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Autonomous and Remote Operation Technologies in the Mining Industry

Benefits and Costs

Brian S. Fisher and Sabine Schnittger

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Foreword

Fundamentally there are two sources of economic growth: increasing the use of inputs such as labour, capital, land and other natural resources such as minerals; or increasing the productivity of those inputs. Over the past century most of the economic growth has been derived from improvements in productivity, that is, improvements in output per unit of input. The ongoing revolution in technology has been crucial in making these productivity improvements possible.

Humans have been mining for at least 40 000 years. Two thousand years ago the Romans developed large scale hydraulic mining methods for use in alluvial gold deposits in Spain. They also developed underground mining techniques. Despite the long human history in mining and the ongoing development of new techniques mining has in the past typically involved much hard labour in often difficult and dangerous work environments.

This report was commissioned by Rio Tinto with the aim of exploring the likely future impacts of automation and other new technologies in the mining industry. Improvements in technology have the potential not only to extend the life of mines and thus increase returns both to the miners and the community more broadly but also to make mining safer for those who work in the industry. This report explores those potential impacts as well as the possible impact of new techniques in mineral exploration.

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Executive summary

Over the past decade, Australia has benefited greatly from its natural resource endowments. The sustained mining boom has contributed significantly to economic growth, investment, employment, as well as taxation and royalty payments to governments, and continues to do so. While some parts of the manufacturing sector have suffered from the appreciation of the Australian dollar, Australia's services sector has played a key role in supporting the growth of the mining sector and has profited accordingly. On recent Reserve Bank of Australia estimates, around half of the cost of new mining investment was spent locally on labour and other inputs. In addition, Australian residents received more than half of the earnings from the mining sector. Moreover, while mining operations are concentrated in the resource-rich states, the distribution of mining receipts has been dispersed across the country and has played a key role in keeping unemployment rates low in all states since the onset of the resources boom.

In the future, the consensus is that the strength in demand for raw materials will be sustained as developing countries industrialise and lift the living standards of their populations. Rising demand and recent higher prices have accordingly fuelled a global exploration and development effort that will result in mining activities expanding in both traditional and emerging minerals producing countries.

Australia has the reserves to remain a major resources producer for many years, but faces a number of challenges in remaining competitive. Productivity improvements in the mining sector have been weak for a number of years, reflecting a declining quality of deposits and increasing difficulties in accessing them. Surface and underground mining is inherently hazardous; the health and safety of employees is a priority for mining companies and must be assured at great cost. The mining sector also faces a shortage of skilled workers that is projected to become more severe in the future. Finally, the impact of mining operations on all aspects of the environment is a key issue and must be addressed as an integral part of all mining operations. This context contrasts with that in many other resource rich countries with significant untapped deposits that have only recently begun to develop their own mining industries. While non-traditional producing countries face a number of hurdles in bringing their mines to full production, a significant development effort with associated large capital flows is directed toward the emerging mining industries in these countries. In order to succeed in the global market place, Australian mining businesses must therefore innovate and change their operations to at least match the costs of their international competitors.

A process of incremental innovation has taken place in the mining industry for many years, but has recently accelerated with the emergence of powerful new technologies. These innovations have delivered a broad range of benefits, including enhanced employee health and safety outcomes, technical efficiencies that make better use of equipment and cut down on materials and energy usage, and improved environmental outcomes. They are also diverse and specifically tailored to a particular mining environment, such as a wide range of safety and monitoring systems developed for underground and surface mines.

