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Managing complexity and risk in large-scale mining developments: strategies for successful operations

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Abstract

Large-scale mining developments, including next-generation 'super caves', are inherently complex, capital-intensive, and high-risk. As surface deposits deplete, the industry is transitioning to bulk underground methods – principally block and panel caving – to access deep orebodies. These projects face unique challenges, including decade-long development timelines and significant technical uncertainties. This paper examines strategies to manage such complexity through phased, modular development versus traditional front-loaded megaprojects. We discuss how embracing flexibility can mitigate risk and achieve economic outcomes often overlooked by conventional discounted cash flow (DCF) methods. By comparing caving techniques, exploring 'super caving' transitions, and analysing case studies like El Teniente and Kamoa-Kakula, we synthesise best practices for securing long-term value through technical simplicity and adaptive planning.

Keywords: *large-scale mining, underground mining, block caving, super caving, risk-based mine planning, phased project development, open pit to underground transition*

1 Introduction

Global mineral demand is driving a transition from large open pits – such as Escondida, Bingham Canyon, and Grasberg – to bulk underground mining methods as surface deposits reach their geotechnical limits. Methods like block and panel caving enable production rates of tens of thousands of tonnes per day, matching the scale of surface operations to keep processing infrastructure fully utilised. In brownfield replacement scenarios, next-generation underground mines must be large enough to amortise high infrastructure costs and uphold the production structures of preceding operations. Key examples include Codelco's Chuquicamata and El Teniente, Freeport's deep mill level zone (DMLZ), and Newmont's Cadia East, all of which target massive throughput to justify decade-long development timelines. Despite their necessity, these developments are true megaprojects characterised by multi-billion-dollar investments and extreme execution risk. The industry track record is sobering: approximately three-quarters of large mining projects exceed initial capital estimates, with average overruns of 25–60%. Flyvbjerg (2017) notes that megaprojects across industries suffer from an 'iron law': over budget, over time, and under benefits. In mining, this is compounded by unique geological and hydrological uncertainties that can confound even thorough feasibility studies (McKinsey & Company 2019), making reference-class forecasting a vital tool for realistic planning. Complexity is further driven by the 'tyranny of schedule', especially when a new mine must replace an existing operation without production gaps. Management is often pressured to 'fill the mill', leading to aggressive schedules with little room for contingency. This pressure is frequently external; politicians and local stakeholders may tie approvals to swift economic growth or election cycles. Such agendas can force shortcuts during construction, creating fragile project setups where unforeseen events rapidly escalate into significant financial and safety issues.

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These pressures are often exacerbated by a reliance on conventional discounted cash flow (DCF) analyses, which assume deterministic inputs and may fail to capture the inherent uncertainties of large-scale operations. A more robust approach utilises multivariable, multipath stochastic simulations to assess a broad spectrum of possible outcomes. By recognising operational and market uncertainties, stakeholders can better balance the urgency of production against the need for methodical development, leading to more resilient economic valuations.

In light of these challenges, this paper examines strategies to manage risk through a philosophy of 'simplicity' in design and execution. We contrast staged, modular development with traditional front-loaded methods and analyse how the choice between block and panel caving affects project flexibility. Through the exploration of 'super caving' operations and real-world case studies, we discuss advanced valuation and risk management techniques. Ultimately, these best practices demonstrate that balancing technical simplicity with adaptive planning can secure long-term value in the face of uncertainty.

2 Complexity and risk in large-scale mining

Large-scale mining projects rank among the most complex industrial ventures. They involve the coordination of several systems – geology, civil excavation, machinery, logistics, human resources, and finance – under conditions of significant uncertainty and dynamic change. Perrow's theory of complex systems (Perrow 1999) applies: a modern multi-billion-dollar mine development has many interactive parts and hidden couplings, making it prone to 'normal accidents' if not carefully managed. In Perrow's framework, the likelihood of such accidents is governed by 2 system properties: interactive complexity – the presence of many components whose interactions are non-linear and cannot all be foreseen – and tight coupling – the absence of slack, buffering or substitutability between steps, so that a disturbance propagates rapidly and cannot easily be isolated. Where both attributes are present, serious failures cease to be mere aberrations and become an inherent, statistically 'normal' property of the system, because individually minor faults can combine in unanticipated ways faster than operators can intervene. A deep cave development displays both characteristics, which is precisely why the redundancy, buffering and loose-coupling measures emphasised throughout this paper – spare drawpoints, orepass and crusher redundancy, and schedule contingency – are so important. In mining, complexity manifests in several dimensions:

- Technical complexity: deep mining requires kilometres of tunnels and massive underground infrastructure – including crushers and conveyor systems – within high-stress rock environments. As mines go deeper, traditional rules of thumb often fail, and the system becomes 'fragile' due to tight coupling; unlike open pits, there is little flexibility to adjust the mining sequence once underway. To address this, Rubio et al. (2008) introduced reliability-centred mine planning, which builds buffers and backups into infrastructure to account for failures or geotechnical events.
- Scale and financial risk: The scale of capital – often 2–7 billion dollars – and long lead times of up to a decade expose projects to major macroeconomic risks and inflation . Historical data shows a 74% probability of exceeding capital estimates, particularly for large, remote projects. Every month of delay results in tens of millions in deferred cash flow, making the risk-adjusted value of the orebody highly sensitive to time.

The projects in Table 1 illustrate the range of capital cost growth and schedule slippage that recent large caving and open pit developments have experienced.

Table 1 Examples of project's delays and cost overruns

Project	Projected initial capex (USD M)	Real initial capex (USD M)	Cost overrun (%)	Delay (months)	Source
Oyu Tolgoi	5,340	6,745	26.3	22.8	MINING.COM 2020; Rio Tinto 2020; S&P Global Market Intelligence 2020
Cadia East (Panel Cave 1 and 2)	2,000	2,100	5.0	12	Engineering & Mining Journal 2010; Newcrest Mining 2014
Grasberg Block Cave	2,300	3,500	52.2	24	Casten et al. 2020; NS Energy 2020
Northparkes E48	800	850	6.3	6	Mining Technology n.d.; Rio Tinto 2006; Snyman et al. 2022
El Teniente New Mine Level	3,400	5,950	75.0	48	MINING.COM 2014; Mining Technology n.d.b
Chuquicamata underground	4,200	6,800	61.9	36	Hatch n.d.; Mining Technology n.d.
Grasberg deep mill level zone	1,100	1,400	27.3	18	Casten et al. 2020; Nugraha et al. 2022

These cases are illustrative only and are not directly comparable: they differ in project scope, cost escalation, reporting currency, reporting period and the estimation criteria applied, and are presented here to indicate the general magnitude of cost and schedule risk rather than to rank individual projects.

- Schedule and operational risk: projects involve a long chain of interdependent tasks where a single delay, such as a ventilation shaft, can cascade through the entire critical path. Roughly 60% of the timeline is dedicated to slow, linear development vulnerable to unexpected ground conditions. Furthermore, the 'tyranny of schedule' often leads to systemic risk-taking and shortcuts during construction, resulting in ramp-up profiles that rarely meet forecast timelines.
- Organisational and external complexity: aligning the conflicting objectives of corporate boards, engineers, and local communities is a delicate task. Communication silos frequently lead to optimistic schedules that ignore site-level realities. External factors, such as regulatory shifts or community opposition, can be fatal; the Pascua-Lama project, suspended after a USD 5 billion investment (Komnenic 2013), illustrates how non-technical risks can cripple even world-class engineering.

In summary, this multifaceted complexity creates a 'fragile' environment with an asymmetric risk profile – there are far more ways for things to go wrong than to exceed expectations. Contending with this complexity is the primary challenge for securing long-term value.

