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Insights and future research directions from a bibliometric mapping of studies in stope layout optimisation

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ABSTRACT

Stope layout optimisation is an important sub-problem of the generic underground mining optimisation problem that contributes towards optimal ore extraction. It is a growing research area as some surface mines transition from open-pit to underground mining. Several researchers acknowledge the complexity of optimising underground mine layouts because exact methods are limited in generating three-dimensional optimal solutions, hence the growing use of metaheuristic approaches to solve the problem in three dimensions. This paper presents a PRISMA-based bibliometric mapping of stope layout optimisation approaches using R-Biblioshiny and VOSviewer software, their concomitant limitations, and suggests potential future research directions in stope layout optimisation.

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KEYWORDS

Underground mine planning circular logic; stope layout optimisation; exact methods; metaheuristic approaches; R-Biblioshiny and VOSviewer software; uncertainty

1. Introduction

The exploration for mineral resources involves geological and geostatistical investigations and analyses that result in the delineation of a mineral deposit in three-dimensional (3D) space since actual mining occurs in 3D space. The deposit is typically sub-divided into regular 3D blocks with spatial attributes that include physical, geological, geometallurgical, and geotechnical spatial information required for subsequent mine design and planning processes. The 3D block model is the starting point for mine design and planning, whether the deposit will be extracted using surface (or open-pit) or underground mining methods. Globally, it is estimated that surface mining methods account for the extraction of about 95% of non-metallic minerals, 90% of metallic minerals, and 60% of coal from existing mining operations [1–3]. When compared in terms of number of mines and run-of-mine (ROM) production, surface (or open-pit) mining accounts for 57% of the mines and 88% of ROM production globally [4]. The predominance of surface mining partly explains why optimisation in surface mine planning is more developed compared to optimisation in underground mine planning. In addition, optimisation in open-pit mine planning is more developed compared to underground mine planning because the open-pit mine planning optimisation problem is easier to formulate. The formulation of the open-pit optimisation problem is easier because the direction of mining is down and outward to pit limits with precedence block and geotechnical constraints, whereas optimisation in underground mining is more complex due to an increased number of constraints and numerous permutations that exist for the direction of mining such as advance and retreat approaches, and concurrent mining multiple operating levels and different mining methods that are practised [5]. However, as near-surface (or shallow) mineral

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deposits become uneconomic to mine using surface mining due factors such as decreasing grades or increased depth of mining, some surface mining operations around the world have transitioned, are transitioning, or are planning to transition to underground mining [6–8], thus, making optimisation in underground mine planning a growing area for research. The main objective of underground mine optimisation process is to develop a plan for exploiting the mineral reserves which are scarce and finite [5]. The optimisation process is subject to constraints that include geological, technical, economic, and environmental constraints.

An overarching optimisation sub-problem for both open-pit and underground mining is that of cut-off grade optimisation which assists in discriminating ore blocks from waste blocks. To date, the pioneering work by Lane [9,10] on value-based cut-off grade optimisation has mostly been used among the mining research fraternity [11]. Lane's cut-off grade optimisation algorithm accounts for constraints associated with production capacities of the mine, mill, and market, resulting in the derivation of six potential cut-off grades from which an optimal cut-off grade can be selected [11]. In underground mining, the determination of capacities and cut-off grades is a complex optimisation process. For example, Minnitt [12] explained that:

- mining capacity is determined from factors like size and configuration of the mineral deposit, mining method selected, infrastructure required for access, and labour availability with its associated costs.
- processing capacity is determined by cost and efficiency limitations associated with processing equipment such as crushers, ball mills, and absorption tanks in the mill.
- marketing capacity can be limited by selling constraints or long-term contracts.

In addition to the cut-off grade optimisation problem, stope-based underground mining methods also encounter dilution as a challenge that must inevitably be considered because it affects the grade delivered to the mill. Dilution can be planned or unplanned. Jang *et al.* [13] defined planned dilution as the inclusion in an ore block, some waste, or low-grade material from within the block unless selective mining is practised, while unplanned dilution is the inclusion of such material from outside the ore block. Dilution is defined and quantified with respect to an idealised (planned) stope boundary, which is influenced by the delineation of the orebody, stope stability and safety considerations [14]. Thus, while dilution is a fundamental problem in underground mining operations, planned dilution is a necessary aspect of stope design and operation to ensure stability and safety [14].

Based on a 3D block model for which underground mining has been selected as the preferred mining method, the generic underground mine planning optimisation problem can be fragmented into the following four broad tractable optimisation sub-problems [5,15–19]:

- development infrastructure layout.
- stope layout.
- production scheduling (including the linking of different mine planning horizons which are strategic, tactical, and operational mine planning horizons, while acknowledging that these horizons use different metrics such as net present value (NPV) for strategic mine plans and minimisation of deviations from planned grade and tonnages for operational mine plans).
- equipment fleet selection and deployment.

The above sub-problem areas are interdependent because they follow an interactive circular logic or 'chicken-and-egg' analogy as described by Musingwini [5], thus, requiring an integrated approach to solving the generic underground mine planning optimisation problem. Figure 1 illustrates the interactive circular logic in underground mine planning optimisation.

Appianing and Ben-Awuah [20], and Musingwini [5] explained the generic process followed in underground mine planning, which depicts the interactive circular logic illustrated by Figure 1. From the 3D block model (i.e. starting point), an appropriate underground mining method is

