

# Critical drivers and considerations in designing open pits and landforms: decisions engineers and planners make and why

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## Abstract

*Do mine closure professionals truly understand the design decisions of mining engineers and planners in open pit mining and waste landform design? Using our combined experience, we unpack, investigate and discuss the primary and secondary drivers in these decision-making practices and the value chain process used in mine development and discuss the discovery of a highly influential and persistent paradox.*

*Waste landforms are among the largest structures at a mine. Poorly designed and constructed waste landforms can become a significant long-term closure liability. Closure professionals are often faced with attempting to rehabilitate poorly planned and/or constructed landforms, which leaves a negative legacy, elevated environmental and business risk, long-term management costs and challenges for regulators, mining companies and the community – a recurring situation extant across mine sites globally, and that we believe is primarily due to the ways mines come into being and are designed primarily on economics. This is a situation we describe as the ‘value chain paradox’.*

*Mining engineers in training today often become the mine planners, senior operational engineers, general managers and chief executive officers of the future. Is training today optimising practice and design toward a positive mine closure legacy? Our review suggests that more integrated team decisions in mine planning, awareness, capacity building and education will be the solution to the paradox, and hence we discuss resolutions in detail.*

*A further aim of this research was to provide closure practitioners, regulators, and stakeholders greater understanding of the constraints and drivers mining engineers and planners must consider in mine and landform design. In this paper, we advise closure practitioners of the linkages between the pit waste and landform construction, throughout mine life to closure, as we believe that in seeking to understand, practitioners gain the capacity to influence the designs and construction of the mine and ultimately to make the change toward a more sustainable post-mining state, returning disturbed land to a stable and productive condition and leaving a positive legacy.*

**Keywords:** *economics, geotechnical, landform construction, mine engineer, training, value chain process, value chain paradox.*

## 1 Introduction

What are the primary and secondary drivers in open cut and waste landform design? How do mining engineers and mine planners make these key decisions, what is the value chain process that they apply to mine design (described in Section 3.2), and how does this influence mine closure? Based on multi-decade experience, we discuss training and education and practices of the past, and present, to determine if there has been a shift in the primary and secondary drivers of design. We discuss pressure on industry to be more

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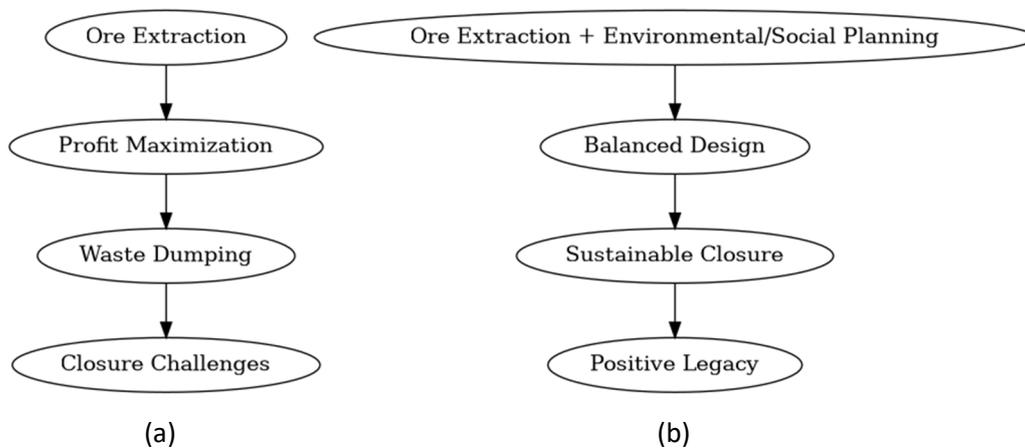
sustainable and if this has impacted on mine waste management and open pit designs and influenced the training and development of the industry’s mining engineers, mine planners and managers. In discussing these questions, we look to provide those not trained in mine engineering the understanding and capability to question and create an effective dialogue to work within design teams constructively.

A major challenge associated with the development of large open cut mines is the successful rehabilitation and closure of mine waste landforms and tailings facilities. Among the most substantial features of the mining process, these facilities bring a raft of challenges often leaving environmental, economic and safety-related legacies as a result (Lacy 2019). Mining and mineral processing are significant waste-generating processes, producing great quantities of waste rock and tailings to win relatively small volumes of minerals. As far back as 2011, it was estimated that, in that year alone, the global mining industry produced 7.1 billion tonnes of tailings and 55.9 billion tonnes of waste rock (Mudd & Boger in Franks 2015). It has become apparent that any post-mining landscape should be considered with the knowledge that it will exist for millennia and be subject to the forces of climate and resultant natural evolution. Therefore, it is important that any landscape be designed and constructed to be functional over millennial time scales (Hancock & Martin Duque 2024).