3 Simplicity in managing complexity

Given the intricate and high-stakes nature of large mining developments, a paradoxical insight has emerged: simplicity is often the key to managing complexity. This does not imply that the project is made simple – by definition a multi-billion-dollar mine is complex – but rather that management and design philosophies should strive for elegant, robust solutions and avoid unnecessary complication. As one mining maxim puts it, "plan the mine – mine the plan", emphasising that a well-thought-out, realistic plan must be in place and then executed with discipline. Several strategies embody the simplicity ethos:

3.1 Robust, fit-for-purpose design

A critical way to impose simplicity is through design choices that favour robustness over optimisation to theoretical extremes. For example, in a caving operation, having reliable, well-distributed drawpoints and a robust material handling system is more valuable than squeezing the absolute maximum ore recovery with a complex layout. Moss et al. (2023) argue that because caving is relatively inflexible once started, the design should err on the side of being 'forgiving' – able to tolerate geological variability and operational missteps – rather than chasing marginal gains that add complexity. In practice, this might mean using slightly wider spacing of extraction drives or extra orepasses and haulage capacity as contingency. While such measures might lower the calculated initial net present value (NPV) (due to a bit more capital or a bit less recovery), they greatly enhance the probability of achieving a steady, sustainable production (which in reality drives value more than an idealised plan that fails to materialise). In short, a simpler, robust design provides a buffer against the unknown. An illustrative anecdote: experienced cave engineers often quip that 'the cave always wins when shortcuts are taken' – if a design is not properly executed or is too clever for its own good, nature will find the weak point. Thus, avoiding shortcuts and designing for resiliency is a form of simplicity.

3.2 Phased and modular implementation

Tackling a huge project in smaller, discrete phases is another way to simplify. Rather than sinking all shafts, building all processing capacity, and developing the entire orebody in one go (a recipe for overwhelming complexity), a modular approach breaks the project into manageable chunks. Each phase is simpler (scope-wise) than the whole, allowing the project team to focus and learn, then apply lessons to the next phase. This concept will be expanded in Section 4, but it is fundamentally about simplifying the task at hand at any given time. Kamoa-Kakula in the Democratic Republic of the Congo, for instance, adopted a phased build-out: an initial 3.8 Mtpa (~10,000 t/d) mine and concentrator, quickly followed by a second of similar size, rather than one giant 7.6 Mtpa step. The result was a rapid start of production in 2021 and a doubling of throughput by 2022, all while keeping each step relatively straightforward to execute. By staging the expansions, the project reduced peak financing requirements and operational risk, embodying the mantra 'start small, then scale up'. Each module had a clear scope, and the success of the first gave confidence (and cash flow) for the second. From a complexity standpoint, this divide-and-conquer strategy makes challenges more tractable.

3.3 Standardisation and proven practices

Simplicity also means avoiding reinventing the wheel where possible. For long-life projects, it's tempting for teams to pursue bespoke, cutting-edge solutions (to match the 'flagship' nature of the project). But an alternate approach is to standardise and use proven technology/practices, even if they are not the absolute latest. For example, instead of designing a brand-new underground haul truck or crusher system, a project might choose models that have been used reliably at other mines, even if a newer version promises slightly higher performance. Benchmarking against successful projects can identify what works and what doesn't. Flyvbjerg (2017) emphasises the "reference class" approach for megaprojects – i.e. compare with a class of similar projects to gauge realistic outcomes and practices. In mining, this could mean studying a dozen block caves worldwide to establish realistic advance rates, fragmentation behaviour, and production ramp curves, then designing your project in line with demonstrated capabilities (rather than optimistic assumptions).

By grounding designs in precedent and standards, we simplify decision-making and reduce the unknowns. This also helps communicate the plan to stakeholders: there is less complexity to explain if one can say “we are using the established method that worked at Mine X, with appropriate adjustments,” as opposed to proposing an untested novel technique.

3.4 Organisational simplicity

Complexity can also be reduced by streamlining project governance and teams. A project run by one integrated owner’s team with a few key contractors may be simpler to manage than one with numerous joint venture partners and fragmented engineering, procurement and construction management contracts. Clear roles, avoiding matrixed responsibility, and ensuring that decision-making lines are short can prevent the complexity of bureaucracy from overwhelming the technical work. Some successful projects have formed dedicated, co-located teams that include owner, contractor, and engineers together (a form of integrated project delivery), which simplifies communication and aligns objectives. In summary, seeking simplicity in a megaproject is about making conscious choices to not push certain extremes. It’s recognising that while we have the capability to design very elaborate systems, the more elaborate, the more that can go wrong. A simpler, phased project stands a better chance of being delivered on time and within budget, and of operating reliably. The trade-off, often, is a slightly reduced theoretical NPV (if you don’t build everything to full capacity day 1) – but as we explore next, that trade-off may be well worth it when properly evaluated under real-world risk.

3.5 Focus on critical path and critical risks

Simplification often comes from focus. In a multifaceted project, not all tasks or risks are equal – some lie on the critical path or carry outsized risk. By identifying the critical path in the schedule and the handful of highest-impact risks in advance, management can concentrate resources and attention there, simplifying the oversight of less critical items. For example, if geotechnical risk in one sector of the orebody is identified as a top risk (potentially slowing the cave or causing collapses), a project might invest in extra drilling, numerical modelling, or a pilot test in that sector well ahead of production – essentially addressing the complexity in that area thoroughly – while using more standard approaches elsewhere. This targeted risk mitigation is a way to simplify the overall risk profile: you tackle the potential show-stoppers methodically so that they do not turn into crises later. In addition, explicitly adding schedule contingency for critical path items is a practice of simplification – it acknowledges uncertainty and avoids the complexity of having to re-baseline the entire project when inevitable delays occur. Unfortunately, as is note, many projects include generous cost contingencies but omit time contingencies. A simple but effective improvement is to build a realistic time buffer into the plan and have trigger action plans (if we start to consume the buffer, what corrective actions are taken?). This reduces the frantic re-planning that often happens when an overly tight schedule slips – essentially simplifying the management of time by admitting from the start that things might take longer. It is worth being explicit about what such a buffer does and does not achieve: schedule contingency does not make the project physically faster – if anything, the planned duration becomes longer – but it lowers the probability of major slippage, emergency re-baselining and the cascading disruption that an unrealistically tight program tends to produce, and so improves the certainty of delivery.

In summary, simplicity in managing complexity means prioritising what matters and not over-complicating what doesn’t. It’s about robust design, phasing, standardisation, strong project culture, and focusing on critical issues. These principles set the stage for how we approach large project development. The next section will apply these ideas specifically to development strategies, examining staged (modular) development versus a front-loaded approach – a choice that fundamentally affects how complexity and risk are distributed over the life of a project.

4 Staged versus front-loaded development approaches

One of the most consequential strategic decisions in planning a large mining project is whether to execute it in stages or commit to full-scale (front-loaded) development from the outset. This choice influences financing requirements, timelines, risk exposure, and flexibility. Both approaches have distinct merits and drawbacks, and the optimal strategy often balances elements of each.