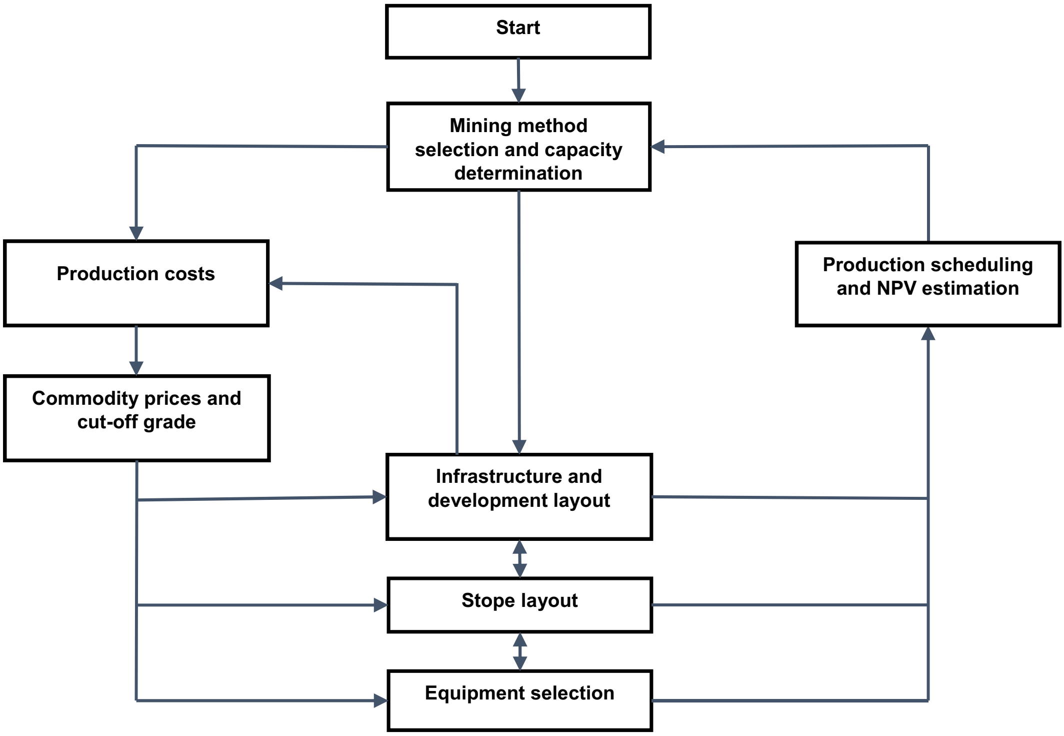

Figure 1. Interactive circular logic encountered in underground mine planning (source [5].

selected, and its annual production capacity is determined using any of the several available capacity determination methods. The development and stope layouts that yield the maximum NPV should then be determined. However, these cannot be determined until the cut-off grade is known. The cut-off grade is a function of mineral commodity prices and production costs. The production costs and cut-off grade can only be determined if the mining layout and production scheduling have been determined; and the development and stope layouts and scheduling cannot be determined unless the mining method and production capacity are known. In addition, the block economic values require inputs such as commodity prices and mining costs which in turn depend on when the blocks are scheduled for extraction, thus, creating the circular logic or 'chicken-and-egg' analogy. To break the circularity, the underground mine planning problem is then fragmented typically into the four broad tractable sub-problem optimisation problems outlined earlier in this paper, although these sub-problems should be solved interactively in an integrated manner for a holistic outcome.

The challenge to an integrated approach in solving large-scale 3D stope layout optimisation problems as encountered in actual mining practice is that the problem becomes an intractable nondeterministic polynomial hard (NP-hard) type problem [5,15,20]. Again, this is partly the reason why the generic underground mine planning optimisation problem is fragmented into sub-problems to facilitate easier solution. This paper focuses on one of the sub-problems, the stope layout optimisation sub-problem, since it contributes towards optimal ore extraction within the generic underground mining optimisation problem.

A stope is an underground excavation from which ore is planned to be extracted, is being extracted or has been extracted. A stope's size and geometry (i.e. its shape and dimensions in 3D space) are constrained by various factors that include mining methods being practised, geotechnical stability constraints, support pillar sizes, and the dimensions and reach of equipment used for development and production. An optimal stope size and geometry (sometimes called stope boundary, stope envelope or stope design) is a key determinant in the location of individual stopes relative to each other and other physical structures such as pillars and development openings in the overall layout of the stopes. The overarching goal of stope layout optimisation is to select the best combination of stopes with the highest ore grades to produce the highest economic value or NPV for a mining operation, of course, subject to applicable constraints [19,20]. However, the stope layout optimisation problem remains largely unsolved holistically because the use of exact methods is limited in generating optimal solutions to large-scale 3D stope layout optimisation problems as encountered in actual mining operations since the optimisation problem formulation becomes an NP-hard problem [5,15,20,21]. This has led to the growing use of metaheuristic approaches to generate solutions to not only solve these NP-hard type problems but reduce inordinately long solution times. Consequently, only a few 3D approaches have been developed for solving the stope layout optimisation in underground mining [20,22], thus, making optimisation in stope layout optimisation a fertile area for emerging and new research. This paper, therefore, sought to qualitatively review and bibliometrically map studies on stope layout optimisation approaches, outline concomitant limitations of stope layout approaches, and suggest potential future research directions for holistically solving the stope layout optimisation problem.

2. Previous stope layout optimisation reviews

Some reviews have already been undertaken in stope layout optimisation, such as the ones by Janiszewski et al. [23], Appianing and Ben-Awuah [20], and Nhleko et al. [24]. However, most of the reviews do not holistically follow a systematic approach to qualitatively and bibliometrically map evidence on the topic, nor identify key concepts, trends, sources, and concomitant limitations (i.e. knowledge gaps). Some of the reviews have also been superseded by new developments due to the passage of time.

For example, Janiszewski et al. [23] undertook a questionnaire-based survey to investigate current practices in stope designs within the mining industry and concluded that empirical and personal experience which are prone to human error, still predominate over more objective numerical methods in the mining industry. In addition, the survey could not identify any dominant or preferred stope optimisation method and noted that there seemed to be a lack of mining industry application of the proposed stope optimisation methods [23]. Janiszewski et al. [23] further stated that currently underground mining stope design, the prevalent empirical methodologies encompass the utilisation of the stability graph technique and its respective applications, the implementation of the Hoek and Brown failure criterion, and the employment of the span design graph. These methods are widely recognised for their applicability in how mines currently conducting their mining operations when it comes to stope design.

Appianing and Ben-Awuah [20], reviewed and analysed existing research undertaken to develop algorithms to solve the stope layout optimisation problem. However, their work did not include a bibliometric mapping to identify trends and patterns emerging from analysing such research as this would inform potential future directions in stope layout optimisation research.

Nhleko et al. [24] reviewed and analysed literature on underground stope boundary optimisation algorithms and noted that there had been a noticeable growth in the number of algorithms developed to optimise stope layouts. However, as presented later in this paper, there has been a surge in stope layout optimisation research post-2018, because data from the Scopus and Web of Science (WoS) databases shows that more than 50% of the published work on stope layout optimisation has been published between 2018 and 2023. Table 1 lists the post-2018 publications extracted from Scopus and WoS databases.

Based on the foregoing shortcomings of previous reviews on stope layout optimisation, it was necessary to undertake a qualitative review combined with a bibliometric mapping as part of improving the methodological and reporting quality required in suggesting improvements in stope layout optimisation research. The methodology was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) technique together with the

Table 1. Research publications from 2019–2023 on stope layout optimisation extracted from Scopus and WoS databases.