The designing of mine waste landforms and the post-mining landscape has become a consideration in the last quarter of the 20<sup>th</sup> century due to increased awareness of the catastrophic failures of waste dumps and tailings storage facilities with loss of life, and as environmental impacts downstream of mines increased (e.g. acid mine drainage and sediment), mine waste materials management attracted legislative and technical attention primarily driven by social outrage (Martin Duque & Lacy 2025).

In response, guidelines and legislated requirements were developed to achieve greater assurance of overall geotechnical stability, improved management of acid-forming or problematic waste via an engineered or conventional reactive approach (Lacy 2019). However, we recognise and discuss the reality that the primary focus of waste landform design was, and remains, on the immediate operational economics, ease of construction, maximisation of waste storage volumes near pits, and minimisation of haul distances and mine footprint. This focus often results in landforms of a steep gradient and mountainous form that become complex to regrade, manage surface runoff and to rehabilitate – commonly the cause of ongoing problems and ultimately creating a negative mine closure legacy.

Waste landform problems are only one example of an impediment we describe as ‘the value chain paradox’ (Figure 1), that constrains an otherwise changing mining industry that has been, for some decades, attempting to address many of its impacts and conflicts with society, and has embraced environmental, social, governance (ESG) with vigour. Yet this ‘paradox’ remains, creating ongoing problems associated with landform failures as a result of limited design and deeper consideration that make it difficult for the industry to close its mines effectively and improve its social licence to operate.



**Figure 1** This flowchart illustrates the 'value chain paradox' in mining, showing how economic drivers dominate mine design decisions, leading to negative closure legacies. The figure contrasts (a) the traditional value chain (focused on short-term profit) with (b) an ideal integrated approach (balancing economics, environmental, and social considerations)

While economic drivers and the maximisation of profits are, and always will have, a level of primacy for a project to proceed, it is also possible by prudent design and operations of waste landform construction to optimise the overall project profitability. It is possible to have a long-term win-win situation, without the potential for high business and environmental risk at the end of the mine life (Dowd & Slight 2006).

## **2 A brief history and advances in mine engineering and design**

Mining has a rich history spanning millennia (Agricola 1950). Mining knowledge grew empirically over that time, with individual technical disciplines developing to extract the target mineral more efficiently, and effectively at a lower cost. The formalisation of knowledge and skills at the tertiary level dates to 1765 with the establishment of the Freiberg Mining Academy in Germany.

This was a pivotal time for mining, because it brought together the State and industry to formalise the skill sets required for the broader science of mineral extraction within a learned institution's framework.

The first Industrial Revolution, powered by the mining of coal, commenced in Europe in 1760. It provided a massive impetus for rapid change in the technology, efficiency, and scale of mining. As a result, technical advancement proliferated around the world wherever the need, foresight and capital were available.

During the 1830s and 1840s the complementary sciences associated with mining advanced considerably. Driven by industrial development, society supported the development of earth sciences, both related to mining and beyond, with advances in many fields, including geology and extractive metallurgy. Many tertiary institutions adopted mining-related earth science curricula – some of which still operate today despite mining not being in vogue around the world.

The evolution of mining knowledge, skills, and methodologies has continued to advance apace, but a significant step change was the introduction of practical and affordable computing in the 1970s and 1980s with both technical and non-technical software applications (Friedman 2007). Repeatable automated computations with expanded datasets marked a significant watershed in mining-related subjects, including mine design and planning. Modern computer networking and business systems support a project-team-based methodology. More collaborative approaches between disciplines such as geology, geotechnical engineering, mineral processing technology, and civil engineering have grown over the last few decades within industry, as well as universities and colleges across the world.

Should we reform mining education to ensure graduates can effectively plan and design landforms for the complete mine life cycle and its challenges? The mining industry can only build competencies and capacity within the industry by working with all educational institutions.

## **3 Decision-making and drivers: changes in practice through time**

### **3.1 Open pits and design**

The development of the industry (Section 2) led to the industry understanding that the evaluation, development and operation of mines required a multidisciplinary and collaborative team. However, within a technical study such as a mining project feasibility study or an operating mine design update, one type of mining professional takes the formal lead in assimilating the information from individual disciplines – generally the mining engineer (engineer). With this information, the engineer evaluates the overall project initially and historically – usually only from an economic perspective. The more enlightened companies do broaden the project's success criteria such that a project must clear several non-financial hurdles, but pure economics remains the primary driver.

Although a simplification, the engineer seeks to use information from several sources in the design process, such as:

- the resource 'block' model from the resource geologist
- pit equipment and mining costs from the mine operations team
- processing recoveries and costs from the metallurgist
- potential pit slope angles from the geotechnical engineers
- financial targets/commodity price predictions/project hurdles from corporate management and the board.

