additional risk factors that cannot be addressed here within detail.

3. Review of Stope Design Methods

Now that the relevance of stoping methods and its fundamental principles have been discussed in detail, it is reasonable to establish detailed knowledge about the available methods to design stopes. With time, several methods for stope design have been developed, based on considerably different methodologies and technology available for this purpose. To create a better understanding of the terminology and assess the current state of stope design research and foresee possible future developments, old methods, as well as current advances in research, are reviewed in this chapter. Due to the complex nature of stope design, which has been explained previously, and due to the focus of the research project on geotechnical methods for stope design this chapter will mainly focus on this discipline of stope design for reviewing the different stope design methods, rather than a more inclusive approach incorporating economic aspects as well. While analyzing the advancements of research economical aspects are however considered a key part of stope design again, as this approach is now a consensus within the academic world.

3.1. Literature Review

The basis for this chapter is a literature review, in order to facilitate this, relevant literature must be found, identified and evaluated. To allow for this it is of essential importance to implement scientific methods during the search process. This process is also protocolled in a detailed way to allow for a better understanding of the applied methods.

3.1.1. Methodology

The methodology applied for the search process to identify the relevant literature and research is described in this subchapter. In order to find the different methods and research related to this topic, various sources have been systematically searched for related papers. Once the primary papers were identified the research activity of the mentioned authors has been checked for papers related to the subject.

After defining the scope and focus of this thesis, the search process was initiated with a simple keyword-based search. This search was initially conducted primarily on the Scopus-database.

The search terms applied to the Scopus-database were:

Stope Design (755 hits), Stope Design Optimization (119), Stope Stability (696), Stope Mining (2187), Stope Optimization (236)

Based on these same keywords other databases were searched as well, as not all literature can be found by searching a single database. The other databases that were searched are:

- Scopus (www.scopus.com), First accessed on: 18th of March 2019
- ResearchGate (www.researchgate.net), First accessed on: 19th of March 2019
- AaltoFinna (aalto.finna.fi), First accessed on: 19th of March 2019)
- University Library RWTH Aachen University (www.ub.rwth-aachen.de), First accessed on: 21st of March 2019
- TU Delft Library (www.tudelft.nl/en/library), First accessed on: 29th of March 2019
- Google Scholar (scholar.google.com), First accessed on: 1st of April 2019
- Australian Centre for Geomechanics Online Repository (papers.acg.uwa.edu.au), First accessed on: 8th of May 2019
- Onepetro (www.onepetro.org), First accessed on: 16th of May 2019

The scientific literature found by this search was reviewed for relevance and relevant authors and related articles were identified. Due to being enrolled at three universities the access from Aachen University, Aalto University and TU Delft were utilized to access relevant literature.

3.1.2. Results

The research resulted in the identification of diverse literature related to the topic. The types of identified literature are books, conference papers, journal papers, scientific articles, doctoral dissertations as well as bachelor´s and master´s theses. Overall, more than 149 documents by more than 200 authors were gathered and reviewed. These documents are focused on stope design and the research related to the topic. For the literature related to stope design research, a focus was put on the incorporation of a high degree of actuality. This was done in order to adequately address the recent increase in research activity within the area as well as to gather the most recent developments of research within this area.

3.2. Stope Design Methods

Geomechanical and rock engineering design methods, which are the basis for stope design, can generally be grouped in two distinct groups, the empirical and the numerical approach.

Both sides represent quite fundamentally different schools of thought, namely the “empiricists” and the “mechanicists”.

The empiricist approach is based on the belief that the assumption that the behavior of the rock mass can be adequately described based on empirical evaluation of behavior observed in other rock mass (Suorineni, 2014) They argue that assumptions established for numerical approaches are too idealistic and/or simple and thus not capable to adequately capture and simulate the real behavior of the rock mass.

The opponents of the empirical approach typically argue that this approach never adequately represents the physical processes of a problem and thus never allows to adequately understand these problems. A fundamental belief of “empiricists” it that the complexity of the rock mass and its interaction with its inherent structures are accounted for within the empirical methods. This supposedly holds true to an extent that adequately compensates for our lack of understanding as well as uncertainties. This is based on the assumption that most rock mechanics problems fall in the data limited region (Starfield & Cundall, 1988). A third group promotes the benefits of applying both methods together whenever possible, in order to utilize benefits and compensate for potential disadvantages of either method (Suorineni, 2014). Unfortunately, both methods are rarely used in a combined manner, which can be considered a result of the fundamental division between “empiricists” and “mechanicists”, which rather resembles religious beliefs than scientific opinions. This blocks scientific discussions and reasonable discussion about the topic and results in choices of the applied system being made based on ideology rather than pragmatism (Suorineni, 2014).

This separation within the rock mechanics community is commonly related to the field of rock mechanics research being dominated by quite a few people, with considerably strong opinions, due to the complex nature associated to the topic which limits the possibility to check the correctness of certain statements and calculations specifically (Personal opinion based on discussions with industry and research experts)

The inherent fundamental separation between these two schools of thought also directly impacts the available methods for stope design. The basic methods that are commonly used for stope design can also be divided into empirical and numerical methods, however, an additional method that is rather an analytical approach is also commonly used and will be discussed in detail here. These methods exist in a broad variety of sophistications and are commonly used in combination with one another, as should be expected due to the previously mentioned complexity inherent to this topic. Due to this complexity it is to question why it is still common practice in industry to manually design stope boundaries, despite developed software is available and has proven benefits over manual methods (Erdogan, 2017).

Still, nowadays typically stopes are designed using empirical methods (Mark, 2016).

3.2.1. Empirical Methods for Stope Design

Empirical methods are commonly used in geomechanics since their development in the 1970s. Their principle assumes that these methods allow for quantified judgment based on experience. This is commonly supported by the argument that these methods would often prove to be closer to the observed behavior than the assumedly more adequate predictions from theoretical analysis. Usually, empirical methods based on real data should be considered a baseline to which the theoretical predictions can be measured and judged (Suorineni, 2014). An overview of the most common empirical methods within geomechanics (Suorineni, 2014) can be found here:

- Rock Mass Rating (RMR) system (Bieniawski, 1973)
- Mining Rock Mass Rating (MRMR) system (Laubscher, 1990)
- Laubscher block caving rules (Laubscher, 1994)
- Tunneling Quality Index (TQI), more commonly: Q-system (Barton, Lien and Lunde, 1974)
- Hard rock pillar design chart (Lunder and Pakalnis, 1997)
- Geological strength index (GSI) (Hoek, 1994)

For stope design these empirical methods can be grouped within 3 different design methods commonly used in the mining industry (Milne, 2012):

- Stability graph method and its derivatives (Mathews et al, 1981 and adaptations)
- Hoek and Brown failure criterion (Hoek and Brown, 1980; Hoek and Marinos, 2007)
- Span Design Graph (Lang, 1994; Wang et al., 2002)

These three methods will be discussed in detail with the most detail being put into the most relevant one, the stability graph method.

Stability graph method (Mathews et al, 1981 and adaptations):

The most commonly known empirical method for stope design is the stability graph method. Since the development of the “Mathew´s stability graph”-method (Mathews et al., 1981) based on empirical estimation, its principle has been applied and modified several times.

The stability graph is based on the principle of plotting two factors against each other. For the original stability graph, these were, namely, the shape factor S and the stability number (N). The underlying principle is illustrated in Figure 8.

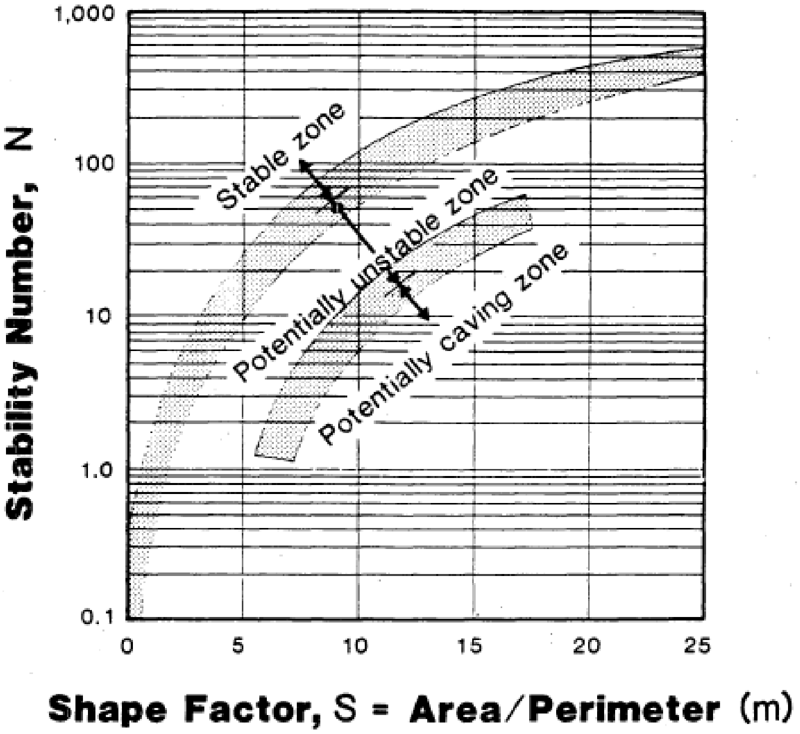


Figure 8: Mathews Relationship of Hydraulic Radius to Stability (Potvin, 1988)

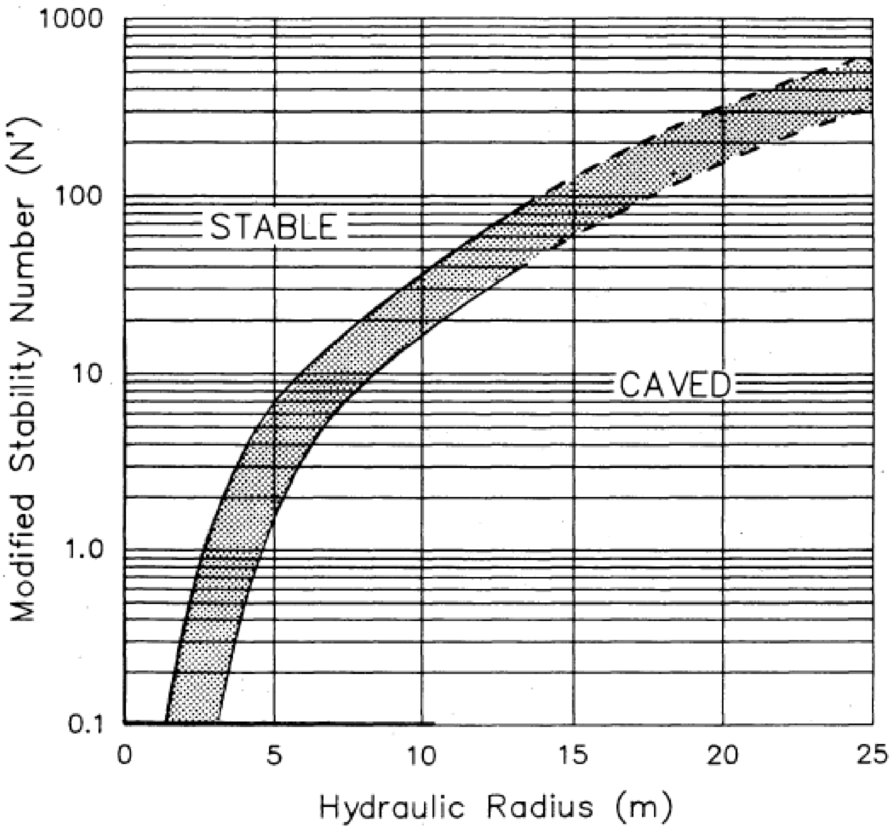


Figure 9: The Modified Stability Graph (Potvin, 1988)

The still commonly used modified stability graph is based on plotting two slightly adapted factors against each other the hydraulic radius and the modified stability number (N´).

The following equation describes the modified stability number, while the modified stability graph is illustrated in Figure 9:

$$N' = Q' \times A \times B \times C$$

Where:

Q´ = Modified TQI value (SRF set to 1)

A = Stress Reduction Factor

B = Joint Orientation Factor

C = Gravity Adjustment Factor

The Hoek and Brown failure criterion (Hoek and Brown, 1980; Hoek et al., 2002):

As common for empirical methods also this method was prone to some fundamental modifications since it was first published. This in-detail description will focus on the modification from 2002. The Hoek and Brown failure criterion is based on the stress-based m and s failure criteria. It can be used to perform an estimation where rock mass failure is most likely to occur, mainly for open stopes and drifts (Milne, 2012). The failure criterion mainly relies on 4 equations mainly:

Eq. 1: $\frac{m}{m_i} = e^{\frac{GSI-100}{28-14D}}$

Eq. 2: $s = e^{\frac{GSI-100}{9-3D}}$

Eq. 3: $0.5 + \frac{1}{6}\left(e^{\frac{GSI}{15}} - e^{\frac{20}{3}}\right)$

Eq. 4: $SF = \frac{\sigma'_3 + \left(m\sigma_{UCS}\sigma'_3 + s{\sigma'_C}^2\right)^a}{\sigma'_1}$

Where: m_i = constant based on lithology

m, s, and a= parameters within the failure criterion

D = blast damage variable

GSI = Geological Strength Index (Rock classification value)

SF = Safety factor

The span design graph (Lang, 1994; Wang et al., 2002):

This empirical design method relies on comparing rock mass data and geometry of stope designs to case histories. In this, the **RMR**$_{76}$ (**R**ock **M**ass **R**ating) system is used. It is plotting the RMR$_{76}$ classification against the desired span while taking into account rudimentarily the joint orientations and stress levels.

Limitations:

The argument that empirical methods are supposedly closer to the "truth" than other methods is relativized by the limitation of the databases for the creation of these methods, the necessity for a thorough understanding of the fundamental assumptions and also the limitations of these assumptions. Finally, the empirical methods should never be extrapolated outside of their database limitations. The empirical methods, however, offer considerably simple solutions to very complex problems and are thus commonly applied by individuals who did not obtain the necessary background knowledge and understanding necessary for guaranteeing an adequate utilization of these methods. Thus, the inherent risks and limitations of empirical methods are sometimes unmentionable and commonly ignored. The limitations and problems of empirical methods in rock mechanics and stope design are summarized in a more detailed manner (Suorineni, 2014).

3.2.2. Numerical Methods for Stope Design

Numerical modeling in geotechnics has become ever more important with the progression of time. This holds also true for modeling underground mines and designing underground stopes. Along with the advancements in computer science and information technology ever more powerful computing capacities have become available which allow for solving ever more complex scenarios. With the availability of increasing amounts of computing power, it became not only possible but also feasible to numerically model the behavior of rock mass for increasingly complex scenarios. The possibilities that came along with this development have been and are still extensively researched (Razavi et al, 2011; García Mendive, 2016, Heidarzadeh, 2018; Napa-Garcia et al, 2019).

Numerical modeling can be divided into two different methods for underground stope and mine design; continuous and discontinuous methods. These methods can be used in both 2D and 3D. These methods are implemented in commercial software as illustrated, consecutively.

Continuum-based:

1. Finite Element Method (FEM):
    a. Phases (Carvalho et al., 1991)

2. Boundary Element Method (BEM)
    a. Examine 2D (Curran & Corkum, 1994)
    b. FRACOD 2D (Shen et al., 2014)
    c. Map3D (Wiles, 1995)
    d. Examine 3D (Curran & Corkum, 1993)
    e. FRACOD 3D (Shen, 2018)
3. Finite Difference Methods:
    a. FLAC 2D (FLAC 2D)
    b. FLAC 3D (FLAC 3D)

In order to utilize continuum-based software, the geometry of the stopes, geomechanical properties of the rock mass and stress field have to be characterized and implemented into the code correctly. It is to be kept in mind that these modeling methods are not adequate for discontinuities and non-homogeneous nature of fractured rock masses, which is typically the case around stopes.

Thus, methods based on numerical discontinuities such as Discrete Element Methods, Discontinuity Displacement Analysis (DDA) and Distinct Element Method (DEM)) combined with Discrete Fracture Network (DFN) were developed (Jing and Stephenson, 2007) and used in different stope designs (Kleine et al, 1997; Elmo and Stead, 2010; Grenon et al., 2016).

Since these numerical methods for stope stability analysis are based on characteristic mechanical properties of rock mass, in order to utilize them adequately it is essential to first evaluate the deformability and strength properties of fractured rock masses, before stability analysis is conducted.

The potential benefits of numerical methods for stope design is the possibility of receiving numerical and quantifiable results, that can be incorporated and used within other software. Thus, this approach not only for modeling but also bears the potential for initiating an optimization process. The basis for this lies in defining the scope of the optimization and understanding and defining the importance of the parameters applied for stope and mine optimization, this is done by creating algorithms which are desired to adequately represent the present conditions.

A common criticism towards numerical models is that they can be influenced by means of calibration and through the utilization of “convenient” input parameters to give the desired answer for a specific case. Also due to the interactions of the rock mass with the progression of the mining operation, the numerical model has to be constantly adapted and checked in order to allow for a considerable degree of reliability (Suorineni, 2014).

3.2.3. Analytical Stope Design

Analytical stope design represents a third category of stope design methods. It assumes that rock mass is a continuous anisotropic medium. It is different from empirical and numerical methods in a way that it typically shows a strong correlation with both methods since the principle of analytical methods can reach from empirical to analytical methods. In essence analytical methods are however based on stability analysis (Grenon and Hadjigeorgiou, 2003) and an attempt to identify correlations between strength and deformability of jointed block masses by analyzing the properties of intact specimens (Amedie and Savage, 1993; Nasseri et al., 2003). Currently, exclusively analytical methods for stope design are developed, aiming for minimizing financial and mineral resource wasting (Nikbin et al., 2019)

Another method that is commonly considered an analytical method is the back-analysis method for stope design. This back-analysis process consists of comparing how previous stope design behaved compared to their expected behavior. This allows for a reconciliation process, where the results from this back-analysis are used to adapt the design of future stopes (Cepuritis, 2006).

3.2.4. Personal Expertise for Stope Design

This method should not be considered a truly scientific or standardized stope design method but is still worth being mentioned, however. Where the other methods try to use empirical correlations and evidence or modeling the behavior and interactions within the rock mass with the aim to get a reliable estimation of what will happen. This method is rather based on the personal expertise of stope design experts. These will try to utilize their personal expertise and knowledge about the rock mass and its structure in order to adequately dimension and shape the stopes to be. This method is nowadays typically applied in combination with the other ones and it should not be forgotten that it finally is the engineer’s responsibility to proof-check the applicability and estimate the reliability of a certain model. As stope design and rock engineering are such complex disciplines the other methods should never be blindly applied and always be checked for reliability in relation to the given circumstances (Wagner, 2019).

Several factors that influence the stope design and stope performance are typically neglected and their correlation is commonly overlooked. For example, the measured stope performance is not only relying on the stope design with an adequate estimation of the rock mechanical parameters but rather also on an adequate approach to reaching the desired stope boundaries. For example, the drilling pattern, explosive product, powder factor, charge concentration, and delay timing need to be considered to reduce overbreak and blast damage (Scoble, 1997). While the charging work itself is relying on the skillful performance of the charging personnel, which is then related to the skill level of the workforce in the mine. To perform an adequate back-analysis also these parameters and several more that can be easily overlooked but need to be considered rather than neglected. The complexity of the stope design process due to its various interactions between several factors (e.g. bigger stopes can result in higher overbreak) results in the necessity to validate the previously given estimations

Keeping in mind the variety of these factors and their interdependencies a certain degree of uncertainty should be assumed, as is already commonly for grade estimations. A high level of detail in stope design could possibly be counterproductive, by creating the need for excessive resources (computing power and working time) and offering the impression of a high degree of accuracy, which is not adequate considering the given circumstances.

3.3. Stope Design Research

To more adequately understand the proceedings in stope design research, the recent research activity is analyzed and concluded in a comprehensive form, within this subchapter. First, general aspects of stope design research are represented, before specific topics are reviewed in detail. The topics are the improvements in empirical methods, algorithms, and software for stope design.

There are several challenges for strategic mine planning and recommended solutions for them are commonly also applying to stope design (Dowd et al., 2016). Research related to stope design has not achieved the same extent as research in other mining-related areas, this lack of research is being linked to the following reasons (Sotoudeh, 2017):

1. Generality: The are various underground mining methods, associated with very different processes and geotechnical requirements, thus the creation of a general algorithm for optimizing all these different methods is considerably difficult
2. Complexity: The varying conditions and restrictions of underground mining optimization (geological, geomechanical and economic) modeling of these parameters are considerably more complex

3. Acceptability: The act of examining and proving the realized benefits of a new stope design method or an improvement within one. As every stope is unique and thus extensive case studies are needed but represent a considerable hurdle for research and implementation.

The focus of the stope design research has drastically changed in the past 20 years as several flaws, with Mathew´s stability graph method, have become evident (Suorineni, 2012). In accordance with the possibility to gather geotechnical data by different means and numerically model also bigger rock masses in a feasible time, research has split in two directions, that have slowly become more and more divergent. The rather “classic” empirical approach and an approach of applying novel possibilities from utilizing computing capabilities and software.

The focus of research in stoping related underground mining can be mainly condensed to the following topics (Erdogan, 2017): Optimization of stope boundaries, production schedule, and development activities.

An overview of specific research topics with a selection of featured research papers is given here:

- The incorporation of grade uncertainty and minimization of associated risk on stope design optimization (Grieco & Dimitrakopoulos, 2007; Villallba, 2019)
- Iterative cut-off grade optimization (Bootsma, 2013; Will, 2018)
- Integration of stope design into mine planning (Hou et al., 2019)
- Empirical software to create deposit specific case-studies (Vallejos, 2017)
- Finding novel mining methods that allow for facilitated optimization methods (Mousavi, 2019)
- Utilization of big data analytics and artificial intelligence in mining geomechanics (McGaughey, 2019)
- Stope Sequencing Optimization (Bouzeran, 2019)
- Improvements in the efficiency of algorithms (Algorithms for Stope Design)

In general, several fundamentally different methods are still applied within the industry, even though they are clearly not optimal have been identified and research has been focused to prove the benefits of novel methods to promote their implementation. Thus, for example, the necessity for individual stope design, not general mine-wide stope design is obvious but is still no implemented within the whole industry (Amedjoe, 2015).