Year	Authors	Optimisation Technique
2023	Esmaeili A, Hamidi J, Mousavi A [25]	Network Flow Algorithm using Mining Rock Mass Rating and Geo-mechanical constraints
2022a	e Faria F M, Dimitrakopoulos R, Pinto C [26]	Two-stage Stochastic Integer Programming (SIP) model
2022	Nhleko A, Musingwini C [15]	Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm combined into a Dual Interchange Algorithm (DIA)
2022b	e Faria F M, Dimitrakopoulos R, Pinto C [27]	Stochastic Integer Program (SIP) model
2022	Morales N, Mancilla D, Miranda R, Vallejos J [28]	Fast heuristic method
2022	Nikbin V, Mardaneh E, Asad M, Topal E [29]	Greedy algorithm and pattern search technique utilising an Integer Programming (IP) model
2022	Shami-Qalandari M, Rahmanpour M, Mahdi M S [30]	Iterative heuristic approach
2022	Janiszewski M, Pontow S, Rinne M [23]	Review paper
2021a	Sari Y, Kumral M [31]	Iterative Heuristic approach
2021b	Sari Y, Kumral M [32]	Dynamic Programming (DP) and Greedy Heuristic Algorithm
2021	Shenavar M, Ataee-Pour M, Rahmanpour M [33]	Floating Cone Algorithm
2021	Samanta G, Dey T, Samanta B, Sinha S [34]	Mixed Integer Programming (MIP)
2020	Sari Y, Kumral M [35]	Mixed Integer Programming (MIP)
2020	Kumral M, Sari Y [36]	Review paper
2020	Sotoudeh F, Ataei M, Khalookakaie R [37]	Heuristic approach
2020	Nikbin V, Ataee-Pour M, Anani A [38]	Integer Programming (IP) and Dynamic Programming (DP)
2020	Nikbin V, Ataee-Pour M, Shahriar K, Pourrahimian Y [39]	Dynamic Programming (DP) and Greedy Heuristic Algorithm
2019a	Villalba Matamoros, M E and Kumral, M [40]	Genetic Algorithm (GA)
2019	Foroughi S, Hamidi J, Monjezi M, Nehring M [41]	Genetic Algorithm (GA) and Integer Programming (IP)
2019b	Villalba Matamoros M E, Kumral M [42]	Genetic Algorithm (GA) based formulation
2019	Idris M, Nordlund E [43]	Probabilistic approach
2019c	Villalba Matamoros, M E and Kumral, M [44]	Genetic Algorithm (GA)
2019	Hou J, Xu C, Dowd P, Li G [45]	Mixed nonlinear programming and Genetic Algorithm (GA)
2019	Hou J, Li G, Hu N, Wang H [46]	Integer Programming (IP)
2019	Nikbin V, Ataee-Pour M, Shahriar K, Pourrahimian Y, Mirhassani S [47]	Integer Programming (IP)

VOSviewer and R-Biblioshiny bibliometric software to aid visual interpretation. The qualitative review assisted in contextualising the analysis. This integrated approach would provide more insights on emerging stope layout optimisation approaches, prominent researchers, articles, and countries that are actively addressing this research area. Such information is not only valuable to the mining industry but also to other researchers who are considering contributing to this field of research.

3. Databases used as sources of data and software used for bibliometric analysis

According to Zyoud and Fuchs-Hanusch [48] the most common databases that contain research articles are Scopus, WoS, Google Scholar, and PubMed. This paper used Scopus and WoS databases as the primary sources of research articles addressing the stope layout optimisation problem. These databases were selected because as argued by De Groote and Raszewski [49], they are the most extensively used and regarded as authoritative citation indexes by the global research community. In addition, De Groote and Raszewski [49] also argued that the two databases are compatible with most bibliometric analysis tools and software. Their outputs can also be easily exported to MS Excel for further analysis. The major drawback with using these two databases is that their lists of publications can sometimes overlap by approximately 43% to 66% depending on the subject matter being reviewed and the period of review [50]. Therefore, it is necessary to always merge the lists of publications obtained from each of these two databases into a single list to enable the elimination of duplicates, hence avoid the double-accounting of any research paper. The integrated list of publications can then be subjected to analysis using appropriate bibliometric analysis software.

Some of the available bibliometric analysis software include R-Biblioshiny which was developed by Aria and Cuccurullo [51], VOSviewer, CiteSpace, Gephi, Bib Excel, and Histcite [52]. This paper utilised the R-Biblioshiny and VOSviewer bibliometric software for the following reasons:

- Both the R-Biblioshiny and VOSviewer software can be freely downloaded from the public domain for academic research purposes, and both are easy to use without requiring formal training. Additionally, the VOSviewer software also has a clustering visualisation capability that enables similar research papers to be grouped into a category or cluster for subsequent focused analyses.
- Bib Excel is more difficult to use unless a user possesses some expertise and experience normally obtained through formal training [52].
- Fahimnia *et al.* [53] indicated that it is not possible to use Histcite for interpreting Scopus data, yet Scopus was one of the two databases selected as sources of data in this paper, thus ruling out the use of Histcite.
- The CiteSpace and Gephi full-suite software both require licences for a user to perform detailed analyses. However, licences were not readily available so that the software could be used in the study undertaken and presented in this paper.

The merged data obtained from Scopus and WoS was subsequently analysed using the methodology described in the next section.

4. Methodology

This study used a three-step PRISMA-based approach (Figure 2), which was developed following the approach used in the study by Harichandan et al. [54].

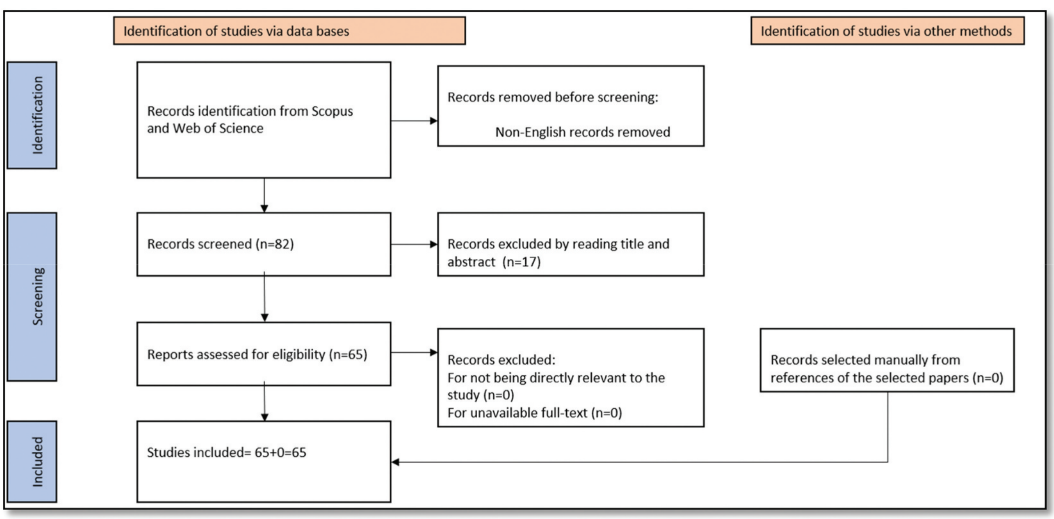

Figure 2. Three-step PRISMA-based approach used in selecting papers on stope layout optimisation.