Today, the focus in mining innovation has turned to the development of remotely operated and autonomous mining equipment and systems. These technologies represent a class of innovations that involve a step-change in the research and development (R&D) effort and are likely to profoundly change how minerals are mined and processed in the future. Automated systems allow humans to communicate with and control machinery remotely without exposure to hazardous mining environments, reduce or entirely eliminate health and safety risks, and make for a more attractive work place, including for women. Automated equipment can be better utilised, operates in a more controlled and precise manner and has a longer useful life, resulting in significant efficiency improvements. In many instances, efficiency improvements translate into reduced requirements for energy and consumables, as well as less waste, and therefore better environmental outcomes. Examples of existing innovations range from specific pieces of equipment such as remote controlled or autonomous vehicles and drilling equipment, to entire mines that have been designed and built around automated systems so as to minimise the human presence in a dangerous mining environment. Such automated mines also deliver material improvements at the system level, in terms of the ability to monitor and control all aspects of an operation in real-time. In Australia, Rio Tinto's ambitious 'Mine of the Future™' program to automate and remotely control almost all aspects of the company's Pilbara operations from Perth is the most high-profile of these initiatives.

While the direct benefits of automated mining operations, in terms of improved safety, efficiency and environmental outcomes are immediately apparent, these systems also come at a significant cost. Automated mining relies on an array of new technologies in the fields of computing, signalling and sensing technologies, as well as sophisticated communications systems. Developing these technologies for a particular mining environment is correspondingly complex and requires collaboration between experts from different scientific fields, as well as between mining companies and equipment producers. The full-scale roll-out and commercial use of these technologies can only occur after extensive R&D and multiple intermediate testing stages; a process characterised by very high rates of failure.

In spite of these challenges, Australia today is a global leader in research into mining automation. Institutions such as the CSIRO and CRCMining that are funded partly by government and partly by business, have developed a number of mining and associated processing innovations, including in the field of mine automation. Rio Tinto funds three Australian research centres, including the Rio Tinto Centre for Mine Automation, as well as two centres located overseas. A notable development alongside Australia's world-class mining R&D capability is the emergence of an Australian mining technology services and equipment (MTSE) sector. That sector consists of small to medium-sized companies, and has become a dominant presence in the global market for the supply of innovative products and services for the mining industry.

Overall, and while the costs and associated challenges involved in mine automation are substantial, they are potentially far outweighed by the benefits they can deliver to Australians and the Australian economy. Such innovations can significantly reduce the risks to human health and safety, as well as delivering process and systems efficiencies and environmental benefits. These benefits may help to counteract a number of the challenges currently facing the industry, including persistent skills and labour shortages, declining ore grades and more complex mining environments, as well as environmental challenges arising from the need to reduce emissions and impacts on the environment. From a longer-term perspective, increased automation may sustain Australia's competitiveness compared to a

situation where resource exports decline in importance relative to those from competitor countries with equally good or better resource endowments but fewer constraints. In addition, the Australian mining technology services and equipment sector is now a dominant presence in the global market for the supply and development of technology goods and services for the minerals industry. As technologies have progressed, the range of applications has also widened and a number of companies now supply industries beyond mining. This industry is set to become a major export earner as a spin-off from the mining industry. Longer-term, and if trends over the past decade are anything to go by, the corresponding economic benefits for the economy are likely to be substantial.

1 Introduction

The mining industry is going through a period of rapid change. There is a broad consensus that the demand for mineral resources will continue to grow strongly as developing countries industrialise and lift the living standards of their populations. As a country that is rich in minerals, Australia should be well placed to benefit from rising demand for minerals.

At the same time, Australian minerals producers face a number of challenges:

- Competition in global commodities markets is intense. Australia is only one of many countries with minerals resources, and new deposits are constantly being developed. To remain competitive, producers must constantly improve their efficiency.

- Within Australia (as in other countries with existing production) recoverable mineral deposits are declining in quality or otherwise becoming less accessible.

- The health and safety of employees has increasingly become a priority for mining companies.

- Australia faces a shortage of skilled workers that is projected to become more severe in the future.

- The impact of mining operations on all aspects of the environment is a key concern for mining companies.

The mining industry must therefore operate in an environment where more (regulatory and other) demands are made of it and where there are more constraints. In order to compete in this context, miners must adapt their operation to produce large volumes at a cost where they remain competitive.