The engineer generally undertakes an economic evaluation and optimisation study using established methodologies and software (using a geostatistical geology block model and Lerch–Grossman optimisation techniques), whereby blocks of rock are reduced to their economic value – a positive value if the block is potentially ore, and a negative value if it is solely waste. Based on the nominated pit slope arcs, the spatial relationship is calculated between the potentially economic blocks and the natural surface. The aggregation of positive economic blocks (ore), along with the required negative economic blocks (waste and sub-grade), leads to the generation of potential open pit 'shells', which denote the most profitable pit at a particular mineral price. Clearly, this is a profit-maximising model we describe as the 'value chain process'. This value chain doesn't directly relate to minerals with product blending requirements or another product/ore feed constraint, and it's unlikely that the cost to rehabilitate and close the mine once the orebody is exhausted is captured within the process, unless specifically provided in the block model economics (normally mining, milling, and management costs per unit of metal recovered) are the primary measures.

This broad outline in the preceding paragraph is in the language of engineering to demonstrate a very specific science, and that ultimately the primary driver for the evaluation of the deposit/pit/orebody is profit, i.e. economic value and return to shareholders. This is exemplified by such phrases as 'grade is king' as it drives the block modelling and optimisation process in the study phase. Following this value chain process leads to chasing the mineral from the orebody model, excavation of ore in the pit, haulage to the plant, processing, and through to refinement of the mineral or the ultimate saleable product. The engineers and all the personnel in the production chain will strive to achieve this, albeit safely, but certainly with profit in mind, and potential personal incentives, and career advancement as a result. The existing management and mining support systems reinforcing this value chain process – and from our perspective it has become 'the paradox'.

The design team and the original evaluation team are often only involved with the mining project on a short-term basis and are rarely very experienced in the complete life-of-mine cycle. Hence, they rarely consider the post-mine-closure landscape and constructed closure liabilities that will be created during the mine life by these designed landforms. This issue is exacerbated with the usually high turnover, career advancement, and desire for the 'next' project of the evaluation team engineers resulting in a lack of real long-term ownership of the design during the mine development and operations of the project. They are not confronted in the design phase with the scenario of a mature mine that has rapidly advancing mine closure and associated closure liabilities as the ore bodies are exhausted.

It is difficult to overcome this issue without some recognition and improvement of the capacity and competency attributes within the engineers. These attributes will need to be encouraged and instilled within the education of the engineers at the university level, through cadetships and early career training arrangements within mining companies after graduation, and leadership from mining industry executives.

This rusted-on process of the value chain leads back to the original tertiary education of mining engineers and those of the supporting professions in resource economics, and financial and minerals consulting. The significance of this training is that these very same engineers are trapped within a tunnel of limited vision, on a career path enroute to becoming planners, senior operational engineers, mine managers, general managers, chief executive officers and directors of mining corporations and companies worldwide.

The continuation of the value chain process, while economically necessary but restrictive in its vision, is indeed a paradox as it results in missed opportunities, loss of social license and profit, and could be avoided through an integrated approach during the mine life cycle by the creation of mine landforms that are relatively free of closure liability, easily stabilised, able to be rehabilitated, and meet closure criteria, future land use options and regulatory requirements at the closure of the mine and beyond.

Clearly, this is an oversimplification of what happens in a mine during the pre-production feasibility study and potentially the operational phases. Contentiously, around the world all we have to do is look at the vast numbers of sites that are a negative legacy to see the result of the paradox. Even sites from recent mining activities can provide a substantial challenge at closure, suggesting the primacy and subsequent results of following the current form of the value chain.

Many companies show significant enlightenment in areas not directly related to this value chain. In this paper, we have focused on one area that is clearly in the design bailiwick of the engineer but not directly on the traditionally viewed value chain – that of the waste landform or waste dump, which houses the waste materials generated from the exploitation of the mineral. We demonstrate in this section and the subsequent Sections 3.2–3.4 the single-minded drivers of the value chain that drive economic-only processes and summarise this in Section 4. In the subsequent Sections 5–7, we unpack those activities we believe could lead to changes to the value chain – providing integrated design thinking and a reduction in the effect of the paradox.

### 3.2 Waste landform design and waste management

The importance of the waste landform should not be understated. It is likely to be the second-largest structure in the mine by footprint (after the tailings storage facility). It has the strong potential to adversely impact the environment physically, chemically, and visually. From a closure perspective, it can and will be a major cost centre if not designed, constructed and closed well. The importance of getting it right the first time cannot be overemphasised.