The three-step approach was used in conjunction with the R-Biblioshiny software for analysis and results were subsequently visualised using VOSviewer software. The PRISMA method is becoming an increasingly preferred method for systematic bibliometric analysis as more reviews are being done because it improves transparency in the review process [55–57]. The PRISMA method is useful to researchers because it enables them to identify and analyse several aspects of a manuscript, which include but are not limited to the manuscript's title, abstract, introduction, methods, results, discussion, and any sources of funding used support the manuscript's research. Bibliometric mapping surveys and reviews can be used to quantify the impact of research, analyse large databases, and assess research topics globally, thus, making them more beneficial than traditional literature reviews.

4.1. Search strategy and selection criteria

A search strategy was developed to identify literature from Scopus and WoS that could be included for analysis in this study. The following terms where used: ('Stope layout' OR 'Stope design' OR 'Stope Boundary' OR 'Stope limits') AND optimi*. In the Scopus database, using an asterisk (*) after 'optimi' broadens the search to include word variations like 'optimisation', 'optimising', 'optimising', 'optimise', and 'optimise'. For a similar search on WoS, the asterisk (*) was replaced with a dollar sign ($) to align with the correct search convention. The search included all the literature from the inception of the databases until the present year, 2023. The search for documents published in English only included journal articles, review papers, conference proceedings, research reports, and book chapters. Given the search limitations inherent in database searches, a qualitative review of the titles, abstracts, and keywords of the compiled articles. This was done to ensure the inclusion of all relevant publications, while preventing an overload of irrelevant articles which could potentially distort the search results.

4.2. Quality assessment

The study focused on mapping existing literature on stope layout optimisation (i.e. optimisation of stope boundary, stope envelope, or stope design) by utilising the search strategy explained in the preceding section. All articles on underground stope optimisation with author affiliations from any country but written in English were included in the search, giving a total of 107 records split as 79 articles from Scopus and 28 articles from WoS. Data from both databases was exported to MS Excel for further analysis using the selected bibliometric software. There was only one paper which was not in English but had an English abstract translation and therefore was excluded from the review as the focus was on papers written in English, thus leaving a total of 106 records for further analysis. The records were then merged into one data file for bibliometric analysis using R-Biblioshiny, an R-tool for comprehensive science mapping analysis. The R-tool was used to remove duplicate records, which totalled 24 duplicates, resulting in the remaining articles in the merged file being a total of 82 records as illustrated in Figure 2. The examination of titles and abstracts assisted in identifying the methods and algorithms that authors employed to address the stope layout optimisation problem. From reading the paper titles and abstracts, a further 17 records were identified as irrelevant because they did not directly address stope layout optimisation but mentioned it in passing. This resulted in 65 records to which no further exclusion criteria could be applied, as they were all directly relevant to the study. Lastly, a consideration was made to ensure that only full-text papers were used in the final analysis, and all papers were full-text papers hence none were further excluded. No additional records could be added from other searches, thus, the remaining articles obtained after applying inclusion and exclusion criteria where 65 records.

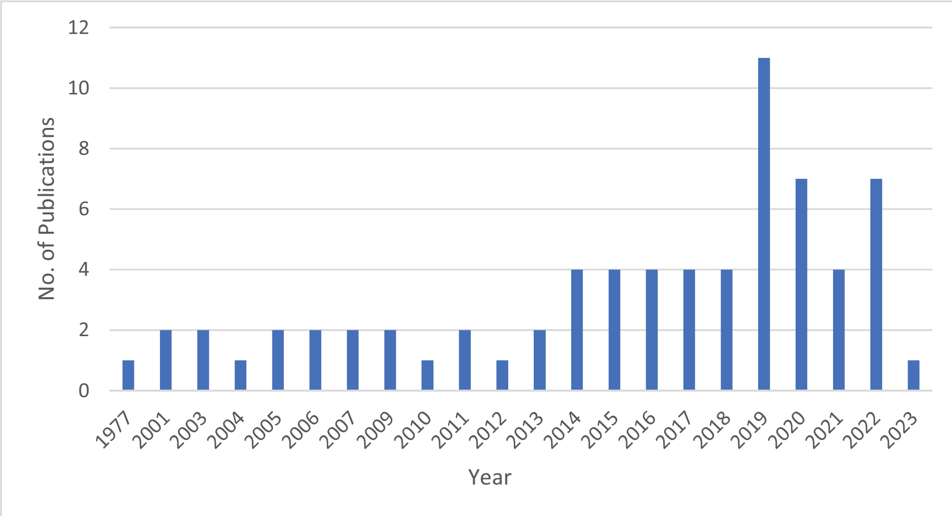

Figure 3. Published stope layout optimisation papers indicated by year.

5. Findings from bibliometric analysis

The results of the bibliometric analysis of the merged and cleaned file of 65 research articles are now presented in the next sections. Figure 3 illustrates the trend of the number of articles by year, which as noted earlier in this paper shows that more than 50% of the published articles were published post-2018 (i.e. between 2019 and 2023), while noting that there was a 24-year lull from the 1977 publication by Allen and Van Barneveldt [58] to the two papers in 2001 when interest in stope layout optimisation started growing. This upsurge shows that there is a growing interest from researchers to solve the stope layout optimisation problem.

5.1. Most featured countries of author affiliation

The analysis revealed that the countries that prominently featured in author affiliations were Canada and Australia (Figures 4,5). These are countries with some of the most developed underground mines that serve as 'live laboratories' for research activities. These are the countries that researchers should keep on their radar for purposes of future research collaboration. Despite the existence of a few publications from South Africa, the country's researchers can be expected to make a substantial future contribution in the field of stope layout optimisation, because the country is known for hosting some of the deepest stope-based underground mines in the world.

Figure 5 shows that Canada has witnessed a rapid growth in research on stope layout optimisation post-2015 to become the leading country in this research area. However, there seemed to a lack of collaboration across geographies, suggesting that there is an opportunity to explore collaborations globally in trying to solve the stope layout optimisation problem, given that it is a complex problem to solve.

5.2. Most featured institutions

The institutions that featured the most among author affiliations are presented in Figure 6. These are the institutions that researchers should consider collaborating with in future as they have already made some inroads in trying to solve the stope layout optimisation problem.