Traditional ways for stope layout and design optimization can be very time consuming due to the high number of iterations. Manual methods for stope boundary optimization depend on individual experience and are thus comparable to individualized empirical methods, that are deemed result in suboptimal solutions (Bootsma, 2013)

A large number of studies was done stope design and its optimization. (Topal, 2008; Topal, 2010; Copland et. al, 2016; Ovanic et. al, 1995; Ovanic, 1999; Cawrse, 2001; Ataee-Pour, 2005; Alford et. al 2007; Alford et. al, 2009; Bai et. al, 2013; Sandanayake, 2015; Keane, 2010; Bootsma, 2013; Little, 2012

Additionally theses papers were consecutively reviewed and evaluated in context (Erdogan et. al, 2017; Sotoudeh et. al, 2017; Nikbin, 2018

This can be understood as an effort to create a higher degree of confidentiality within the assessment and takes away biasedness to a considerable degree. Though it seems reasonable to critically review the results of these comparison studies, due to the considerable impact they are deemed to have on the future developments for stope design.

Another aspect that challenges the implementation of novel research is the time value of money. Commonly money spend on exploration is very scarce, resulting in considerably costly errors in planning. For example, it has been proven beneficial to spend more money on grade control practices early in the mining process, since this allows for better selectivity to reduce dilution and enhance the achieved grade at the end of stoping (Amedjoe, 2015).

Some amount of ore should be left in stope before blasting or mass blasting should be performed in order to reduce dilution from persistent ground vibrations of separate firing ring patterns. When stope failure has been observed, smaller equipment should be utilized, and more grade control samples should be obtained (Amedjoe, 2015).

3.3.1. Improvements in Empirical Methods

Since several flaws in the empirical stope stability estimation have become evident (Suorineni, 2014), research activity has focused on trying to eradicate these flaws.

Due to the dominance of the stability graph method within the empirical methods, the focus here is laid on this empirical method. As mentioned for empirical methods in general several issues were identified to be inherent to the stability graph with time, also (e.g. the limited database) (Suorineni, 2012). Along with other issues, this led to a continuous focus of research aiming to eliminate these flaws. Thus, the original stability graph was extended, modified, and the underlying system adapted to different needs and challenges of stope design, resulting from various mining methods, mine environments, and geological conditions. The history of modifications to the stability graph from the 1980s to 2011 is illustrated comprehensively in Table 2.

Since the classical stability graph only delivered qualitative assumptions on the state of the stopes, for practical purposes it is however more interesting to assess factors that have a direct financial impact on the mining operation such as dilution. This led to the development of the dilution-based stability graph.

Table 2: Modification History of the Stability Graph (After Suorineni, 2010)

Period	Developments
1980 - 1985	Introduction of stability graph – 26 case histories (Mathews et al., 1981)
1985 - 1990	Calibration of stability graph factors and zones – 175 cases (Potvin, 1988)
1990 - 1995	Tentative cablebolt support line (Potvin & Milne, 1992) Re-definition of unstable/cave (supportable transition boundary – cablebolt support line) (Nickson, 1992) 1st partial statistical definition of stable/unstable zone (Nickson, 1992) Proposed dilution lines added to stability graph (Scoble & Moss, 1994)
1995 - 2000	Re-definition of the transition zones (Stewart & Forsyth, 1995) Modified gravity factor for sliding failure (Hadjigeorgiou, Leclaire & Potvin, 1995) Second partial statistical definition of stable/unstable zones (Hadjigeorgiou et al., 1995) Introduction of radius factor *RF* (Milne, Pakalnis & Lunder,1996) Calibration of proposed dilution lines (*ELOS* Clark & Pakalnis, 1997) Modified gravity factor for footwalls with shallow dips <70° (Clark & Pakalnis, 1997) Proposed volumetric index (Germain & Hadjigeorgiou, 1998) First complete statistical analysis of stability graph using Baysian likelihood statistic (Suorineni, 1998) Introduction of fault factor (Suorineni, 1998; Suorineni et al. 1999) Modified stress factor to include tension and stress-dependent transition zones (Diederichs & Kaiser, 1999)
2000 - 2005	Expanded database to about 400 cases and modified stability graph zones from Australian database (Trueman et al., 2000; Mawdesley et al., 2001) Second complete statistical analysis using logistic regression – 483 case histories (Trueman & Mawdesley, 2003) Time-dependent stability graph (Suorineni, Henning & Kaiser, 2001a)
2005-2010	Numerical modeling to validate the B-factor (Bewick & Kaiser, 2009)
2010 – to date	Second modification to stress factor to include tension (Mitri, Hughes, & Zhang, 2011)

The now available and used and modified forms of the stability graph methods are:

- Mathew´s stability graph
- The modified stability graph
- The extended stability graph
- Dilution graph
- Revised Dilution graph
- The equivalent linear overbreak slough (ELOS) stability graph

This diversity illustrates how widespread the empirical methods have become with time and how many different methods are actually still gathered in one group of empirical methods.

The issue with most empirical methods lies within their creation, which is why specific scientific concepts should be followed in order to allow for the development of reliable methods (Mark, 2016).

One of the most recent developments within the empirical methods was the following:

Vallejos et al., 2017: The creation of a novel empirical software, that allows the creation of regional and mine specific case studies.

3.3.2. Algorithms for Stope Design

With the advancements in computer science, research from the stope design sector has been focused on finding and identifying more adequate algorithms, which then allowed for a better stope design. Historically due to limited computing power, the factors that were taken into consideration were quite limited in their nature.

Still nowadays, with such excessive computing capacities, computing time is still a limiting factor, and considerable resources need to be dedicated to considering the various different scenarios. Due to the previously mentioned complexity and resulting difficulty to represent all necessary parameters in a model, the necessity to create adequate and efficient algorithms capable of designing stopes fitting all requirements is especially challenging. The transition from algorithms working in 2D towards algorithms realizing a truly 3D optimization is still advancing and in the focus of research. Currently, there is still only a considerably limited number of algorithms available. These do not guarantee an optimal solution in 3D (Sotoudeh, 2017) and do not satisfactorily represent local geotechnical aspects and the time value of money.

The developed algorithms can be divided into two groups: Level-oriented and field-oriented (Sotoudeh et al., 2017), a selection of algorithms, with a short explanation shall be given here. In detail information can be taken from the related papers.

Level oriented algorithms:

Dynamic Programming (Riddle, 1977):

In 1977 Riddle proposed a dynamic programming-based algorithm as an extension of a 3D dynamic programming method, which had originally been developed for ultimate pit limit optimization (Johnson & Sharp, 1971). The algorithm was developed in Fortran and implemented on hypothetical economical block models. The algorithm was capable of defining stope boundaries of block caving operations, but only in 2D space, so that optimization in 3D space is not guaranteed (Sotoudeh, 2017).

Branch and Bound Method (Ovanic & Young 1995; 1999), Mixed Integer Programming (Grieco & Dimitrakopoulos, 2007):

Mixed Integer Programming (MIP) combined with a piecewise linear function, allows to optimize the starting and ending location of mining within each row of blocks (Erdogan, 2017).

Optimum Limit integrated probable stope (OLIPS) (Jalali & Ataee-Pour, 2004; Jalali et al., 2007a):

The OLIPS algorithm was developed based on the dynamic programming method. The algorithm obeys all defined technical and geometric constraints while delivering mathematical proof. It is divided into two principal steps. The first step involves the creation of a conventional economic model of a mining panel, while in the second step, the probable stope economical model and integrated probable stope economic model are derived from the conventional model. Based on this algorithm, the Stope Boundary Optimizer (Jalali et al., 2007b) computer program was developed and validated by 2D hypothetical models (Sotoudeh, 2017).

Global optimization for underground mining area (GOUMA) algorithm (Jalali et al., 2016): New comprehensive algorithm, which varies the value of underground mining area blocks according to geometry and location of panel and level. The algorithm runs on a special model named ´Variable Value Economic Model´(VVEM). To run the algorithm on large scale problems the GOUMA-CP computer program was written (Sotoudeh, 2017).

Field-Oriented Algorithms:

Floating Stope Algorithm (Alford 1995; Alford et al. 2007): Determine the stope boundaries of mineable ore block within a resource block model. Separating the fixed block model in ore and waste. Maximize ore tons, contained metal, ore grade, or economic value within ore body model. Heuristic Algorithm that lets a stope, with defined origin and dimensions, float through the entire block model. The creation of Datamine is based on this algorithm. The main shortcoming can be seen in the creation of overlapping stopes, sharing high-grade blocks (Erdogan, 2017; Nikbin, 2018).

Multiple Pass Floating Stope Process (MPFSP) (Cawrse, 2001): Developed to overcome some shortcomings of the floating stope algorithm. Defining sets of parameters: head grade, cut-off grade, and maximum waste inclusion. Creation of a stope envelope for each set of parameters. Envelopes provide additional information for mine design process= increase profitability. Rather assistance in stope boundary selection than optimum stope layout creation. (Erdogan, 2017; Sotoudeh, 2017)

Maximum Value Neighbourhood Method (Ataee-Pour, 2000; 2005): Heuristic approach for optimization of stope boundaries. The algorithm works based on the neighborhood concept, searching for an optimal neighborhood based on economic value for each block/stope in an ore body model. Works with a fixed 3D block model to find the best neighborhood of a block to guarantee maximum net value, still taking into account the geotechnical and mining constraints (e.g., minimum stope size and maximum stope height). In the optimization process, initially, the economic values of the individual blocks are calculated. Consecutively the value of the block and its surrounding block neighborhood is calculated to create the neighborhood block value (NBV) for each neighborhood. The neighborhood size should be selected to be equal to the minimum stope size (in terms of blocks). Finally, the neighborhood values are compared and the neighborhoods with the highest economic values are accumulated into economic stope boundaries and the stopes are assigned codes, indicating their values. It was used as the basis for Stope Limit Optimizer (SLO), which works in 3D space. (Erdogan, 2017; Sotoudeh, 2017)

Automated Stope Design (Nested Stopes) (Alford, 2009): Method for automated stope design. Optimization is run at a sequence of cut-off grades to generate a series of nested stopes, similar to nested pits. The method identifies best extraction levels and stope heights but does not consider mining cost in relation to the size and shape of a stope. Also, the cut-off grade is specified in the design process, so it does not allow for an optimal solution (Erdogan, 2017).

<u>Heuristic approaches</u>

Topal and Sens, 2010:

Optimizes underground stope layout with different stope sizes and strategies in 3D space. During the optimization process, all stopes specified height, width and length are generated based on their economic values in MATLAB. Three basic parts: Block converter (to convert different size blocks block model into a uniquely sized one. Stope optimizer uses this regularized block model to define optimum stope boundaries, based on specific economic parameters (e.g., costs and metal price). The stope boundaries can be created using fixed and variable stope sizes and different selection strategies. In the end, the visualizer shows the examinable results. The algorithm avoids overlapping stopes unlike the floating stope algorithm, stope selection however is partly user´s preference (economic value max to min). This limits the variety of stope combination considerations (Nikbin, 2018).

Sandanayake, 2015: New 3D heuristic algorithm for stope layout optimization. Determining a unique solution, maximizing the economic value of stope layout under physical and geotechnical constraints. Recommends a unique solution and generates non-overlapping stopes. Facilitates consideration of multiple stope sizes including or excluding pillars, satisfying mining and geotechnical constraints. For finding an optimal solution however the algorithm requires significant computing capacities, to consider all possible unique solutions, this is to be considered challenging for large scale operations (Erdogan, 2017).

Network Flow Method (Bai et al. 2013, 2014): Stope optimization based on stability graph theory, with special applicability for sublevel stoping. The network flow algorithm is based on a cylindrical coordinate system, defined around vertical raises. The process consists of selecting an individual mining block for a stope by considering the reference distance to the raise along with stope width design parameters under geotechnical constraints on hanging and footwall stopes. After this, the algorithm is aiming to optimize the stope profit as a function of location and height of raise. The algorithm is somewhat limited to small sub-vertical deposits mined by sublevel stoping. (Sotoudeh, 2017; Nikbin, 2018)

Octree-Division (Cheimanoff et al., 1989):

A recent development that seems promising is the creation of a rather integrated underground mine planning approach, which could possibly substitute the current state-of-the-art stope optimizing only approach. (Erdogan, 2017; Sotoudeh, 2017)

Integrated optimization of stope boundary and access layout for underground mining operations (Hou et al., 2019):

Integrated approach based on the interactions and interdependencies between access infrastructure and stopes by a dynamic access development cost analysis based on recursive computations. Mixed-integer non-linear programming is used to maximize the overall economic value subject to the constraints of generating optimal stopes and access layout, which is solved by a Genetic Algorithm modified for computational efficiency. A stratiform gold deposit was used within a case study to demonstrate the algorithm´s benefits (Hou et al., 2019).

3.3.3. Software for Stope and Mine Design

As opposed to open-pit mining where scheduler and optimization software is already well established in the industry, the optimization of underground mines by software is still a quite recent development and rather limited. This is partially accreditable due to the lower degree of automation and mechanization in underground mines, which allows for more feasible utilization of software, and partly due to the increased complexity of underground mining operations, like the integration of mine ventilation planning. There has been a big variety of underground mine planning and optimization software implemented recently however, as computing capacities have increased drastically, and more efficient algorithms have been developed and consecutively implemented. In general, the recent developments can be understood as a growing trend towards developing new and improving old software tools, in order to overcome design, plan, scheduling and operational problems inherent to underground mines. This development is still on its way as can be concluded from the continuous algorithm development. Due to the constant changes within the software and no reliable overview of which software is applied dominantly an extensive review would be misleading here.

Some of the software for stope design and mine planning and their working principles are explained here, however, due to the variety of available software and the inherent complexity, this should just be considered a very short summary.

Minable Shape Optimizer, Datamine Studio 3:

Strategic Mine Planning Tool, searching for optimal mineable shapes taking into account the orebody geometry and tries to generate the optimal size, shape, and location of stopes for underground mine design in a block model based upon input parameters by the user such as minimum and maximum stope widths, cut-off grade, etc.

Based on the Floating Stope Algorithm, it uses an economic block model, sets cut-off-grade and head grade, optimization method: maximizing grade to select optimum smallest mining unit position. Stope dimensions and a step size for the floating stope relocation need to be defined as input parameters. The software creates envelopes with overlapping stopes (Alford, 2007). It should be considered a simple and generalized process without the specification of the mining method applied. Created overlapping stopes when stopes share high-grade blocks. Neither Geotechnical nor operational constraints are considered in any way, and the stope size is predefined, mining levels and pillars are neglected. It should only be considered as a guidance tool for the engineer´s final stope boundary determination (Erdogan, 2017).

Mineable Shape Optimizer, Alford Systems (implemented in Datamine):

Needs input block model, providing grade or value and density of the mineral resource. From this block model, the cut-off grade value is used to find optimal mineable shapes. From this, a mineable shape framework is created, which contains the mineable shapes. In the framework the approximate stope size, location, and shape (seed shape) are determined, respecting defined design constraints. These seed shapes are created using slices in relation to dip and strike of the orebody. Utilizing the defined cut-off, the MSO aims to create an optimal basic seed shape for stopes and pillars. Consecutively the seed shape is re-dimensioned to the final stope shape, subjected to stope and pillar geometry constraints. This stage creates more adequate stope shapes. The MSO is unique in its efficiency to generate and evaluate thousands of iterations of stope geometry, geological and geotechnical constraints to find optimal shapes for stopes and pillars, maximizing the mine´s economic value. Adequately applied the software allows for adequate addressing of hanging and footwall constraints, stopes, pillars. Additionally, it can be utilized for a wide range of different mining methods and provides solutions for massive sub-vertical and horizontal deposits. The most significant limitations are the preliminary overall definition of a cut-off grade (Alford, 2009) This can only lead to considerably suboptimal results (Erdogan, 2017).

MineSight Stope (MSStope), MineSight 3D:

Utilizes Maximum Value Neighborhood (MVN) method. Searches for the best possible combination of blocks to produce maximum profit. Minimum stope dimensions can be defined for each production level. The resulting block model is color-coded based on the ore grade. The result does not show mineable stopes but rather feasible stopes. The MVN algorithm avoids the problem of generating overlapping stopes from the Floating Stope Algorithm. It is to consider that there is only limited consideration of variable stope sizes, geotechnical (stope constraints) and operational aspects (Erdogan, 2017).

For completeness, the survey responses regarding applied stope design software shall be mentioned here. They can be found in Stope Design Methods.

3.4. Evaluation of Stope Design Methodology and Research

After identifying the different stope design methods and analyzing the research activity in the area, it can be concluded that the implementation of software in underground mine planning and stope design especially is increasing. There are four considerably different approaches within the mining industry, which are all applied in their own distinct areas. Out of these the previously dominant pure empirical methods are decreasing in importance with the progression of research. The void is being filled by the implementation of numerical methods and algorithms which are being implemented in new planning software. The focus on promoting new stope design methods, algorithms and software lies within the creation of case studies. This allows for comparing the achieved benefits of new methods. That there are so many case studies promoting benefits that show the competitions within this area of stope design research, though the creation of case studies by the software developer is to be considered a potential source for biasedness. It seems that most research related to stope design is currently neglecting or only addressing geotechnical aspects in a very limited form. Though there are some exceptions (Machuca, 2015; Andrews, 2019)

The focus within software development is rather laid upon production scheduling and algorithm efficiency improvements, while transforming the optimization process of algorithms from 2D to 3D. The reasons for this could lie within the applied search parameters, as there is diverse numerical software for stope stability estimation. This could be due to the fact that these approaches are not primarily created with respect to stope design but rather on rock mechanics. The approach towards turning stope design into a more inclusive and integrated part of mine planning rather than considering it to be a stand-alone approach seems to be especially reasonable considering the inherent complexity of this discipline.

4. Industry Overview

After the focus of the latest research as well as the available software for stope design have been analyzed, but the question of how much and which of the research, methods, and software is applied in the industry remains unanswered. Also, there is no overview of what the professionals, who are directly working with stope design, consider to be the biggest challenge in their domain and what kind of requirements they identify as inevitable for the implementation of potential improvements.

In order to adequately identify the degree of research implementation achieved within the mining industry and in order to identify the most urgent challenges related to stope design, it was necessary to directly approach mining industry professionals who are working with stope design. This will help to address the goals and requirements of and for the GAGS-project better and will thus be of great help for creating suitable guidance for the research project.

As this chapter is considerably extensive a small overview of the topics covered within it shall be given here. Initially, the questionnaire and survey are described with their key characteristics, then the survey responses are assessed, and the related meta-data analyzed and evaluated. Consecutively, the directly quantifiable survey results are presented before the results of an in-depth analysis are illustrated. Then the survey results are critically discussed. Following this, a short summary of a mine visit and an interview with a mine plannerare illustrated and the gained insights presented. Later the results from the survey, mine visit, and interview are summarized and evaluated inclusively.

4.1. Survey

For gathering an overview of the state-of-the-art of stope design applied in the industry, it was necessary to access people from this professional environment. The option to create a questionnaire and conduct a survey was chosen. Thus, a questionnaire following the most recent principles of questionnaire design and statistical science (Guidelines of the Questionnaire Design Tip Sheet, Harvard University Program on Survey Research, and Survey Monkey) has been created and reviewed by several mining industry and university professionals. The surveyed data was then thoroughly analyzed to identify potential trends and insights. This allows for an optimal and least biased way of collecting industry expert´s opinions in a feasible, comprehensive and measurable way.

Here some additional information, about the creation of the questionnaire and the means of conducting the survey, is provided. Initially, a literature study was conducted in order to acquire adequate background knowledge about stope design, to allow for the creation of a relevant and adequate questionnaire. As part of this, a survey population was identified and then the questionnaire created. For the creation of the questionnaire the professional online survey platform WebRoPol (https://webropol.com/) was used for the online questionnaire creation. The questionnaire followed a double funnel approach, starting with general questions, evolving into very detailed questions about stope design later on, while every question initially asks for basic responses but also allowed for detailed free-text answers.

The questionnaire consisted of a general introduction and detailed explanation of the GAGS-project and 19 questions, the exact questions are given in subchapter 4.3 together with the graphic illustration of the results. Here the topics in order of appearance within the questionnaire are illustrated:

Q1. Contact information and background of respondent
Q2. Desired notification about the results of the survey
Q3. Utilized Mining Method
Q4. Changes in the mining method
Q5. Previously applied mining methods
Q6. Applied stope design methods
Q7. Start and duration of stope design and number of people involved in the process
Q8. Importance of different stope design parameters
Q9. Geological Conditions in the mine
Q10. Stope Check for accuracy and stability
Q11. Recommendation of own stope design and stability estimation method
Q12. Most valuable improvement for stope design
Q13. Utilization of geotechnical methods
Q14. Planned utilization of geotechnical methods
Q15. Interest in application of LIBS (Laser-Induced Breakdown Spectroscopy)
Q16. Interest in the application of new in-situ rock mass characterization methods
Q17. Estimation of the time frame to make new geotechnical data available
Q18. Considering the implementation of changes in stope design and conditions for it
Q19. General comments and remarks

An approximate survey population of approximately 250 international stoping mines was identified by stope mine search. An representation of the identified mines can be found in

Mine List. The desired sample size was then calculated based on the following formula (Suresh, 2012):

$$Sample\ Size = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left(\frac{z^2 \times p(1-p)}{e^2 \times N}\right)}$$

N = Population size; e = Margin of error; z = z-score (standard deviation); p = expected proportion

The parameters are the survey population of 250 mines a z-score of 1.65 (represents a confidence level of 90%), an expected proportion of 50% and a margin of error of 15%. Following these input parameters, a minimum sample size benchmark goal of 27 responses was defined.

The questionnaire was then distributed to mining professionals working with stope design in mines and consultancies by 3 different means (Email, LinkedIn and Forum Posts). In order to allow for the collection of more detailed source data, the survey was divided into three separate surveys, to trace the responses by means of distribution. In total, about 500 people were contacted directly, and a total of 36 responses were gathered, resulting in an estimated response rate of roughly 7%. During the process of sending out the survey the responses were continuously checked for adequacy, in order to identify and fix potential errors within the questionnaire, fortunately, no errors requiring corrections were encountered.

4.2. Survey Evaluation

As important as the creation of an adequate questionnaire was the evaluation of the results in order to extract as much information as possible from the survey.

The survey was made available for three months from the beginning of May 2019 until the end of July 2019, in order to allow for respondents to be contacted reached and get an opportunity to reply in an adequate time window. Once the survey was conducted the different answers were gathered and the evaluation process initiated.

Due to the creation of different response origin subgroups it was possible to analyze where most responses originated, and which form of contact achieved the best results. In general, the internationality of the participants of the survey should be considered remarkable. As mining professionals working in more than 20 different countries were present in the survey. The origin of the respondents by contact form and region can be seen in Figure 10.

It was of crucial importance to validate the adequacy and reliability of the responses. Due to the previously mentioned complexity and broad range of different tasks related to stope design, it should be considered desirable to have a big variety within the area of expertise of the respondents. Thus, it is analyzed which specific job related to stope design the participants execute and in what kind of mines and with what kind of commodities they are working and how big the annual mine ore production is.

