Chapter 11
The Future of Gold and Silver Industry

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Future sustainability of the gold and silver industry is highly dependent on how mining companies, communities, governments, and nongovernment organizations work together in an ecosystem that promotes well-being of all stakeholders. Mining companies must be proactive and demonstrate their sincerity in resolving various conflicting interests to earn the "license to operate" reward so-to-speak.

This chapter highlights various multifaceted initiatives involving corporate social innovation, developing breakthroughs in mining and processing technologies along with creating innovative solutions to various environmental challenges associated with water, energy, tailings, and waste management.

11.1 Corporate Social Responsibility to Corporate Social Innovation

11.1.1 Corporate Social Responsibility (CSR)

Corporate social responsibility (CSR) has been defined by Government of Canada as "The voluntary activities undertaken by companies to operate in an economically, socially and environmentally sustainable manner beyond the minimum required by law" (Natural Resources Canada 2011).

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Government of Canada has advanced "Building the Canadian Advantage" initiative that is founded on four complementary pillars designed to engage multiple stakeholders and foster different aspects of CSR. The four pillars of this strategy are (Natural Resources Canada 2011):

1. Support for initiatives to enhance the capacities of developing countries to manage the development of minerals and oil and gas, and to benefit from these resources to reduce poverty.
2. Promotion of the following widely recognized international CSR performance guidelines with Canadian extractive companies operating abroad:
   - *Organisation for Economic Co-operation and Development (OECD) Guidelines for Multinational Enterprises*
   - *International Finance Corporation Performance Standards on Social & Environmental Sustainability* for extractive projects with potential adverse social or environmental impacts
   - *Voluntary Principles on Security and Human Rights* for projects involving private or public security forces
   - *Global Reporting Initiative for CSR* reporting by the extractive sector to enhance transparency and encourage market-based rewards for good CSR performance
3. The Office of the Extractive Sector CSR Counsellor to assist stakeholders in the resolution of CSR issues pertaining to the activities of Canadian extractive sector companies abroad.
4. The CSR Centre of Excellence to encourage the Canadian international extractive sector to implement these voluntary performance guidelines by developing and disseminating high-quality CSR information, training, and tools.

Government of Canada established the position of the extractive sector CSR counsellor in 2009 as part of its first CSR strategy for the Canadian extractive (mining, oil, and gas) sector called "Building the Canadian Advantage: A Corporate Social Responsibility Strategy for the Canadian International Extractive Sector" (Global Affairs Canada 2018). This strategy was designed to enhance the ability of Canadian extractive companies working outside Canada to manage social and environmental risks, to contribute to their success abroad, and to reflect Canadian values and leadership in responsible business practice.

The Government of Canada launched an updated CSR strategy in November 2014 called "Doing Business the Canadian Way: A Strategy to Advance Corporate Social Responsibility in Canada's Extractive Sector Abroad" (Global Affairs Canada 2018). This updated strategy outlined the Government of Canada's expectation that Canadian companies operating abroad respect human rights and all applicable local and international laws, and meet or exceed widely recognized international standards for responsible business conduct. This update gave the following mandate to the CSR counsellor and its office:

- Promote CSR guidelines to the extractive sector
- Advise companies on incorporating these guidelines into their operations

- Prevent, detect, and resolve disputes in their early stages
- Work closely with Canada's National Contact Point for the *OECD's Guidelines for Multinational Enterprises* on responsible business conduct
- Provide support to Canadian embassies, trade commissioners, and other Government of Canada officials promoting CSR to Canadian extractive companies operating internationally

The Government of Canada contributed to the creation of the CSR Centre for Excellence (CfE) as one of four pillars of its original 2009 federal CSR Extractive Sector Strategy. The CfE is a multistakeholder body and is currently hosted by the Canadian Institute of Mining, Metallurgy and Petroleum (CIM). The CfE is a focal point for the development and dissemination of practical tools and information for use by a broad range of extractive sector stakeholders. CfE has following accomplishments to its credit (CIM 2019):

- CfE participation in numerous extractive sector conferences/activities (e.g., multistakeholder discussions at CIM Conferences, participation at Prospectors & Developers Association of Canada (PDAC) Conferences).
- CfE identification of three priority areas where practical guidance is needed:
  - The UN Guiding Principles on Business and Human Rights
  - The OECD MNE Guidelines
  - The Voluntary Principles on Security and Human Rights
- Holding of CfE multistakeholder workshops to explore relevant issues:
  - January 16, 2015 CfE Workshop on Respect for Human Rights throughout the Supply Chain
  - March 31, 2015 CfE Workshop on Integrating Human Rights at the Site Level
  - March 28, 2014 CfE Workshop on the Remedy Aspect of the UN Guiding Principles on Business and Human Rights
- In conjunction with the federal Trade Commissioners' office, development of short handouts on relevant issues:
  - Community Stakeholder Engagement
  - Managing Requests for Community Support
  - Hiring Responsibly
- Development of video: "A Human Rights Primer for Mining Personnel."

Under the CSR Strategy of the Government of Canada, companies are expected to participate in the dispute resolution mechanisms of the CSR Counsellor's Office or Canada's National Contact Point ("NCP") for the Organisation for Economic Co-operation and Development ("OECD") Guidelines for Multinational Enterprises. Participating companies are eligible for enhanced economic diplomacy by the Government of Canada, while companies not employing CSR best practices and those refusing to participate in the dispute resolution mechanisms lose access to the Trade Commissioner services and other Government of Canada services, which include the issuance of letters of support, advocacy efforts in foreign markets, and participation in Government of Canada trade missions. A designation of noncompliance will also affect financing or other support by the Government of Canada's financing crown corporation, Export Development Canada (McMillan 2014).