4.1 Front-loaded development

This traditional model designs the ultimate mine plan for maximum capacity, building all necessary infrastructure before commencing production. Front-loading is often driven by DCF optimisation: spending more earlier allows for high throughput sooner, maximising NPV. Investors and corporate boards frequently favour this approach for its impressive production profiles. For example, a front-loaded block cave might involve developing an entire 500 × 500 m footprint before extraction, aiming for a direct ramp-up to 100,000 tpd. However, the risks are substantial as front-loaded projects concentrate capital expenditure in early years with no room for error. If geology or execution proves challenging, the project can suffer massive overruns since the entire scope is 'in play'. Oyu Tolgoi is a case in point: the original 'big-bang' plan required re-scoping due to unforeseen conditions, resulting in billions in overruns before underground revenue was realised. Enormous initial outlays can also strain balance sheets; Newcrest's Cadia East required over AUD 2 billion (Newcrest Mining 2018) and a seven-year lead time before commercial production. In sum, front-loading maximises rewards in best-case scenarios but lacks the flexibility to course-correct after adverse events.

4.2 Staged (phased) development

A staged approach breaks the project into 2 or more phases, starting with a smaller initial mine and expanding as the project matures. The first stage might target 30–50% of eventual capacity, reducing capital at risk and shortening the development schedule. Once stage one proves the mining method and economics, subsequent stages reach full scale incrementally. Benefits include improved financing – it is often easier to fund a $500 million project that grows via reinvested cash flow than a $1.5 billion project with years of negative cash flow. Ivanhoe Mines' Kamoa-Kakula followed this phased plan: Phase one (3.8 Mtpa) was completed in 2021, and its cash flows supported a phase 2 expansion by 2022. Similarly, the Santa Elena mine used an initial open pit to generate cash for its underground transition. This captures 'real options' value, allowing companies to adapt based on stage one outcomes – accelerating expansion if grades are better than predicted or redesigning if dilution is worse.

4.3 Hybrid approaches

In practice, many projects combine these models by front-loading critical infrastructure (e.g. shafts sized for ultimate capacity) while staging production levels to avoid future bottlenecks. Freeport's Grasberg transition illustrates this: while investing early in major access declines and ventilation, they sequenced production starting with the deep ore zone (DOZ) before the larger Grasberg Block Cave (GBC). The DOZ provided operational experience that significantly de-risked the full transition. It should be noted, however, that this sequence was conditioned primarily by the operational life of the Grasberg open pit rather than being a purely staged production strategy: the deeper underground horizons were brought online as the open pit approached and reached the end of its economic life, so the timing of the DOZ and the GBC was driven by depletion of the pit as much as by the wish to build caving experience.

4.4 Financial evaluation of approaches

Traditional DCF analysis typically biases toward front-loading due to early throughput but fails to account for asymmetric risk. While a front-loaded project may show a high NPV if successful, it faces a high probability of disastrously low outcomes if delays occur. We argue that DCF alone does not capture the value of flexibility or risk exposure in multi-decade operations. Consequently, companies are supplementing DCF with advanced methods:

- Monte Carlo simulations: these vary key inputs (prices, grade, schedule) to generate a distribution of NPV outcomes, revealing the probability of missing base-case targets.

- Real options analysis (ROA): This values management decisions as options – the right, but not the obligation, to defer, expand, or abandon an investment. For example, the option to expand Copper World into phase 2 has quantifiable value missed by stand-alone DCF.

5 Mining methods for large-scale developments (block versus panel caving)

When a large underground mining development is pursued – especially for low-grade, massive ore deposits – the choice of mining method is fundamental. For very large, deep orebodies, the 2 primary methods are block caving and panel caving. Both utilise induced caving of the rock, where the ore collapses under its own weight after undercutting, to achieve high production. The difference lies in how the orebody is divided: large orebodies typically require panel caving to manage caving over the life of the mine, while block caving is used mostly for smaller footprints to cave quickly. This choice fundamentally affects project development, complexity, and production ramp-up.

5.1 Block caving

In a block cave, the entire orebody (or a large block of it) is undercut in one stage. Footprints can range from a few hundred metres to over 1 km, with drawpoints arranged in a regular grid under the block . The hallmark of this method is uniform draw, intended to have the cave propagate and subsidence develop consistently over the whole area. Block caving is generally simpler in operation: there is a single cave to manage, one cave back to monitor, and draw control is coordinated across the entire footprint. Block caves have been the choice for many deep copper porphyries, such as Newcrest's Cadia East or earlier lifts at El Teniente, where the deposit size was moderate enough to cave as one unit. One advantage is that once the cave is established, production can ramp-up to a high rate – attaining 10,000–100,000+ tpd – and then be sustained without the need to continuously develop new mining fronts. However, the method requires a caveable rock mass and substantial initial development under the whole block. If an orebody is too large to realistically develop all at once, block caving may not be feasible.

5.2 Panel caving

Panel caving is an adaptation of traditional block caving tailored for large or irregular orebodies, often those exceeding 500 m in at least one dimension. Instead of a single continuous undercut, the orebody is subdivided into multiple panels that are undercut and allowed to cave in sequence. Historically, block caving was applied to smaller bodies like diamond pipes or skarns with rates around 25–50 ktpd, where infrastructure could be located outside the footprint. When orebodies grow beyond these limits, panel caving provides a practical solution for safe and effective extraction. At Codelco's El Teniente, which extends for more than 2 km, the deposit was divided into multiple panels mined in succession. Because undercutting proceeds throughout much of the mine's life, significant infrastructure – such as ventilation raises and orepasses – must be developed within the footprint. The cave front advances panel by panel, typically resulting in an inclined cave back geometry that necessitates careful draw control to maintain an optimal ore–waste interface. A key advantage of panel caving is scalability and flexibility. It allows for extremely high total production by having multiple panels in production simultaneously; combined throughput at El Teniente has reached 130,000–140,000 tpd. This method also aligns with staged development: one panel can be started to generate revenue while others are prepared, a strategy used at Freeport's Grasberg. However, operational complexity is higher, as engineers must juggle multiple caving areas, manage dilution, and handle persistent stresses on pillars that can lead to rockburst hazards.

5.3 Criteria for choice: when block versus panel

The decision between block and panel caving largely comes down to the geometry of the orebody and production requirements:

- Orebody footprint and height: If the horizontal extent exceeds 500 m, panel caving is likely required. The vertical column height also matters, as cave behaviour changes with extreme heights.
- Geotechnical domains: variability in rock conditions may suggest a panel approach to cave weaker sections first.
- Infrastructure and sequencing: block caves size a single set of infrastructure for full production, whereas panel caving can split infrastructure across panels, potentially reducing peak capacity requirements for individual elements.

In practice, many large mines evolve: they might begin with a block cave on the highest-grade or most-manageable section of the ore, and then as that cave matures, start another panel. Over decades, the distinction blurs because you end up mining multiple neighbouring caves (panels) sequentially – a hybrid approach. The bottom line is that the mining method is tailored to the orebody and business goals – block caving is preferred for its operational simplicity and lower upfront development (one cave) when it's feasible; panel caving is employed to handle larger footprints or to stage investment, even though it requires more complex coordination. Neither method is universally 'better' – it's about the right tool for the ore geometry.

To avoid a common misconception: block caving is not inherently 'better' or panel caving inherently 'more advanced' – they are 2 flavours of the same concept. Panel caving is essentially block caving applied in pieces. The real determinant of project complexity is the orebody size and conditions. A small block cave can be relatively straightforward, while a huge panel cave project can be extremely complex – but that's because of scale, not because we called it 'panel'. Modern design practices and learnings (Laubscher's rules [Laubscher 1994], propagation modelling, flow modelling) are applied to both. As a final note, ongoing research continues to propose innovative variants (like the so-called 'incline caving' or 'massive synchronous caving') (van As & Guest 2020), but block versus panel remain the foundational choices.