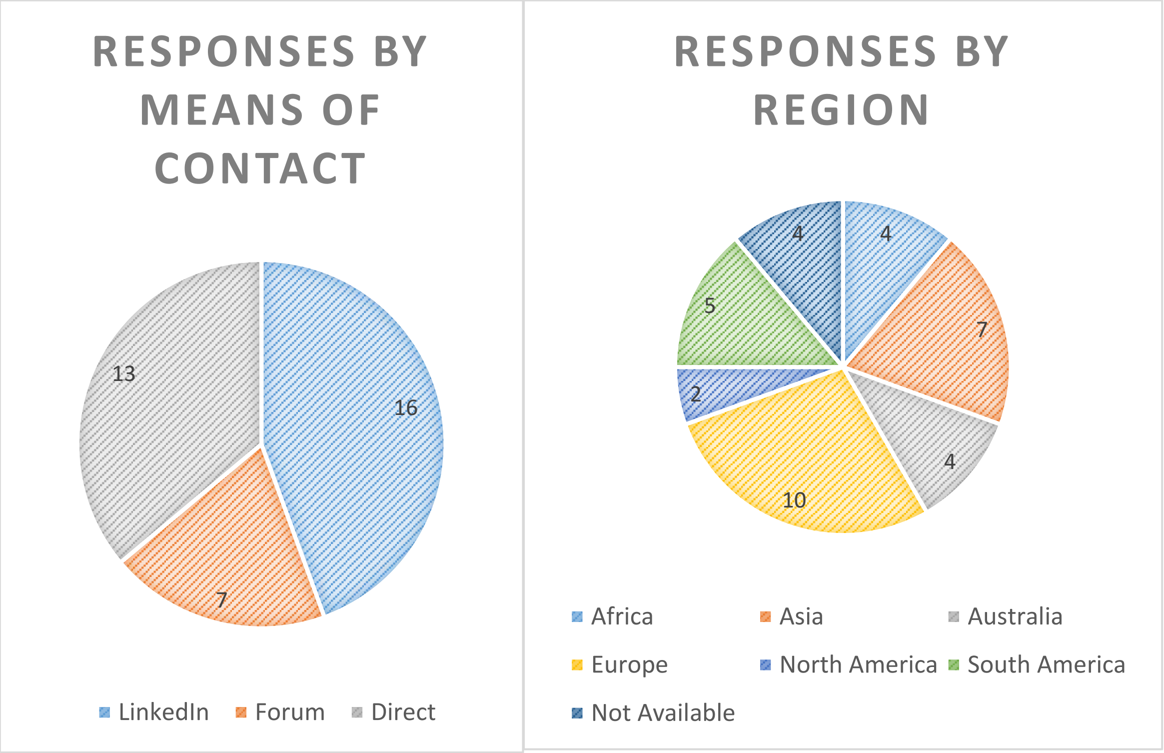


Figure 10: Response Origins

By analysis of the responses, it is possible to conclude that a broad variety of different areas of expertise, were reached and responded to the survey, as the job titles of the respondents cover a broad variety from Mine Managers and Mining Engineers over Rock Mechanics Engineers, Geotechnical Engineers, and Geologists to Project Engineers. Since the geotechnical departments are in some cases outsourced to consulting companies it should be considered enriching for the diversity of the survey population that 5 of the responses originated from consultants.

In Figure 11 it is illustrated that a considerable divergence within the mine size is present within the response, the average annual ore production within the survey is quite representable with about 1,800 kilotons of annual ore production. Figure 12 illustrates that the dominant commodity mined by the respondents is by far gold. Additionally, it should be mentioned that gold mines were also amongst the only single commodity mines.

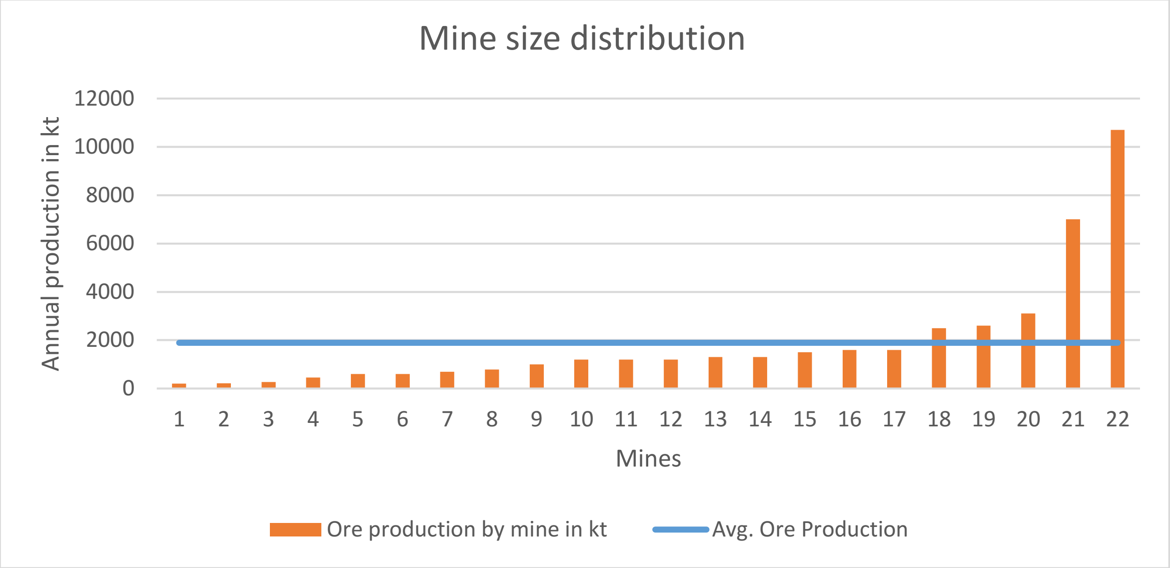


Figure 11: Mine Size Distribution per Mine by annual Ore Production in kilotons (kt)

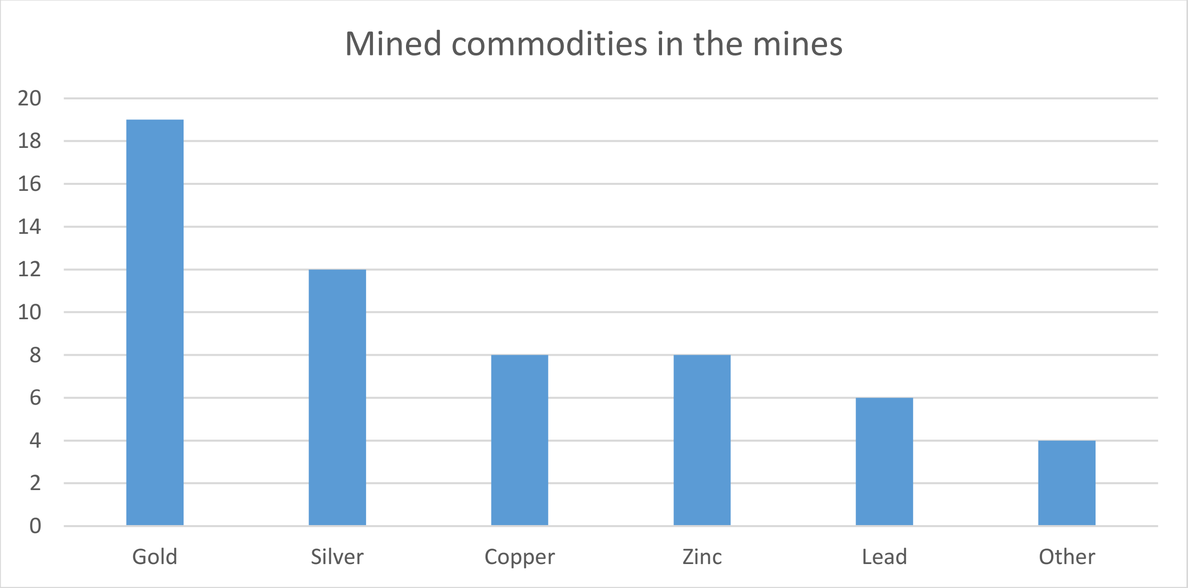


Figure 12: Mined Commodities

4.2.1. Survey Participant Assessment

During the evaluation process, the responses were initially checked for their information value and inadequate and unsatisfying answers eliminated from the response pool. Due to an identified high degree of variety within the answer complexity and quality the decision was taken to establish a general response quality/complexity-evaluation. One of the issues related to this evaluation process was that if not carefully executed a certain degree of biasedness stemming from subjective judgment would impact the results, to minimize this subjective impact on the evaluation process and the resulting biasedness from it, considerably objective response quality/complexity indicators (average free-text-answer-length, total response time) were chosen. These indicators were then used to create an objective “Response Quality Classification System”. Once established this system was used to classify the answers. As part of the system´s implementation, every response was assigned a single class, the responses were then divided into four categories as can be seen in Table 3.

In order to extract a maximum of information from the obtained responses, it was essential to check the responses for possible correlations and interdependencies, following individual as well as global aspects. On one side of the evaluation process were the objectively assessable multiple-choice answers, which were to be considered predestined to give a general idea of the respondents´ ideas, opinion, and their background; on the other side are the individual free-text answers that allowed for more detailed understanding of the given answers and identified trends.

Due to the free-text answer approach of the survey, which gives the possibility to express one´s personal opinion and comments on almost every single answer, several non-quantifiable answers need to be subjectively evaluated and assessed for their value and underlying scheme.

Table 3: Response Quality Classification System

Class	Value	Description
Disqualified	0	Disqualified response; due to unsatisfying response quality.
Low Quality	1	Minimum standard, at least 80 % of the questions answered, Free-Text answer length below 4 words on average or repetitive
Satisfying	2	Considerably complex answers for most part, multiple phrase free-text responses in some parts but not consistently
Excellent	3	Very complex answers, stretching over several phrases, respondent shows effort to explain his point of view and allows for thorough understanding

4.2.2. Meta-data analysis

The responses were grouped, analyzed and checked for possible correlations according to several different factors. The possibilities for analysis reach from using the form of contact, over specific responses to specific questions and regional origin, up to the response quality classification. In Table 4 the results from the global response evaluation can be seen, as grouped by contact scheme group. It can be concluded that the Linked-In responses show the highest response quality, while the forum responses show the longest average response times. A more detailed overview of the meta-data analysis can be found in appendix 0.

Table 4: Overview Responses by Means of Contact

	Linked-In	Forum	Direct Mail	Global
Total Responses	16	7	13	36
Usable responses	16	6	12	34
Avg. Response quality	2.1	1.6	1.8	1.89
Excellent Responses	5	2	3	10
Share of Exc. Responses	31 %	29%	23%	28%
Avg. Response Time in Minutes	32.5	47	29.7	34.3

4.3. Survey Results

This subchapter analyzes the results of conducting the survey. Here the survey results are presented in a way that guarantees a minimum level of biasedness, by considering only direct and unfiltered survey results, while stating uncommented responses from the free-text answer section, to not lose their informational value. Where explanations and possible interpretations seemed reasonable, they are shortly mentioned, and clearly explained. It is to note that this interpretation approaches mainly rely on personal expertise. The results are mainly visualized in a graphical form, to allow for an improved understanding.

For representability purposes, the exact structure of the questionnaire is not followed, but a rather more comprehensive approach allowing for more structured understanding is established.

Thus, the following structure is chosen:

1. Applied Mining Methods
2. Geological Conditions
3. Stope Design Methods
4. Reliability of Stope Design Methods
5. Stope Performance
6. Most important Improvements for Stope Design
7. Utilization of Geotechnical Methods
8. Improvement Implementation and Conditions

4.3.1. Applied Mining Methods

The distribution of the applied mining methods the survey respondents are working with is illustrated in Figure 13. The surveyed population shows a strong dominance of the sublevel stoping mining method, with about 46% of the responses stating that this is their applied mining method, followed by Cut & Fill with 22%. Due to the dominance of sublevel stoping, it is further analyzed which exact sublevel stoping method is commonly utilized within the survey population, this is illustrated in the second graph within Figure 13. It can be concluded that long hole stoping is the dominant sublevel stoping method with 70%. With respect to the mining methods mentioned in the free-text answers, the dominance of the AVOCA mining method stood out with significant utilization, other mining methods and their variations such as toe mining should be only encountered in single cases and are thus not mentioned here.

In order to allow for a better insight into the consistency of the applied mining methods, it is evaluated whether the currently applied mining methods have been used since the beginning of the life-of-mine or changes have been applied to them. Figure 14 illustrates that changes in the mining method were reported in 69% of the responses. The reasons for the changes in the applied mining methods are reaching over a broad variety from economical, over geological up to technical and geotechnical reasons. Thus, the mining methods should not be considered as such a limiting factor as was previously assumed.

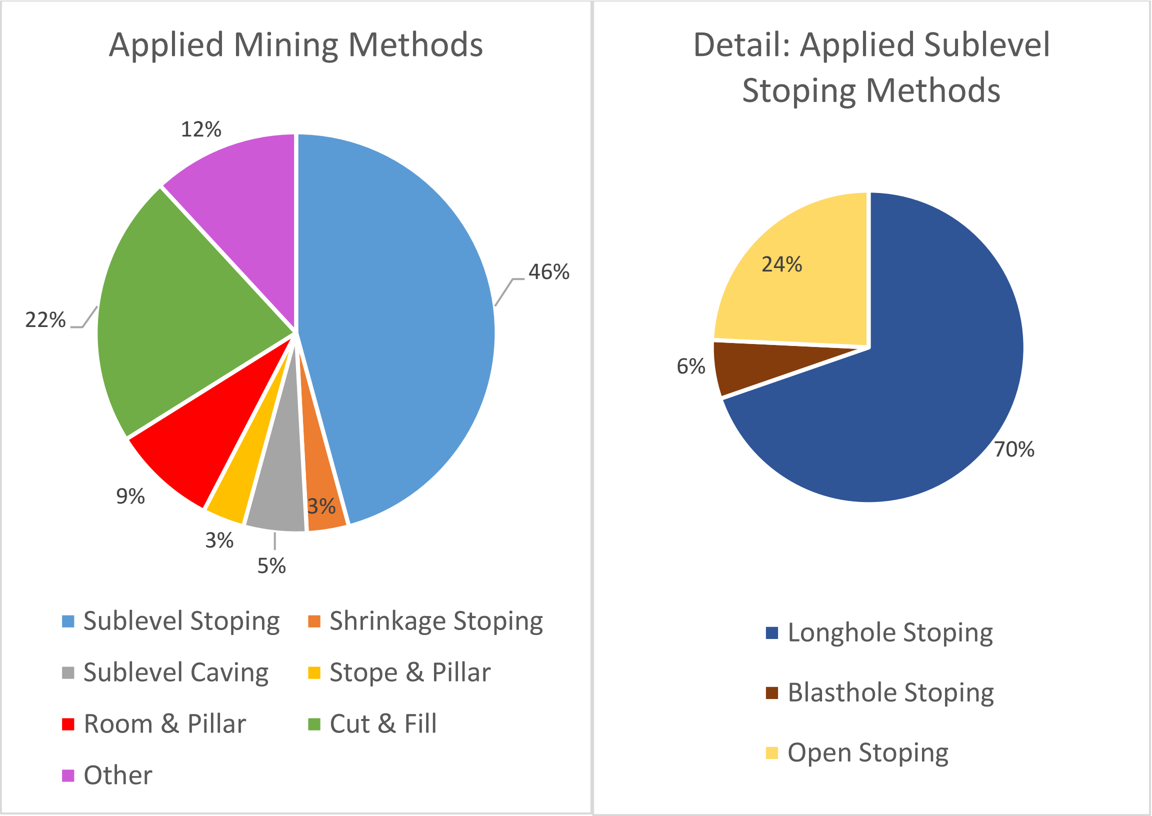


Figure 13: Applied Mining Methods

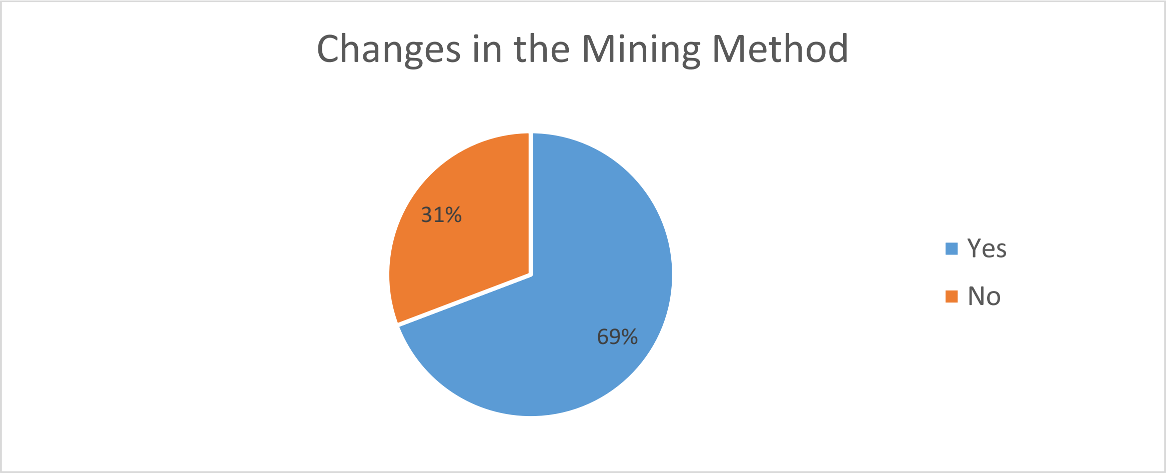


Figure 14: Have there been changes in the applied mining/stoping methods?

4.3.2. Geological Conditions

This subchapter gives an overview of how the participants evaluate the geological conditions in their mines. It can be concluded that more than 80% of the respondents consider their mine´s geological conditions as “challenging” or “very challenging”, this result is illustrated in Figure 15. The exact question asked here was: “How challenging are the geological conditions in your deposit?" This distribution can either stem from the generally challenging geological conditions presently encountered within stoping operations or with the willingness of recipients of the survey itinerary to respond when they are confronted with this challenge.

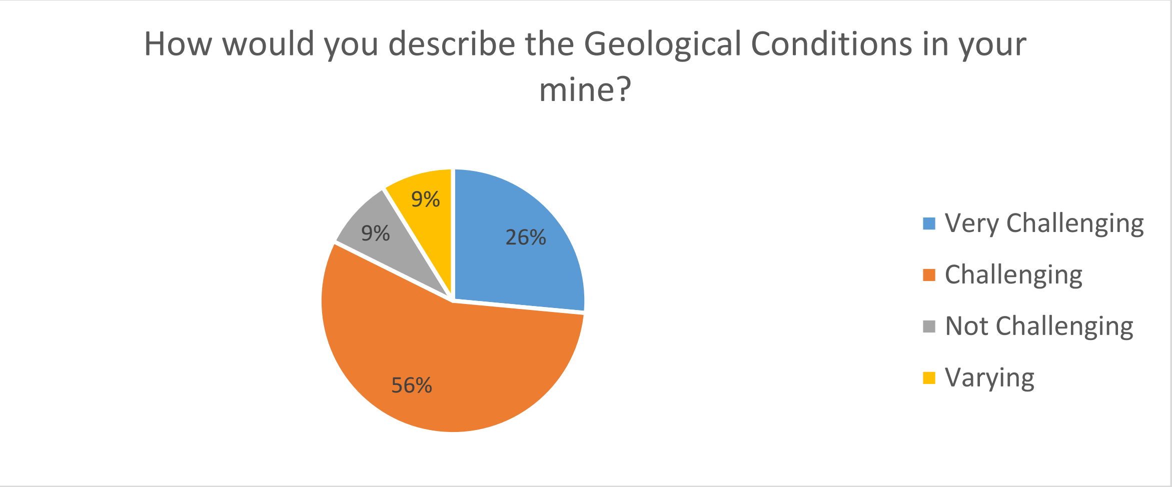


Figure 15: Geological Conditions

4.3.3. Stope Design Methods

With respect to the various methods for stope design, it is important to assess which of these are actually utilized in the industry. As depicted in Figure 16 personal expertise and numerical methods are showing a significantly higher share than empirical methods. It is to note that, while personal and numerical methods are sometimes stand-alone approaches, this is not the case for empirical methods, which are always combined with either numerical and/or personal expertise.

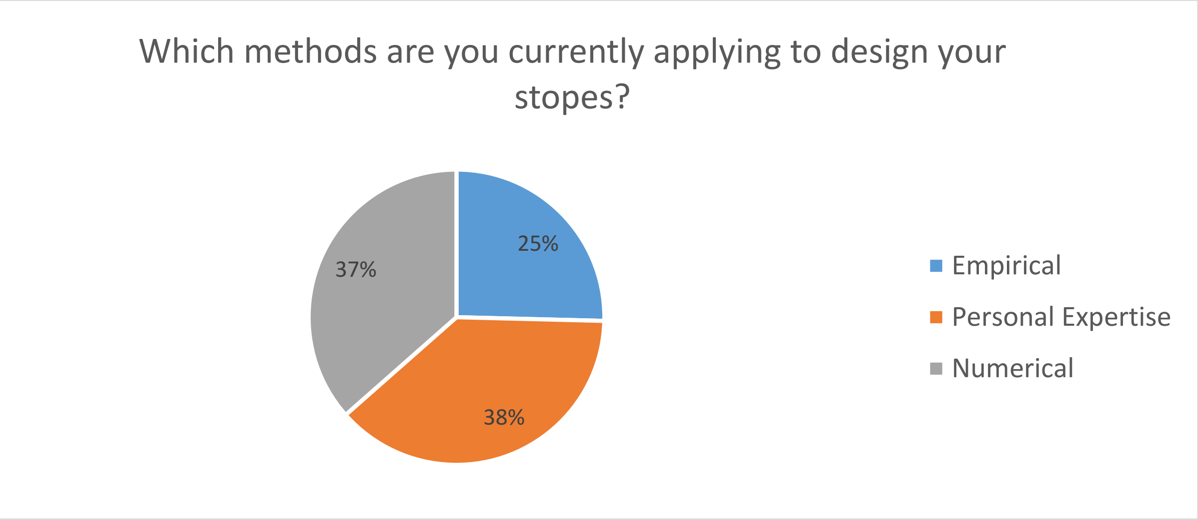


Figure 16: Applied Stope Design Methods

The broad variety of utilized methods in detail shall be explained in the following:

Empirical Methods are mainly limited to the application of the Mathew´s stability graph and the modified Mathew´s stability graph and utilization of the Rock Mass Rating system in general, as illustrated in Figure 17.