The industry is addressing these challenges by undertaking significant investment in the development and deployment of innovative new technologies across all aspects of the minerals exploration, mining, processing and transportation chain. A central focus of these efforts is the increasing application of automated systems that operate in the field largely or entirely without direct human involvement. These new technologies have the potential to deliver significant advances in safety, improved process productivity and better utilisation of resources, labour and equipment. Overall, the trend toward automation will profoundly change how mines and associated facilities operate.

The aim in this paper is to explore the broader benefits and costs of trends toward greater automation within the mining industry for the Australian economy in qualitative terms.

This paper is organised as follows. Section 2 describes the mining industry and the broader economic and policy context in which it operates. Section 3 explores the history of innovation in the mining industry and describes recent trends in the use of remotely operated and autonomous technologies in the industry. Section 4 considers the identified benefits and costs of automation within an economic cost-benefit framework.

2   Today's mining industry in context

The minerals industry encompasses a broad spectrum of activities and final products, many of which are traded as commodities in intensely competitive global markets. Australia is well placed to benefit from strong projected demand for minerals, but must remain competitive relative to other existing and emerging producers and address a number of broader challenges facing the industry.

2.1   What is mining?

Mining is a diverse industry. In many situations mining involves breaking apart in-situ materials and hauling these out of a mine, but this definition hardly does justice to the multiplicity and range of distinct activities undertaken by the sector. Mining involves the extraction of a heterogeneous range of commodities, the deposits of which are distributed unevenly in terms of geographic location and qualities or grades, and a variety of extraction and processing techniques (Topp et al. (PC), 2008). Although there are a number of common mining methods, the techniques applied within these broad groupings vary widely:[1]

- Surface mining entails removing vegetation, top soil, and overburden materials above a mineral deposit and removing the deposit. In open-pit mining, waste is transported to a disposal site, and ores are transported to a downstream processing site.[2] In area-strip mining used for mining coal and phosphate, a trench is dug through the overburden to expose and mine the deposit.

- In underground mining the deposit is accessed from the surface via vertical shafts, horizontal adits, or inclines. The deposit itself is developed by traversing the orebody to enable human access, the extraction of blocks of ore, the transport of ore and waste and ventilation. For 'soft' deposits such as coal, potash or salt, mechanical means can be used to cut and load the deposit. In hard-rock mines drilling and blasting techniques are used.

- Other mining methods rely on the use of high-pressure fluids such as water. Solution mining uses fluids to pump out the resource (and sometimes to reinject other fluids), and is mainly used in the oil and gas sector, but also for potash or uranium production. Hydraulic mining (used for gold, tin and other metals) uses water power to fracture and transport earth or gravel for further processing.

The mining process itself is typically only one of many steps that must be undertaken to produce a saleable product and meet broader environmental, social and other obligations placed on mining companies. In most cases, mined products require further processing (beneficiation) to improve product quality. Beneficiation encompasses a great variety of processes that depend on the specific characteristics of the resource. Mining operations also often incorporate transportation facilities, including trucks, trains, conveyor belts or other means to deliver the finished product to port or customers. Taking an even broader view, the

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[1] In this report the focus is on traded mineral resources, as distinct from industrial minerals. Industrial minerals comprise crushed stone, sand, and gravel (aggregate); limestone and other construction materials; phosphates and other materials used in agriculture; many compounds used in the chemical industries; and other products. For most industrial minerals, international competition is limited.

[2] Quarrying is similar to open-pit mining, but generally refers to the extraction of dimension stone and aggregates.

mining process begins with minerals exploration, which in turn encompasses many different activities depending on the stage of exploration, the size of the area being explored and the type of information sought. Finally, mine reclamation activities take place throughout the life cycle of a mine and, once a mine has reached the end of its economic life, in order to deal with disturbed land, mineral waste, and water and other environmental impacts.

2.2   A global context

Over the past decade, the minerals industry has experienced both a dramatic increase in demand for globally traded commodities, as well as a rapid supply response from existing and non-traditional producing countries.