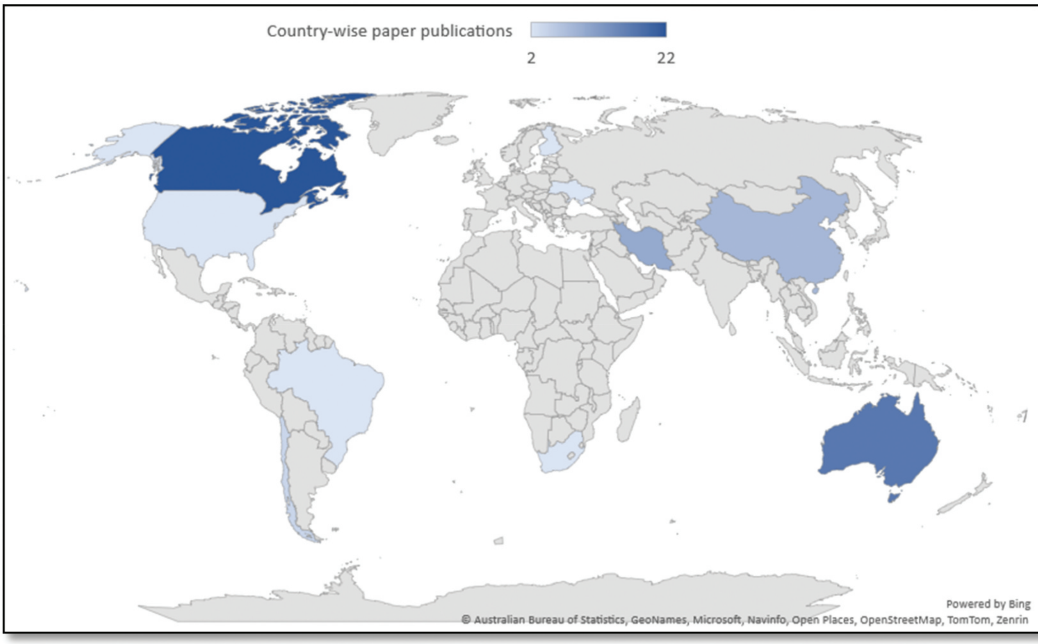

Figure 4. Geographic distribution of publications with darker shades of blue indicating countries with the most author affiliations.

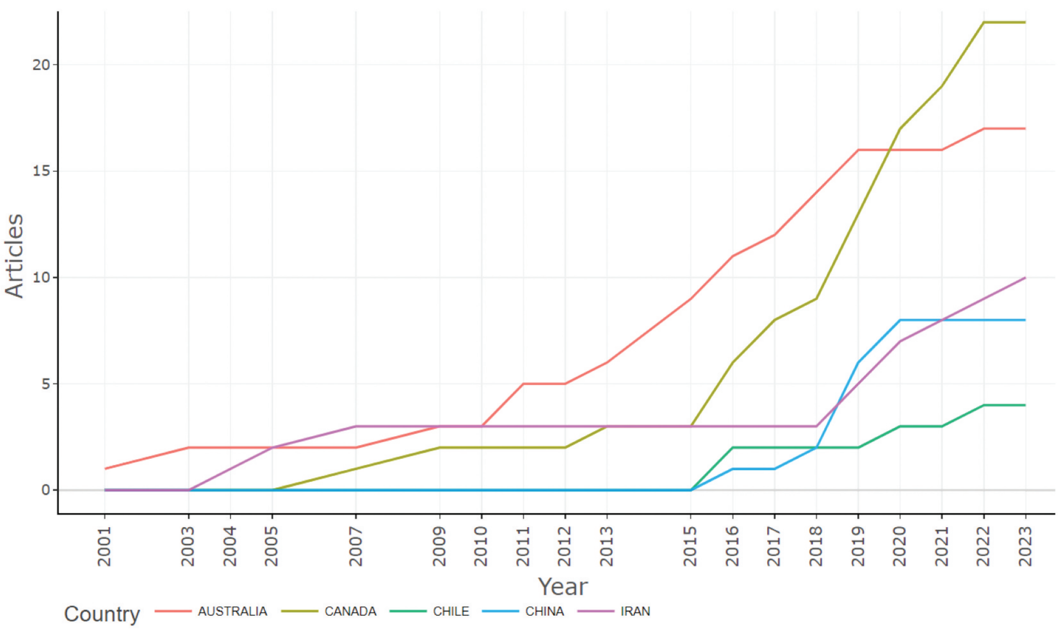

Figure 5. Trend in production of stope layout optimisation articles by country for countries with the most publications.

5.3. *Most featured authors and mining method*

The prominent authors in terms of generating research articles in stope layout optimisation are indicated in Figure 7. Most of their publications are on optimisation of stope limits of sublevel stoping, which they asserted to be a commonly used underground mining method. This argument is also

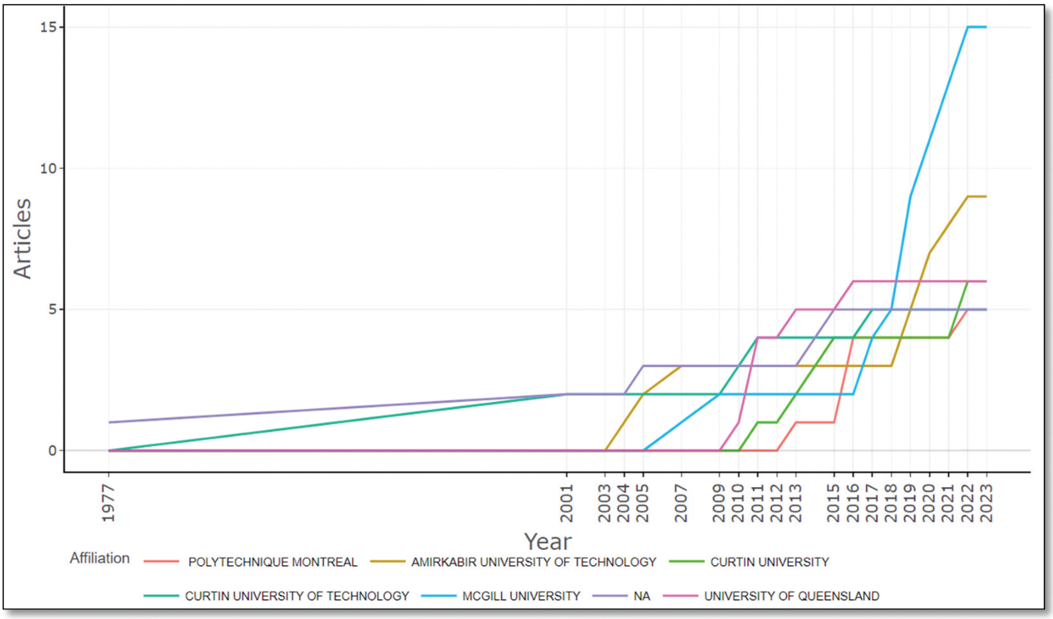

Figure 6. Trend in production of stope layout optimisation articles by country for countries with the most publications.