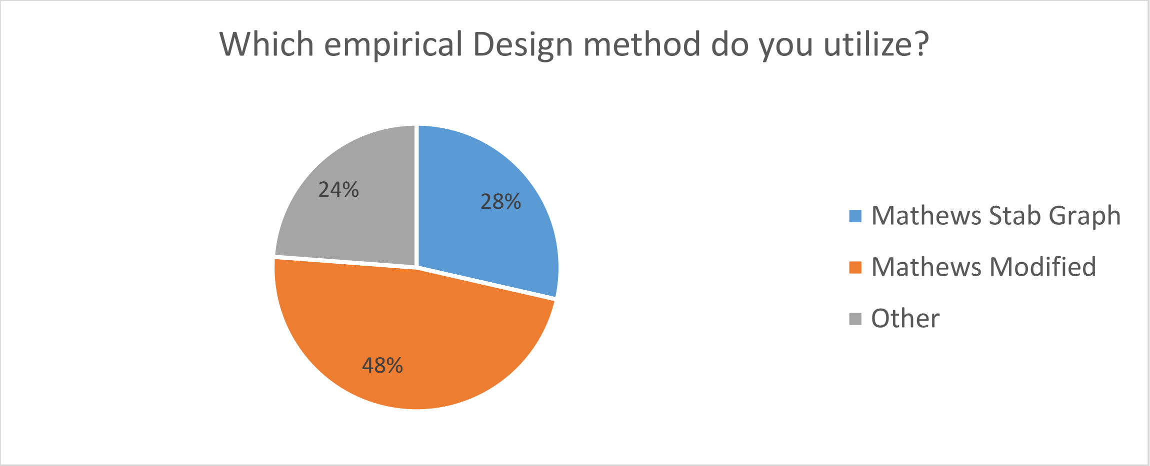


Figure 17: Applied empirical Stope Design Methods

Personal expertise is utilized in the form of a broad variety of personnel from different disciplines: Mine Planners, Drill & Blast Engineers, Geologists, Rock Mechanic, Mining and Geotechnical Engineers amongst others. Commonly they utilize their personally gathered experiences within the specific geological settings. Thus, it can be considered a personal empirical approach.

The utilized numerical methods and software are Micromine, AutoCAD, Map3D, Surpac, Maptek Vulcan, Gantt Scheduler, Deswik (Microstation), Auto Stope Designer and Stope Optimizer, Rocscience (RS2, Slide, Phase2, Examine, DIPS, Unwedge and CPillar), Recursos Mineros. Quantifiable values are not available since these methods were only assessed in the free-text answers.

As important as understanding how stopes are designed is to assess when the stope design process is performed, Figure 18 illustrates in which state of mining the principal stope design is done. It is to be noted, that an iterative approach is executed by only 6 respondents.

Additionally, it is important to gather information on the duration of how long it takes to design stopes. Figure 19 gives an overview of the stope design process duration, it is to be concluded that mainly stope design requires less than a week. Though this question did not clearly diversify into stope design and mine planning, thus answers of more than 6 months were registered. In general, it should be noted that some stopes were stated to be designed as fast as in a matter of minutes, whereas other answers stated several weeks.

The correlation of stope size and geological complexity with the necessary time to perform stope design was frequently mentioned as a factor with strong influence.

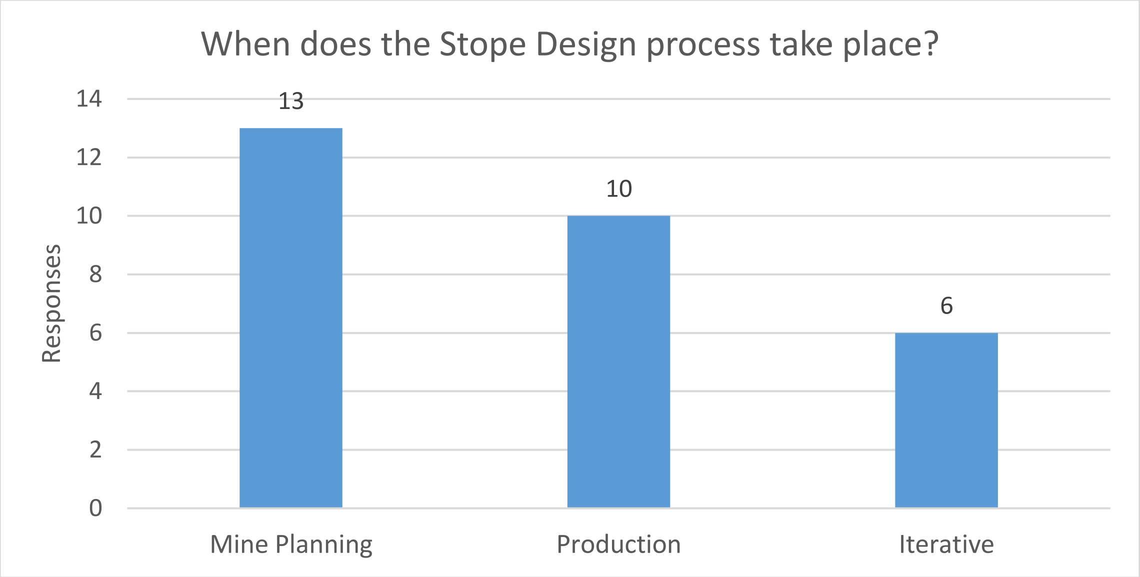


Figure 18: Stope Design Stages

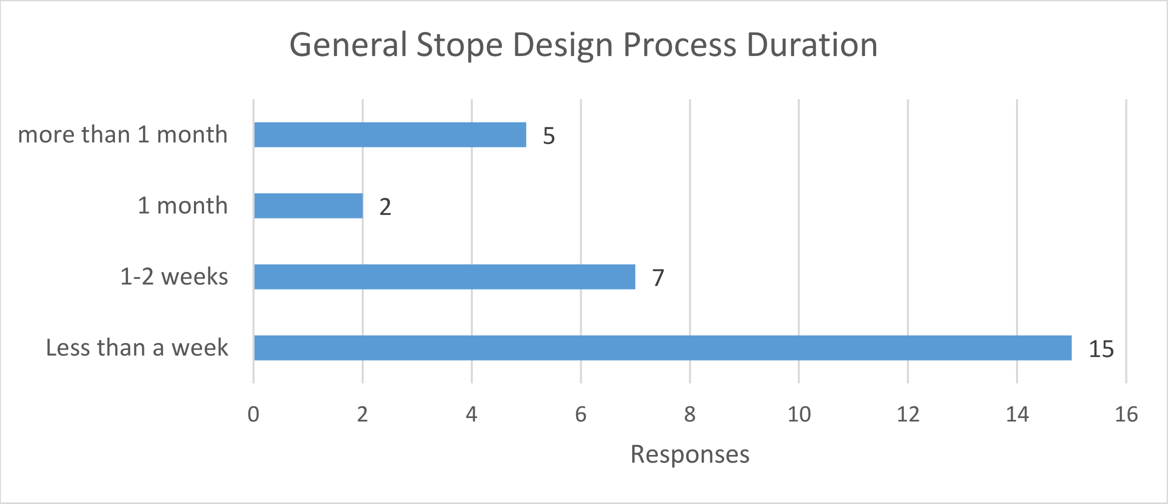


Figure 19: Duration of Stope Design

An additional interesting aspect of stope design is the number of people involved in the process. By assessing the results of the survey, we can conclude that the average number of people involved in stope design is three, though numbers as low as a single person and a maximum of 15 people were stated. Also, it is to be noted that it was commented that the number of involved people depends on how much of the previously planning work is to be counted as part of it, as the stope design is to be considered the final step in a long chain of actions (Figure 3)

Finally, due to the various parameters influencing stope design, it was crucial to assess the importance of these individual parameters. The detailed results of the evaluation are illustrated in Figure 20 and Figure 21, where Figure 21 allows an easier visual identification of the differences. It can be concluded that cutoff grade and dilution are the most important parameters, though no single factor represents an outstanding importance. After checking the data for outliers and answer schemes, it must be noted that some of the respondents seem to have confused the values on the answer scale. After trying to correct the errors resulting from this confusion by visual assessing a color-coded answer sheet, the importance of the cutoff grade was significantly outstanding. Additionally, it should be noted that several additional factors were mentioned to have a considerable influence on stope design, they can unfortunately not be assessed quantitatively as they were individual free-text answers, these factors were: Productivity, Ventilation, Mining Cost, Sequencing, Drill & Blast, Flexibility in Mine Planning, Rock Mass of Stope, Labor Efficiency, Selectivity, **S**elective **M**ining **U**nit (**SMU**) and Safety.

An explanation for these factors is hard to come by since no possibility for explanation was given in this case, however, they should be considered as factors that should not be neglected. Factors like ventilation would most likely intend that the factor of a feasible stope ventilation during production and general ventilation should not be ignored while designing, sequencing and placing stopes.

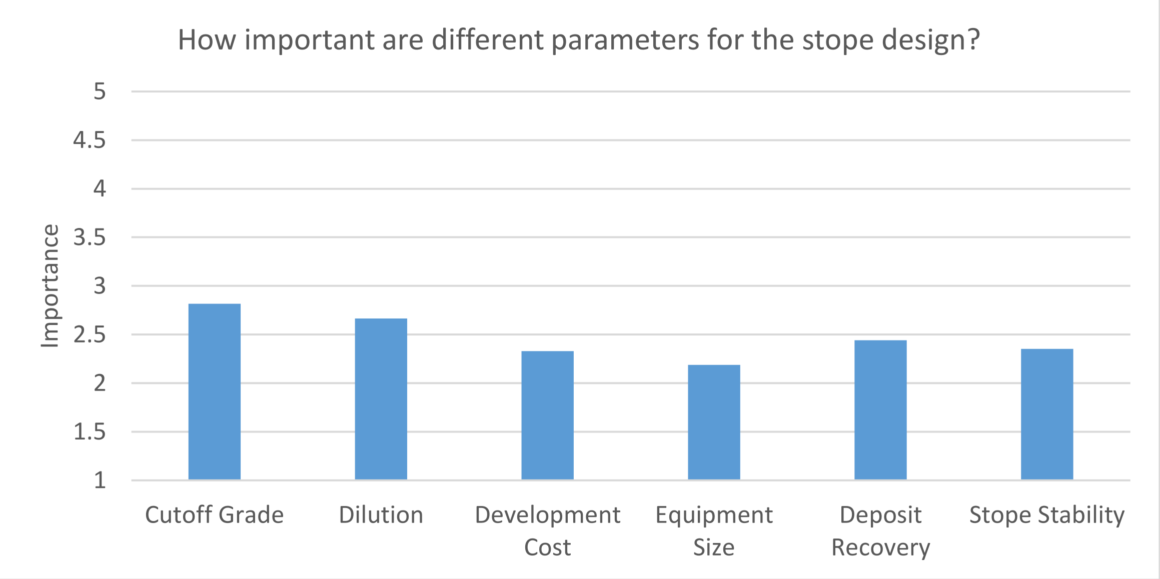


Figure 20: Impact of Factors on Stope Design (Values: 1= very unimportant to 5= very important)

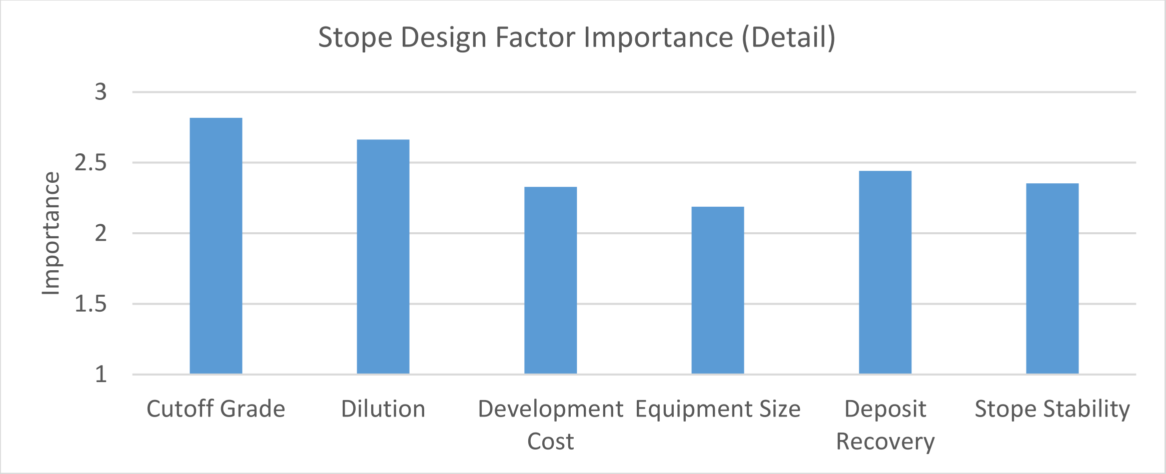


Figure 21: Detail View on Stope Design Factor Importance (scale adjusted to 1 to 3)

4.3.4. Reliability of Stope Design Methods

In order to evaluate the performance and grade of satisfaction with the current state of the process of designing stopes, the next step was to find out whether the respondents were satisfied with their currently applied stope design methods and would thus tend to recommend it. The underlying idea of this question was that a fully satisfied engineer would recommend his method. Figure 22 illustrates that less than 50% of the participants would recommend their stope design method. The reason, however, was not purely due to a lack of satisfaction with the own stope design method but rather related to the adequate insight, that the method how stopes were to be designed is strongly dependent on the deposit and geological conditions. So, it was commonly emphasized that any method for designing stopes needs to be adjusted to the specific conditions.

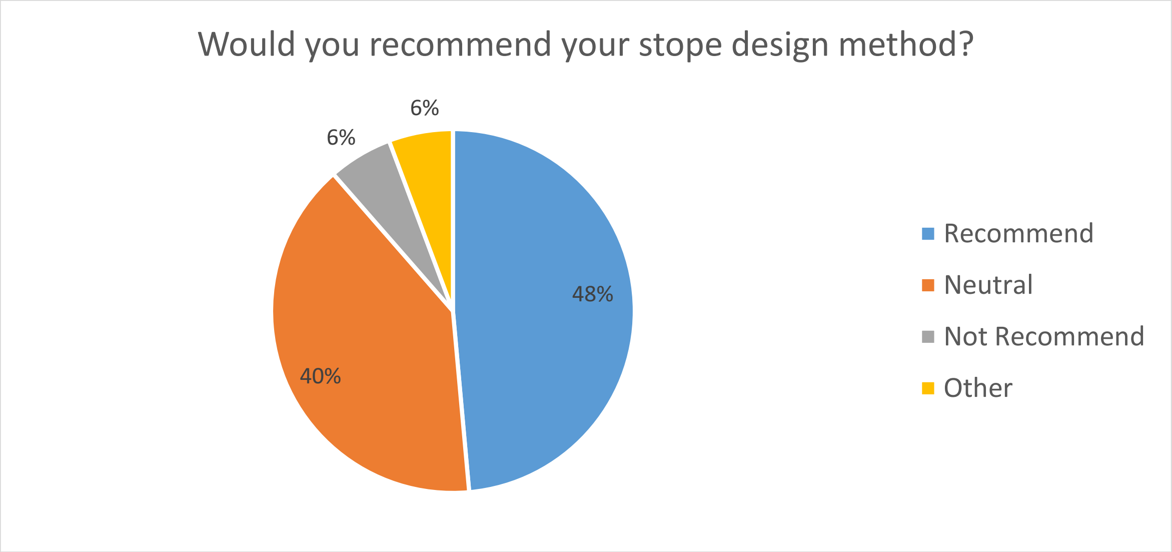


Figure 22: Recommendability of Stope Design Approach

4.3.5. Stope Performance

In order to more adequately assess whether stope performance is commonly tracked and analyzed, the application of stope stability and accuracy measurements is assessed. Figure 23 illustrates that 97% of the respondents stated that this is the case. While depicting that this is done by means of **C**avity **M**onitoring **S**ystems (**CMS**) in 77% of the cases. The other methods are relying on comparing planned and mucked tons, visual inspections, seismic controls, borehole extensometers, and independent laser scanning with point cloud data.

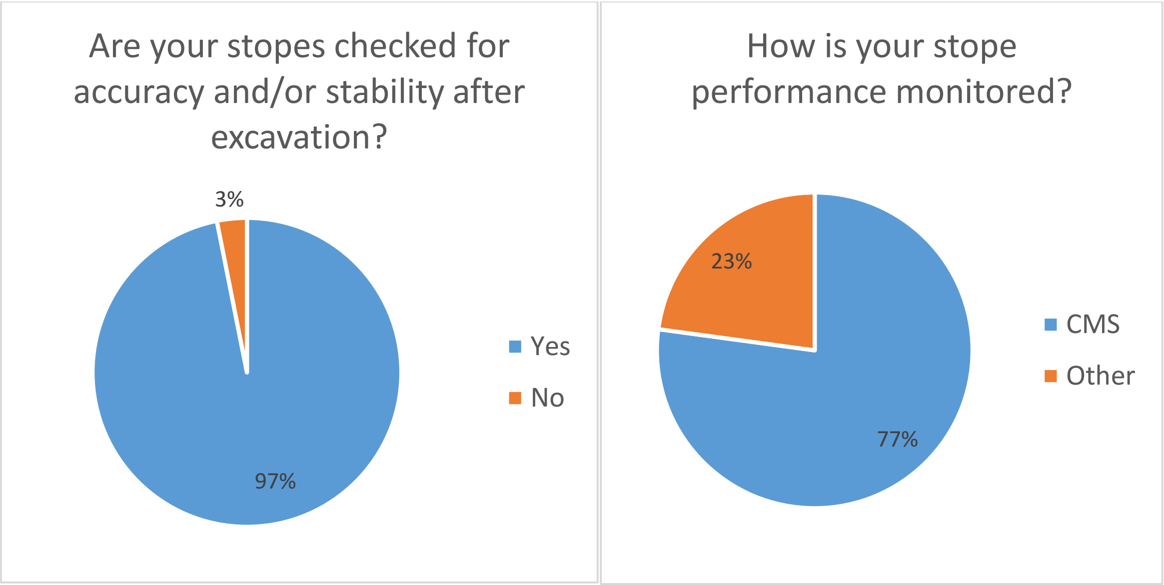


Figure 23: Stope Performance and Control

4.3.6. Most important Improvements for Stope Design

Next, expert opinion on the most important improvements to the stope design process is assessed. Figure 24 illustrates that the implementation of additional geotechnical data, improvements in the software, and the integration into general mine planning are the improvements most urgently desired. Unfortunately, there is considerable diversity within the methods, which indicates that there are several considerable aspects for improvement that should be considered when attempting to improve the stope design process. It should be noted that the aspect of making additional geotechnical data accessible is exactly what the GAGS-project is aiming to offer for stope design.

Several other areas for improvement are mentioned, these are the implementation of more reliable grade data, a variable cut-off, reliable performance indication for dilution-cable-bolt utilization, and utilization of hanging wall offset to decrease dilution.

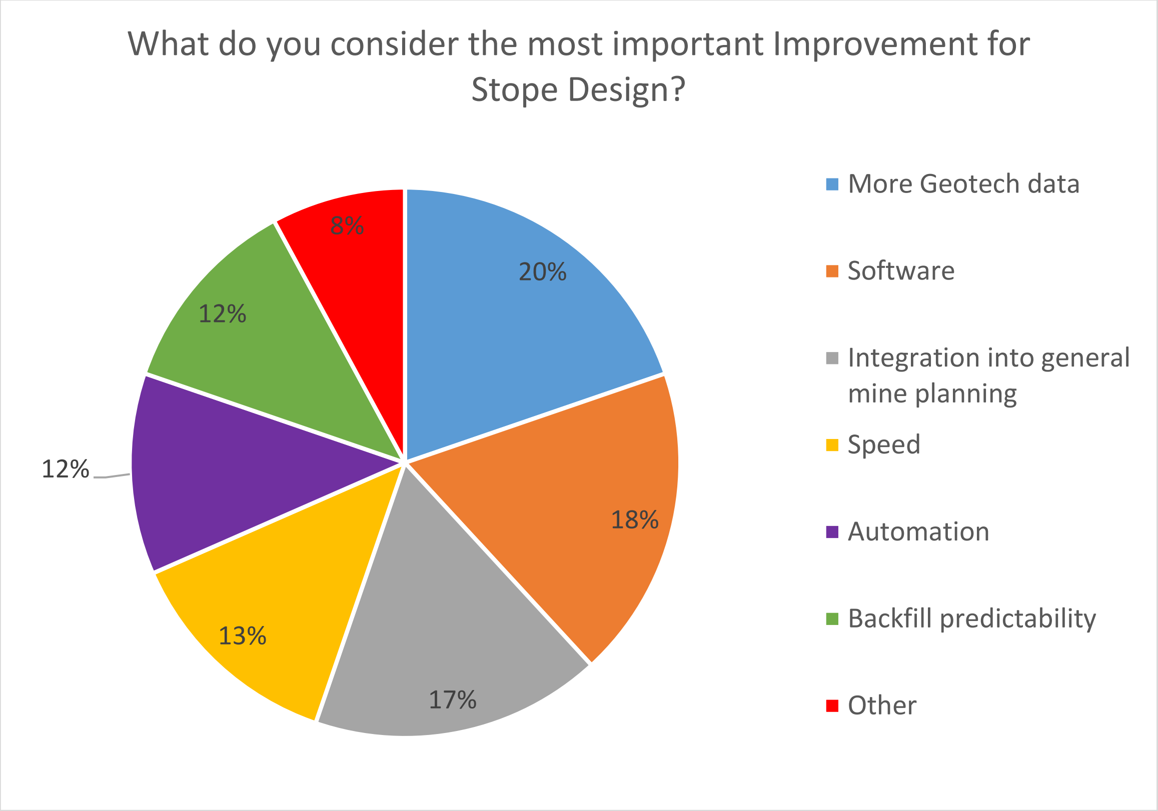


Figure 24: Most important Improvement for Stope Design

4.3.7. Utilization of Geotechnical Methods

Consecutively, the utilization of geotechnical methods within the mining industry was assessed, this served as an orientation on how new geotechnical methods should be presented and promoted and how likely a potential implementation of specific methods within the industry should be considered.

Initially, the utilization of geotechnical investigation methods was asked for. Figure 25 illustrates that 45% of the respondents have utilized some kind of geotechnical investigation method until the present day. While most of the applied geotechnical methods were from the area of geomechanics, reaching a share of 73%.