Definitely, at a mine operation, there could be a mix of methods. Often block caving is used to establish caving, and to progress, panel caving is adopted in order to manage large footprints. Recently a combination of block and panel caving has been implemented at several operations, in which the footprint is divided into modules (or panels) and inside of these modules a conventional panel cave is performed. The first large panel cave operation design and operated as a modular panel cave was Andina III Panel of Andina (Codelco). Then, others mines, such as Diablo Regimiento of El Teniente (Codelco) mine, DOZ of PT Freeport, Chuquicamata underground mine (Codelco), DMLZ of Freeport Indonesia, Oyu Tolgoi of Rio Tinto, have divided the footprints into modules and each of them were designed, planned and constructing according to the orebody characteristics.

The advantages of modular panel caving are that several aspects of stress management can be taken into account, such as drawpoint pillar design (more or less robust), size of the cave front, rate of undercutting progression, height of draw column, etc. Perhaps one of the main disadvantages is that several long pillars need to be left behind in order to place the material handling and ventilation infrastructure.

Section 6 builds on this discussion by looking at operations that push caving to extreme scales – often involving multiple caves, great depths, and novel practices – and how the industry is addressing the challenges they present.

6 Super caving operations

'Super caving' is an emergent term referring to ultra-large caving operations that significantly exceed historical norms in terms of scale, depth, and production rates. While no formal definition exists, a 'super cave' might be characterised by production in the order of >100,000 tpd, cave footprints measuring in the hundreds of thousands of square metres, and lift heights well above 500 m. These operations are essentially the next generation of block and panel caves – deeper, bigger, and more complex than ever before. Examples on the horizon (or in early execution) include the deeper lifts at Freeport's GBC (Indonesia), Codelco's future expansions at El Teniente and Chuquicamata underground (Chile), and possibly Oyu Tolgoi's later stages (Mongolia). With 'super' scale comes a magnification of challenges. In this section, we integrate insights of the industry to discuss key considerations in super caving: the transition from surface to underground, risk management for these megaprojects, infrastructure requirements, and staged caving techniques used to manage the enormous scale.

6.1 Pit-to-underground interaction

One immediate complexity is that the open pit and the underground workings can interfere with each other. Often, the underground development must start while the pit is still active (to avoid a long production gap). However, caving under a working pit can destabilise the slopes, and conversely, the pit can impose stress or blasting impacts on the underground. Careful sequencing is required. A common strategy is to time the cave initiation to occur just as the pit finishes, but if that's not possible, interim measures like leaving a protective crown pillar or coordinating deformations are needed. At Grasberg, open pit production and underground caving overlapped rather than following a clean gap: undercutting of the GBC began in late 2018 while the open pit continued for roughly a further 18 months until it was completed at the end of 2019, with the transition managed under strict geotechnical control and a separation of about 175 m maintained between the pit floor and the advancing cave (Casten et al. 2020). Even so, some surface instability occurred, as expected, when the cave broke through. Design buffers (like an artificial crown pillar or pre-planned backfill of the pit) can mitigate extreme events.

6.2 Infrastructure handover and legacy issues

In a transition, the new underground mine often reuses some infrastructure from the surface mine – for example, road access, power supply, maybe the processing plant. This is beneficial (saves cost) but it means the underground project schedule is sometimes constrained by the surface mine's closure or changeover of facilities. For instance, if the conveyor to surface for the cave is planned to use a corridor currently in use by the pit's operations, there has to be a carefully managed switch. Chuquicamata's transition involved repurposing the existing mill (the same mill that served the pit now handles underground ore), which required a brief mill shutdown to tie in the new conveying systems. Such tie-in outages need to be minimised and are often on the project's critical path.

6.3 Steep ramp-up and production reliability

Replacing a big open pit with an underground mine is akin to replacing a marathon runner with a sprinter – the underground must 'sprint' to high throughput to avoid a production shortfall for the company. This places pressure on achieving the ramp-up profile. As noted earlier, aggressive ramp-ups with insufficient buffers are a common pitfall. One way to improve reliability is to build redundancy and buffers into the mine design. Rubio's doctoral research (Rubio 2006) focused on production reliability in block caving, highlighting how the reliability of infrastructure (like the percentage of drawpoints that become unavailable due to collapses or hang-ups, or the downtime of a crusher) can critically impact whether the planned tonnage is met. By analysing historical failure rates and designing for it (for example, having extra drawpoints beyond the minimum, or a spare crusher chamber ready), the underground mine can better sustain the target throughput. This reliability-centred planning has been applied in some modern caves: for instance, mines like Freeport's DOZ/DMLZ incorporated numerous drawpoints (857 in DOZ), knowing not all will be available at any given time, and diversified ore handling (multiple orepasses) to reduce single points of failure.

Moreover, modular or panel development can enhance reliability during ramp-up. Chuquicamata underground, for instance, is ramping up in stages (panels zero, one, 2 sequentially) so that lessons from early panels can inform later ones and so that each panel's ramp-up is smaller in scale than trying to start the whole 140 ktpd at once. This approach aligns with the modular theme discussed and indeed was informed by past issues at El Teniente and others, where trying to do too much at once led to delays. In fairness, Chuquicamata underground itself has faced significant challenges during its own ramp-up: the build-up to nominal capacity has been slower than originally planned, and the operation has had to contend with demanding geomechanical and seismic conditions at depth, so that full design throughput is now expected only towards the end of the decade. These difficulties are noted here not as a criticism of the project but as a reminder that even a carefully engineered, staged ramp-up of a super cave remains inherently complex.

6.4 Geotechnical risk management

Super caves often push the envelope on cave dimensions and depths, raising geotechnical uncertainties (Flores-González 2019). Preconditioning (hydraulic fracturing, explosives) is widely used now to assist caving in strong rock and to induce caving on schedule. The sequencing of undercut and extraction level development is carefully optimised using modelling (e.g. flow modelling to predict fragmentation and draw, stress modelling to predict where breakoffs might occur). Many projects have experienced seismicity (rockbursting) as a significant risk – e.g. El Teniente and Grasberg both have had notable seismic events during caving. Within the Grasberg district in particular, the DMLZ has accumulated a considerably longer and more severe record of mining-induced seismicity than the GBC, so the 2 should not be treated as carrying equivalent seismic hazard. Mitigations include de-stress blasting, dynamic ground support (yielding bolts, fibre shotcrete), and microseismic monitoring systems to give early warning. Essentially, a super cave project requires a robust geotechnical risk management plan that is at least as sophisticated as that of a deep open pit (just the mechanics differ). Ground monitoring (extensometers, microseismic, surface subsidence tracking via InSAR or radar) is employed to track cave behaviour in real-time. This data is used to adjust draw control to keep the cave healthy (avoid air gaps or stress build-ups).

6.5 Operational readiness and staffing

A frequently understated challenge is assembling the right team and skill sets to run such a mine. Block caving is still a niche skill in the industry – global experts are few. Companies transitioning to caving often bring in personnel from other successful caves (e.g. Newcrest's team assisting at Oyu Tolgoi, or caving consultants from Northparkes/Palabora experiences). Training local operators in the very different techniques of cave mining (compared to open pit) is also critical. It's been said that cave mines require an 'operational maturity' to manage the nuances of draw, water, and seismicity, so some companies set up extensive training programs or even use experienced contractors to operate initially. For example, when PT Freeport Indonesia began its block caving, it relied heavily on expat experts and then gradually localised the knowledge.