The value chain paradox often leads to critical closure structures, like waste landforms, being inadequately considered during initial mine design. These landforms should be integrated into the overall mine optimisation process, as their economic drivers differ significantly from open pit operations – waste itself carries direct value.

Current practice typically estimates waste haulage costs during pit optimisation based on equipment specifications, operational costs, and assumed haul distances to a notional waste landform centroid. While some operations refine these estimates iteratively, many accept initial approximations, believing they minimally impact overall mine economics. This approach reflects a systemic undervaluation of waste landform planning, deferring proper consideration until closure – a clear symptom of the value chain paradox.

Empirically, we believe there is, in the main, insufficient engineering design and control of waste landforms.

How do we know this? The authors of the paper have over 100 years' collective experience working globally in all aspects of mine design, development, production, mine management, operational rehabilitation, environmental management, closure cost estimation, and closure and post-closure implementation.

Industry experience demonstrates that waste landform designs in feasibility studies frequently lack sufficient capacity to accommodate generated waste volumes. Analysis suggests approximately 30% of designs are under capacity by as much as 30%, often without alternative disposal plans. These capacity shortfalls reveal fundamental gaps in the process as it informs mine design. Such deficiencies highlight the need for more rigorous integration of waste management planning throughout the mine design and optimisation process.

Secondly, why do so many waste landforms take so much time and cost to close out? Why must large volumes of rock be relocated by dozer or truck? Reshaping high slope faces is costly. Importing waste onto the dump for armouring or deleterious waste capping is even more costly. On the face of it, if the correct design had been applied and the waste material positioned in its correct and final position, then closure of the landform would have been a reasonably quick and low-cost exercise. Some mines are so costly to rehabilitate, including their waste landform, that the rehabilitation would fall on the State without extensive forward provisioning.

Yet it needn't be the case. With good design and construction control, the rehabilitation and closure of the waste landform can be both low-cost and easy to undertake, and quick to complete.

### 3.3 Waste landform objectives and drivers

So, what should the objective be for the waste landform optimisation and design?

Some are obvious, such as:

- safe, stable and non-polluting
- the lowest cost possible to construct
- it complies with all regulatory requirements
- it is easy and low-cost to rehabilitate and relinquish at closure.

These are really overarching (motherhood?) statements and miss out on the nuances of establishing the best waste landform design for that site in that environment and regulatory framework. The initial starting point for the engineer should be that they are designing a structure, not for 20 or 30 years but millennia – a timeframe in which some are not used to working with.

Additionally, many of the inputs may be site-specific, but in general they may include:

- Design for the maximum term, not just an assumed relinquishment timeframe.
- Allow for climate-change-specific conditions.
- Plan for the climate, particularly rainfall, during construction, and not just at the end of the mine's life.
- Potential runoff from exposed deleterious waste should be prevented or at least minimised and controlled. Determine whether runoff should be contained or shed from the structure.
- What are the structures required at the toe of the landform?
- How far from hard limits do they need to be positioned? What is the maximum toe position for waste landform?
- Understand the physical and geochemical behaviour of all materials to be dumped, not just by their geological code but by their positional requirements within the waste landform. Develop a waste landform construction schedule based on these classifications.
- Undertake detailed, period-by-period scheduling of the landform construction based on the final and the conservative sub-designs.
- What level of management control and supervision is required to construct the landform?
- Understand that there is no perfect knowledge here. Embrace forward-looking audits to redefine the landform construction periodically. This will reduce business risk and unplanned/excessive expenditure at closure.
- Where are topsoils and sub-soils to be stored, and in what condition? How will they be used in rehabilitation? How will the topsoil be applied and moved into position?
- What is the rock specification for the cover immediately below the topsoil?

On the face of it, the engineer is the key person during feasibility who is most equipped to develop the best possible waste landform design to meet both economic and sustainability outcomes. In addition to tertiary education and access to a plethora of technical software, the engineer generally has direct access to the information (or the persons who can generate the information), with much of it coming from the pit optimisation work such as:

- The economics of haulage, including waste haulage.
- The physical and economics of dump construction equipment for pre and post-mining activities.
- The location of infrastructure, restricted areas and lease boundaries.
- The mining schedule showing waste material to be mined over time.
- The resource model, including information concerning waste classification. Geological and geochemical support will probably be required to develop the best model.
- Develop detailed post-closure designs, including outer faces, berms (if appropriate) and upper surfaces with specific reference to water handling on the structure.
- Determine beneficial waste suitable for landform cover, e.g. armouring, supporting surface vegetation; deleterious waste, e.g. dispersive and potentially acid generating; and positionally benign, e.g. robust but unsuitable for the landform outer surface.
- Embark on scheduling the landform construction, understanding that initial runs may well fail.
- Persevere using alternative, acceptable sub-designs and stockpiling of final cover material. Initially, the stockpiling will be to 'a phantom location', but actual stockpile designs will be required once the gross volumetric requirement is established.
- The difficulty of scheduling the dump by computer is the corollary of how hard it will be to construct and, therefore, the construction supervision and control required.