The CSR strategy endorses the United Nations' Guiding Principles on Business and Human Rights (the "UN GP") and the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from conflict-affected and high-risk areas (the "OECD Guide"). The UN GP identifies three principles to guide the companies and governments regarding human rights: (1) the state's duty to protect against human rights abuses by third parties, including business; (2) the corporate responsibility to respect human rights through due diligence; and (3) ensuring greater access to effective remedies for victims (McMillan 2014). The OECD Guide provides guidelines to multinational mineral extraction companies for avoiding fueling conflict and responsibly sourcing and trading minerals in conflict-affected and high-risk areas.

Mining companies have undertaken a number of activities under the CSR initiative. These activities include investments in infrastructure (e.g., schools, roads, hospitals, health equipment, electricity, clean water, and drainage repairs), investments in building social capital (e.g., information on HIV prevention, family planning, and improving hygiene), investments in human capital (e.g., providing education, training, and skills), fostering microbusiness, aquaculture, crop cultivation, animal rearing, and textile production (E&MJ 2013).

Mining companies have realized that doing the right things in the communities where they operate is important. They are actively pursuing activities that mitigate the economic, social, and environmental impacts of mining on local communities. Endeavour Silver planted more than 40,000 trees as part of its commitment to reclaiming and restoring land disturbed during the mining process in 2014. Rio Tinto has spent over billion dollars on education and clean water projects in Ghana. IAMGOLD is running skills development programs in Burkina Faso. Barrick Gold is funding business loan programs in Peru (mining.com 2015).

Mining companies have realized that an investment in the people living where they work can have outsized returns in human impact terms, permitting time, and even the ability to continue operating (mining.com 2015). These programs need to be designed in cooperation with local communities to have a lasting impact.

11.1.2 Corporate Social Innovation

The concept of Corporate Social Responsibility (CSR) has been constantly evolving since it began in the 1990s when many companies across the globe embraced worthy community causes in areas where they operated. Most of these programs focused mainly on the company's reputation and license to operate, with little direct connection to their bottom line.

Since 2011, there has been a global movement to make CSR impacts more integral to a company's business strategy focusing on *creating shared value*. SABMiller, the world's second-largest brewer, was an early adopter. The company targeted more than 380,000 small retailers in their biggest Latin American markets: Colombia, Peru, Ecuador, Panama, Honduras, and El Salvador, with an aim to improve small retailer's business performance and therefore quality of life and leadership abilities through a combination of classroom training and in-store mentoring on business, life skills, and leadership. This involved strengthening the broader "business ecosystems" in which the retailers operate, with a special focus on improving their access to financing and technology. The effort is aimed at strengthening SABMiller's retail network and sales. The company's success hinges on the success of its retailers—a win–win situation—creating shared value (IDB Invest 2015).

The latest evolution on this CSR continuum is the advent of Corporate Social Innovation (CSI). The World Economic Forum launched the Global Agenda Council on Social Innovation in 2014, bringing together corporate leaders, impact investors, and development executives, and offered a definition for CSI that builds on shared value concepts. In this the companies proactively design and implement business models that increase incomes and better the quality of life of underserved or vulnerable communities.

One interesting feature of CSI is that a new alignment is emerging among corporate venture capitalists and impact investors. The corporate venture capitalist is seeking returns for the company and new capabilities or access to markets that are aligned with its long-term business strategy. The impact investor is interested in placing capital into companies and generating measurable social and environmental impact, together with a financial return. The impact investor also wants to expand effective development solutions and—together with development finance institutions—is beginning to understand that working with large companies may be the best route. Companies that set up corporate venture funds also have in-house expertise and distribution channels that allow them to scale up successful projects.

One example of CSI is the philanthropic arm of the oil giant Shell Foundation, who formed a strategic partnership with Husk Power Systems, a biomass electricity generator. In 5 years, Husk has installed 84 mini-power plants, providing electricity to more than 200,000 people in 300 rural villages in India. By electrifying villages, Husk is promoting economic development, as businesses are able to stay open after dark and children can study at night. Impact investors Acumen and Oasis Fund have contributed funding to the venture.

It is important to realize that business leaders have the opportunity to transform societies through driving innovation. A growing number of companies worldwide are now accepting that CSR and innovation are the foundation of business competencies. With the emergence of digital technologies and better connectivity, the ability to tackle the issues such as social justices, poverty, and climate change through innovative approaches has now enhanced. The only successful brands of the future, including that for mining and resources companies, will be the ones that see these challenges as opportunities for innovation, rather than risks to be alleviated.

According to the UK trade and industry, CSR represents "the integrity with which a company govern itself, fulfils its mission, lives by its value, engages with its stakeholders, measures its impact and reports on its activities."

It is time that mining companies should embrace CSR in the form of social entrepreneurship as change agents for the society, seizing opportunities, inventing new approaches, and developing solutions to make this world a better place to live. It is not too far away when Eco-Innovation will emerge as a new discipline with the purpose of redefining businesses, including mining, and its products and processes in terms of their contribution to sustainable development.

11.2 Breakthroughs in Mining and Metal Extraction

11.2.1 Integrated Mining and Metal Extraction

As discussed in Chaps. 2–4, an integrated approach to geology, mining, and metal extraction along with environmental and social considerations is clearly the future of gold and silver industry. This has now been possible due to various technology disruptions that have emerged or are rapidly emerging in the areas of digital, automation, artificial intelligence, robotics, augmented and virtual reality. In addition, the core mining technologies are also evolving rapidly such as the 3D seismic surveying, hyperspectral automated core scanning, continuous rock cutting technology for hard rocks, hydraulic ore pumping, ore sorting for early waste rejection, in-place or in situ leaching, bio-oxidation for refractory ores, alternative lixiviants for gold and silver, dry stacking of tailings, and ultimately these technologies are progressing toward a near zero waste mining scenario. The onus is now on the mining industry as to how quickly these technologies are embraced to make the industry safer, more efficient, sustainable, and also meet the growing expectations of communities, governments, and other stakeholders. Also, it is important to realize the future of mining industry depends on attracting the new generation who are digital savvy and expects the digital way of working as the new norm.