6.6 Managing stakeholder expectations

During the transition phase, production often dips (because the pit is winding down and the underground has not yet ramped up fully). This can cause concern for shareholders, governments, and employees. Proactive communication and expectation management is key: stakeholders need to understand that a temporary decline is part of the plan and will be recovered once the underground is at capacity. Codelco, for instance, announced that its production would be lower for a few years during the construction of new underground mines, but emphasised the long-term gains once they come online. Governments that depend on the mine's revenue had to be aligned with this plan (which ties back to earlier discussion on political pressure – sometimes governments push "just get the production up", which can conflict with the reality of a safe ramp-up pace).

In mitigating the above risks, some best practices have emerged for super cave projects:

- Start early on the underground development (even while pit is operating) to give as much schedule float as possible.
- Use independent reviews and peer assists (like the independent report on Oyu Tolgoi delays) to catch problems in design or execution biases.
- Implement rigorous project controls and risk monitoring – treat it truly as a megaproject with stage-gates and risk registers that include technical and external risks.
- Consider intermediate milestones that create checkpoints: for instance, have a 'production trial' at a smaller scale, or intermediate draw targets, to ensure everything works before scaling up.

- Maintain strong collaboration between surface and underground teams during transition – sometimes even keeping one management team responsible for both until the pit closure is complete, to avoid silo thinking.

Ultimately, successful transition operations like those at Grasberg (which, despite some delays, managed to largely replace the pit by the block cave by 2023) or Palabora (which extended mine life by converting to a block cave) show that the risks can be managed with thorough planning and flexibility. However, there are also cautionary tales, like the early closure of the Premier mine's cave in South Africa due to dilution issues, or the struggles at Henderson (USA) when block cave fragmentation didn't go as planned. Learning from both successes and failures is crucial – and indeed, the industry has developed a much stronger knowledge base on cave mining in the last 2 decades through forums like MassMin conferences and shared research consortia.

7 Case studies of successful large mining projects

Examining real-world projects provides insight into how the principles discussed are applied and what factors drive success or difficulty. Below, we review several notable large-scale mining developments, highlighting key lessons in their planning and execution. It should be acknowledged that 3 of the operations discussed below experienced significant safety incidents during 2025: a fatal rockburst at El Teniente in July 2025, a fatal mud rush at the GBC in September 2025, and seismically induced flooding at Kakula (Kamoa-Kakula) in May 2025, each of which caused fatalities or a major suspension of production. These recent events are a sobering reminder that even mature, well-regarded operations remain exposed to the complex, low-probability and high-consequence hazards that are central to this paper; they reinforce rather than contradict the lessons drawn here.

7.1 Case study one: Codelco El Teniente (Chile): sustained success through panel staging

El Teniente is the world's largest underground copper mine, operated by Codelco. It has been in production for over a century and has continually expanded through new mining levels and sectors. In recent decades, El Teniente moved from classic open-stoping methods to panel caving to handle its immense orebody. A major project, the New Mine Level (NML), was designed to further deepen and extend the mine's life. El Teniente's success largely comes from treating mine development as an ongoing, staged process rather than a one-off project. Multiple panel caves (Esmeralda, Reservas Norte, Diablo Regimiento, etc.) have been orchestrated such that as one panel's output declines, a new panel starts up, keeping total production relatively steady – in the order of 130,000–140,000 tpd in the 2010s. This approach avoided the boom-and-bust output cycles that can happen when a single cave is relied upon. It also allowed Codelco to spread capital expenditure over time and learn from each panel to improve the next. For example, after the early panel caves, El Teniente engineers improved their undercutting techniques and draw control to reduce ore dilution in subsequent projects. One challenge faced was seismicity: as the mine went deeper, stress-related rockbursts occurred. Codelco invested in a world-class seismic monitoring system (Codelco 2021) and refined its ground support (using yielding bolts and heavy mesh) to mitigate this risk – a risk management practice now standard in deep caves. Another issue was a tragic accident in 2017 (a sector collapse during development) which prompted a re-evaluation of ground characterisation and monitoring. Codelco temporarily slowed the NML project, applied additional geotechnical analysis, and only resumed once a safer plan was in place. The lessons from El Teniente are the value of a long-term, evolutionary approach: treat each expansion as part of a continuum, maintain organisational knowledge, and continuously integrate feedback. The project also underscores the importance of government backing and steady funding – as a state-owned company, Codelco was able to justify sustained investment in El Teniente's expansion as a national priority, insulating it somewhat from short-term market fluctuations that might derail a private company's project. More recently, however, El Teniente was struck by a serious accident on 31 July 2025, when a strong seismic event triggered a rockburst and collapse in the Andesita sector that killed 6 workers and injured several others, the deadliest incident at the mine in decades. Production was fully suspended and then restarted only gradually, and output for 2025 was reduced to roughly 316,000 t, underscoring that even a mature, well-managed panel caving operation remains exposed to deep-seated seismic hazard.

7.2 Case study 2: Freeport-McMoRan Grasberg/Ertsberg (Indonesia): managing a complex transition

Freeport's Grasberg mine in Papua, Indonesia, is a legendary operation – first an open pit extracting one of the richest gold/copper deposits, and now transitioning to a group of block/panel caves (GBC, DMLZ, Big Gossan, etc.). This transition, which took place primarily from 2018–2022, is one of the largest ever, effectively replacing ~140 million tonnes per year of open pit ore with underground ore. It is worth emphasising that underground mining in the Ertsberg–Grasberg district is not new: Freeport has operated caving mines here since the early 1980s, beginning with the Gunung Bijih Timur (Ertsberg East) block cave in 1981, and subsequently mined a succession of progressively deeper horizons in the East Ertsberg Skarn System (including the intermediate ore zone, DOZ and DMLZ) in parallel with the open pit (Casten et al. 2020). The 2018–2022 step therefore represents the latest stage of a long-running underground operation rather than its beginning. Successes in this transition included the prior development of the DOZ panel cave which provided valuable experience in caving and some interim production as the open pit was winding down. Freeport also executed an aggressive development program: over 400 km of tunnels were driven (a cumulative figure that spans the whole Grasberg minerals district over several decades and several underground mines, rather than development completed in advance for the GBC alone), including a rail haulage system and multiple ore passes and crusher stations. They front-loaded a lot of infrastructure (e.g. developed 2 underground crusher levels for the Grasberg cave to ensure high throughput). Despite such preparation, the project encountered major challenges. In 2019, as the cave was propagating, they realised parts of the cave were not breaking as quickly – likely due to variations in rock mass – so they had to reassess draw strategies. There were also setbacks in development: a significant tunnel collapse in an access drift caused by a localised weakness, and water inflow issues in some drives that slowed progress. Additionally, the mine had to navigate complex stakeholder issues, including the Indonesian government increasing its ownership (which led to some uncertainty and shifts in funding). Nevertheless, by 2022 the GBC and DMLZ were in production ramp-up and approaching their combined target of over 130,000 tpd. A key learning is how Freeport managed ramp-up and expectation. They were transparent that full ramp-up would take years and repeatedly updated the market on milestones, thereby avoiding some of the backlash that companies get when ramps are slower than promised. They also phased the ramp-up: they prioritised certain drawpoint clusters to quickly establish initial production, then systematically expanded draw to others rather than trying to open all drawpoints at once. This managed approach helped them control cave shape and handle operational issues incrementally. Today, Grasberg's underground mines are considered a qualified success – they replaced the iconic open pit, though not without delays and cost overruns. Freeport's ability to adapt (e.g. install an autonomous rail haulage to improve material movement, or adjust mining sequences in real-time) has been crucial. The Grasberg transition underscores the importance of detailed planning for transitions (they had to stockpile open pit ore to blend during the switch, to keep mill feed constant) and the value of corporate commitment (there were moments the costs ballooned, but Freeport's leadership stayed the course knowing the resource value was enormous). This qualified success was, however, severely tested on 8 September 2025, when a major mud rush at the GBC allowed roughly 800,000 t of wet material to enter the workings from the former open pit through an undetected pathway across several levels, killing 7 workers. Freeport declared force majeure and suspended the whole district; Big Gossan and the DMLZ resumed late in October 2025, while the GBC was scheduled for a phased restart from the second quarter of 2026, with normal production rates not expected until around 2027. The company described the event as unprecedented in its multi-decade block caving history, a stark reminder that the pit-to-underground interaction and wet-muck hazards discussed earlier persist well beyond the formal transition.