### 3.4 Software systems to support design

#### 3.4.1 *Open pits*

Geological evaluation and general mine design packages abound since their inception in the 1980s. Many current mining software companies trace their origins back to that era. There are approximately 10 mine design suites available today that can be described as general mining packages (GMPs). These GMPs vie for adoption on a worldwide basis with the majority offering niche products that support the design and operation of mines. Additionally, there are numerous specialist packages covering a wide range of optimisation, modelling and analysis subjects which integrate and supplement the GMPs. This market can best be described as crowded with strong user loyalty due to the time and complexity of changing GMP. There are some 40 years of knowledge of how to optimise and design an open pit excavation using a GMP and specialist software (e.g. Whittle 4D), including numerous workshops specifically on the topic.

#### 3.4.2 *Mine waste landforms*

While many GMPs profess to cover the waste landform optimisation, design and scheduling, none appear to be fully up to the task. The general consideration of a waste landform being an inverted open pit for design purposes, which is the form of output most GMPs provide, falls far short of the requirements. Equally, the GMP giving the engineers a series of 3D design tools alone is inadequate.

There are limited software packages available that cover all aspects of landform design. Some proprietary software exists (Russell 2008; Russell & Lacy 2015). There are a number of erosional and landform evolution modelling (LEM) software programs in one, two and three dimensions – RUSLE (1D), WEPP (2D), CAESAR and SIBERIA (3D) are some used extensively (Hancock & Willgoose 2017; Evans & Riley 1994 and Willgoose 1989

as cited in in Hancock et al. 2003. However, none of these cover the mining design aspects within the value chain process currently.

There are advanced earthworks and tailings modelling software available that can create, analyse, and visualise landforms quickly, such as Muk3D™ (MineBridge Software Inc n.d.), LHS (Deswick n.d.), and Truescape (Truescape Ltd n.d.), however, there is only one design tool that we are aware of – GeoFluv™ (GeoFluv n.d.) (Bugosh 2000) – that provides something approaching advanced design for landforms. GeoFluv is a geomorphic design method, implemented within the ‘Carlson’ Natural Regrade and civil computer aided design (CAD) software product. The tool looks to emulate local landscapes in the mine region in its design process (Bugosh & Eckels 2006; Bugosh & Epp 2019).

## 4 Critical drivers and considerations in design: overview

We define a critical driver as primary to a mine design and essential to the value chain process, i.e. without the information it’s not possible to complete a design. Secondary in the design are considerations that, although in certain circumstances are important and can certainly influence design, are not essential to the engineering and construction of the open cut/pit and hence secondary to the current value chain process.

Table 1 provides descriptions and reasons for the position of drivers of open cuts/pits. Table 2 does the same for waste landforms.

**Table 1 Primary (P) drivers and secondary (S) considerations in design of open cuts/pits**

Driver	Description and reason
(P) Geology – ore and waste definition	Basis for mine. Describes ore/mineral/waste rock. Determines mine scale and size, ore reserves and resources, mineral processing and mining methods, drilling and blasting, grade control
(P) Geotechnical, stability during operations and beyond	Key determinate for pit slope stability and Factor of Safety for operations (not necessarily for closure). Strip ratios effected
(P) Mining method, and operational economics	Equipment selection, equipment productivity, and production schedules, grade control and selectivity in ore/waste excavation
(P) Haul road and ramp design for access into and out of pit to waste rock landform/run of mine	Ease of access, multi-entrances, avoidance of ore zones within ramps, widths scaled to maximum haulage unit (autonomous haulage considerations), haulage units rimpull-speed-grades, braking performance
(S) Open pit optimisation and design, staged construction, groundwater influences	Open pit phasing, cutback size and scale, pit dewatering phases ahead of mining
(S) Waste types (geochemistry) and volumes	Selective mining and control of problematic wastes, haulage profiles, dump locations
(S) Minimising haul distances (centroids) and the mine footprint	Minimising haul truck wear, tyre fires on long hauls and braking performance
(S) Options – potential for backfilling	Staged pit design, orebody dependant

The reader may be surprised to see the differences between the value chain considerations for open cuts/pits. Secondary considerations, such as water, dewatering, and waste types, are unlikely to become a primary driver – unless they appear as a high-risk factor requiring a design response.