2.2.1   Increasing demand for resources

Over the past ten or so years, industrialisation and urbanisation in China and elsewhere in Asia have significantly increased the global demand for resources, a trend from which Australia and other exporters of bulk commodities have benefited greatly. Over the medium term, most analysts expect strong demand for minerals commodities to continue, driven by rapid and continued growth of economies across Asia (Figure 2-1). While these economies will need to address a number of challenges, including the need to undertake structural reforms, manage inflationary pressures and reduce their current account surpluses, the fundamental drivers for economic growth are strong (Huang and Wang (RBA), 2011). On current expectations, Asian economies will account for 40 per cent of world gross domestic product (GDP) in purchasing power parity (PPP) terms by 2020, and will become not only prominent producers but also major consumers of finished goods.

Figure 2-1. Economic growth projections - real PPP GDP (index 100 = 2000)

REAL PPP GDP
Index 100 = 2000

	Average growth p.a.					
	'00-05	'05-10	'10-15	'15-20	'20-25	'25-30
China	9.6%	11.1%	8.9%	7.6%	6.5%	5.7%
India	6.4%	8.0%	8.5%	8.6%	6.8%	6.0%
Vietnam	7.4%	7.0%	7.2%	6.8%	6.5%	6.0%
Indonesia	4.5%	5.7%	6.7%	5.1%	5.0%	5.0%
Other emerging/ developing countries	4.5%	4.0%	4.5%	4.1%	3.8%	3.7%
Developed	2.1%	1.0%	2.5%	2.2%	2.1%	2.1%
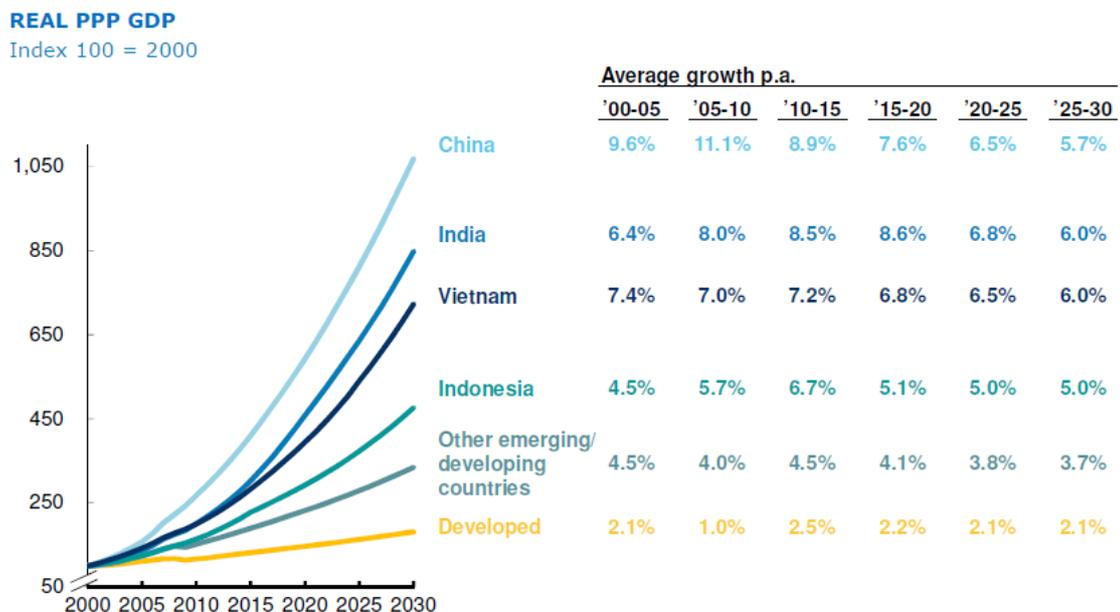
Source: IMF WEO, 2010; World Bank; Global Insight; Oxford Economic Forecasting; US Department of Agriculture Economic Research Service, 2010; PJP analysis

Source: Port Jackson Partners (2011).