7.3 Case study 3: Ivanhoe mines Kamoa-Kakula (Democratic Republic of Congo): phased development for rapid success

Kamoa-Kakula is a relatively new project, but often cited as a model of phased development delivering results. It's a massive high-grade copper deposit in the Democratic Republic of Congo. Instead of trying to build a giant mine upfront, Ivanhoe Mines (along with partner Zijin) opted to start with Kakula phase one, a 3.8 Mtpa underground mine and concentrator, targeting first production in 2021. This was achieved on time and within budget, a noteworthy feat for a remote project. Almost immediately, they launched phase 2, an identical concentrator and expanded mining area, which doubled production by Q2 2022 (Ivanhoe Mines 2021). The staggered approach meant that lessons from phase one (e.g. on mining equipment productivity and mill tuning) were applied to phase 2, which started even more smoothly. Financially, the early cash flow from phase one improved the project's funding for phase 2 – essentially self-funding growth. The project's internal rate of return (IRR) benefited, and risk was reduced. Now Kamoa-Kakula is working on phase 3 (another expansion including a smelter) and has plans for phase 4. The deposit is being unrolled step by step. The keys to this success include: flexible mine planning (they started in the highest-grade section to get quick payback), strong partnerships (Chinese investment helped ensure funding for expansions), and robust technical management (the project did extensive pilot testing and simulations upfront). Kamoa-Kakula also highlights the advantage of moderate initial scope – by not overreaching at first, they hit their targets and built stakeholder confidence. From a complexity viewpoint, each phase was complex but manageable; the alternative of a single 12 Mtpa project might have been too much at once in a challenging location. The staged approach allowed adaptation to the region (transport, supply chains, workforce training) gradually. A lesson here is that in mining environments with extra uncertainties (political, infrastructural), staging can make an otherwise untenable project work by building success progressively and giving flexibility to respond to external changes. Even this widely praised operation was not immune to a major setback: on 18 May 2025, seismic activity in the eastern part of the Kakula mine led to severe underground flooding. Mining was suspended and all personnel were safely evacuated with no injuries, but the eastern area was allowed to flood as its sidewalls deteriorated, the western side restarted on 7 June 2025, 2025 guidance was cut by about 28% (from 520–580 kt to 370–420 kt), and the 2026 target was withdrawn pending an independent review (it should be noted that Kakula is mined by drift-and-fill rather than caving, so this is a water-and-seismicity case rather than a caving failure). The episode reinforces the paper's central point that even a model phased development remains exposed to low-probability, high-consequence geotechnical events.

7.4 Case study 4: Barrick Gold's Pascua-Lama (Chile/Argentina): a cautionary tale

Not all large projects succeed; learning from failures is equally important. Pascua-Lama was intended to be a massive gold–silver mine straddling the border of Chile and Argentina, with an open pit and extensive processing facilities at ~4,500 m elevation. Although not an underground caving project, it's a megaproject case worth mentioning for risk management lessons. Barrick spent over USD 5 billion on Pascua-Lama (earthworks, tunnels, processing plant), but due to environmental permit issues, community opposition, and technical difficulties (managing high-altitude glaciers and water), the project was halted and ultimately mothballed. The failure of Pascua-Lama illustrates how ignoring external and complexity-related risks can be fatal: Barrick initially downplayed the difficulty of water management in a glacial environment and the potential for cross-border regulatory tangles. They front-loaded huge investments assuming they could sort out these issues, but once opposition mounted and legal challenges froze construction, the sunk cost became nearly unrecoverable. An important lesson is to secure stakeholder alignment (government, community) before committing full capital – a staged approach might have revealed the brewing issues earlier at lower cost. Pascua-Lama's fate has made investors and companies far more cautious; it is often cited alongside other megaproject blow-ups in mining as justification for the phased, risk-gated strategies we have discussed. In essence, a technologically feasible project can still collapse if complexity in social/environmental aspects is underestimated. Today, thorough environmental social impact assessments, local engagement, and building projects in increments (to prove out concepts and benefits) are part of standard risk management to avoid another Pascua-Lama scenario.

7.5 Case study 5: Newcrest's Cadia East (Australia): overcoming initial setbacks

Cadia East is one of the world's largest gold-copper block caves, developed by Newcrest Mining. It was a greenfield block cave adjacent to the Cadia Hill open pit. The project required a high upfront investment (over AUD 2 billion) and took about 7 years to start production. Early on, Cadia East struggled with typical cave issues: a slow ramp-up, higher-than-expected dilution as the cave breakthrough to surface created a large subsidence crater in 2010 (about 15 m deep), and a major seismic event in 2017 that temporarily halted operations. Despite these, Cadia East became a success: it reached its full production rate (around 30+ million tonnes per year) and is today one of the lowest-cost gold producers globally, thanks to the economies of scale of caving. How Newcrest responded to setbacks is instructive. After the 2010 subsidence (an early cave breakthrough), they reinforced procedures for monitoring ground and adjusted their draw strategy to better control cave progression. Post-2017's big earthquake (which caused significant damage to the underground workings and a production outage), Newcrest invested in enhanced ground support (for dynamic loads) and a comprehensive review of its panel cave sequence. They also began using extensive preconditioning via hydraulic fracturing to reduce seismic energy release. Essentially, they learned and adapted, turning a near-disaster into an opportunity to improve the operation. Cadia East's experience highlights the importance of resilience and adaptability in large projects. Despite front-loading (2 caves built together), they had to adapt as if staging: the second panel (Panel Cave 2) was started after Panel Cave 1, and when Panel Cave 1 encountered trouble, Panel Cave 2's game plan was modified accordingly. Now, Cadia East is looking to a next lift (a new cave below) with those hard-won lessons. Investors initially were concerned at the delays and incidents, but Newcrest's transparent and effective response eventually restored confidence. The mine has since paid back its investment many times over. The big takeaway: even if a project doesn't meet initial expectations, strong technical management and willingness to change can salvage and lead to eventual success – provided the orebody fundamentals are sound.

These case studies underscore various points: El Teniente and Grasberg show the value of phased and flexible planning in ultra-large operations, Kamoa-Kakula demonstrates the power of a modular approach with quick wins, Pascua-Lama warns of neglecting non-technical risk, and Cadia East emphasises learning and adaptation during ramp-up. Common to successful outcomes are early risk identification, staged investment, continuous monitoring and adaptation, and maintaining a long-term view (not giving up at the first hurdle, but adjusting course). In the next section, we distil some of these lessons into general principles of risk management for large mining developments.

8 Risk management in large mining developments

Effective risk management is the linchpin that holds a complex mining project together. Given the multitude of risks (technical, financial, safety, environmental, etc.) and their potentially cascading effects in large-scale developments, a systematic and proactive risk management approach is essential. Here, we outline key practices and considerations for risk management in the context of large mining projects, building on themes from earlier sections and industry best practices.