**Table 2 Primary (P) drivers and secondary (S) considerations in design of waste landforms**

Driver	Description and reason
(P) Waste rock construction parameters/constraints – machinery type, operating conditions	Survey control, ease of management and supervision, tip head control and safety, cross dump haulage road surfaces
(P) The landform footprint and mine lease constraints	Various jurisdiction and policies, sometimes tenure, restrain physical footprint
(P) Maximising waste storage volumes near pits (centroid), final pit design, open pit zone of instability influences	Haulage distances, dump heights, standoff distances from pit zone of instability, potential dump expansions with changing economics
(P) Geotechnical stability during construction and beyond	Safety – safe/stable. Core requirement during and post construction of structures in perpetuity, hence landforms rarely designed to remain at angle of repose (75%)
(P) Operational economics of waste rock landform construction	Haulage distances, dump heights, dump haul road sheeting, drainage, support equipment requirements (lighting plants, graders, tip head dozers, cost of pre- and post-mining activities).
(S) Ease of construction	End tipping versus paddock dumping. Complexity of scheduling and containment of deleterious waste. Tiphead dynamics.
(S) Geology – waste types, low grade and handling	Describes waste rock/low grade management, informs style of landform, however primary task is to deliver the specific material to its destination
(S) Geology – geochemical characterisation sulphur/acid mine drainage, and non-target minerals management	Problematic wastes separation and encapsulation. Waste rock beneficial to closure isolated, reserved and stockpiled
(S) Aesthetics, community/social licence	Dump height, mine life versus progressive rehabilitation. Shape of the top surface. Visual amenity from likely viewing points.
(S) Environmental and social considerations	Proximity to areas of sensitivity, ethnographic or archaeological Proximity to population centres and specialised habitat and features
(S) Rehabilitation/reclamation requirements	Commitments, policy, requirements. Often legal and licences require. Social licence. Assumed will be achieved in design
(S) Closure requirements – statutory/policy	Commitments and requirement to achieve. Often legal. Assumed will be achieved in design. Depending on local statutory requirement, could be primary or statutory

Again, we see a separation of primary and secondary value chain considerations – in this instance, five primary drivers driving design, with secondary matters such as requirements, heights, regulations, geochemistry relegated unless assessed to be of high risk, or a mandatory or statutory requirement.

## 5 Mining engineer education and support

We have already established that the engineer has much work to do when it comes to mine design and planning, but does that person have the competency and capacity to overcome the value chain paradox and to develop a more sustainable long-term mine design? We strongly argue that, with some limited exceptions, the answer is no, and we outline likely gaps in understanding (Section 5.2) and suggest an advancement in curriculum as described in Section 5.3.

### 5.1 Current status

It is easy to criticise mining educational institutions for not producing mining engineers with the relevant skills and aptitude for working on more sustainable mine waste landforms, specifically their design, construction and closure, and we acknowledge many universities are starting to address these questions, with units such as MINE4166 Geotechnology of Mine Waste Management and CIVL4121 Geotechnical and Geoenvironmental Engineering provided within Mine Engineering at The University of Western Australia (Australia), for example (see <https://www.uwa.edu.au/study/courses/mining-engineering>).

However, the mining industry must first give the institutions clear signals that these are the required skills. This message is absent or weak to date, and the process of design is captured in an endless repeat of the value chain paradox (Figure 1). Without recognition of the current form of the value chain and a subsequent articulated demand of the industry, the paradox will cause ongoing problems for the industry that only the industry can resolve. We cannot, at this stage, point to specific research that supports a demand for change in curricula for mining engineering, however, mine closure education itself was identified as a major gap in education (CRC TiME 2024). We cannot find any indication that institutions training mine engineers are aware of, or even address, the paradox, hence the issue is a field for further research. Nothing is likely to change in the specialised field of mine design until the industry recognises the paradox and acknowledges the importance of developing competencies within the training and education of all future resource industry students.

### 5.2 Likely deficits in the training of mine engineering

All modern mining engineers (those who graduated after the 1990s explosion in mining software) will generally have an excellent grasp of spatial relationships, particularly those used to the planning and design functions – engineers in operational roles, possibly less so, but all are generally proficient. Equally, the pit optimisation process forces the engineer to have a reasonably good grasp of mining economics. So, the main deficit in knowledge will generally revolve around the following six points:

- Waste materials properties – both geochemically and physically in the environment.
- Hydrology – particularly the behaviour of surface water on a waste landform.
- The post-closure landscape – a vision of what this should be and how to construct landforms to bring that vision into reality, so there is landscape integration.
- Environment – those environmental conditions and behaviours that need to be specifically integrated into the design and construction.
- Understanding the concepts of future land use beyond mining.
- Integration of the multiple demands (above) to develop optimal waste landforms.