The projections for an increasing demand for raw materials, but also for energy and food are driven by the aspirations of developing countries to modernise their economies and raise the standard of living of their populations. As economies develop an industrial base and employment shifts away from subsistence agriculture, populations relocate to urban centres and incomes begin to rise. In these circumstances, a large proportion of growing incomes is spent on better housing, consumer durables such as household appliances and cars, and on the provision by governments of improved urban infrastructure such as roads, railways, water and sewerage, and electricity generation and distribution infrastructure (Eslake 2011). Meeting the demand for better living standards is resource intensive and is expected to translate in turn into increasing demand for energy commodities such as gas, thermal coal, crude oil and uranium; steel making inputs such as iron ore and metallurgical coal; as well as for base metals such as copper, nickel, aluminium and zinc.

Further pressure on the demand for commodities, including for food commodities, is expected to come from rapidly growing populations in some parts of the world. The United Nations (2007) forecasts that the world's population will surpass 9 billion by 2050, an increase from around 7 billion today. Furthermore, while the population of developed countries is expected to remain virtually unchanged, the populations of the 50 least developed countries will likely more than double from 0.8 billion to 1.7 billion by 2050, while growth in the remainder of developing countries, although somewhat slower, is also robust with populations projected to increase from 4.6 billion to 6.2 billion in 2050. Overall, between 2005-2050, just eight countries are expected to account for half of the world's projected population increase, including India and China.

### 2.2.2   Global competition

Given Australia's wealth in mineral resources and its proximity to Asia, growing demand for resources can potentially underpin economic growth in this country for many years to come. Port Jackson Partners (2011) estimate that Australia could achieve a total commodity export revenue growth rate significantly faster than overall GDP for the next two decades. On reasonable estimates, total commodity exports could reach around $480 billion in real terms by 2030 from a base of $210 billion in 2010. If these projections come to pass, commodity exports would increase to more than 20 per cent of GDP.

Forecasts of rapidly growing minerals exports presuppose that Australian production remains competitive in the global marketplace. Today, large consumers, such as Chinese steel mills care less about long-established relationships and supply reliability, and focus increasingly on price and on spot trades. Prices are highly transparent. Non-ferrous metals (copper, tin, aluminium and aluminium alloys, lead, nickel and zinc), minor metals (cobalt, molybdenum) and precious metals (gold, silver) are traded on commodity exchanges. Spot and contract prices for iron ore, coal and uranium are routinely published by industry publications such as Platts, The Tex Report and the McCloskey Group, as are spot freight rates and vessel fixtures.

In the future, the evolution of the Australian mining sector will be shaped in a context where it is necessary to produce at costs that are determined by international competition. Mining businesses competing in global markets must maintain and improve the efficiency of their operations to maintain their competitiveness over time, not just relative to existing other producers but also to emerging producers as new deposits are developed. While Australia and other traditional producers such as Canada, the Russian Federation and the United States hold a significant proportion of world reserves of many important commodities, many other countries also have large reserves of energy and mineral commodities (Figure 2-2). China is

itself a leading producer of aluminium, coal, copper, gold, iron ore and coal, magnesium, manganese, rare earths, tin, tungsten, zinc and many other commodities (USGS 2009).