This chapter will discuss various other emerging technologies that have the potential to transform the gold and silver industry.

11.2.2 Bio-oxidation

Outotec Biomin, South Africa, has developed the MesoTherm process which utilizes a combination of the traditional BIOX mesophile process for the primary bio-oxidation stage followed by a thermophile bio-oxidation stage to complete the oxidation. The higher oxidation rates and more complete oxidation at the higher temperature result in lower cyanide consumption during subsequent leaching of the bio-oxidation product. Development of the process included several stages of batch and continuous pilot plant testing. The final stage in the development is the successful operation of a 21 m^3 demonstration tank at the Fairview BIOX plant which has shown a 50% reduction in cyanide consumption for similar sulfide oxidation to the commercial plant (Seaman et al. 2019). They have also introduced the OKTOP® 3105 dual impeller to give superior gas handling and oxygen mass transfer rates under typical BIOX operating conditions. It was tested in water and BIOX slurry using a 21 m^3 test reactor at the Fairview Mine in South Africa, and the results indicated overall savings for the agitator and blower of 5% in capex and 5% in OPEX compared with the benchmark dual hydrofoil (Van Niekerk et al. 2018). The second successful commercial implementation of the HiTeCC technology to combat the preg-robbing of double refractory ore has been achieved at Nordgold's Suzdal mine in Kazakhstan which treats double refractory ore with both visible and invisible gold hosted in sulfide associations of pyrite and arsenopyrite, and also carbonaceous black shale. Following extensive laboratory and demonstration scale testing of the Outotec HiTeCC technology over the period of 2012–2015, Suzdal commenced the construction of a 385 tons per day facility. The plant was designed to recover gold from both the current and historic Carbon in Leach (CIL) tailings and was successfully commissioned in 2016. In the process, the preg-robbed gold is efficiently desorbed from the carbonaceous matter by manipulating the ionic strength and temperature of the Suzdal CIL product leading to enhanced metal recovery (van Buuren et al. 2018).

The first commercially successful bio-oxidation plant was built in 2001 at Laizhou Gold Processing Plant in Shandong Province with a capacity of 100 tons/day, adopting MetBytes for BacTech technology. The largest was built in 2007 in Guizhou Jinfeng with a capacity of 750 tons/day, utilizing BIOX™ technology. The typical plant has three stages of agitation tanks in parallel for primary oxidation, and three to four stages of agitation tanks in series for secondary oxidation. Air is introduced into the tanks and dispersed with an agitator to achieve oxidation of the sulfur in pyrite concentrates. The temperature is usually controlled at 38–45 °C using cooling water in an indirect heat exchanger to provide an optimum environment for the bacteria, and the pH is controlled at 1.5–2.0 by limestone to neutralize acid, produced by oxidation of sulfur. Under suitable conditions the bacteria can be adopted to oxidize gold arsenopyrite concentrates with an arsenic content of less than 3% (van Buuren et al. 2018).

11.2.3 Pressure Oxidation

Unique operating conditions have driven designers and manufacturers to use explosion welded titanium clad construction for the world's largest pressure oxidation gold autoclave for the expansion of Polymetal International's gold processing facility in Amursk, Eastern Russia. The decision is based on titanium clad being considered to be a more economical and reliable solution than the commonly used acid resistant brick lining system (Pearson 2019). This is the first use of Ti clad for the gold POX that NobelClad is aware of. While some pilot lines use titanium for autoclaves, and have for many years, this is its first use in a full commercial production plant (Salt 2019).

11.2.4 Rapid Oxidative Leach (ROL) Process

FLSmidth, USA, is developing the application of their mechanochemical pretreatment process to oxidize refractory sulfide gold ores and concentrates under atmospheric pressure without ultrafine grinding and at temperatures much lower than traditional roasting or autoclave pretreatment (Roy et al. 2018). They are particularly targeting refractory low-grade ores with >3 g/ton gold coupled with small resources, and existing operations with low-grade stockpiles to be processed at end of mine life. Laboratory testwork indicates >70% gold extraction in 8 h. They are working with several gold producers with the goal of progressing to pilot scale testing in 2019. Projected advantages include low capex and lower environmental impact compared with existing technologies. The process is a direct application of technology developed for copper chalcopyrite ores which has been successfully piloted and is moving toward a demonstration plant in South America in 2019 (Barlow 2018; Gleeson 2019a, 2019b).

11.2.5 Heap Leaching of Refractory Gold Ores

There is an industry trend toward lower ore grades, and refractory ore types with higher arsenic level which is driving research and development into improvements to existing processes as well as the application of new technology.

Chloride leaching is being developed for heap leaching of low-grade chalcopyrite copper ores, and may have potential for low-grade refractory gold ores.

Heap leaching of refractory gold ore by integrating enhanced bio-oxidation of pyrite and chloride-based gold leaching is under research by Barrick Gold and University of British Columbia. This process involves bio-oxidation of pyrite as pretreatment to expose gold, followed by chloride-based leaching of gold.

Although refractory gold heap leaching is very cost effective, it is a possible process for recovering a number of elements from sulfide ores.