### 5.3 Desirable subjects in curriculums

Supposing it is necessary to categorise an education module, it should best be classed as ‘environmental aspects of mine design’. It should be taken later in the syllabus after the requisite skills in geology, mining economics, and materials handling (trucks) have been established. It should cover:

- Closure criteria, what does this mean and how does it relate to mine design, best practice, and as submitted in the mining proposal?
- Local natural landforms, slopes and total heights.
- Local climate with emphasis on average and maximum rainfall events and requirements for establishing the basis of design to manage rainfall events on the landforms.
- For the potential landform’s footprint area, the surface hydrology, soil/sub-soil thickness, culturally sensitive areas, other areas restricting development, etc.
- Landform construction options include:
  - haulage economics
  - pre-landform construction costs related to the footprint include clearing/grubbing, topsoil/sub-soil removal physicals and costs, etc.
  - progressive rehabilitation opportunities in design and construction
  - post-landform bulk waste construction costs for reshaping, armouring, topsoil placement, seeding, water handling structures, toe structures, etc.
- Economic optimisation strategies for the landform.
- Classification methods for waste material.
- Handling of deleterious waste material both during the landform’s construction and for closure.
- Handling, storage and use of beneficial waste material, generally used on the base and outer surface of the landform, or for post-mine-use closure/storage or segregation/as assets.
- Design methodologies for waste landforms, including critical area, water handling, control of all waste types, outer and upper surfaces, access and contingencies for changes in material classification.
- Construction methodology sequencing for short-term and long-term containment of deleterious waste.
- Construction methodology for early closure of parts of the landform.
- Business and environmental risks associated with waste landforms.

In this section, we expanded on those secondary considerations (Section 4) identified as likely gaps in knowledge (Section 5.2). These then become items that should be developed in curricula and provided as indicative of material that institutions training mine engineers could consider (Section 5.3), and as a field for further research with focus on the nature of the value chain paradox and its resolution.

## 6 Design and operation: a team approach

Despite the suggested improvement in the education and training of mining engineers, input and information from specialist ‘subject matter experts’ is required to develop mine design with the engineer during the value chain process, and the best possible designs for mine waste landforms. It is, therefore, logical for a team approach to be used, with each specialist understanding the use of the information they generate. A team approach would likely combine the use of resource geologists, geochemists, geotechnical engineers, hydrologists and environmentalists, along with the engineering and pit supervisors – a powerful combination of skill sets. A group of similar professionals should be part of regular reviews (1-2-3 years) in mine design depending on the scale of change.

Integrated mine and closure planning, at all phases of the mine life cycle, will improve closure outcomes including the design and construction of successful landforms. The greater context is to integrate all planning, including design, within the mine operating system where a review of integration and effective processes are formally established, i.e. as extensively discussed within Lacy et al. (2019). The closure of pits and landforms that all form part of the same continuum in design, perhaps for backfilling, for multiple uses are linked as a landform.

Understanding of the critical drivers of a successful landform design relies on input from all elements that an integrated team provides, including:

- mining life planning
- environmental context
- legal requirements
- corporate policies and standards
- financial aspects
- community and stakeholders.

This integration approach to waste landform design provides the most benefits when it comes to the decision-making process. The team needs to explore, unpack and test the design during the review process asking:

- Where are the gaps in the current design?
- What are the risks associated with the design (short-, medium-, and long-term)?
- What are the costs associated with the design, both operational and at closure?
- What does the landform look like at closure, and how does it fit into the closure vision for the site?
- Will the landform be able to be rehabilitated/reclaimed effectively?
- Will the landforms integrate into landscape and be geomorphically aligned with the surrounds?
- What impact does the design have on operational planning, scheduling and costs?
- Does the design cater for changes in operational performance due to commodity prices, operational costs and ore body extensions?

Post team design, review if there is any doubt with any of these checklist items, then the design should be revisited to address those doubts and retested again. In that way, an integrated outcome satisfying all drivers (primary and secondary) of the design will be achieved leading to more sustainable outcomes.

## 7 Influencing design: how to

We have described primary drivers, secondary considerations and aspects of mine design for pits and landforms considered by engineers and design teams within Section 3, and tabulated in Section 4. The process of one affects the other as they are inexorably linked in creating the mine waste landforms. Within a mining organisation, mine closure planners and subject matter experts provide the opportunity to close those value chain gaps identified in Section 5 and applied in Section 6, and this knowledge provides the opportunity for any qualified individual to contribute effectively to influencing the design through the consultation and discussion/review process. To have an effective seat at the table of a design team, you must understand what primary and secondary drivers are, particularly for the engineers, what they will wrestle with, how they are informed and the hierarchy of influence created by the value chain process, hence we recommend closure professionals:

- Engage with the mine design team from the earliest stages.
- Understand and get involved post exploration and discovery, as resource definition drilling is a key stage – particularly for ore and waste geochemistry, waste geology, understanding the target and non-target minerals, and presence and absence of deleterious minerals (e.g. sulphur).
- Question, during the pre-feasibility study, when information is gathered regarding where capital expenditure and key design parameters and processes are developed and established as part of the value chain decision-making process. This is a point where simple questions can be asked (Section 6 and below) and investment decisions made in additional knowledge gathering, that sit outside the value chain process and will provide broader scientific understanding for landform design and mine closure.