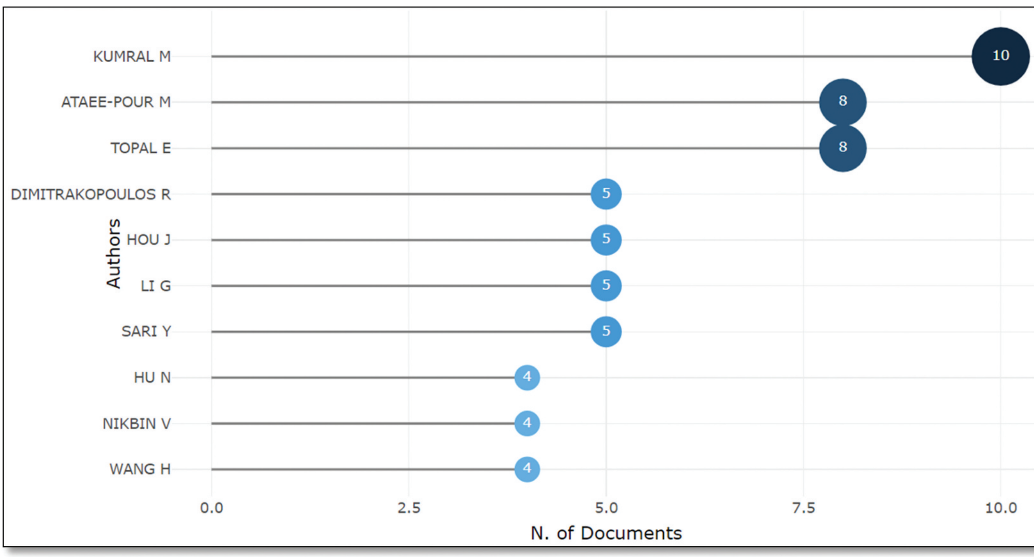

Figure 7. Authors featuring prominently in research publications on stope layout optimisation.

supported by the findings of Martino et al. [4] which confirm stoping as the most practised mining method at about 60% of operations, followed by cut and fill at 20%, room-and-pillar at 7%, sublevel caving at block caving at 4%, sublevel caving at 3% and other mining methods collectively accounting for the remainder. Another reason could be that sublevel stoping is easier to formulate and solve compared to the other stoping methods. The authors that feature prominently in Figure 7, are the ones that other researchers should consider collaborating with when applying for research grants since they already have a track record in solving the stope layout optimisation problem.

5.4. Key thematic areas in stope layout optimisation identified through keyword and co-occurrence analyses

Keyword and co-occurrence analyses are useful in bibliometric analysis because they assist in identifying research trends, relevant studies, and insights into the inter-relationships existing between different concepts and themes within a research focus area. Keywords provide some insights to researchers regarding the main themes and key research aspects covered by a research article. Co-occurrence network analysis of keywords assists in interpreting the inter-relationships that exist between different research concepts and themes within a specialised field of research. Additionally, co-occurrence network analysis assists researchers to identify research hotspots and emerging trends on a research topic. Keyword and co-occurrence analyses, therefore, provide a comprehensive overview of a research focus area, thus, providing guidance on future research directions in that area of research. Keyword and co-occurrence analyses enhance bibliometric mapping in the following main ways, which are that they:

- provide insights on inter-relationships among research papers.
- reveal research trends and research hotspots.
- assist with categorising research papers into clusters for further analysis by clusters.

Figures 8 to 10 illustrate the different word network analyses of the literature on stope layout optimisation. Figure 8 shows the principal themes within the predominant research domains that are pertinent to stope layout optimisation and is constructed based on keywords listed in research articles. This analysis generates clusters which can be represented as bubbles of different sizes as depicted in Figure 8, where the size of a bubble indicates the degree of significance of a cluster. According to Madsen et al. [59], thematic maps encompass two dimensions where the x-axis

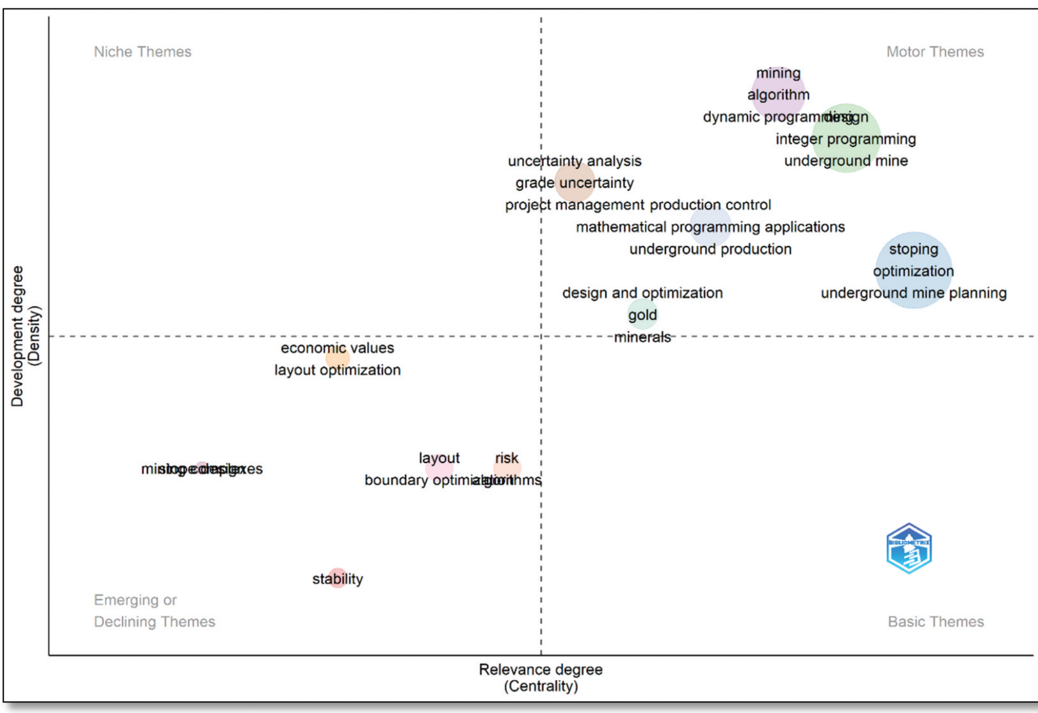

Figure 8. Thematic plot by quadrant of research publications on stope layout optimisation.

represents centrality, and the y-axis represents density. Centrality indicates the significance of a specific theme, while density indicates the theme's evolution.

The first quadrant comprises of motor themes that represent the most frequently discussed research themes. Figure 8 shows that the motor themes include 'stoping', 'optimization', 'underground mine planning', 'integer programming', and 'uncertainty analysis', among others. The magnitude of a theme's bubble is directly proportional to the frequency of its appearance in the keywords. The second and fourth quadrants comprise of themes that are basic or niche themes, respectively. Figure 8 indicates that no theme is currently basic nor niche in stope layout optimisation.

The third quadrant encompasses themes that are either emerging or in decline. In Figure 8, the themes generated include 'economic values', 'layout optimization', 'boundary optimization algorithms', 'mining complexes' and 'risk analysis'. Given that stope layout optimisation has been gaining momentum, as evidenced by the fact that over 50% of the articles analysed in this study were published post-2018, it can be inferred that the themes in the third quadrant are emerging themes.