The methods named in the free-text answer session were: Geomechanical [**R**ock **Q**uality **D**esignation (**RQD**) , **R**ock **M**ass **R**ating (**RMR**), **M**ining **R**ock **M**ass **R**ating (**MRMR**), **L**ife **O**f **M**ine (**LOM**) Stress Model, Deformation Monitoring, Core Logging, Q-system, ELOS-Chart and Hoek-Brown failure-criterion], geophysical [**ATV** and **OTV** (**A**coustical and **O**ptical **T**ele**V**iewer) and gravimetric testing] and geochemical [**AAS** (**A**tomic **A**bsorption **S**pectroscopy) and Fire Assay].

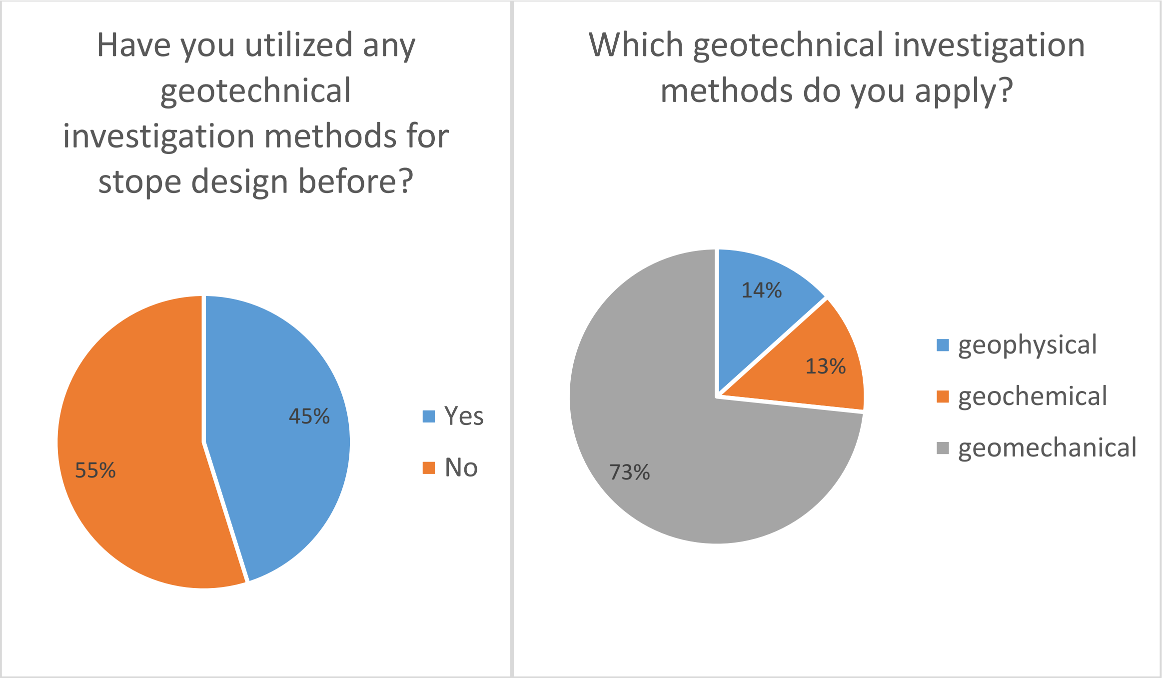


Figure 25:Utilization of Geotechnical Methods in the Mines

Next, the situation of planned future implementation of geotechnical methods into the stope design process was assessed. After analyzing the responses, it can be concluded that there is a slight trend towards the implementation of geotechnical methods in the future as compared to the present implementation, this is illustrated in Figure 26.

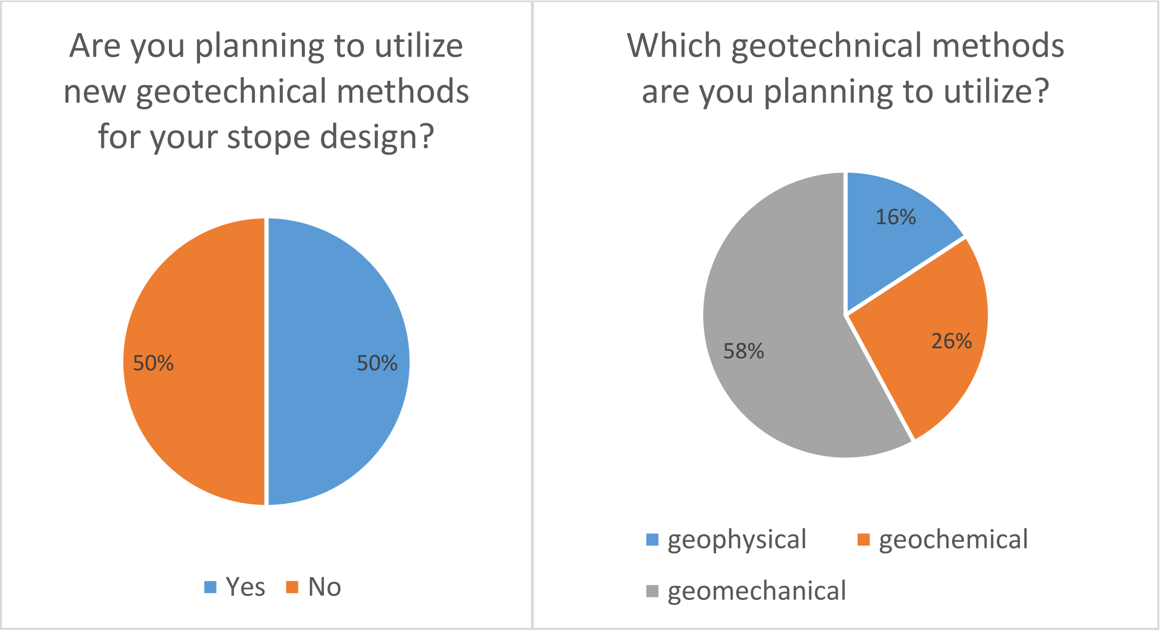


Figure 26: Planned Implementation of Geotechnical Methods for Stope Design

While the utilization rate of geotechnical methods only increases marginally, interestingly, there is a considerable trend towards the implementation of geophysical and geochemical methods for stope design in the future.

4.3.8. Improvement Implementation and Conditions

After establishing the general situation of current and planned utilization of geotechnical methods, it is of essential importance to assess whether the mining industry would be willing and interested in the implementation of the methods developed within the GAGS project. Therefore, this situation is assessed consecutively assessed.

Figure 27 illustrates that the interest in the implementation of LIBS (Laser-Induced Breakdown Spectroscopy) and new in-situ rock mass characterization methods are ranging between 65% and 70%, and thus at considerably higher rates, than the rates for the implementation of geotechnical methods in general, as assessed in previous questions. This should be understood as an indication that by explaining the specific methods and their associated benefits in detail, the potential for implementation for the proposed methods could be increased considerably.

Consecutively, it seemed reasonable to assess whether there is a general willingness to implement changes in the stope design process, and which conditions and requirements would be associated with these changes. Thus, initially the general willingness to apply changes was assessed, then the required conditions were defined and finally, the tolerable timescale for possible improvements was identified.

The general willingness to implement changes in the stope design process is considerably high, reaching a value of 87%, as illustrated in Figure 28. It is to be concluded that the conditions for the implementation of such changes were mainly proven feasibility and the implementation within a software. Other requirements identified are realized benefits, reliability, predictability, faster process, and new personnel.

From these insights, it can be seen that general changes to stope design that are not limited to geotechnical methods are more likely to find implementation, which seems reasonable as this is to be considered the unrestricted question related to the topic.

The conditions of delivering proven feasibility and software implementation in order to allow for potential implementation in the software should be considered directly applicable to the GAGS-project research, as data should be compatible with mining software and feasibility should be proven, possibly by means of case studies.

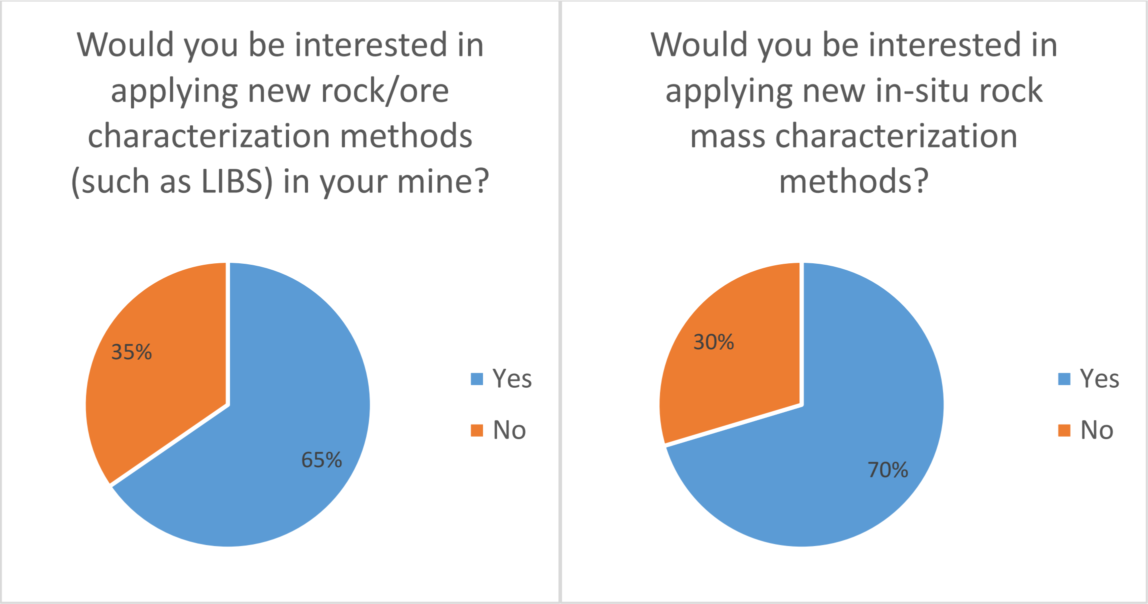


Figure 27: Interest in GAGS-project Research Implementation

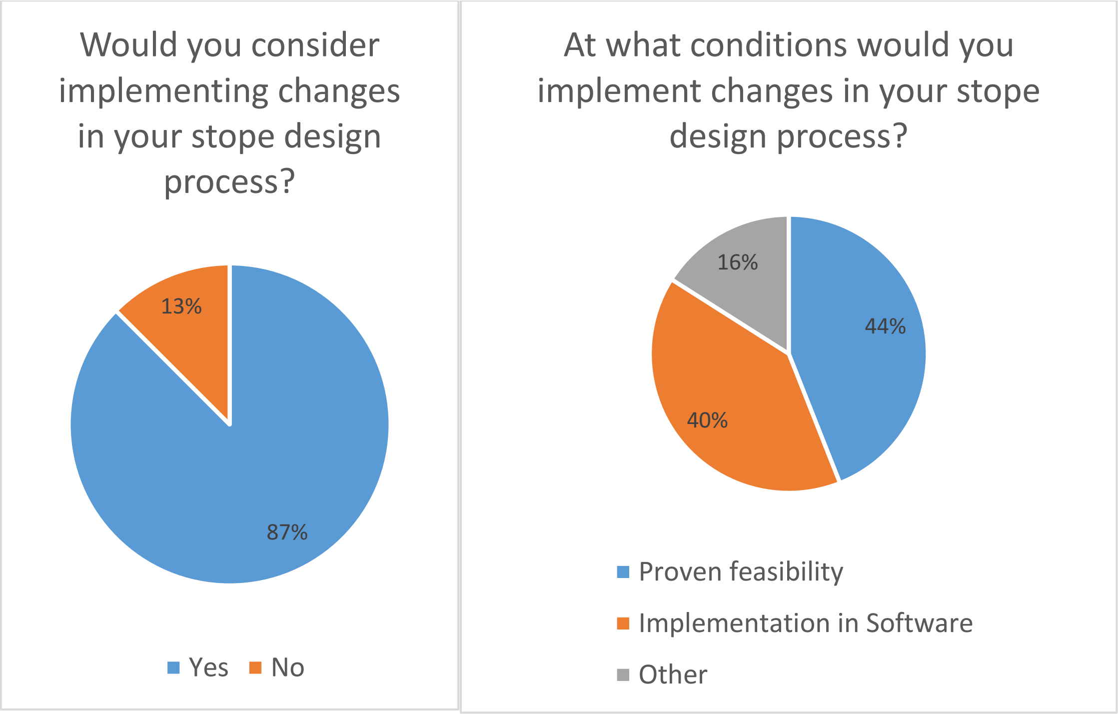


Figure 28 Willingness to implement Changes in the Stope Design Process

Since the timeframe for the availability of additional geotechnical data to be acquired was identified as a potential key issue, for the implementation, utilization, and ease of use of the new technology, the requirements regarding this issue were specifically assessed. The results are illustrated in Figure 29.

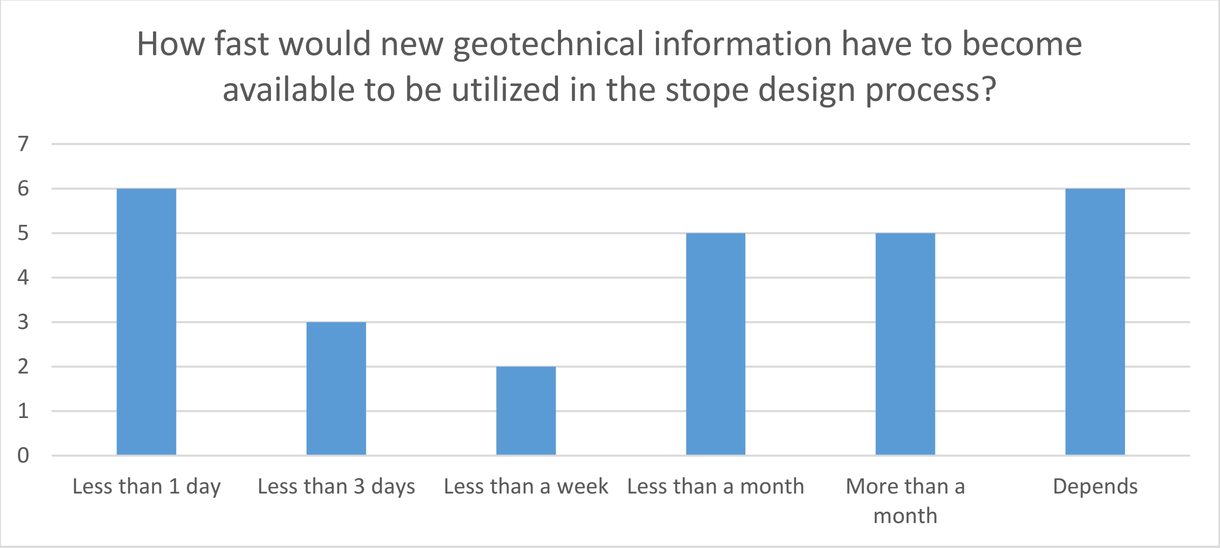


Figure 29:Tolerable Time for Measurement-Data to become available

It can be concluded that results that would be available within three days would satisfy the needs of more than 70% of the respondents. Though a considerable number of responses stated that the timeframe to be allowed for obtaining the data of additional measurements would strongly depend on the value-added of the data to the stope design process.

Due to the early project stage of the GAGS-project, a separation of the required timeframe between data from LIBS and geophysical methods was not specifically asked for. Since both methods could be applied individually this information seems very reasonable to be assessed in the future.

4.4. In-depth Analysis

After assessing and presenting the directly evaluable responses to the survey the next logical step was to follow-up on the initial response group pattern recognition in the form of an in-depth analysis. This in-depth analysis was primarily performed by means of a correlation analysis. Besides the correlation analysis, a hypothesis analysis was performed.

4.4.1. Correlation Analysis

A correlation analysis can achieve a deeper level of understanding of data acquired with a survey (Friedman, 2012). In this case, the correlation analysis was desired to identify correlations between different responses and response groups. The intention of performing a correlation analysis was to identify dependencies and links between and within specific groups within the questionnaire respondents.

An issue with the execution of the correlation analysis lies within the limited availability of quantifiable values and the limited response count. After transforming the free-text answers into quantifiable values and groups, however, a rudimentary correlation analysis was performed. This correlation analysis was limited to identifying outstanding correlations with specific observed parameters.

A parameter that should be closely observed is the answer quality as it can be an indication of interest. Thus, specific correlations to this factor are observed within the survey. Regarding the answer quality, the best results can be seen from mines that mine gold exclusively, with average answer quality values reaching a quality score of 2.5, compared to the overall average of 1.89. This correlation is illustrated in Figure 30.

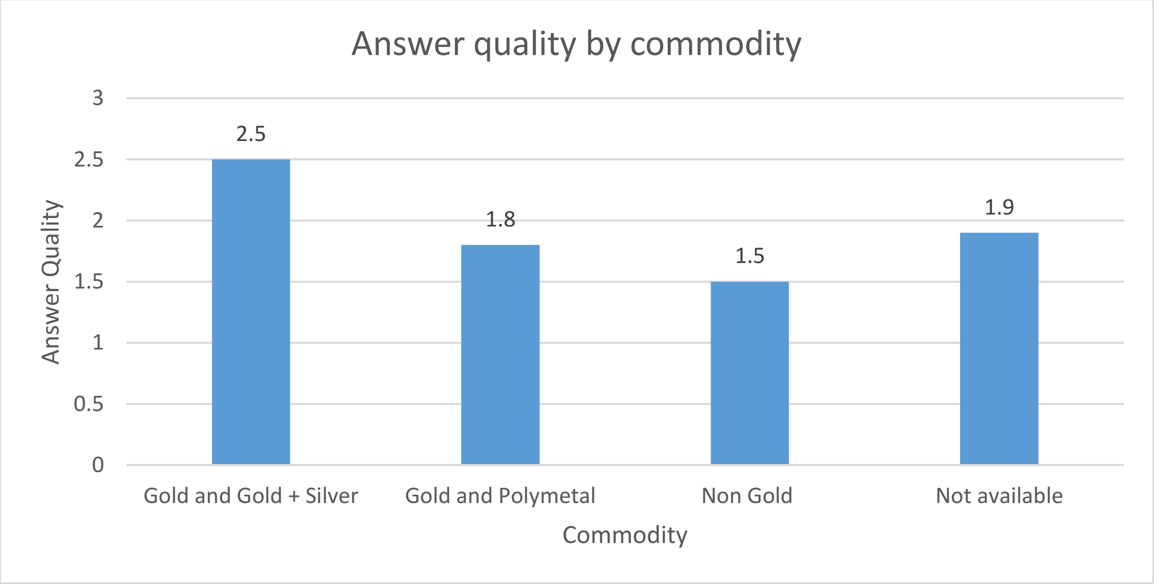


Figure 30: Correlation: Answer-Quality to Commodity (0 = disqualified to 3 = excellent)

This can be interpreted as an indication that professionals from gold mines are especially aware and focused on solving the current issues and struggles related to stope design.

Interestingly another correlation identified was that the answers which did oppose recommending their own stope design method were all classified to be excellent. This could possibly indicate a correlation of the awareness of the specificity of the stope design process with the dedication to advance stope design research.

As the majority of the respondents took part in the survey out of goodwill rather than being obliged by being asked by a relative person it could also be concluded that the pattern that most responses originated from gold mining operations is due to the interest in the topic from mining professionals working with this commodity.

An additional parameter that was worth observing were correlations that were associated with the mine size. The mine size, in this case, is defined by the tons of ore mined annually. The following correlations were observed.

A bigger mine size is correlated to:

More diverse mining methods, higher recommendation rate of own stope design method, increasing share of polymetallic mines, increasingly challenging geological conditions, and more identified improvement factors for stope design

In the following, some assumptions are drawn to explain these correlations and possible conclusions from these are established:

1. More diverse mining methods:

A bigger mine size and the thus typically bigger orebody deems a wider range of mining methods necessary to properly execute the mining operation. This also allows to address diverse geological conditions and irregularities present within the orebody.

2. Higher recommendation rate of the own stope design method:

This could indicate that in bigger mines more reliability and universality are accredited to be inherent within the own stope design methods. Maybe a certain lack of doubt can be assumed here. This can have a negative implication towards the willingness to implement changes and thus adapt the innovations to be developed as part of the GAGS-project.

3. Increasing share of polymetallic mines:

A bigger mine size is related to a higher abundance of polymetallic mines, this can be related to the deposit sizes and geological conditions as well as lower mining cost due to the economy of scale. Explaining the underlying concepts of possible implications and causes for this phenomenon would exceed the scope of this chapter

4. Increasingly complex geological conditions:

Bigger mines commonly state more challenging geological conditions. This could be due to the more frequent encounter of challenging situations during production. Possibly this correlation is to be seen as a simple result from the bigger production size.

5. More identified improvement factors for stope design:

More diverse factors are put forward regarding the possibilities to improve stope design. This might be related to encountering a broader variety of challenges and problems within the production of a mining operation.

While analyzing the importance of stope design parameters, it became apparent that the parameter “Cut-off”-grade is correlated with the “Development Cost”- parameter, this correlation and the reasons for it should be further investigated, as only the correlation and not the underlying reasons can be identified in this survey. The correlation is visualized in the correlation graph in Figure 31.

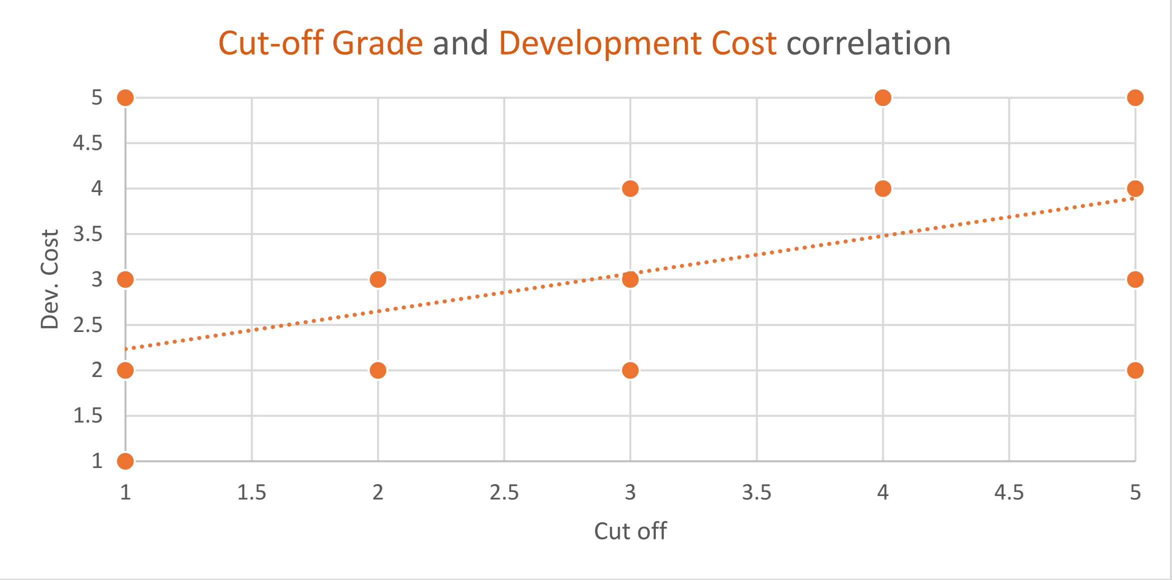


Figure 31: Correlation: Cut-off to Development Cost

4.4.2. Hypothesis Testing / Analysis

Due to the limited applicability of the correlation analysis, resulting from the obtained survey data an additional in-depth analysis in the form of a hypotheses analysis was performed.