11.2.6 Mixed-Chloride Technology

Process Research Ortech (PRO), Canada, has developed an innovative atmospheric mixed-chloride leaching process for the recovery of gold from gold-bearing complex ores, concentrates, and tailings. Mixed chloride technology applied for the recovery of several products including gold from refractory ores, titanium dioxide from ilmenite ores, Rare earth element (REE) from aluminosilicate ores, base metals and PGM from sulfide ores, and base metals from laterite ores (Lakshmanan et al. 2013a; 2013b).

PRO process uses mixed chloride lixiviant ($HCl + MgCl_2$) to bring gold and silver in solution. The HCl leaching system provides the opportunity to regenerate the acid by pyrohydrolysis, while the presence of $MgCl_2$ in the lixiviant enhances the activity of the hydrogen ion by orders of magnitude, making the lixiviant very aggressive. This results in high recoveries of precious and base metals. Precious and base metals are separated from pregnant leach solution (PLS) successively using innovative solvent extraction steps (Lakshmanan et al. 2013a, 2013b).

A mixed-chloride process flowsheet, which developed by PRO for the recovery of Au from gold-bearing materials, is shown in Fig. 11.1. This process has several advantages such as (1) it is environmentally friendly as no cyanidation is involved and it can be applied in jurisdictions where use of cyanide is not permitted, (2)

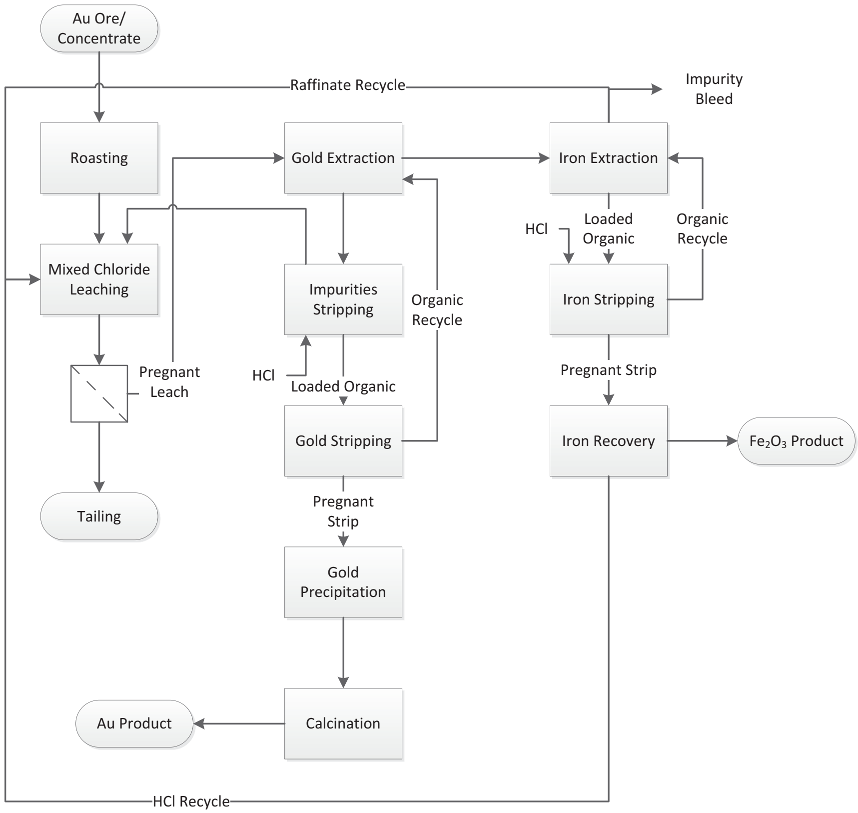

Fig. 11.1 PRO mixed-chloride process flowsheet for the recovery of gold from gold-bearing materials

selective extraction of Au from the pregnant leach solution followed by stripping, precipitation, and calcination avoid the use of cyanide, (3) this route offers economic advantage by eliminating the cyanide ion in subsequent management of process effluents and solid wastes, and (4) minimizes reagent costs by recycling HCl and iron raffinate to the leaching stage (Lakshmanan et al. 2018).

11.2.7 Nano Gold Catalyst

Recently, there has been considerable research into developing new catalysts that can selectively and efficiently convert CO_2 into fuels with steady operation for hundreds of hours. One of the most promising of these is based on gold. A recent discovery of gold nanostructured catalysts by researchers at the University of Toronto (Kauffmann et al. 2016) represents a significant advance in the field and has paved the way for selective and efficient CO_2 reduction to carbon monoxide (CO), a precursor to synthetic fuels. The nanostructured gold catalyst is shaped in a needle just a few microns thick. When supplied with electrical potential, the gold nano needle catalyst converts CO_2 into CO with high activity and selectivity. Once the carbon monoxide has been produced, it can be combined with hydrogen gas to make syngas, a precursor to many fuels such as gasoline. The US Government's National Energy Technology Laboratory (NETL) is also heavily involved in the search for advanced clean-tech catalysts. Researchers have developed a special engineered form of nanoparticle catalyst composed of 25 atoms of gold, which has shown considerable potential for use in the carbon dioxide reduction reaction. Indeed, the researchers believe that renewable energy sources, such as wind and solar, could power large-scale CO_2 conversion plants in the future, effectively providing a potential route to a carbon-negative energy cycle. While a number of catalysts are being considered, the current evidence suggests that gold is the best-in-class catalyst for the highly active and selective reduction of CO_2 to CO. A recent discovery of gold nanostructured catalysts by researchers at the University of Toronto represents a significant advance in the field and has paved the way for selective and efficient CO_2 reduction to carbon monoxide (CO), a precursor to synthetic fuels (World Gold Council 2018).