The potential relationship between interrelated concepts to further gain valuable insights into the structure and progression of the research field is further explored in co-occurrence analysis. In Figure 9, the colour of each point on the map represents the density of the term from the analysed articles. Yellow represents high density, with gradational changes to green, blue, and purple with the lowest density. Figure 9 indicates research hotspots as 'stoping', 'optimization', 'underground mining' and 'integer programming', which can be inferred to mean that integer programming is a focal point in optimisation techniques or approaches used in research on underground stope optimisation, to reflect the inclusion of binary decisions. Keywords such as 'layout optimization',

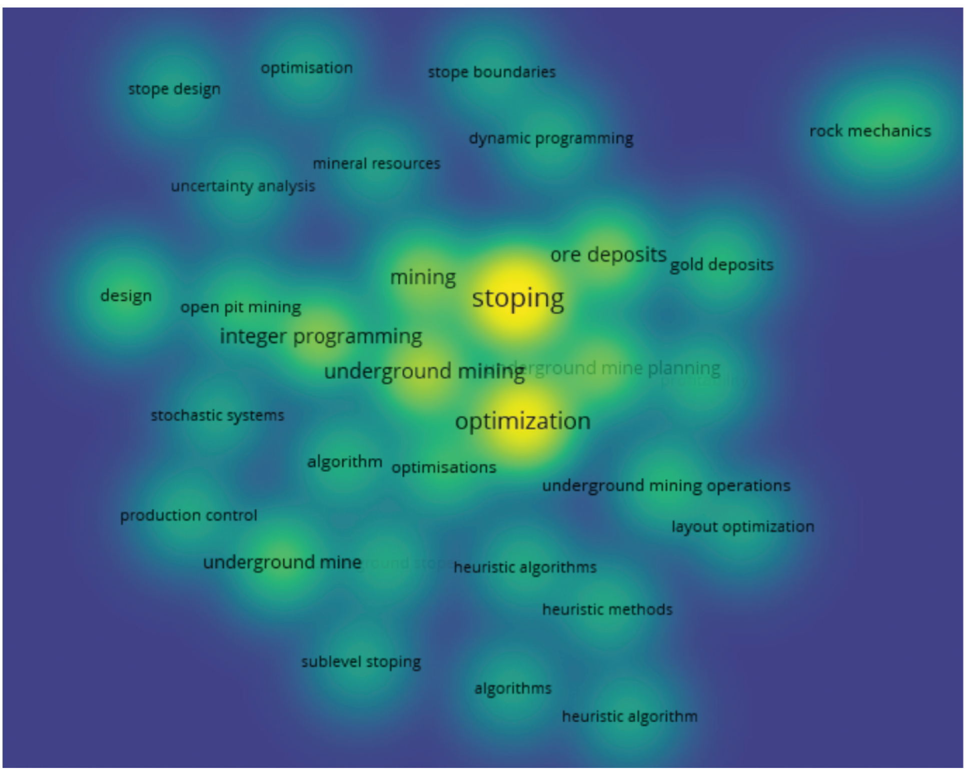

Figure 9. A VOSviewer output of co-occurrence analysis of research publications on stope layout optimisation.

Figure 10. R-Biblioshiny word cloud visualisation of research publications on stope layout optimisation.

'stochastic systems', 'uncertainty analysis' and 'heuristic algorithms', among others, might be emerging themes and possible future research focus areas in stope layout optimisation.

Figure 10 is a R-Biblioshiny word cloud visualisation of the results of keywords from the 65 research papers. The size of letters as depicted in Figure 10 represents the frequency of keywords in the research papers with large fonts depicting high frequency of occurrence. The font sizes gradually transition into smaller font which indicate lower frequency of occurrence of the respective keywords. Figure 10 indicates the research focus of the articles as being in 'stoping', 'optimization', 'underground mining', 'underground mine planning', 'integer programming', and 'integrated optimization' which can be inferred to mean that integer programming is a focal optimisation technique as depicted earlier in Figure 9. In addition, this can also be inferred to mean that there is a growing realisation to focus on integrated optimisation instead of fragmenting the underground optimisation problem into sub-problems as this will ensure holistic outcomes that are amenable to adoption by the mining industry. e Faria et al. [26,27] provide an example of such an approach.

Machine learning (ML) or artificial intelligence (AI) techniques do not currently feature in stope layout optimisation as seen from Figures 8 to 10, even though stope layout optimisation is embedded in an interactive circular logic that exists when considering an integrated approach to solving the generic underground mine planning optimisation problem. This suggests that there is scope to incorporate ML and AI techniques in future research on stope layout optimisation.

One might reasonably expect that ML could play a crucial role in developing stable and optimal stope layouts by leveraging off historical data for this purpose. Concurrently, AI could be applied to devise sophisticated optimisation algorithms that yield near-optimal solutions within reasonable timeframes. The integration of ML and AI could potentially lead to the development of algorithms capable of simultaneously optimising stope layouts and production sequencing in more efficient ways.

6. Findings from qualitative review

A qualitative review informed by findings from the bibliometric analysis was undertaken to firstly, establish thematic areas pertinent to stope layout optimisation, techniques that have been applied to date to try and solve the stope layout optimisation problem, and secondly, identify their concomitant shortcomings based on recent studies. This qualitative review assisted in providing some insights on potential future research directions in stope layout optimisation.

6.1. Overview of some recent stope layout studies

Recently, stope layout optimisation has been increasingly receiving attention from mine planning researchers as evident from the increasing number of publications. Several researchers have developed or modified algorithms to improve the economic value of the mining projects compared to current industry practices. However, Samanta *et al* [34] noted that none of the researchers have developed a solution that gives the true optimum due to the complexity of the stope layout optimisation for large-scale 3D problems as encountered in actual mining practice. Nikbin *et al* [29]. noted that the Stope Boundary Optimization (SBO) problem is computationally intensive. To address this challenge, they developed a hybrid algorithm that uses dynamic programming and a greedy heuristic algorithm which produced solutions that are better compared to the floating stope, maximum value neighbourhood (MVN) and greedy algorithms.

Since different algorithms or models developed by researchers so far do not adequately address the stope layout optimisation problem in an integrated way, this could be reason why Janisiszewki *et al.* (2021) noted the mining industry still relies heavily on empirical and personal experience rather than the numerical methods for stope layout design. Some recent studies seem to have come up with new ways to better optimise stope layouts. For example, Nhleko and Musingwini [15], presented the Dual Interchange Algorithm (DIA) which demonstrated superior performance over the Mineable Shape Optimizer (MSO) in terms of Stope Layout Economic Value (SLEV) across various design scenarios in 3D space. However, their proposed algorithm still lacked the ability to produce designs in shorter solution times, hence requires improvement in computational efficiency. In a previous attempt to solve the stope layout problem [32] developed a new dynamic programming approach that solves smaller problems within a larger problem and improves solution time using memorisation to reduce solution times. In larger problems, a heuristic approach produced solutions in 99% less time compared to using an exact approach, even though the exact approach produced 1% better results.