In order to perform this analysis, initially, hypotheses related to the surveyed subject had to be defined. These hypotheses were then evaluated by assessing the responses from the survey. This allowed to judge whether the survey supports or refutes the defined hypotheses. A hypothesis analysis was favorable due to the amount of free-text answers and the elaborated complexity of the questionnaire since it allowed to apply a specific focus on specific points of interest that stood out to an informed individual (Lynn, 2007)

The hypotheses defined were related to the focus of the research project, results from evaluating the survey responses and assumptions of a mining engineer. The underlying assumptions for the hypotheses definitions are given here:

A1: Geological conditions influence geotechnical methods for stope design

A2: Geological conditions influence applied stope design methods

A3: The commodity influences the importance of stope design parameters

A4: The size of a mine influences the number of identified parameters for improving the stope design process

A5: The methods for stope design are correlated with the importance of stope design parameters.

The hypotheses based on these assumptions were formulated, analyzed and then evaluated consecutively.

H1. The more challenging the geological conditions the more geotechnical methods are applied for stope design:

In order to analyze this hypothesis, it was necessary to analyze the correlation between the geological conditions and the geotechnical methods utilized. As also the future development was to be assessed not only in the situation with currently applied geotechnical methods for stope design was analyzed, but also the situation of planned for future implementation of geotechnical methods within the stope design process was assessed. The results of this analysis are visualized in Figure 32. There was a clear trend towards an increase in the utilization of geotechnical methods with increasingly challenging geological conditions. The more interesting conclusions lie within the strong increase for the future implementation of geotechnical methods in the stope design process. Applied to the GAGS-project, it can be concluded that the implementation of novel geotechnical methods should be most likely within very challenging geological settings. It should be noted that the most reliable observations have been made for "challenging" and "very challenging" geological conditions as the response count for varying and not challenging geological conditions was too small to be held reliably accountable for. It can be concluded the first hypothesis holds true and can thus be considered confirmed.

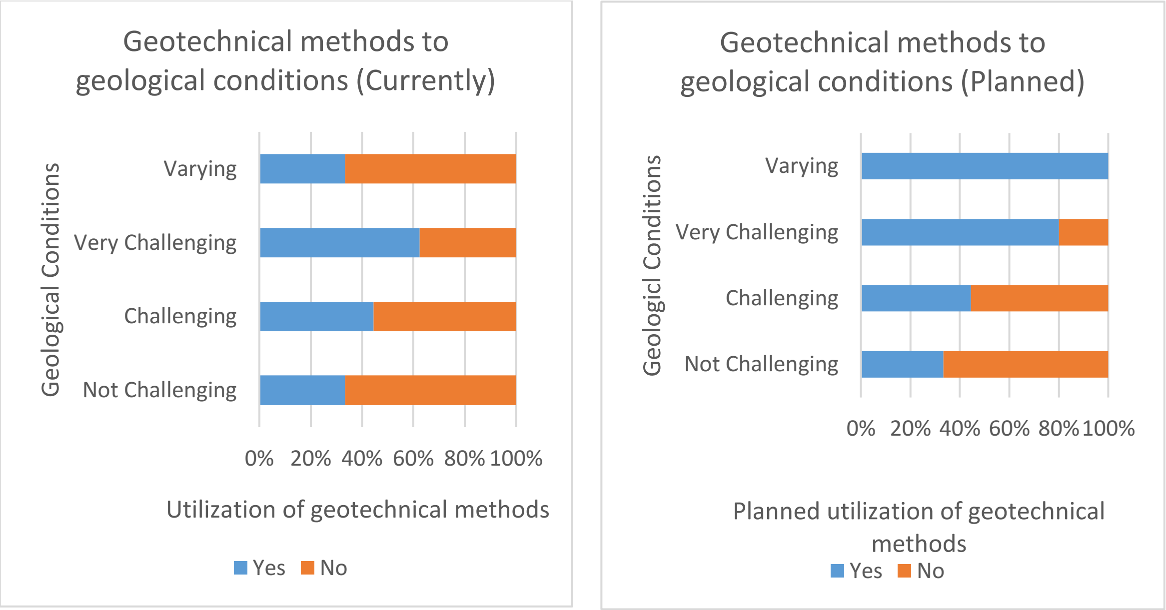
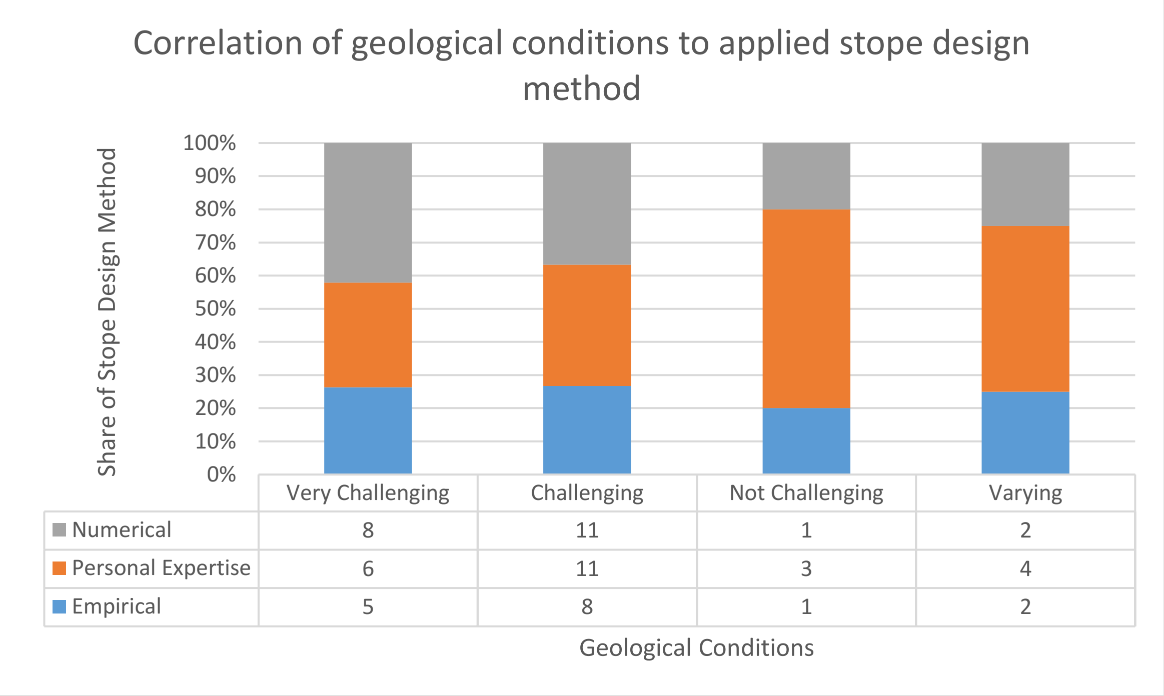


Figure 32: Correlation of currently utilized (left) and planned (right) Geotechnical Methods to the encountered Geological Conditions

H2. More challenging geological conditions will result in less common utilization of empirical methods for stope design:

For analyzing this hypothesis, it was reasonable to correlate the geological conditions to the stope design methods. As can be seen in Figure 33 the only clear trend that could be extracted from analyzing the correlation between these two factors was that under varying and not challenging geological conditions the utilization of personal expertise in stope design shows a steep incline, though this conclusion should be further investigated as there was only a very limited share of the survey population that quoted these geological conditions.

It should be noted that this hypothesis had to be rejected and as a conclusion, an increase in the utilization of personal expertise within "Not Challenging" and "Varying" geological conditions can be observed, which was however not reliable due to the small response count.



	Very Challenging	Challenging	Not Challenging	Varying
Numerical	8	11	1	2
Personal Expertise	6	11	3	4
Empirical	5	8	1	2

Figure 33: Correlation of geological Conditions to applied Stope Design Method

H3. Respondents working with high-value commodities are considering the cut-off grade as a more important factor for stope design than lower-priced commodities:

A closer investigation of the "Cut-off"-grade parameter was reasonable since it proved to be the most important parameter within all stope design parameters, within the survey. However, most of the responses are associated with gold mining which was to be considered a high-priced commodity. Underground mining in general, due to the higher specific mining cost is also correlated with higher-priced commodities. Analysis of this hypothesis was conceptually limited, and the survey data required regrouping to investigate the adequacy of this hypothesis.

The new grouping of the responses chosen for this analysis was:

1. Gold and Gold & Silver: Responses from mines which are exclusively mining gold and gold and silver only
2. Non-Gold: Responses from single or two metal mines excluding gold
3. Polymetallic: Considering any response mining 3 or more than 3 commodities
4. Not available: Responses lacking information about the mined commodity
5. Global Average: The global weighted average of all responses

The results from the performed analysis can be seen in Figure 34. It can be concluded that the highest importance for the cut-off grade is found within the "Gold and Gold & Silver" group. Whereas the lowest importance towards the cut-off grade was found within the "Non-Gold" group. Thus, it is plausible to say that this hypothesis can be confirmed. Additionally, the encountered importance of the cut-off grade within the whole survey can be explained partially by this analysis.

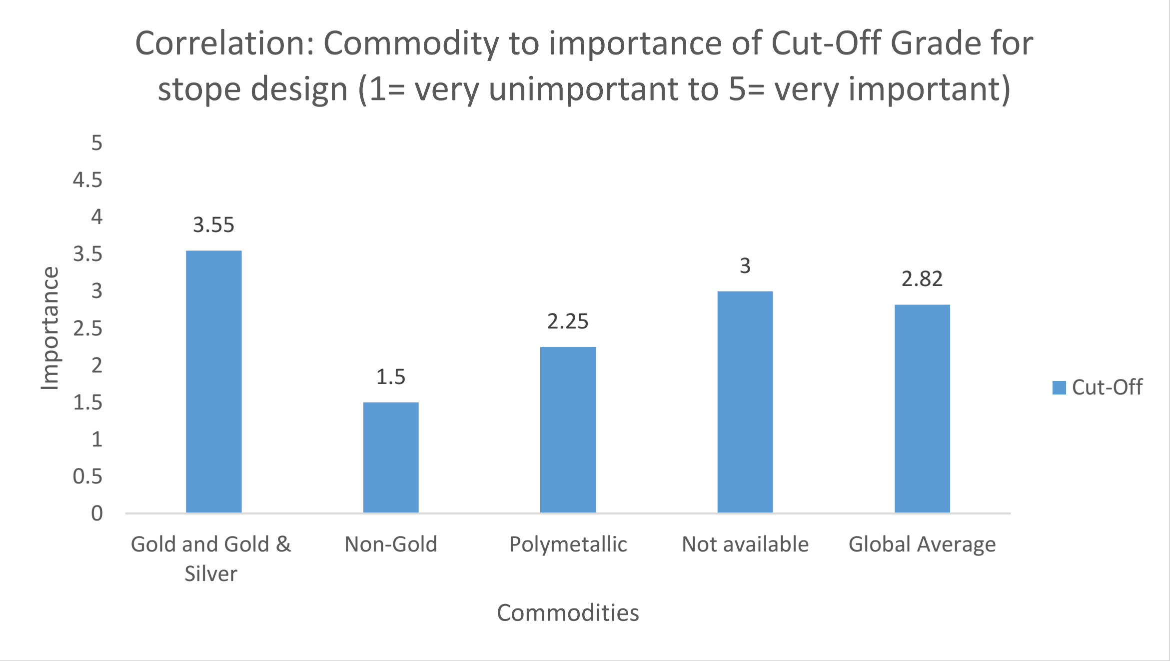


Figure 34: Correlation of Commodity to Importance of Cut-off Grade

H4. The bigger the mine the more different factors are considered important for stope design:

Due to the variable mine sizes, the analysis of this hypothesis requires a regrouping of the survey results, thus it was chosen to divide the survey data into 2 groups one group reaching an annual ore production of up to 1,000,000 tons of ore per year and the other group exceeding this value.

The results of this regrouping process are visualized in Figure 35. Following this analysis, it can be concluded that an increase in mine size was associated with an increase in identified factors for improvement.

Thus, it can be concluded that this hypothesis holds to be true.

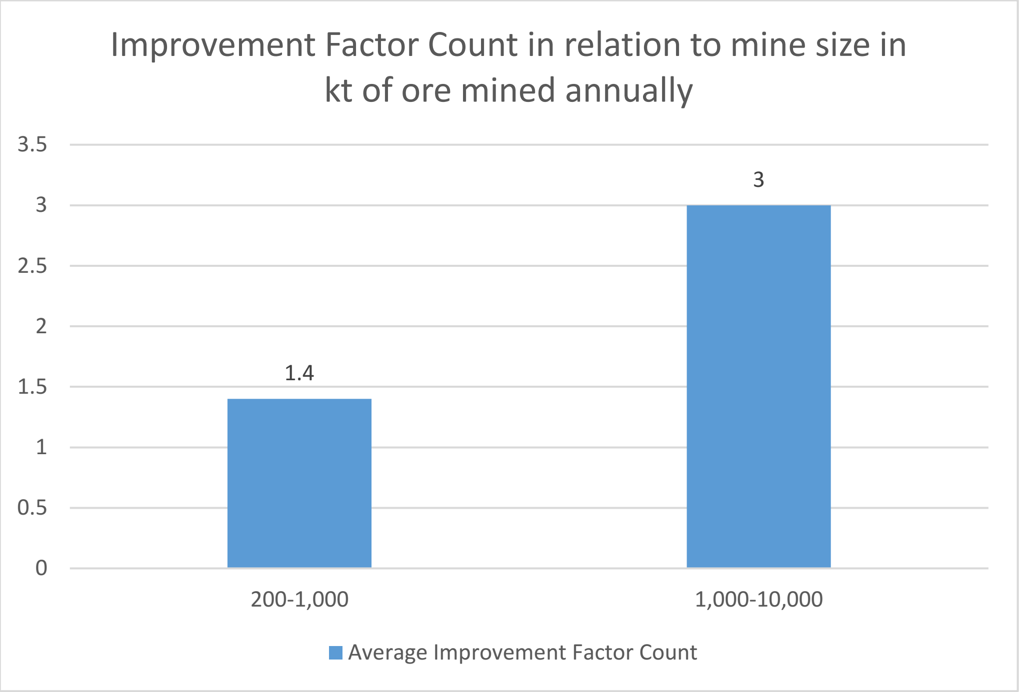


Figure 35: Number of Improvement Factors by Mine Size (Improvement factor: number of individually named improvement factors

H5. Stope design methods show a correlation to the importance of stope design parameters:

Even after a thorough analysis of the data, a correlation between the stope design method and the importance of stope design parameters could not be identified by any means, thus this hypothesis had to be refuted.

4.5. Discussion of Survey Results

4.5.1. Importance of the Meta Data-Analysis

By analyzing the meta-data of the survey responses, it could be observed that an extensive interest in improvements for stope design exists within the international mining industry. It is most promising to reach mining industry professionals by a highly personalized contact approach by using LinkedIn and all other possible channels for contacting potential respondents. A higher answer quality on average could be observed by totally unrelated respondents, who answer the survey in extensive detail, potentially out of interest in the research topic or goodwill. It is to question whether the high response rate from gold mines stems from a concentration within underground mines or an increased problem awareness of stope design within this part of the mining industry.

4.5.2. Important Observations from Survey Responses

The general survey responses allowed for very detailed and interesting insights within the mining industry. It is difficult to evaluate which of these was most interesting. Thus, a simple selection will be covered here. It is impressive how dominant sublevel stoping methods were in the survey and how challenging the geological conditions were considered by the respondents in general.

The insight that numerical methods and personal expertise outweighed empirical methods by a margin is an important observation and the implication of this for the GAGS-project will be discussed in chapter 5. Another important factor was the dominant application of stope performance control methods and within this part, the dominance of **C**avity **M**onitoring **S**ystems (**CMS**), can be interpreted as the existence of an inherent doubt towards the reliability of stope design methods.

Consecutively observing how many respondents consider the availability of more geotechnical data, the integration of stope design into mine planning, and improvements in stope design software most important should be considered a potential guideline for any research related to stope design.

The direct interest in improvements should be considered interesting and promising for stope design research. The timescale to make results from measurements available within a timeframe of three days should be considered a very interesting guidance. Together with the desired proven feasibility and implementation within software.

4.5.3. Important Observations of the in-depth Analysis

The attempt to evaluate the free-text answers by means of an in-depth analysis should be considered a successful approach as several additional insights were gained by performing this analysis. Since this analysis relies on specific assumptions it is important to see the conclusions within context, which is why the chapter should be read by itself. As an interesting observation, it should be mentioned that a possible explanation for the importance of the cut-off grade for stope design was found in the abundance of gold mining operations within survey responses, which influenced the other operations.

4.5.4. Possible Improvements for Survey Conduction

For conducting the survey, the most successful method, which also resulted in the best answer quality is to be considered LinkedIn. The method to utilize direct contacts might be feasible for a very well-known and respected person in the area, but not for a typical student at the beginning of his professional career. Forum posts were not very successful, possibly due to the lacking possibility to directly address the possible reader. The best answers were received from mainly totally unknown individuals, these individuals probably believed in the value of related research and this survey. Thus, they did fill in the questionnaire out of goodwill rather than feeling obliged to do so. Support for this assumption can be seen from the increased answer quality within this group. In general, it is interesting to observe how much time people were willing to spend on responding to the survey and in which kind of high-quality answers, allowing for valuable insights were received. It seemed to be a good idea to split the survey into 3 separate surveys in order to allow for tracing back the response origins in a more detailed manner, unfortunately, this resulted in issues with the automatic response analysis tools, lost information and a lot of additional manual labor. It is hard to judge whether the insight that LinkedIn was the best source of responses was worth those issues.

In general, the questionnaire was adequate for its purpose, even though some minor questions like mine size and mined commodities were initially not considered and thus missing. These lacking questions could be compensated for by manual research. The lack of diversifying the questions about stope design into the separate design stages, however, is an unfortunate mistake. The reasons for this can be found within an insufficient background knowledge related to the stope design process of the survey author at the time of the questionnaire creation.

The issue related to excessive free-text answers for several questions was identified beforehand. Despite the expected difficulties to quantify and group the answers to be received, it can now be concluded that the increase in answer quality and detail was worth taking the associated risks and additional work. By still acquiring multiple choice values and due to the limited survey population, an adequate evaluation and analysis of the acquired data could still be achieved. Due to the insightful high-quality answers, this approach can be considered successful.

Regarding the diverse field of stope design and its various disciplines, it should be considered fortunate that so many different industry professionals from such different fields of stope design replied. Mining professionals from different areas replied, there was a high degree of internationality and different positions within hierarchy were adequately represented.

4.6. Mine Visit and Interview

In order to achieve an in-depth and detailed understanding of the background of stoping based mining operations, a mine-visit and an interview with mining professionals from a Finnish stoping mine were conducted. The additional purpose of this process was the attempt to identify a potential partner mine for the GAGS-project. During the mine visit, additional points of interest for the research were identified. The preparation of the mine visit, interview and the gained insights from these, shall be presented here.

4.6.1. Mine Visit Observations

The mine visit was hosted by the responsible Mine Planner of a Finnish underground stoping mine and performed on the 26th of June 2019. To allow for a better understanding of the practicalities and real-life limitations of stope design and its performance the conditions in a mining operation were identified during this visit. Additionally, the project-specific requirements were presented to the responsible personnel in the mine in order to assess the potential of founding a strategic partnership with the mine for the research project. This is necessary to test and apply the methods that will be developed as part of the GAGS-project under real conditions.

During the mine visit, the applied process for stope design and its role within mine planning, in general, were critically observed, analyzed and evaluated.

The stope design process is performed following the scheme underneath: “General mine plan is updated at least once per year and it covers the general layout and stoping plans (person #1). These plans are used as guidance when more detailed development and stoping plans are made (persons #1 and #2). Blast planning could be divided into the general blast plan (“these drill fans will be in this blast“, person #2) and detailed plan for timing of the charges (person #3).” (Interview protocol)

The most important observations are listed here:

The ore body delineation is commonly assessed by sludge drilling, due to its cost-efficiency, while the geotechnical parameters are assessed by means of RQD measurements and point load tests from drill cores, the results are checked for reliability by visual inspections.

Rock support like cable-bolting for increasing stope stability/ dimensions is not commonly used.

It was insightful to observe how the whole stope design and mine planning process had to be performed by only two mine planning engineers. This process also included the back-analysis and reconciliation process. This seems to be an interesting approach for a mining operation which is based on the results of this planning process for its very production. Additionally, it should be noted that no specific stope planning software was utilized. Rather the stope designs were manually implemented into Surpac based on personal expertise. It seemed interesting that the back-analysis of stope designs had been on hold for a considerable time due to lack of sufficient human resources to perform the work, this should, however, be seen in the context of the limited mine life.

The occurrence of rock bursts due to the increasing mine depth and stress concentrations resulting from the progression of the mining process was an interesting observation and can be possibly related to design or scheduling issues but is mainly to be accredited to the increasing mine depth. Though the negative impacts from this were successfully controlled by applying additional rock support.

4.6.2. Methodology and Structure of the Interview

The interview was based on certain questions and answers from the questionnaire on one hand and observations from the mine visits on the other hand. Additionally, the insights gained by performing the literature review and research analysis, the interest of the research project and questionnaire answers that needed clarification were identified, and specific questions prepared. In order to allow for adequate incorporation of the insights gained during the mine visit, to allow for excellent answer quality and due to the long-distance to the mine site, the interview was conducted in a written form by mail contact.

The detailed interview questions, answers, and comments can be in the appendix here: Interview protocol.

4.6.3. Important Interview Results

Since the interview and preliminary communication were very informative and insightful but also equally extensive, only the most important conclusions and insights from the interview will be presented here. If desired the detailed interview protocol can be found here: Interview protocol.