11.3 Novel Design and Engineering

The pressures on mine operators are varied and constantly increasing, declining ore grades, more remote locations and increasing environmental concerns. The challenge facing the mining industry is to find new ways to process ores which are more efficient and less costly and to control them better. This requires a fundamental rethink in the way in which the projects are developed; it is no longer good enough to just replicate what has been done before.

The future success stories will not simply be incremental improvements based on cost cutting and continuous improvement techniques. Most companies have already exhausted this route. The key to enhancing value is to do more with less, both in terms of capital and operating costs. Our focus is on processing as early as possible in the value chain and pushing the boundaries on cost, energy, water, and labor efficiencies through employing innovative processing techniques. The plant of the future will be smaller and more agile.

To make the improvements performance changes are required. First, through increased use of available and emerging technology. The second is through the identification of new design principles which address the key constraints to improvement.

The new design principles initiative seeks to facilitate step changes in performance for both greenfield and brownfield projects by addressing the key underlying constraints under which the project has to operate. It uses a divergent/convergent approach, Fig. 11.2, to identify and analyze the issues. It begins with divergent thinking in an open and collaborative workshop environment. The aim here is to answer the question what are the perceived constraints, strengths, and weaknesses. The points identified are then classified into four quadrants, strengths/weaknesses and can change/cannot change. Thinking then converges to identify what are the real problems we have to solve which are then distilled into a set of new design principles. These represent the key design principles necessary to enable the proposed project or improvement to be implemented. They may be such principles as autonomous underground ore handling, minimum tailings footprint, zero water discharge, maximum local community involvement, process underground (or as early as possible), and/or maximum use of renewable energy.

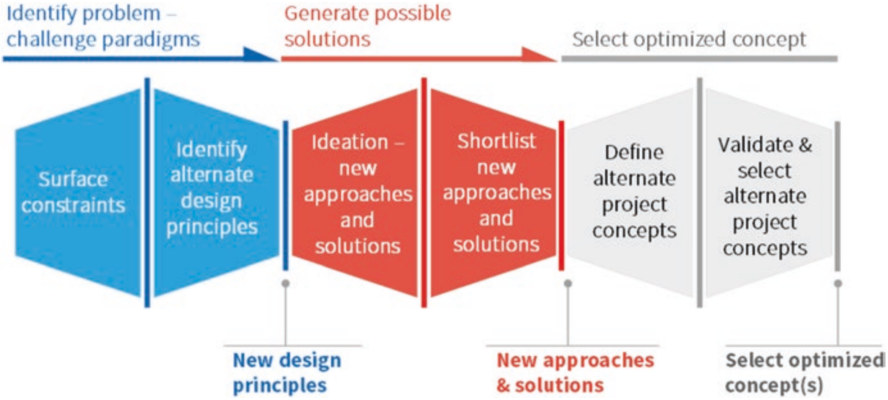

Fig. 11.2 New design principles process (Bunyard and Mullany 2017)

11.3.1 Integrated Underground System Design

A conceptual example of an integrated underground mining and surface processing system is an underground mine with ore sorting, tailings segregation, paste backfill, and tailings dewatering for water recovery and reuse. The result of such an integrated flowsheet would have multiple economic and environmental benefits, including:

– Underground mining generates minimal waste rock that would otherwise be dumped on surface.
– Underground preconcentration reduces costs for ore haulage to surface and reduces quantities of tailings produced.
– Separation and segregation of sulfide tailings reduces acid rock drainage (ARD) risks.
– Paste backfill significantly reduces size of surface tailings storage facility (TSF), reducing risk; in addition, paste backfill provides support in the mine, allowing more mining of remnant pillars, increasing mining reserves.
– Tailings dewatering and reclaim increases water recycling and reduces make-up water requirements.

11.3.2 Tailing Disposal

The long-established practice of disposing of the process tailings as slurry in an impoundment area is both an environmental risk, as several recent failure incidents attest, and a source of significant water entrainment and evaporative loss. Those operations that can use tailings as underground fill or have an exhausted open pit which can be filled are the fortunate few. The two pressures of environmental concern and water use efficiency are driving tailings disposal toward dry stacking and co-deposition with waste rock. Tailings disposal by dry stacking adds considerably to the upfront capital and operating costs of a processing operation by the addition of a filtration step. It has the advantage, however, of containing virtually all of the water within the process plant area where it can be treated and recycled with minimal loss. It also minimizes the tailings storage footprint and provides improved stability of the stored material (Fig. 11.3). The reduction in stored volume afforded by dry stacking also reduces the sustaining costs of embankment raises throughout the mine life. For current operations which have slurry impoundment storage facilities it is possible to dry stack on top of an existing tailings dam, consolidating the previously deposited tailings in the process, so removing the need to expand the footprint to store future tailings arising. Despite the increased equipment cost it is likely that environmental concerns will make dry stacking a requirement for many projects and mines, especially gold operation, in the future. The alternatives to reduce tailing contamination failure risk are explained in Table 11.1.

Fig. 11.3 Dry stacked tailings disposal La Coipa, Chile

11.3.3 In Situ Leaching

Many ore deposits are currently uneconomic due to low grades or being too deeply buried. In situ leaching (ISL) may allow economic extraction of these resources.

In-situ leaching (ISL) is receiving renewed attention as open pit mining operations face increasing pressure around decreasing ore grades, higher strip ratios, higher operating costs, safety, tailings disposal, water quality, and a range of environmental approval and community issues. This method of recovering metals directly from the underground ore body offers solutions to many of the objections to mining in the traditional manner. The surface footprint and visual pollution are significantly reduced with no headframes and smaller process buildings, noise, and dust are eliminated, heavy vehicle transport needs are reduced and energy consumption is minimized.