Some of these studies complement each other. For example, Esmaeili et al. [25] using the Network Flow Algorithm to design maximum stable stope width in sublevel stoping while upholding geotechnical constraints. This approach complemented the work by e Faria et al. [26,27], who designed risk-resilient stopes to manage risks due grade uncertainty. To achieve this, e Faria et al. [26,27] proposed a two-step SIP approach that concurrently optimised the stopes, development networks and production schedules under grade uncertainty, to solve the stope layout optimisation problem in an integrated manner. The integration of grade uncertainty in stope design is now an accepted practice in mine planning optimisation research due to the anisotropic nature of mineral deposits. To develop risk-resilient stopes, Shami-Qalandari et al. [30] developed block caving stopes that incorporate grade uncertainty, using the floating stope algorithm, the maximum upside/minimum downside, and the value-at-risk criteria.

The above articles indicate advancements in research on stope layout optimisation. These advancements highlight the ongoing efforts to improve stope layout design and optimisation by balancing economic value with risk and computational efficiency.

Table 2. Categorisation of approaches that were applied or discussed in the identified studies.

Exact methods	Metaheuristic methods
Integer programming (IP); mixed integer programming (MIP) or mixed integer linear programming (MILP); stochastic integer programming (SIP); dynamic programming (DP); downstream division approach; branch and bound technique; network flow method.	floating stope algorithm; multiple pass floating stope process (MPFSP); maximum value neighbourhood (MVN) algorithm; simulated annealing (SA); dual interchange algorithm (DIA); particle swarm optimisation (PSO) algorithm; genetic algorithm (GA)

6.2. Approaches considered in stope layout optimisation

From Figures 8 to 10 and a reading of the papers comprising the merged database of 65 articles, it was observed that the approaches considered in solving the stope layout optimisation problem are generally in two categories (Table 2), which shows that both exact methods and metaheuristic approaches have been used. In a 3D context, there is a strong leaning towards the use of metaheuristic approaches.

6.3. Identified limitations and scope for future research

With a few exceptions, such as for example, MSO which was developed by Alford [60] based on the floating stope algorithm and is embedded as a module in Datamine commercial software, there is a general lack of mining industry adoption of current approaches for solving the stope layout optimisation problem. This is partly due to several limitations that still exist with the approaches to solve large-scale 3D problems as encountered in actual mining practice. Some of these limitations were identified earlier in this paper. In addition, as noted earlier, there seems to be limited collaboration among researchers working this area of

Table 3. Identified limitations and proposed future research directions.

Limitations	Proposed future research directions
Geological, technical, and economic uncertainties are inherent to stope optimisation. However, existing approaches do not always incorporate uncertainty.	By incorporating geological, technical, and economic uncertainties into problem formulations, it should be possible to develop probability stopes or risk-based stope optimisation formulations.
Stope layout optimisation is more computationally difficult than the open pit equivalent. Therefore, most stope optimisation approaches take inordinately long solution times as compared to open pit optimisation making them unattractive for embedding into commercial software.	Opportunities exist to modify metaheuristic approaches to converge to near-optimal solutions in shorter timeframes.
Current stope optimisation approaches do not solve the problem holistically in an integrated way with the other sub-problems of the generic underground mining optimisation problem to generate simultaneous optimisation of stope layout and stope sequencing with computationally efficient ways.	Future research should place more emphasis on concurrent optimisation of development layout, stope layout, production scheduling and equipment selection and deployment, using more computationally efficient ways.
Current stope layout optimisation approaches do not yet fully address large-scale 3D problems as encountered in actual mining practice.	Existing approaches suggest that there are opportunities to modify metaheuristic approaches to generate solutions to large-scale 3D stope layout problems because exact methods generally become intractable in 3D space.
Current approaches to stope layout optimisation have focused mainly on the sub-level mining method.	Future research should place more emphasis on other underground methods as this will likely increase the uptake of stope layout optimisation approaches by the broader mining industry.
Researchers are mostly currently working in isolation and not collaboratively to solve the stope layout optimisation problem, hence solutions are fragmented leading to poor uptake by the mining industry, partly due to current solution times being inordinately long for practical use. This is despite the importance and practical relevance of the research area to the mining industry.	A coordinated approach is required due to complexity of the stope layout optimisation problem. Establishment of a community of practice in this complex optimisation area could go a long way in enabling researchers to produce solutions that are more useful to the mining industry and having short solution times. This could lead to more mining industry funding to support research in this area.

the generic underground mining optimisation problem. Table 3 tabulates some of these limitations and proposed future research directions to try and overcome the limitations. It is hoped that in future some of the proposed future research directions may aid increased adoption of stope layout optimisation approaches by the mining industry and software companies. The proposals may also be useful to some researchers planning to solve the stope layout optimisation problem in an integrated way with other sub-problems of the generic underground mining optimisation problem.

7. Concluding remarks

This paper presented a qualitative review and bibliometric analysis of the stope layout optimisation problem as a sub-problem of the generic underground mine planning optimisation problem. The optimisation hinges on generating solutions that enable the optimal extraction of mineral resources within an underground mining context. The qualitative review and bibliometric mapping and analysis indicated that:

- Exact methods are limited in generating optimal solutions to large-scale stope layout optimisation problems in 3D space as encountered in actual mining operations because the formulation becomes intractable by being NP-hard [5,15,20]. However, metaheuristic approaches can generate solutions to NP-hard problems and computational problems for which exact methods generate solutions but in prohibitively long solutions times.
- For metaheuristic approaches to be more efficient in terms of solution times, it is important that they are formulated such that they can converge quicker to near-optimal solutions. In this way, it becomes attractive to embed them into commercial underground mine planning software.
- Due to the interactive circular logic in which stope layout optimisation is embedded, there is scope to use ML or AI techniques to solve the stope layout optimisation which is intrinsically complex especially when solved in an integrated approach for solving the generic underground mine planning optimisation problem.
- It was observed that sublevel stoping is the commonly analysed mining method in stope layout optimisation. There are prospects for future research to consider other underground mining methods, again, this will facilitate adoption of the developed techniques by the mining industry.

Several limitations and proposed future research directions were outlined with a view to facilitate better uptake by the mining industry of the approaches to solving the stope layout optimisation problem and for researchers to work collaboratively in solving the complex stope layout optimisation problem.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Credit authorship contribution statement

Cuthbert Musingwini conceptualised the research study and designed the research methodology. Bright Mutandwa conducted the literature review, collected data from Scopus and Web of Science databases and analysed it using

R-Biblioshiny and VOSviewer software and edited the draft manuscript. Cuthbert Musingwini compiled the original draft manuscript, provided overall supervision, reviewing, editing of the manuscript, and responding to reviewer comments.

Ethical compliance

The work reported in this paper did not utilise any human nor animal participants, hence did not require ethical clearance. However, care was taken in conducting the work ethically.

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