Regarding the general stope design and its process, the following explanation is to be considered very insightful:

Parameters for general stope designs:

- ore geometry (stope design is mostly an optimization process: take as much ore and as little dilution as possible)
- stoping order and schedule
- main horizontal stress direction
- weakness zones in and around the orebody
- separation of different ore types

Remarks for general stope design: “General stoping plan should not be too detailed (unless the final stope designs have been already done), because changes are likely. Ore reserve is updated once per year, but more detailed stope design is done with updated ore model and mill parameters, prices & terms.”

The mining cost calculations typically include the personnel cost for planning, however, stope specific calculations, that would allow for stope specific cut-off grade estimation verification, are not performed. It should be noted that mining depth and development costs, however, are considered as variables in feasibility calculations.

In relation to the stope design parameter importance from the survey, the difficulty to compare the individual issues was explained. As the importance of the parameters commonly is to be considered especially stope specific, due to the differences in ore grade, and its impact on economics of the mining operation.

An interesting aspect regarding the stope design process was the mentioned availability of integrated software, which incorporates planning, scheduling, and production tracking, and that this option is however not implemented in the mine, due to applied individual incompatible software. It should be noted that the importance of data integration within the stope design process was specifically addressed, and the statement that data should be readily available, to allow for quickly altering the drill plan, should not be neglected.

Fracture mapping was commonly performed from drill cores and face mapping of underground drifts. Fracture mapping includes these factors: set, orientation, intensity, persistence, spacing, and aperture. The data used in stope design was mainly the number, orientation, and location of the fractures. Due to the worsening rock-conditions, fracture mapping was performed more frequently, nowadays than in the past.

The general issue about limited-data availability in the planning stage of a mining project should be considered an essential aspect of stope design as can be seen from the following quote: “The 'grand design' of production levels is where the costliest mistakes are done. We e.g. have built infrastructure in places which we later discovered were in ore. That causes some major difficulties not only in recovering the ore but also using the infrastructure for its main purpose. Stope design is always closely linked to the development plans. The information from production holes of course helps, but the economic benefits at that point are much smaller. I guess its benefit is more in making the operative work smoother, particularly if you combine it with programs where you can change drill plans on the fly depending on the structural/geological data. And of course, all additional data helps to revise the geological/geomechanical models.”

4.6.4. Evaluation of Interview and Mine Visit

Most importantly, it should be noted which parameters and processes are used for stope design. In general, the importance of having reliable grade estimations and orebody delineation as early as possible should be considered crucial as here the most impactful decisions about stope and infrastructure locations are taken. Thus, it should be carefully evaluated whether expenditures for exploration and fracture mapping, preliminary to mine development could not be compensated for by potential benefits in mine layout and sequencing. Additionally, the availability of the data gathered during development should be implemented as fast as possible to allow for maximizing benefits.

Unfortunately, it was not possible to enter a strategic partnership with this mine as initially intended. This was mainly due to the limited mine life left for the operation. This impacted the scheduling options as well as the availability of locations within the mine where the necessary testing could be performed. Additionally, it would not be likely that the mine would benefit too much from the improvements in stope design that are to be realized, due to the same issue.

4.7. Summary and Evaluation of Survey and Interview Results

After executing the survey result evaluation and in-depth analysis, the results are to be concluded in a more compressed and comprehensive form.

Overall, the survey can be considered as a very insightful approach. An international audience was reached, adequately representing the diverse environment present in the mining industry. Based on how long and well-informed the responses were, this topic clearly is considered an important cornerstone for the implementation of innovation within the mining industry.

A factor important for the implementation of new technologies the mining methods are predominantly Sublevel Stoping and Cut & Fill, they are however not to be considered as a too strict factor limiting applicability, as changes do frequently occur.

In general, there is no dominant stope design method, but rather the reliability of empirical stope design methods as a stand-alone approach is not considered to be sufficient, whereas other methods work without auxiliary support by additional methods. The utilized software is diversified, as very different programs, based on different methods and algorithms, are utilized. The stope design process either occurs within mine planning or production, the utilization of an iterative approach for stope design is not yet well established, whereas the duration for designing stopes shows great variety. It should be noted that most professionals are well aware that stope design requires very specific adaptions to the local geological settings, which then results in low recommendation rates of their own stoping methods. The most important factors for stope design are cut-off grade and dilution, which would specifically serve the desired purpose of the elements to be developed within the GAGS-project.

For the duration to make new geotechnical data available a time frame of three days is considered to be sufficient for about 70% of the survey participants. The possibility to implement and utilize methods within back-analysis should be considered as guaranteed, since almost every respondent performs these checks, while it is mainly executed by utilizing Cavity Monitoring Systems (CMS).

Most professionals consider the geological conditions of their deposit challenging to very challenging, while the very challenging group shows a tendency towards the implementation of solutions for gathering more geotechnical data. In general, there is a trend towards the future implementation of geotechnical methods, which then again shifts away from mainly being based on geomechanical methods, towards the equal utilization of geomechanical, geochemical, and geophysical methods. This goes along with the mentioned challenges and desired improvements for stope design, which states that mainly more geotechnical data and improvements in the software are desired.

It should be noted that the acceptance rates for specific geotechnical methods are considerably higher after explaining them in detail, then when asking about the utilization of geotechnical methods in general. Thus, the importance of an in-detail explanation of the method and its realized or planned benefits should be considered to be of outstanding importance.

From the mine visit and interview, it was possible to gain additional in-depth insight into the specific processes related to stope design and mine planning. Thus, it should be considered beneficial to perform additional exploration prior to initiating mine planning and incorporate the results gathered during the development process within the planning process.

The requirements to provide proven feasibility and software implementation/compatibility in order to allow for a potential implementation shows that the newly acquired data should preferably be compatible with mine planning software and the feasibility of methods proven by executing extensive case studies.

5. Industry to Research (Discussion)

In this chapter, the focus of research in relation to the identified needs on one side and the value of the investigation for the GAGS project shall be discussed. This will allow to judge whether the research focus is adequate for the industry´s needs and to define the value of the thesis itself

5.1. Correlation of identified Problems

Here the challenges for stope design, identified within industry are compared to the focus of research activity and their convergence with each other is evaluated.

Since it has been identified that the main focus of research is currently in the area of developing algorithms related to stope design, and implementing them within software, while researching methods integrating stope design into mine planning, making stope design more flexible and iterative as well as automated. Additionally, the integration of grade uncertainty into the stope design process is being established into stope boundary optimization currently.

When looking towards the industry´s perspective of things, it can be concluded that the applied methods for stope design, have a great variety of methods applied commonly in addition to each other. This shows that no single method is to be considered sufficiently reliable. Additionally, this shows that new methods do not have to substitute old methods, but can rather be seen as potentially complementary to each other. Also, stope design is still commonly performed manually based on personal expertise, even though this has been proven to commonly yield considerably sub-optimal results. The biggest desire from industry is to make more geotechnical data available for stope planning, improve software, and integrate stope design into general mine planning to a bigger extent.

Thus, in comparison, it can be concluded that the research considers most of the desired aspects identified for stope design within the industry. However, the most important aspect, to make more geotechnical data available, seems to be neglected to a considerable extent. It should be considered a very promising approach to allow for more optimal stope design to gather this data as early as possible. This will also limit the negative impact resulting from the limited-data issue of stope design and mine planning. Additionally, empirical methods don’t seem to be sufficiently reliable to satisfy industry needs.

Potential improvements are simple yet considerable in their effect, take this example: The stress in underground openings generally increases with depth but many operations maintain the same stope dimensions during the whole life of mine, even though this can be optimized for different conditions, which shows that in practice there still should be a high potential for improvements.

5.2. Value of Investigation

The value of this investigation lies within the creation of an adequate assessment of the research focus on one hand and the identification of industry needs on the other hand, as well as the correlation of both aspects. This satisfies the needs of this novel approach which aims to orient the development of a research project in accordance with the industry´s needs.

Whereas the research analysis was confronted with several hurdles due to the complexity of the topic and the variety of related research, the survey, mine visit, and interview fulfilled their purpose completely and allowed to gather valuable insights, for stope design, the GAGS-project and conducting professional surveys in general.

Finally, it can be seen that the stope design research really is an important topic and professionals working with it are eagerly desiring and committed to make improvements happen. Just identifying this urgent need for improvement and the confirmation of the relevance of the GAGS-project should be considered valuable enough.

6. Implications and Recommendations for GAGS

It can be seen that the GAGS-project is exactly at the center of the improvements desired for stope design. Making more geotechnical data available for stope design is the most desired improvement in this area and exactly what the GAGS-project is aiming to achieve. If the other identified requirements are respected there should not be any problem to guarantee a high application possibility for the developed methods.

The most important aspects that need to be kept in mind for the GAGS project are the following:

Software implementation:

The trend in stope design and underground mine planning is going towards more extensive, complex, and adequate software. This trend should be regarded for a possible implementation of the GAGS-project. It might be possible to enter a cooperation with a stope design software company, but it should at least be considered essential that the resulting data is produced in a format that is easy to implement within a preferably broad range of different software.

Fast data-availability:

Since the GAGS-project is currently aiming to deliver production-based drilling and scanning data for final stope design, time is of essential importance. From the survey, it can be concluded that about three days between evaluating the data and implementing it within the software would still be tolerable for 70% of the respondents. Due to the limited adaptability of stope design, it should be investigated how new geophysical methods could possibly be utilized at earlier stages of stope design and mine planning since this would take away urgent time pressure and allow for a bigger scope of changes possible to be implemented.

Proven feasibility:

Mining professionals working with stope design are aware of the suboptimal results their current methods are commonly yielding, thus they are considerably willing towards the implementation of changes. A crucial part of the implementation of these changes is however that the methods have been previously applied and their feasibility is proven. Especially for this purpose, it is important to have an in-depth cooperation with a desired partner mine, which fulfills the most common parameters of the survey. From this cooperation a case-study that comprehensively explains the methodology and realized benefits should be created. The preferable parameters to focus on are NPV, dilution and stope stability, as they are commonly used in other case studies realized in the area.

Man-power:

An issue that could raise considerable problems is the limited availability of professionals working with stope design and the special difficulty to acquire professionals with sufficient background in the area of geotechnics. It has been stated that novel methods can only be implemented with new personnel and if they do not require additional work or their benefits considerably outweigh the required effort.

Key aspects:

The most essential features of the methods to be developed should be considered the ore grade estimation, orebody delineation, and stope stability estimations. These are factors that are commonly used to assess stope performance and are desired to be improved by industry professionals.

7. Conclusion

Stope design is an essential and considerably complex aspect of underground mine planning. Several factors influence its execution. There is a magnitude of fundamentally and infinitesimally diverging methods, that have been developed to perform this task.

It can be concluded that stope design is still one of the most complex and not satisfyingly solved challenges within mining engineering. Considerable efforts trying to allow for providing optimized solutions for stope design have not been successful at solving this challenge yet, even though considerable improvements have been realized with time. The current focus of research is on the development and implementation of novel algorithms and software, which is slowly allowing to optimize stope boundaries in 3D rather than only 2D. The aspect of geotechnics seems to be underrepresented considerably within research, however. The strongly damaged rock mass commonly encountered in stoping operations required adequate simulation of fractured rock mass behavior.

By means of utilizing novel approaches for contact acquisition for survey conduction, it was possible to reach a considerably international audience. Industry professionals working with stope design are dedicated to helping research identifying even better solutions towards stope design. This dedication indicates an urgent need and desire for improvements, also several encouraging comments indicated a positive attitude towards research related to stope design.

Several interesting insights and guidance for stope design research in general and the GAGS-project in specific could be achieved. These included the desirable characteristics of the methods to be developed, e.g. the time frame, feasibility, and software implementation.

In order to finally conclude this thesis, the previously defined research questions, are checked and answered in a detailed and comprehensive manner.

Identification of common practice in industry and desired areas for improvement:

1. **What are the current methods for stope design used in mines?**

Empirical, Numerical, Analytical and Personal expertise are all applied to considerable shares. Empirical methods are however not as dominant as were expected.

2. **How can the stope performance of new designing methods be measured, and improvements be demonstrated?**

Industry-standard to solve this issue is a case study, therefore the new methods need to have a standardized form, however; e.g. software implementation or algorithm formulation.

3. **What are the needs of the industry concerning stope design?**

The need for industry for stope design lies mainly within making more geotechnical data available for stope design as early as possible, integration of stope design into general mine planning, and improvements within the software.

Reviewing, summarizing and analyzing recent research in the area:

4. **Which methods for stope design have been researched and what are their limitations?**

The methods available for stope design researched and developed in the past can be mainly divided into 3 groups: analytical, empirical, and numerical. The diversity of individual methods and the competition between them has resulted in showcasing several reliability issues within them. To this day no stope design method can claim for itself to be completely reliable and strict limitations need to be applied commonly, especially for the scope of optimization achievable.

5. **What is the focus of recent research activity related to underground stoping?**

The research focus has shifted away from mainly improving empirical methods towards a more algorithm and software optimized approach. It seems that sometimes geotechnical aspects have been neglected and scheduling has been more emphasized.

6. **How has the stope design research developed and changed focus with the time?**

Stope design research firstly started with empirical methods in the 70´s and 80´s, though initial software was also developed during this time, limited computing power didn´t allow to address the inherent complexity of underground mine planning to an extent sufficient to allow for software implementation on a considerable scale. With the development of optimization software for open-pit mining, the growth in computing power, and the ever becoming more evident flaws of empirical methods the research has focused on numerical methods and algorithms in the past 20 years.

Correlation between research and industry needs:

7. **How can research meet the needs of the industry?**

In order to meet the needs of the industry research hast constantly identify the inherent struggles present within stope design. For now, it seems most reasonable to consider the implementation of additional geotechnical data as an approach that would allow us to meet most industry demands.

8. **How can the results of the GAGS project be promoted towards implementation by the industry?**

In order to allow for an implementation of the geophysical and geochemical methods developed within the GAGS-project the methods should be preferably implemented within a stope design or mine planning software or at least the data should be easy to import into such a format. In order to promote the benefits a case study should be performed preferably in a stoping based gold mine.

9. **How can the benefits of the novel methods over currently applied stope design methods be measured and evaluated?**

The measurement and evaluation should be integrated parts of the case study to be performed. The parameters destined for such evaluation are the NPV of the stope design, dilution and stope stability.

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Appendix

A. Mine List

As part of the preliminary mine identification, a mine list containing 250 different stoping mines has been created with the help of the mine intelligence database. The contained information is the Continent, Country, Mine name, Mining Method, Primary Commodity, Other commodities, Mining Company, and Contact information where available. A snippet to demonstrate the structure is given here

Mines:		Mine Name	Commodity (Primary in Capitals)	Mining Methods	Mining Company (Country)
Europe:					
Europe	**Sweden:**				
Europe	Sweden:	Zinkgruvan	ZINC, Copper, Lead, Silver	Sublevel Stoping, Longhole Stoping, Bench and Fill	Lundin Mining
Europe	Sweden:	Garpenberg	ZINC, Copper, Gold, Lead, Silver	Underhand Cut & Fill	Boliden (Sweden)
Europe	Sweden:	Bjorkdal	Gold	Longhole Stoping, Blasthole Stoping	Mandalay Resources
Europe	Sweden:	Kiruna	Iron Ore	Sublevel Caving	LKAB
Europe	Sweden:	Malmberget	Iron Ore	Sublevel Caving	LKAB
Europe	Sweden:	Renstrom	ZINC, Copper, Gold, Lead, Silver	Cut & Fill	Boliden AB (Sweden)
Europe	Sweden:	Kristineberg	ZINC, Copper, Gold, Lead, Silver	Cut & Fill	Boliden AB (Sweden)
Europe	**Norway:**				
Europe	Norway:	Kvanevann	Iron Ore	Open Stoping, sublevel caving (now)	Rana Gruber (Norway)
Europe					
Europe	**Finland:**				
Europe	Finland:	Pyhäsalmi	COPPER, ZINC	Bulk open-stoping	First Quantum Minerals Ltd.
Europe	Finland:	Kittilä	Gold, Silver	Long Hole Stoping, Open Stoping	Agnico Eagle
Europe	Finland:	Jokisivu	Gold		Dragon Mining Ltd
Europe	Finland:	Kemi	Chromite	Sublevel Stoping	Outokumpu
Europe	Finland:	Orivesi	Gold	??? Stoping?	Dragon Mining Ltd.
Europe	Finland:	Kylylahti	COBALT, COPPER, Gold, Nickel, Silver, Zinc	Stoping?	Boliden
Europe	Finland:	Pampalo	Gold	Selective Mining	Endomines (Sweden)
Europe	**Great Britain:**				
Europe	Great Britain:	Cononish	Gold	Longhole Stoping	Scotgold Resources
Europe	Great Britain:	Aberpgwm	Coal	Room & Pillar ?	Walter Energy (USA)
Europe	Great Britain:	Thoresby	Coal	Roam & Pillar ?	UK Coal (UK)
Europe	Great Britain:	Kellingley	Coal	Room & Pillar ?	UK Coal (UK)
Europe	Great Britain:	Boulby	Potash, Salt, Potash Sulphate	Room & Pillar	Israel Chemicals (Israel)
Europe	**Ireland:**				
Europe	Ireland:	Tara	Zinc, Lead, Silver	Blast Hole Stoping	Boliden
Europe	**Portugal:**				
Europe	Portugal:	Neves-Corvo	ZINC, Copper, Lead, Silver, Tin	Drift & Fill, Bench & Fill	Lundin Mining
Europe	Portugal:	Panasqueira	Tungsten	Stope and Pillar	Almonty Industries

B. Questionnaire

Questionnaire Methodology

The questionnaire is to be an adequate possibility to gather and access the professional expertise of an international group of mining industry professionals, in a timely manner. In order to achieve desirable answer quality it is however not only necessary to identify the desired participants and contact them, but to also get them to be involved personally, this should be executed most reliably by the creation of an engaging questionnaire, which awakens responsibility within the participants, in order to guarantee for high-quality answers. It is also favorable to provide the insight that the questionnaire was created and to be evaluated by a person familiar with the topic and the specific mining terminology. Additionally, the specific methods to research as part of the GAGS-project need to be explained in detail, as they are not to be considered common knowledge.

In order to not scare potential participants with too many detailed questions, a multilayer-funnel-approach was chosen for the creation of the survey. The general information though not directly important for the research project is still desirable in order to give the possibility to create and check for possible correlations within the respondent groups.

Questionnaire Creation

In order to allow for the creation of a questionnaire satisfying the high quality demands it was necessary to familiarize initially with the specifics area and state-of-the-art of stope design. This was to give the possibility to ask questions that were relevant and of interest for the stope design process, additionally the details of the methods to be developed within the research project and their potential implementation needed to be thoroughly understood in order to be explained to the questionnaire respondents.

In total, about one month of literature study was used to gather this background knowledge. For the creation of the questionnaire itself, the most urgent question was which platform to choose in order to reach a broad audience, thus the WebRoPol electronic survey system was utilized. This allowed for the creation of various interactive features and facilitated the distribution of the questionnaire as well as the evaluation of the results.

The creation of the questionnaire was deemed to be visually appealing, easy to understand and straight-forward, giving background information and not intimidating by its response complexity, while still giving the possibility to give detailed and free-text feedback when desired or needed.

In order to facilitate later used as part of the survey evaluation process and allow for visualization of the responses, several multiple-choice answers were included.

Questionnaire Structure

The structure of the questionnaire can be described in the following manner, initially, the research project and the relevance of it are explained in a detailed manner, then contact data and details of the respondent are gathered, in order to allow for contact the participants for eventual in detail questioning.

Consecutively this is followed by questions about the area of expertise and applied mining methods of the survey participants is gathered, with due respect to recent changes in the mining methods.

This broad introduction, to gather some background data is followed by several questions on how the stope designing process is currently conducted. Later the importance of several parameters for the stope designing process is questioned.

The general geological conditions of the mines are assessed and information about the applied methods for ensuring stope accuracy and stability are gathered, coupled with a question about the willingness to recommend the own stope design method for other mines. Consecutively the opinion on the most important improvement for the stope design process is gathered.

After this, the methods that are to be developed and implemented as part of the GAGS-project such as Laser-Induced Breakdown Spectroscopy (LIBS) and in-situ borehole geophysics are explained in detail to give more detailed knowledge about the research project.

After this information about the utilization of geotechnical methods for stope design is asked, followed by the question if their utilization in the future is already planned.

Afterward, the willingness to potentially utilize the methods to be developed within the GAGS project and the requirements for a potential evaluation are being assessed.

The questionnaire then closes with a last question about the willingness and requirements for the implementation of changes in the stope design process, followed by the possibility to provide general comments and remarks.

As state-of-the-art survey methodologies have been applied, their impact on the structure and certain characteristics of the questionnaire needs to be adequately represented here.

1. **Balanced Multiple-Choice answer possibilities:**

Multiple-Choice questions were always checked for giving the possibility of equally weighed and thus unbiased answer possibilities.

2. **Non-Mandatory Responses:**

Due to potential confidentially issues that were expected it was important to create a questionnaire that also allows to neglect and not answer a specific question.

3. **English as questionnaire language:**

The questionnaire was created and conducted in English only. English was chosen due to its dominance in the world of business and within the international mining industry especially. Additionally, a single language was chosen to avoid potential biasedness by translation.

4. **Randomized answer option order:**

The order of multiple-choice answer options within questions where opinions were involved have been randomized in order to avoid biasedness by participants simply clicking on the first option.

5. **Spread answer sheets:**

In order to avoid frustration, the questionnaire was spread into several small pages, based on specific topics. To minimize information overflow, additional answer options only start to show when the previous option is selected. In order to allow for a feeling of progress, an advance-rate-indicator is used.

6. **Multilayer-Funnel-approach:**

This means to say that methodologically the whole questionnaire general information is gathered which then becomes more specific and detailed with every question to be asked, while each question itself repeats this scheme, by asking for a general answer in the beginning before asking for more specific details.

7. **Contact Information:**

In order to allow for contacting the participants for further questioning in case of unclear responses as well as excellent responses and to send the results of the survey to the individuals interested in them the contact information and their interest in the research project are gathered

8. **Confidentiality:**

In order to allow for authentic answers and with respect to the potential of confidentiality issues, absolute confidentiality is guaranteed. The results of the survey will only be made available in an anonymized form outside the research project in order to prevent any confidentiality issues.

9. Questionnaire Continuation:

In order to facilitate the survey, the possibility to take a break while answering the survey and continuing right where the respondent had left off was incorporated within the survey. This was beneficial in case a more urgent matter might interrupt the participant during the response process.

10. Short Response Time:

The survey was designed in a way that a meaningful answer could be submitted in about 10 minutes in order to allow for not scaring away potential participants.

Questionnaire Target

The right target of a questionnaire is as essential for conducting an insightful survey as the creation of the questionnaire itself. Since there is no international register of stoping mines, the Mining Intelligence database was used to manually create a database, containing 250 international mines using stoping methods.