Electrokinetic in situ leaching (EK-ISL) is a novel in situ mining technology that uses an electric field to induce the migration of lixiviant through the subsurface to extract target commodities. The combination of electrokinetics and in situ leaching (EK-ISL) provides a unique opportunity to overcome the shortcomings of ISL in low permeability media (Martens et al. 2018).

11.3.4 Cyanide Alleviation

Factors driving new developments in gold technology include increasing environmental concern and government regulation over the use of cyanide, the trend toward refractory, complex, and lower grade resources, and the pressure to reduce operating

Table 11.1 Alternatives to reduce tailings containment failure risks

Category	Option	Opportunities	Obstacles
Generate less tons of tailings for surface disposal	Selective mining	Leads to higher mill head grade and lower processing costs	May reduce reserves and mine life
	Preconcentration	Rejecting a fraction of liberated gangue in mill feed will reduce milling costs. If mill is bottleneck, can provide relief and increase metal production	May have substantial metal losses. Some ores may not be amenable, and performance of preconcentration circuit may vary
	Flowsheets incorporating heap and dump leach	Can segregate lower grade ore and direct to heap leach operation. Lower grade ore matched with lower process OPEX	Ore may not be amenable to heap leach. May be difficult to practically segregate ore and optimize economics
	Backfill	Paste backfill can improve underground mine safety and enhance pillar recovery, increasing mining reserves and mine life	Cost: Some materials may not have suitable properties. Not all tailings can be backfilled due to expansion/swell factor.
	Beneficial reuse of fraction of tailings	May be additional source of revenue, and reduce disposal costs	Quality specifications for transport and customer delivery may be costly to overcome (e.g., impurities and size distribution)
Manage embankment design, dewatering, and deposition	Change TSF Siting (e.g., lower line of fire risks)	Improved stakeholder acceptance of project	Siting locations may be restricted by topography and land ownership position. Tailings and reclaim water transport costs may increase
	Improve drainage	Enhanced water recovery	May be limitations in effectiveness
	Increase tailings dewatering, that is, paste thicken or dry stack	Increased dewatering costs. Some materials are difficult to dewater to high solids content (e.g., clays and fines)	Significantly reduces volume of TSF, and increases water recycling
	Coarsen particle Size in tailings	Coarse tailings are cheaper and easier to dewater. Reduces comminution costs	May reduce metal recovery due to losses in coarse particle fractions

cost and increase plant performance efficiency. Alleviation of the issues around the use of cyanide, noncyanide lixiviant, processes for refractory ores and concentrates, improvements in analytical, control and monitoring systems, and upgrading of gold resources by sensor-based automatic ore sorting are reviewed in this section.

11.3.4.1 RECYN Process

Green Gold Engineering has been awarded a ReCYN™ Process design to detoxify tailings and recover cyanide and copper at its Martabe gold–silver operation in Sumatra, Indonesia (Gleeson 2019a, 2019b). Using an innovative resin-bead absorbent, known as the RECYN Process, allows for the economic recovery of cyanide from gold/silver plant tailings. RECYN Process typically reduces cyanide consumption by 50% by recovering free cyanide from the plant tailings and recycling it back into the leach circuit, while recovering dissolved base metals for sale as a by-product. The combination of recovery steps produces a fully decontaminated tailings stream from the process plant and overcomes any need for further detoxification of the tailings, also a net cost changing to a positive return. These advantages, both economic and environmental, can help change the negativity associated with cyanide.

The Mirah Gold Project in Central Kalimantan, Indonesia has, for over 2 years, successfully operated a commercial scale plant (1Mtpa ore) for the recovery and recycle of cyanide on a continuous basis. An average of 1 ton/day of NaCN has been recycled at a cost of 50% of new cyanide, with no further detoxification of the tailings required to meet environmental compliance levels (Paterson 2017).

11.3.4.2 Colorant in Cyanide

The use of a colorant in cyanide has been approved by the ICMI Board (International Cyanide Management Institute 2017). The purpose is to provide a means of visual identification of leaks or spills at mine sites or during transportation. It will require that dye be included in high-strength cyanide solutions prior to delivery at the mining operation and to solid cyanide prior to or at the time of mixing. High-strength cyanide solutions are defined as those with a minimum cyanide concentration of 15%, which would provide coverage to cyanide in both liquid and briquette form. ICIMI's decision was influenced by the use of dye addition by the Newmont Goldcorp Group, Canada, which originated at the Musselwhite Mill, Ontario, after the operations team heard about its use at the Placer Dome Mine, Ontario. After further development in cooperation with the dye supplier and cyanide supplier, Chemours, USA, the present practice of adding red dye at the manufacturing level to eliminate the need for a mixing system at site was adopted. The practice spread to other Goldcorp sites and is now mandatory company-wide (GoldCorp 2018).

The incorporation of dye to reagent-strength cyanide as a requirement of the Cyanide Code offers an opportunity to enhance protection of personnel and the environment. Use of dye by companies is believed to enhance product awareness, personnel safety, and provide a quick indication of cyanide leaks and spillages.

11.3.4.3 On-site Cyanide Generation

Synergen Met, Australia, is continuing to progress its onsite cyanide production process toward full-scale commercial application following the successful operation of a 60 tons/year pilot plant at an operating gold mine in Australia (Dunks 2018). It is targeting a modular design rated at 450–750 tons/year, with additional modules to be added for larger output. An average mine uses 500–1000 tons/year rising to over 10,000 tons/year at some large-scale operations (Leonida 2015). The process involves combining nitrogen directly from the air with methane from a hydrocarbon gas source using a plasma torch at 10,000 °C then quenching to form HCN. The HCN gas is mixed with NaOH to form NaCN, and the remaining hydrogen and nitrogen are vented to atmosphere. The NaCN solution is produced at the concentration and dosage required by the plant, and is pumped directly into a holding tank in a closed system without any handling by personnel (Synergen Met Pty Ltd 2019). Key benefits include elimination of risk of spills during transport, alleviation of environmental and community opposition, security of supply for remote sites, avoidance of worker exposure during handling and dilution, reduced cost in niche markets such as highly rugged terrain and remote mining sites, and reduced insurance cost and liability of toxic chemical storage.