8.1 Risk identification and categorisation

The first step is comprehensive risk identification across all project domains. Teams typically conduct risk workshops during the feasibility stage, bringing together geologists, engineers, construction managers, financiers, and other stakeholders to brainstorm everything that could significantly derail the project. These risks are then categorised – common categories include geotechnical (ground control, seismicity, cave performance), operational (equipment reliability, productivity shortfalls), financial (cost overruns, commodity price collapse), safety (accidents, fatalities), environmental/social (permitting issues, community protests), and political (regime change, policy shifts). Using techniques like checklists derived from past projects (e.g. referencing known issues from case studies such as rockburst at Mine X or contractor performance at Project Y) helps ensure no major category is overlooked.

8.2 Qualitative and quantitative risk analysis

Once identified, risks are often assessed qualitatively using a risk matrix, rating each risk's probability and consequence to prioritise them. For example, a risk of "air blast in cave causing fatalities and production halt" might be rated unlikely but catastrophic, giving it a high risk ranking that demands attention. Conversely, "groundwater inflow slows development" might be likely but of minor impact if managed, perhaps a medium risk. This matrix approach is a staple in mining companies to ensure a focus on high-priority risks and to communicate risk levels in a simple visual manner to executives. In tandem, quantitative methods are used for certain risks: Monte Carlo simulation can model potential cost and schedule outcomes, yielding a probability distribution of, say, final project cost. Management might choose a confidence level (e.g. P80) to set contingency. For schedules, tools like program evaluation and review technique or critical path analysis with probabilistic task durations can identify the likelihood of meeting key milestones. Large projects often employ specialised risk analysts who run these models and update them as the project progresses and uncertainties resolve.

8.3 Mitigation planning

For each significant risk, a mitigation plan is developed – essentially answering, "what can we do to reduce the likelihood of this risk, or soften its impact if it occurs?" Mitigations should be concrete actions, assigned to owners, and ideally budgeted/scheduled. For geotechnical risks, mitigations might include additional drilling to better characterise the rock, employing conservative design (e.g. extra ground support, smaller blasting rounds near sensitive faults), or adopting new technologies like microseismic monitoring from day one. In cave mining, a typical mitigation for cave performance risk is to plan for an extensive cave monitoring system (sensors, smart markers in the ore) and to have a detailed draw control strategy that can be adjusted – basically creating an operational mitigation: "if cave does not propagate by X date or shows sign of stalling, then take action Y (like initiate auxiliary blasts or intensify draw in certain areas)." For financial risks like cost overrun, mitigations include contracting strategies (e.g. lump-sum contracts for certain construction packages to transfer risk, or alliances with contractors to incentivise on-time delivery) and maintaining contingency funds. One noteworthy approach is to also consider contingency plans: "if risk A materialises despite mitigation, what is plan B?" For instance, if a main ventilation shaft encounters heavy water and is delayed, perhaps a contingency plan is to accelerate a backup raisebore or to rent heavy-duty fans for an existing opening as an interim solution. Moss et al. (2023) highlight that many projects fail to plan for time contingencies – so a mitigation there could be explicitly adding float to the schedule or preparing alternate sequences that could bypass a trouble spot if needed.

8.4 Monitoring and response

Risk management is not a one-time exercise; it must continue through execution and operation. This entails setting up a risk register that is updated regularly. To be useful, this register must be genuinely dynamic rather than a static document: it should capture conditional probabilities and the interdependence between risks (for example, the likelihood of a mud rush is not fixed but rises sharply when wet muck and an airgap are present at the same time), and it must be re-evaluated whenever the project context changes materially – for instance after a merger or acquisition, a change of ownership or operator, a change of government or regulator, a major permitting decision, or a significant shift in the external environment. Project managers often review major risks in their monthly meetings: Has the likelihood changed? Are mitigation actions on track? Do new risks emerge? For a caving project, as development progresses, new information (say a fault zone was encountered earlier than predicted) might escalate a risk ("potential cave water inflow") or introduce a new one. Effective projects implement trigger action response plans (TARPs) for key risks – these are predefined thresholds and responses. For example, a TARP for seismicity might state: if daily energy release exceeds a certain level, trigger level yellow – which means pull people out of certain areas, review ground support; if it exceeds a higher level, trigger red – halt production, etc. TARPs make responses systematic and not ad hoc. Another example: a water inflow TARP would have trigger flow rates that prompt emergency pumping capacity or evacuation if exceeded. By planning these, the project can respond quickly and avoid paralysis when a crisis hits.

8.5 Organisational and governance aspects

Large projects often establish dedicated risk management teams or committees. For instance, a project risk committee that includes senior managers can oversee the risk process, ensuring that high-level support and resources are given to mitigation efforts. It's also common to involve independent experts in risk reviews – an external geotechnical review board might convene annually to review a block cave's plans and validate that geotechnical risks are being properly managed, providing recommendations. Governance might also require stage-gate sign-offs, where at the end of feasibility or after one year of construction, the risk profile is reassessed and the project must get approval to proceed to the next stage (incorporating any scope changes needed to mitigate emerging risks). This is aligned with the concept of not being locked into a flawed plan – the project remains responsive.

8.6 Culture of risk awareness

Beyond processes and analyses, successful risk management stems from a culture where people are encouraged to voice concerns and 'bad news' travels quickly to decision-makers (rather than being buried). Recall that complexity can breed a tendency to withhold bad news (hoping to fix it quietly). Projects that instil a culture of transparency and proactive problem-solving tend to catch issues early. For example, if a blasting crew notices unusual vibration or groundwater while driving an undercut level, do they feel empowered to halt and report it, or pressured to push on and meet the schedule? The latter could lead to a bigger mess later. Training and leadership must emphasise safety and long-term success over short-term schedule push, so that the whole team contributes to risk management.

8.7 Case in point: managing a specific risk (mudrush)

To illustrate how these elements come together, consider the mudrush risk in a caving mine (as introduced earlier). Identification: mudrush is identified due to presence of clays and water in the orebody. Analysis: qualitatively high risk (low-probability, very high consequence of fatalities and lost production). Mitigation: engineering controls like installing drawpoint barricades (barriers so that if mud flows it doesn't hit personnel/equipment directly), operational controls like ensuring drawpoints are kept dry (drain holes, vacuum filters) and using remote-operated load–haul-dumpers in areas with potential for mud. Monitoring: measuring moisture content of drawpoint muck, have a trigger (e.g. if a drawpoint starts issuing wet muck above a threshold, declare it closed until investigated). Response plan: if a suspected mudrush occurs, all personnel retreat to refuge, use remote scoops to clear the flow if possible, etc. By pre-planning these, the mine turned a potentially catastrophic risk into a manageable hazard that, while still present, is much less likely to result in harm or major disruption.

8.8 Continuous Learning

Risk management doesn't end once the mine is operational either. Long projects will have turnovers in staff and new challenges as the mine matures. A principle of 'continuous improvement' should apply – incidents and near-misses are analysed (Why did that pressure bump occur? How did water get into that drive?), and lessons are documented and shared. Mining companies often conduct post-mortems on projects – e.g. after construction, reviewing what risks were underestimated or new ones discovered, and feeding that back into guidelines for the next project. Over time, industry-wide learning also occurs, through conferences and publications where case studies (including those in Section 7) educate others. For example, the cave mining community has significantly improved knowledge on managing seismic risks by learning from places like Cadia and El Teniente (leading to better support design and preconditioning practices globally).

In conclusion, risk management in large mining projects is an active, ongoing discipline that permeates all stages of the project. It transforms the uncertain elements from frightening unknowns into quantified and controllable aspects as much as possible. While risk can never be eliminated – mining by nature has unpredictability – the goal is to avoid surprises as far as practicable and to be well-prepared to act when surprises do occur. As Moss et al. (2023) emphasise, acknowledging the inherent risks and fragility of these projects is the first step; with that mindset, companies can organise themselves to confront and mitigate risks effectively rather than be caught off-guard by them.