Example questions (suggested as a checklist) can be raised within a design team at the appropriate stage. Factors for consideration and considered valuable in informing landform design include:

- Have we identified all the physical constraints that will impact on the final dump design?
- Have we considered and identified all environmental factors and impacts to the environment during both construction and closure, i.e. surface water, ground water, geochemistry, geotechnical and surface stability, and visual amenity?
- How does the landform integrate within the future land use proposed for the site at closure?
- Will the geometry of the design contain the total volume of waste materials likely to require storage during the whole mine life cycle, and can the design cater for project expansion or contraction and concurrent changes in waste volumes?
- How is the need to minimise haulage distances effecting height elevation and manageability of the landform for rehabilitation and final closure?
- Are there opportunities to consider strategic placement of ramps, pit exits and entries, and the waste dump scheduling to optimise landform construction while maintaining profitability?
- Have we planned for, and can we optimise, operational and closure costs through strategic segregation and placement of waste types, scheduling of pit optimised cutbacks and progressive rehabilitation?
- Will the waste dump construction method, i.e. end tipping via dump benching versus paddock dump layering, provide us with the capacity to allow for either segregation or integration of wastes that we need to manage, based on physical and geochemical properties and characterisation?
- Has the waste landform been scheduled out period by period? Has it been clearly demonstrated (visually) that all deleterious waste has been encapsulated or otherwise contained? Has final capping material been accounted for in an appropriate location?

- How are we going to manage surface water and sediment flowing from the landform and haulage routes during construction and will the design cater for the post-closure water management and runoff from the closed and rehabilitated landform?
- Can we expect infiltration and wetting of the waste rock as the landform is constructed, would there be any deleterious impacts and, if so, will we need to provide for seepage management during operations?
- Is there likely to be an impact post closure from sub-surface seepage to ground water post closure of the landform and resulting seepage management?

In summary, we recommend taking part and challenging and testing the capacity of the design team to go beyond the value chain process. As outlined in Sections 3–6 actions and knowledge of processes you can apply as an individual becoming a part of design teams can mitigate the effects of the current paradox by asking the right questions, seeking to resolve these design matters early, and can change the life of mine design process with the aim of mining with the ‘end in mind’ (Lacy & Koontz 2002) leaving a post-mining landscape that will be a positive legacy, and can be assimilated back into its post-mining land use.

## 8 Conclusion

The mining industry has advanced and changed considerably in over three centuries and yet we believe that the primary focus of mine design is, and remains, on the immediate operational economics of profit. We believe that open pit and waste landform design is captured within a long-standing value chain process that currently determines the intellectual pathway of all involved in funding, developing and designing mining projects, and we describe as the ‘value chain paradox’.

We believe this paradox has become an impediment that has constrained an otherwise changing mining industry that has, for some decades, attempted to address many of its impacts and conflicts with society and, despite its embrace of ESG, problems remain, and is a self-inflicted historic and ongoing problem for the mining industry. We believe the paradox causes an ongoing negative legacy of poorly designed landforms that make it difficult for the industry to close its mines effectively and improve its social licence to operate.

The first process in resolving a problem and creating positive change is to identify, define and describe the problem, as we have with the existing value chain process. We believe education and a change in those tertiary institutions training the mining professionals of the future hold the key to that change. Once industry is aware of the paradox, it is hoped they will signal to institutions that a change is needed and, as we describe in Section 5, look to improve the existing mine engineering curriculum.

We have identified that there are critical drivers (primary and secondary) considered in the process of pit and landform design, outlined in Section 3 and tabulated in Section 4, to inform and expose the non-engineer to their ranking. In conducting that exercise, it became clear that the often all important secondary considerations are not considered, resulting in the failure of landforms to meet closure expectations due to limitations in the value chain process being captured by the value chain paradox.

As members of the mining industry, we are a part of a team that can make decisions, through advancing our understanding of the processes and factors in mine design, that influence that process. We become more capable of engaging with and influencing mining engineers and mine planners, even while the ‘paradox’ exists. We outline why you should seek to be part of mine design teams either as a subject matter expert or closure planner, and we recommend asking the questions necessary and contribute as described in Sections 6 and 7. As a team member more aware of the drivers effecting design, you can contribute to change within the mining industry as it pursues the goal of leaving positive legacies post its operations.

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