11.3.4.4 Development of Alternative Lixiviant

Mixed Chloride

Process Research Ortech, Canada, has developed a Mixed Chloride lixiviant for gold leaching that has excellent stability and shown extensive applicability in the laboratory and pilot scale. The PRO's lixiviant is an alternative to cyanide and has particular application where cyanide cannot be used.

The lixiviant is containing HCl and $MgCl_2$ and acts at the atmospheric pressure leaching. In the leaching process, the leach slurry is subjected to a liquid/solid separation step to produce pregnant leach solution and subsequent solvent extraction steps to recover gold from the pregnant leach liquor. For example, a gold-bearing material containing 3.48 kg/ton of gold was subjected to mixed chloride leaching with a lixiviant of 4 N HCl, 225 g/L $MgCl_2$, at a temperature of 90 °C and pulp density of 10% solids to bring Au into solution. In addition to Au, Fe was also brought into solution. The leaching time and the oxidation reduction potential were 4 h and 1150 mV, respectively. The leaching mechanism of Au can be shown by the following reaction (Lakshmanan et al. 2018):

$$Au + 8HCl + \mathrm{NaClO_3} = \mathrm{2HAuCl_4} + \mathrm{NaCl} + \mathrm{3H_2O}$$

Thiosulfate

CSIRO, Australia, has developed a thiosulfate-based reagent system for gold leaching that has excellent stability and shown broad applicability in the laboratory compared to the thiosulfate system commercially implemented by Barrick to treat double refractory gold ore following pressure oxidation at its Goldstrike Mine in Nevada, USA. The CSIRO reagent system is an alternative to cyanide and has particular application where cyanide cannot be used and to unlock stranded high-grade deposits. CSIRO in collaboration with Eco Minerals Research Limited, Australia, commenced a project in July 2017 to undertake a demonstration at scale in the field using the CSIRO reagent system. The mobile demonstration plant setup on the Menzies Battery site in Western Australia uses a low capex vat leach process to recover gold from ores having good gold liberation at a p80 greater than 300 μm. In less than 10 months the demonstration project has taken a laboratory developed concept and transformed it into a demonstration plant involving design, build and commissioning through to successfully producing a gold ore bar. The demonstration plant processed up to 30 tons of ore per day by vat leaching and operated successfully for more than 6 months to validate the reagent performance and stability (Breuer and McCulloch 2019). The successful validation in the field at scale has paved the way for commercial application of the technology and a commercial launch is imminent.

Glycine

GlyCat™ leaching is being developed for implementation at Newcrest's Telfer Gold Mine in Western Australia to facilitate a change in circuit design that would then allow for increased concentrations of soluble copper to be tolerated in an expanded gold cyanidation circuit (Seaman et al. 2019). Reusable glycine is added to the leach to enable a fivefold reduction in cyanide usage while eliminating detox requirements. Copper is recovered by either sulfide precipitation or resin ion exchange. Gold is recovered by conventional carbon adsorption or alternatively using gold-selective resins. Over a 2–3-year period, an extensive program of batch testwork has defined the optimum leaching chemistry and proved the effectiveness of downstream processes. Three continuous piloting campaigns have shown that the process is robust and controllable, while verifying the reagent consumptions and gold recovery under steady-state conditions. Bench-scale testwork, process modeling, and engineering studies have narrowed down the circuit configurations to a preferred flowsheet involving single stage leaching and conventional downstream recovery. Implementation at Telfer will require extra leach tanks, solid–liquid separation equipment on the leach feed and discharge, and a copper recovery section. Glycine consumption is anticipated to be less than 3 kg/ton of concentrate while the resulting saving in cyanide is at least 30 kg/ton if the same concentrate was treated using cyanidation leaching alone. Glycine leaching, an environmentally benign leaching process carried out in alkaline conditions, was developed by Curtin

University in Perth. Mining and Process Solutions have acquired exclusive rights to progress the technology through to commercial application. GlyCat™ is the application of glycine with cyanide to mixed base metal and precious metal ores.

11.3.5 Novel Cyanide Analysis Methods

A few areas of improvement with regard to existing technologies include reaching lower detection limits, dealing with turbid waters, dealing with sample preservation, and developing cyanide sensors with simple technologies that can be easier to use, install, and maintain for remote use. Ideally, new technologies will also allow for the detection method to be portable and accurate for complex solutions with potentially different matrices. A key need in industry is the measurement of reliable cyanide concentrations in real time and in remote areas (Manoukian and Ahern 2017).

Quartz Crystal Mass Monitors (QCMMs) have a resonance that is sensitive to very small mass changes. In the case of cyanide, if gold is present in a crystal, and cyanide contacts this crystal, the metal dissolves, the mass decreases, and the resonant frequency increases (Ma and Dasgupta 2010).

A QCMM-based cyanide sensor with detection limits between 0.6 and 0.1 μM has been developed but has not been tested outside of a laboratory setting (Sun et al. 2005). Others have summarized various papers developing cyanide detecting biosensors. Most of the methods are dependent on measuring chemical reaction products based on enzymatic reactions (Breuer and Rumball 2007). The attractiveness of biosensors is associated to their advantages of being portable, easy to use, high selectivity, and cost effective. Despite the amount of research, there is still a lack in analytical biosensors that could be used confidently and independently in the field.