Figure 2-2. Percentage of world reserves for selected commodities
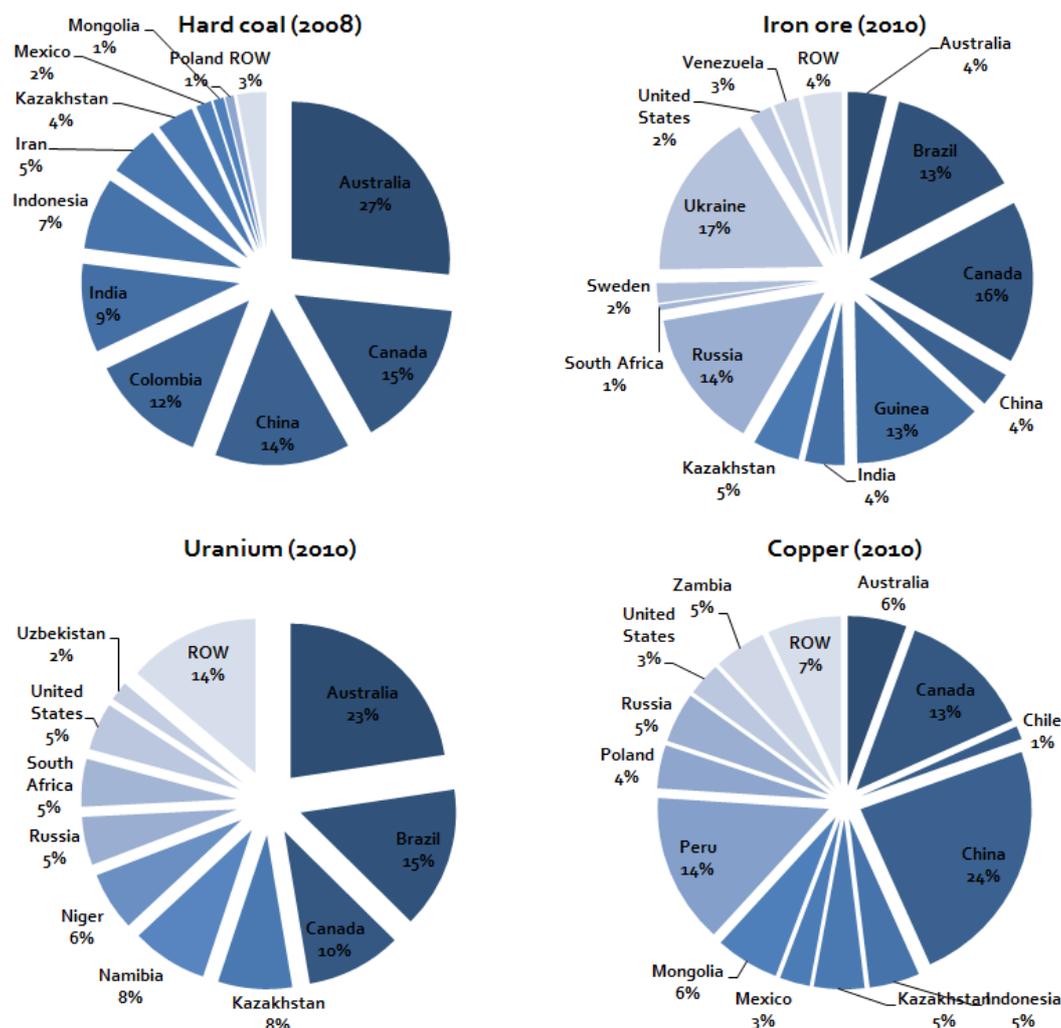
Notes: Uranium reserves refer reserves recoverable at a cost of less than US$ 130/kg Uranium.

Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2011; IAEA, 2011 Red Book; U.S. Energy Information Administration, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=1&pid=7&aid=6 accessed on 7 October 2011.

Outside of Australia a number of significant new mining projects are under development or expanding, many of these in developing countries, to compete for a share of growing demand (Table 2-1). They include:

- for iron ore, the planned expansion of the Carajás Mine in Brazil, which contains the world's largest reserves and concentration of iron ore (as well as manganese, copper, tin and other deposits) and the planned development of the Simandou deposit in Guinea (but also of other deposits in Sierra Leone and Liberia);

- for thermal coal, the expansion of the Cerrejón mine in Colombia, as well as the Ovoot Tolgoi project in Mongolia and the East Kutai project in Indonesia; and

- for coking coal, the Zambeze project in Mozambique and the expansion at Tavan Tolgoi, one of the largest coking coal deposits in the world.