The list contains Continent, Country, Commodity, Mining method, Owner, and Contact information if available.

Once the population size for the survey has been estimated (250 international stoping mines), the aim was to contact as many of these mines as possible. Following the principals of survey science, the desired sample size was estimated according to a confidence level of 90% and a margin of error of 14 %, with the population size of 250, this resulted in an estimated sample size desired to exceed 31 responses. Thus gathering 31 responses was identified as a benchmark goal.

However soon it materialized that it was not as easily possible to reach all the responsible people working in the area of stope design. Mines commonly don't have publicly available contact information and it is not possible to contact specific people in an area by any means. Thus, ways of acquiring additional contact information had to be facilitated.

Thus, an even more personal introduction was created and emphasis on the value of the participant´s contribution to the survey and the research project as a whole was put forward. Additionally, the favorable aspect regarding the novel approach of identifying the industry's needs and thus offering help to the survey participant by offering help facing his issue. This motivation and inspiration seemed necessary since monetary compensation for participation was not an option and would probably not be as successful in a typically high-income group of mining industry professionals.

In an attempt to identify potential participants that could be approached in a personal and more relatable context, certain networks were identified. As part of my degree program the **E**uropean **M**ining **C**ourse (**EMC**) which is part of **E**uropean **M**ining, **M**ineral and **E**nvironmental **P**rogram (**EMMEP)** it was possible to utilize the **F**ederation of **E**uropean **M**inerals **P**rograms (**FEMP**) database, for identifying mining engineers working in the identified companies and establishing initial contact with mining professionals working internationally. Contacting given the background of being part of the same educational program, should create more trust. Several contacts from the identified mining companies were found and contact by mail was established. Later it was understood that most mailing addresses were not existing anymore and the reply rate to mails, in general, was still considerably low.

By trying to identify problems within the process of acquiring potential survey participants it was identified that the potential survey participants might not relate and trust receiving an email and clicking on a hyperlink from some unknown person.

Thus, even though a very personal and careful introduction to the mails was chosen, the concern arose that mining professionals probably worked with confidential data on highly secured networks, thus for reasons of cybersecurity they would probably not be willing or even allowed to take the risk of clicking on a hyperlink to a survey website, when an unknown person would send them a link.

A potential solution to this was to contact the professionals in a more private atmosphere, potentially in their spare time or on a private computer. Which then deemed the idea of contacting unknown people by mail as neglectable.

Due to this, alternative measures for contacting the mines and getting responses for the survey were evaluated. The most promising option seemed to directly contact mining professionals working in the mines, preferably in the area of geotechnics or mine planning, while giving them a certain degree of security and trust.

In order to allow for contacting these people in the desired manner it was considered desirable to utilize a professional social network, "LinkedIn" was thus considered the desired option. As it allowed for the participants to have more background knowledge about who is sending the survey and reaching them in their potential spare time. The problem that arose here was that messages can only be sent to direct contacts freely, and thus these contacts need to be gathered first. About 1000 "LinkedIn"-members were identified and contacted, about 500 were sent the survey. The benefit of this approach was to be considered its unparalleled international reach.

Using personal contacts and contacts of the GAGS-project members it was possible to gather responses from direct mine contacts mainly from European countries.

Additionally, the survey was distributed on mining professionals' networks (Mining Industry Professionals, Mining: Underground) and additionally featured in the June newsletter of this network with about 300,000 members.

In order to allow for tracing back which, form of contact delivered the best results, the survey was split into 3 different groups (Direct, LinkedIn and Forum).

Continuous Response Analysis

During the distribution of the questionnaire, the received answers were continuously evaluated in order to identify eventually misleading suggestions within questions and comments given within the answers.

No general remarks about the structure of the survey were encountered and responses were as expected in order to achieve an optimal result of the survey answers.

In order to ensure the conformity of the different surveys, it was not possible to modify minor flaws that have been identified within the questionnaire. Thus, unfortunately, the annually mined ore, average stope size and mined commodity of the mines were not assessed and could only be partially recovered by means of manual research.

The answer rate, however, was still not very satisfying. So continuous pushing and reminding of the participants was necessary. Further analysis of the reasons for this behavior should be conducted.

Meta-Data Analysis

The regional origin of the excellent answers by region is visualized in Figure 36. It can be concluded that excellent responses are also originating from nearly all regions.

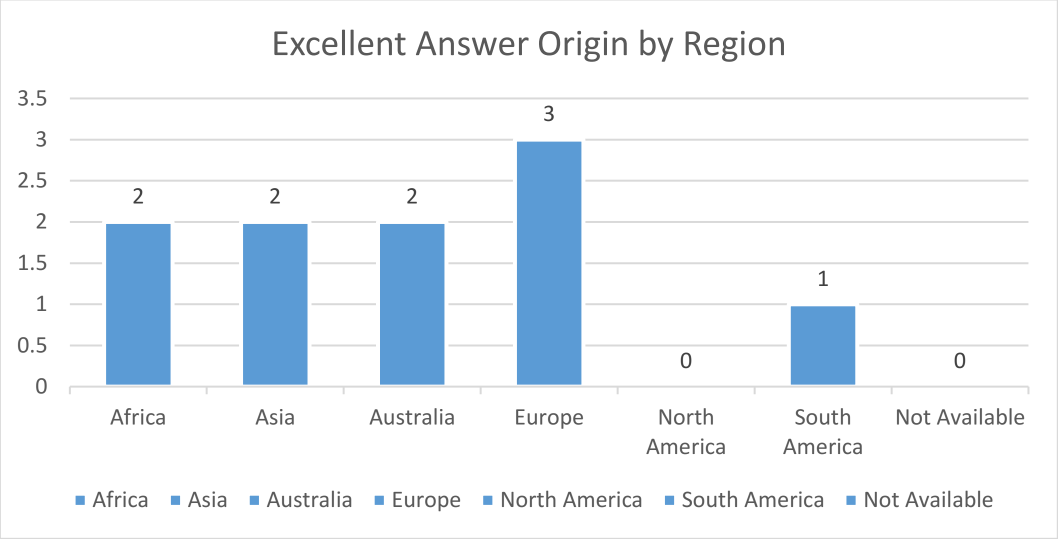
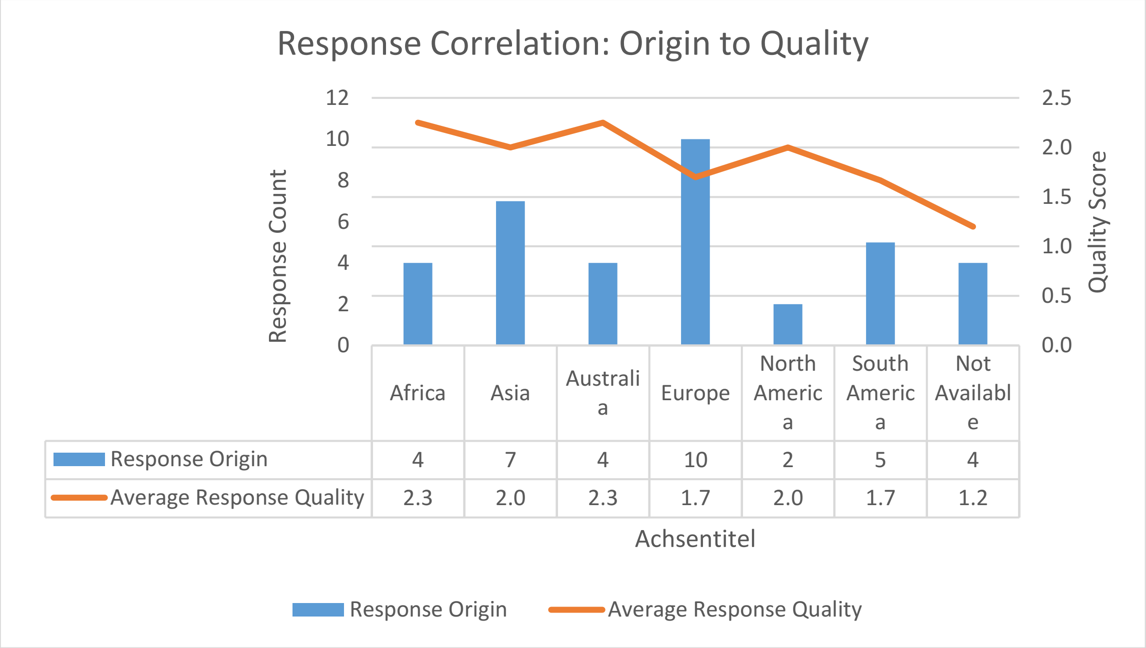


Figure 36: Excellent Answer Origin by Region

The different identified groups can be somewhat identified and grouped according to different parameters. Figure 37 illustrates how the response quality can be correlated with the geographical origin of the response. Thus, it can be concluded that the response quality from the European responses is below average.



	Africa	Asia	Australia	Europe	North America	South America	Not Available
Response Origin	4	7	4	10	2	5	4
Average Response Quality	2.3	2.0	2.3	1.7	2.0	1.7	1.2

Figure 37: Correlation between Geographical Origin and Response Classification

Figure 38 illustrates how meta-data is used for the response analysis; in this case, the response time is correlated with the quality. After analyzing these parameters, it can be concluded that the average response time is exceeding the desired value of 10 minutes by a factor of three-fold. Some excellent answers were created in only 20 minutes, on average an excellent answer required 39 minutes to be created.

It is observed that a response time exceeding 60 minutes, does only show little improvement in the answer quality. The response quality is negatively correlated with the lack of names given in the response. The total response time of about 20 hours shows a considerable time commitment of the survey participants and gives an impression of the importance of an adequate evaluation process.

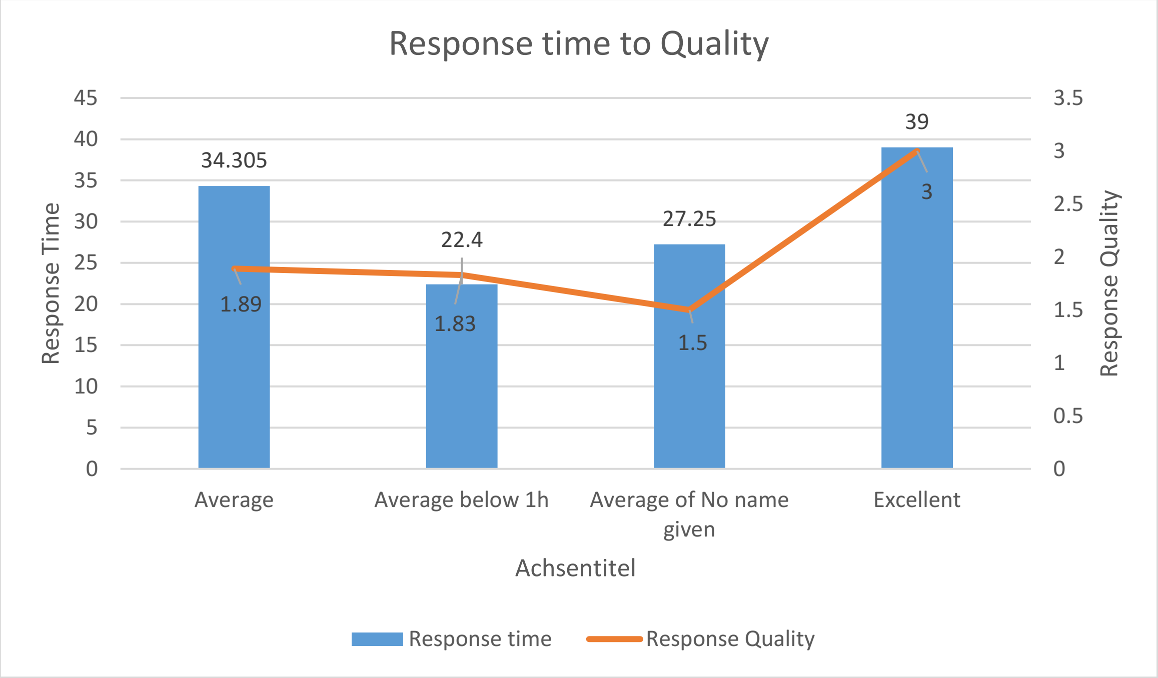


Figure 38: Correlation Analysis of Response Time to Quality

C. Interview protocol

Preliminary correspondence:

1. From a small UG mine designer's point of view, the biggest improvement would be getting detailed geological data well in advance before the development is made. The 'grand design' of production levels is where the costliest mistakes are done. We e.g. have built infrastructure in places which we later discovered were in ore. That causes some major difficulties not only in recovering the ore but also using the infrastructure for its main purpose. Stope design is always closely linked to the development plans. The information from production holes of course helps, but the economic benefits at that point are much smaller. I guess its benefit is more in making the operative work smoother, particularly if you

combine it with programs where you can change drill plans on the fly depending on the structural/geological data. And of course, all additional data helps to revise the geological/geomechanical models.

2. Our mine is definitely not state-of-art when it comes to equipment or software. Most of our machines are basically "pre-digitalization" (in the sense that they're not really integrated into software systems) and we have incompatible planning software (have to send the data between programs through Excel sheets). Having everything integrated and data automatically transferred between systems would be a huge improvement. I've understood that the modern drill rigs collect data from drilling which can then be transferred into planning software and used also for rock mechanics' purposes. This project of yours would be a kind of next step in that evolution. In order to get more than local benefits (e.g. in the drilling and blasting of one stope), you, however, need geological/rock mechanical expertise - some person and software to collect data from different sources and analyze it. As I said, most of the mistakes have been done before stoping, but every bit of information helps in creating the geo/rock mechanics models (especially if the data can be gathered automatically), and the data could definitely help in predicting what can be expected in the nearby stopes. As you said, different mines have different troubles. I have only worked at one, so don't take my answers as generalizations. We have had some interesting times, as the operation was started by a junior mining company and then bought by a big mining corporation. Their priorities are quite different!

Interview (anonymized):

Dear XXX,

these were the questions I prepared beforehand, with the answers that I obtained during the mine visit, in case some of the answers feel incorrect or incomplete to you, I would appreciate it very much if you could help me by getting those answers straight and answering the still unanswered questions.

Also, in the latter part, I added some questions that arose during the mine visit. In case you find a question misleading or don´t feel like answering it feel free to leave it out.

Best regards,

Sebastian

Standardized questions:

1. **Do you use artificial support for stope design?**
    a. Not exactly since rock support bolting grid is only created for different rock mechanical conditions in the general mine design

Cemented rock fill (CRF) could be considered artificial support. If there is an open tunnel that will no longer be used near a stope that is being mined, we normally fill the tunnel with CRF or waste fill. This will prevent larger collapses in the area.

Supporting the sidewall of the stope with cable bolts would in most cases require an additional tunnel from which the cable bolting is done. We don't build such separate support tunnels, but if an existing tunnel happens to be located so that cable bolting can be installed from it, then in those cases we also try to support the stope sidewalls.

2. **How is the overall stability of the rock in the mining area measured?**
    a. By geological mapping and testing of rock samples

RQD and point load tests (hardness of the rock) is done from drill cores. The data is visually inspected during the stope design, but no actual calculations are made.

3. **Back analysis of stope design with CMS?**
    a. Done when possible, due to tight schedule and changing rock mechanical conditions (Becoming more challenging now), it has been on hold recently

Currently, the lack of back analysis is due to not having enough resources to do the work. However, earlier all the mined-out stopes have been analyzed and the data is used to update the dilution & ore loss parameters.

Now to follow up on your previous answers to the survey:

4. **Stope Design divided into 3 steps: Mine planning, Stope Planning and Blast planning, but is it executed by different people in each step or the same person in each step?**

General mine plan is updated at least once per year and it covers the general layout and stoping plans (person #1). These plans are used as guidance when more detailed development and stoping plans are made (persons #1 and #2). Blast planning could be divided into the general blast plan ("these drill fans will be in this blast", person #2) and detailed plan for timing of the charges (person #3).

5. **Qualification of Mine Planner? Worked in different mines before? Stope design and stability estimation: based on some kind of system (Mathew´s Stability Graph/ Individual Stability Assessment?)**

   a. Not Mathew´s graph and no software except for Surpac, Individual expertise is highly valued and stoping plans are discussed within professionals before implementation into mine production.
   b. Qualification of Mine Planners?

This is the first mine where the mine planners work, but now already 7+ years of experience. There have been some more experienced persons and consultants that have helped to improve the planning process, but most of the planning routines are learned here by doing.

6. **The preliminary stope designs made during ore reserve modeling take into account which aspects? (Geotechnical or rather only ore grade?) Constantly updated and accurate to what extent?**

At least the following things need to be considered when making general stope designs:

- ore geometry (stope design is mostly an optimization process: take as much ore and as little dilution as possible)
- stoping order and schedule
- main horizontal stress direction
- weakness zones in and around the orebody
- separation of different ore types

General stoping plan should not be too detailed (unless the final stope designs have been already done), because changes are likely.

Ore reserve is updated once per year, but more detailed stope design is done with updated ore model and mill parameters, prices & terms.

7. **Why is it 1 – 2 mine planners involved? Dependent on stope size?**
   a. Small mine there is only 2 real mine planners.

There should always be at least 2 persons who can do the same thing so that they can cover each other during vacations, sick leave, etc. With many people having left, this is not always possible.

8. **Do you see a specific area in the stope designing process that holds the best and biggest room for improvement for you? General stope design, detailed or drill and blast design?**

There should always be at least 2 persons who can do the same thing so that they can cover each other during vacations, sick leave, etc. With many people having left, this is not always possible.

9. **Stope stability issues? Mine stability issues?**

    a. Only some issues recently with increases in mine depth (rock bursts); before: some dilution and overbreak, but nothing critical.

Primary stopes in transverse stoping typically become “barrel-shaped“ due to stresses on the lower levels.

Secondary stopes have CRF backfill in the long sidewalls, so stope stability is not such an issue. The stability of the hanging pillars on the upper level is the main concern.

Longitudinal stopes typically have a structure along the other sidewall which causes dilution.

10. **Are the general personal costs for stope design including all different professionals registered somewhere and is this cost included in mining cost evaluation?**

All personnel costs are included in the mining cost. However, mining cost is calculated as a total, not stope by stope (only mining depth + development cost are considered as a variable).

11. **Why do you consider the different parameters as almost completely equally important? (From the survey: Equipment size, Development Cost, Cut-off Grade, Dilution, etc.)**

I found it difficult to compare the listed parameters. One comparison, however, is dilution versus recovery. In high-grade ore, we want to maximize recovery while in low-grade ore priority is to minimize dilution. Similarly, in high-grade ore development cost does not matter so much, but in low-grade ore, we should do the development as cheaply as possible. In high-grade ore, cutoff grade doesn’t matter because it’s all ore, but in low-grade ore, we must be very selective what we mine. Etc.

12. **What do you mean by rock mechanical conditions are quite good? Low amount of faults, high rock competency?**
    a. Low amount of faults, high rock competency and only now in high depth critical rock load conditions.

Correct. Around the orebody, however, there are some areas with poor rock quality (soapstone, chlorite schist, faults/structures with graphite)

13. **What kind of support do you commonly utilize in the mine? Stope and drifts?**
    a. Cable bolts and sometimes rock bolts, on a special occasion even with bolt pressure measuring equipment. No Support of stope boundary anymore.

Systematical development bolting with short bolts and shotcrete during development. Meshing when required by rock conditions. Cable bolting for crosscut support and the upper levels of a stope (a bolt profile covering walls and roof). Backfill of tunnels that are no longer used.

14. **Is the data from the CMS automatically used for back analysis of the stope stability estimations and thus for reevaluation of the parameters included? Fault zones and their effect on stability are automatically evaluated?**
    a. No automatic back analysis, back-analysis is executed by mine planner, when time is there.

Yes. Visual checks are made immediately after scanning to make sure there is no ore left in the stope and that it is safe to start backfill

15. **Which software are you actually utilizing for the stope design and mine planning?**
    a. **Surpac… more?**

Surpac for stope design

EPS Enhanced Production Scheduler (Datamine scheduling software)

16. **Integration into general mine planning due to reading-related research or just out of work efficiency analysis?**

Currently, the software companies typically offer planning software, scheduling software and production tracking software, all of which are integrated and work together. However, we have planning software from one company, scheduling software from another, custom in-house software for production tracking and we use Excel to transfer data between them. Not practical.

Having visited Sandvik's test mine and seeing what data new mining machines collect, my own thoughts are that the integration should be expanded so that mining machines and planning software communicate with each other. I know there exists a standard called Iredes (https://iredes.org/) which is designed to allow this communication. However, as far as I know, it's not widely used at the moment, and at least in Surpac, there's no commercial solution that would allow its use.

Data integration is a crucial part of success in the applications of your research project. Since we're talking about getting data from production holes, it needs to be available for planning in real-time so that the plans may be quickly altered if needed. On the other hand, some changes could be done by the drill rig operator, who needs to have a good understanding of the plans (in practice: plans in 3D) in order to make the changes. In both cases, the data transfer and transformation between planning software and mining machine should be as smooth as possible, preferably automated.

17. **Integration of multiple factors like development cost for stopes, roof support, and uncertainty costs neglected or estimated by the engineer responsible for stope design?**

Profitability calculations are not done stope by stope. Only 2 cost variables are used for cutoff calculation: depth of mining and development cost.

18. **Sludge Drilling: Which data does it provide you and why did you start doing it? Reliable? You mainly apply it in stopes or development drifts? How frequently is sludge drilling performed? Depth?**
    a. Ore grade and more detailed geological data.

The grade from sludge drilling is not used for grade estimations (it bears some error). It is used to define the boundary between copper ore and waste rock. It is done after development is completed and the data is used to define the final stope boundaries. Sludge drilling is not used for gold ore because it is not considered a reliable method for that.

Why we started using it: it's much cheaper than diamond drilling and it's good enough for the above-mentioned purpose. The maximum length of sludge holes is about 25m since longer holes start to deviate and their location at the hole end is not reliable.

19. **Fracture Mapping? How exactly do you do it and how do you take it into account?**

Fractures are mapped from drill cores and from face mapping in underground drifts. They are visualized as a surface in Surpac.

> Fracture mapping includes which of these related factors: set, orientation, intensity, persistence, spacing, and aperture

The data used in stope design is mainly the number, orientation, and location of the fractures.

20. **Has Fracture mapping been executed systematically?**

From drill cores when the drill core orientation has been recorded (so only a small fraction of holes). Underground face mapping has been recently systematical but historically the mapping has been irregular.

Due to the ever-worsening rock conditions, we have had lately interest to do more rock mechanics related mapping by our geology team. In the early days of the mine when the conditions were good, the mapping was only done occasionally.