11.4 Concluding Remarks

It is becoming apparent that the future trend of gold and silver mining and processing will involve ores with decreasing head grade with a lower gold to sulfur ratios. The proportion of gold and silver production from highly refractory ore bodies involving various iron sulfides, carbonaceous matter, copper, arsenic, and mercury is expected to increase. Some of the key challenges with these deposits are suboptimal metallurgy, higher operating and capital costs, environmental issues associated with tailings and deleterious elements, increasing mining footprint, lack of resources including energy, quality water, skilled personnel, and ever-growing community issues. Major innovations with a holistic approach are essential to turn these marginal deposits into profitable mining operations in an environmentally friendly and sustainable manner. Some gold and silver mining companies are already looking at breakthroughs and step-change improvements with an integrated approach to problem solving (Bristow 2013; Dunne 2012; Kondos and Gorain 2012; Lakshmanan et al. 2012; Logan and Krishnan 2012). It is always best to address the root cause of a problem for enabling robust solutions to the present and future challenges of gold and silver mining and processing. Our industry has been very innovative, no doubt, with a strong focus on making our existing mining paradigm safer, more efficient, and automated. We have been remarkably successful so far but to address the unique challenges we now face as an industry, there appears to be no choice but to look beyond our existing mining paradigm.

The root cause of most of the problems in the existing mining paradigm is the generation of significant amount of waste and the need for handling, processing, and storing this waste with valuables representing only a very small fraction. The ideal scenario will be the case for zero waste mining, in which mining will target only the valuables without the need to remove the host rock and also all mined material will be used to create value added products with no waste dumps or tailings disposal. This is a daunting task, nevertheless, but if realized the benefits are significant. The underlying premise is that zero waste mining is economically very attractive, environmentally friendly, and fully integrated with the needs of local communities, societies, and other stakeholders. Hence pursuing "zero waste mining" is worthwhile as our ultimate long-term goal, but we must address this in small practical steps with a "horses for courses" approach.

Based on our experience and discussion with various players inside and outside the industry, some major step-change opportunities for gold and silver mining and processing being investigated or pursued by various players in the industry are presented as follows.

1. **Minimal removal of overburden to access ore body**:
   - **Borehole mining**: Use of small diameter drill holes to access the ore body along with use of novel biotechnologies to mine and recover metals (Dunbar 2014; McMullen et al. 2005). This is conceptual at this stage and will need further investigations.
   - **In situ gold leaching**: In situ recovery is presently practiced successfully in the copper, uranium, and potash industry. Companies like Rio Tinto are looking at opportunities with in situ leaching as the "mine of the future" (Batterham 2008). In situ gold leaching has been experimented before by BHP in 1989 and different lixiviants such as chlorides, thiosulfate, humic acid, and biogenic reagents have been proposed previously (McMullen et al. 2005; Zammit et al. 2013). New technologies like Discrete Fracture Networking are evolving to make this practical in an environmentally friendly manner for most ore types (Dershowitz 2011).

2. **Selective liberation of ores early in the mining process**: It is becoming important to ask ourselves "Why create waste in the first place." Comminution begins with mining and a new generation of drilling and blasting for selective mining of ores is critical to avoid or reduce waste removal early on in the mining process. This concept is referred to as "grade engineering" and is becoming a major focus of further development (CRC-ORE 2014).

3. **Minimal haulage of waste**:

    - **Preconcentration**: This allows processing to be closer to the mine site. There is a growing interest in preconcentration technologies such as sensor-based mass sorting (ROM shovels/trucks), classification using screens, stream based ore-sorting, gravity, and dense media separation, which is definitely a positive trend and important implications for the gold industry. Studies have suggested that integrated mining and waste rejection processes have high potential for deep underground mining (Bamber 2008; Batterham 2003; Dammers et al. 2013).

4. **Efficient comminution**: Technologies such as *Chemical Comminution* applied on a smaller mass after preconcentration are also being investigated (Muir 2014). Recent innovations in high intensity selective blasting to reduce footprint of comminution circuits are being tested and pursued by some operations. Use of technologies such as SelFrag to pretreat low grade ores (promoting fractures and high rock permeability) to minimize comminution energy but this technology also has important implications in maximize heap leach recoveries.
5. **Refractory ore processing**:

    - Microbial gold processing: Focus on new generation of low cost bio-heap leaching, bio-oxidation, and cyanide destruction processes using native microbial population along with phylogenetic fingerprinting is gaining momentum and has major potential (Brierley 2017; Zammit et al. 2013; Follink 2010).
    - Breakthrough flotation process: With the advent of new flotation technologies to treat ultrafine particles, and with better understanding of chemistry through state-of-the-art surface analysis capabilities, the possibility of a flotation breakthrough is likely. This has potential for a major breakthrough for processing Carlin type double refractory deposits.
    - Cost-effective sulfide oxidation: Other than innovative bio-oxidation processes, there are significant opportunities to integrate novel ultrafine grinding with new generation of pressure oxidation technologies involving lower capital and operating costs to process fine grained refractory ores that are uneconomical using existing technologies.
    - Alternatives to cyanide leaching: New generation of alternative technologies are needed such as Process Research Ortech's novel chloride leach technology for treating complex ores (Au, Cu, Ag, TCM, and As) with an ability to maximize recovery of gold along with valuable byproducts (Lakshmanan et al. 2012).

It is important to note that parallel development of many of these technologies is already happening. Also, not all these innovations will be relevant to every ore body as technologies must be tailored to suit the individual needs of an ore body. A systematic approach with a multidisciplinary collaboration involving various stakeholders is a must to realize the full benefits from a breakthrough technology.

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