9 Advanced valuation and decision-making for complex projects

As noted in Section 4, the traditional single-outcome DCF model is inadequate for complex, multi-path mining projects. Large-scale developments benefit from sophisticated valuation techniques that account for uncertainty and management's ability to respond to changing conditions. We introduce 2 complementary approaches: probabilistic (stochastic) valuation and ROA.

9.1 Probabilistic (multivariable) valuation

Instead of a fixed NPV, probabilistic valuation utilises distributions for key inputs and runs Monte Carlo simulations to generate a range of possible outcomes. Factors like metal prices (modelled as stochastic processes), construction costs, and ore grades vary within geologically and economically reasonable bounds. By running thousands of iterations, planners can estimate the probability of the NPV exceeding the cost of capital or falling below zero. This is vital for risk assessment; it may reveal a 20% chance of negative NPV even when the base case is positive – data critical for financiers. Furthermore, it helps compare alternatives: a staged approach might yield a lower mean NPV but a much tighter distribution (less downside volatility) than a 'big-bang' approach. This framing allows Flyvbjerg's reference-class forecasting to be implemented by imposing cost distributions based on historical data rather than optimistic assumptions.

9.2 Real options analysis

ROA treats managerial decisions – such as expanding, mothballing, or abandoning – as options rather than set paths. These are analogous to financial options and are valued using Black-Scholes, binomial lattices, or simulations. The primary benefit is revealing the 'hidden' value of flexibility. Consider a two-stage project like Copper World: a static DCF assumes phase 2 either happens or doesn't, but an ROA view sets a decision node. If conditions are favourable (e.g. copper > $3.50), the option to invest in phase 2 is exercised; if not, the mine runs phase one to closure. In Copper World, the phase 2 option adds significant value (USD 555 million NPV) with a high IRR (49%), providing a 'gold mine' if prices jump but losing nothing extra if they stay low. ROA also applies to shutdown/restart decisions, showing a project is viable if it can pause during price troughs.

9.3 Practical challenges

While rigorous ROA is complex and sensitive to volatility assumptions, even a qualitative real options mindset is valuable. It encourages designs that preserve flexibility, such as building a plant that can accommodate an additional semi-autogenous grinding mill later. Many companies informally embed these options to avoid precluding future expansions.

9.4 Integration with decision-making

Ultimately, advanced valuation is about better decision-making under uncertainty. By understanding the probability and impact of various outcomes, management can make more informed choices on project go-ahead, scale, timing, and financing. They might decide to proceed with a marginal project if analysis shows a small chance of huge upside (option value), or conversely, shelve a project that looks good on paper but has a fat tail risk of catastrophic outcome. It moves the conversation from "What is the NPV?" to "What is the probability distribution of NPV and what influences it?"

In the context of our discussion on large projects, advanced valuation supports the idea that bigger is not always better unless risk is accounted for. A project with a $2 billion NPV but 50% chance of failure is not necessarily superior to one with $1 billion NPV and 5% chance of failure. Traditional metrics might miss that distinction; advanced methods capture it.

The mining industry has started to adopt these techniques, especially for capital allocation. Major companies run scenario analyses in their investment committees. Some use internal Monte Carlo models for commodity prices. Consultancies have developed real options models for mines (e.g. to value the option of expanding mill throughput in the future if grades improve). It's still not universally standard, but the trend is towards more rigorous risk-adjusted evaluation – which is crucial for these mega-investments where billions are at stake.

10 Conclusion

Large-scale underground mining projects – the so-called 'super caves' and mega-developments – represent both the future of mining and its most daunting challenge. They are necessary to sustain production as rich open pits are depleted and as demand for minerals increases, yet they come with a level of complexity and risk that must be respected and managed. This document has explored the reasons these projects need to be large and the justification behind their scale: namely, the economic imperative to maintain throughput and amortise massive fixed investments. We have also delved into the sources of complexity (technical, financial, schedule, organisational) and shown that while these projects are inherently complex, the degree of complexity is not fixed. Through thoughtful strategies – simplifying designs, phasing execution, matching mining methods to orebody characteristics, and rigorously planning for uncertainties – we can reduce the effective complexity and risk.

A recurring theme is flexibility. Whether in project design (modularity, panel caving, scalable infrastructure) or in project management (adaptive schedules, option-aware decisions), flexibility is the antidote to the rigidity that makes megaprojects fail. The work of Flyvbjerg and others on megaproject overruns reminds us that optimism and 'uniqueness bias' can blind us – mining teams must assume they are not unique and that problems will occur, and plan accordingly. By studying analogous projects (reference class) and using base-rate data on outcomes, teams can adopt an outside view that tempers the inside technical enthusiasm with historical reality. In practice, that means budgeting more conservatively, building schedule contingency, and setting up governance that challenges assumptions.

We've highlighted how traditional valuation metrics can mislead for these projects, and that embracing probabilistic and real options approaches provides a clearer picture of value versus risk. Investors and stakeholders are increasingly aware of the 'fat tail' risks in mining megaprojects (many have seen high-profile failures), so presenting risk-adjusted evaluations is becoming essential to secure support.

It is also clear that human factors and organisation make a huge difference. The best technical plan can be undermined by poor execution or misaligned stakeholders. Conversely, strong leadership, a learning culture, and stakeholder engagement can overcome even severe technical hurdles. An example in our discussion was how Freeport leveraged global expertise and took an iterative learning approach at Grasberg, effectively creating an organisational knowledge base that allowed them to navigate the unforeseen.

In conclusion, managing complexity and risk in large-scale mine projects requires a multifaceted strategy:

- Understand and justify the scale – ensure that the scale is driven by business need (and indeed, often it is, to replace production), and communicate that clearly to all stakeholders (e.g. why we need 100k tpd, what the benefits are of economies of scale).
- Plan for complexity – don't wish it away; map out the interdependencies, conduct risk assessments, involve experts from different disciplines, and continuously update plans as new information comes.
- Simplify where possible – adopt designs and plans that minimise unnecessary moving parts. Use modular approaches to break the behemoth into chunks.

- Retain flexibility – whether via panel caving layouts, phased project funding, or simply contingency plans, give yourself options. In mining, Mother Nature will throw surprises; your plan B and C are what save the day.
- Use advanced tools and data – leverage the growing pool of data on megaprojects and modern simulation/optimisation tools to guide decisions. Don't rely solely on a single-point estimate. Embrace the uncertainty in analysis, so you can tame it in reality.
- Engage stakeholders continuously – a large project lives or dies by support from shareholders, governments, communities, and employees. Keep them informed, manage expectations (under-promise and over-deliver, rather than the opposite), and share the long-term vision so that short-term setbacks are understood in context.
- Learn and adapt – treat the project as a learning journey. Incorporate feedback loops, such as pilot sections or trial blasts, and be willing to modify plans. As the saying goes, "no battle plan survives first contact with the enemy" – in this case the 'enemy' is the unknown in a new mining frontier; you must adapt your plan when reality unfolds.

The reward for getting it right is substantial: these megaprojects can secure decades of production, substantial cash flows, and supply critical minerals to society. The companies that master the art of managing large-scale mine development will lead the next chapter of the mining industry. By combining engineering excellence with strategic flexibility and robust risk management, we can turn these giant projects from risky ventures into sustainable, value-generating operations.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Anthropic – Claude (Opus 4.8 IA Model) to assist with language editing and to improve the clarity and readability of the manuscript. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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