Table 2-1. Significant international mining expansions

Country	Mine	Minerals	Reserves	Status
Brazil	Carajás	Iron ore, copper, nickel, bauxite, alumina	7.2 b tonnes proven and probable (high grade) reserves	$2.5 b expansion underway
Guinea	Simandou	Iron ore	2.25 b tonnes indicated and inferred (Fe>62%)	Development announced
Guinea	Kalia	Iron ore	2.39 b tonnes of inferred JORC magnetite resources	Planned production of 50 Mtpa by 2014
Cameroon / DR Congo	Mbalam	Iron ore	Probable reserves of 251.5 Mt at 63.57% Fe	Development to production of 35 Mtpa over 20 years
Colombia	Carbones del Cerrejón	Thermal coal	740 Mt of proven and probable reserves	Planned expansion from currently 32 Mt to 50 Mt per year
Mongolia	Ovoot Tolgoi	Thermal coal	150 Mt measured and indicated, 29 Mt inferred	Production ramp up from 1 Mt in 2008, rising to 8 Mt by 2012
Indonesia	East Kutai	Thermal coal	961 Mt proven and probable	Planned expansion to 30 Mtpa over 25 years
Mongolia	Tavan Tolgoi	Coking coal	Reserves estimated at 6 b tonnes	Development to 15 Mtpa
Mozambique	Zambeze	Coking coal	9 b tonnes indicated and inferred resources	Development for production scheduled in 2014
Mongolia	Oyy Tolgoi	Copper and gold	Measured and indicated 36.3 b lbs copper, 20.2 million ounces gold	Current expansion to av. annual prod. > 1 b lbs of copper and 330,000oz of gold for at least 35 years
Zambia	Kansanshi	Copper	235.7 Mt measured and indicated resources	Current expansion from 250,000 t per year to 400,000 t per year by 2015

Source: http://www.mining-technology.com; http://www.businessweek.com; http://www.miningaustralia.com.au; accessed on 21 October 2011.

Many of these new projects must overcome significant obstacles before minerals products can be delivered to market, one of the key ones being poorly developed infrastructure. But as global demand for resources has increased, competition for undeveloped resources has also intensified with many large mining businesses now offering to undertake significant

development efforts to gain access to minerals. Governments of developing countries also have strong incentives to attract foreign investment and know-how.

2.3 Other industry trends

Given this broader competitive context, a number of other factors are shaping how modern mines are operated and designed.

2.3.1 More complex ore bodies

There is a general trend that deposits, at least in countries with long-established mining operations, are becoming more difficult to mine over time. This is a reflection of the course of development that ordinarily occurs in mining projects.

In the production of mineral commodities, high-grade minerals or those that can be extracted most cost-effectively are generally extracted first (Sandu and Petchey 2009). Over time, and as mineral reserves closer to the surface are depleted, the remaining deposits tend to be of a lower grade, in more remote locations, deeper in the ground, mixed with more impurities, and other factors that make extraction more difficult and costly:

- as the quality and accessibility of deposits decline, more capital and labour are generally needed to extract them;
- when deposits are deeper, more development work is needed to access and mine the resources; and
- if there are more impurities, greater costs are incurred in extracting and processing the material into a saleable product.

2.3.1.1 Trends in mining yields in Australia

Overall, more 'effort' is needed to produce a unit of output, and there is some evidence to suggest that this effect is occurring in Australia. Geoscience Australia (2008) reports that between 2002-03 and 2006-07 the depth of metres drilled increased by 64 per cent, reflecting the need for companies to drill deeper in their exploration efforts. Based on a detailed analysis of minerals production in Australia since its beginning, Mudd (2009a) reports (Figure 2-3):

- long-term declines in average ore grades processed for copper, gold, lead, zinc, uranium, nickel and silver; and
- dramatic increases in the extent of overburden for coal, copper, gold and uranium since the mid twentieth century and especially since the 1980s.

Figure 2-3: Trends in average ore grades for base and precious metals (Australia)
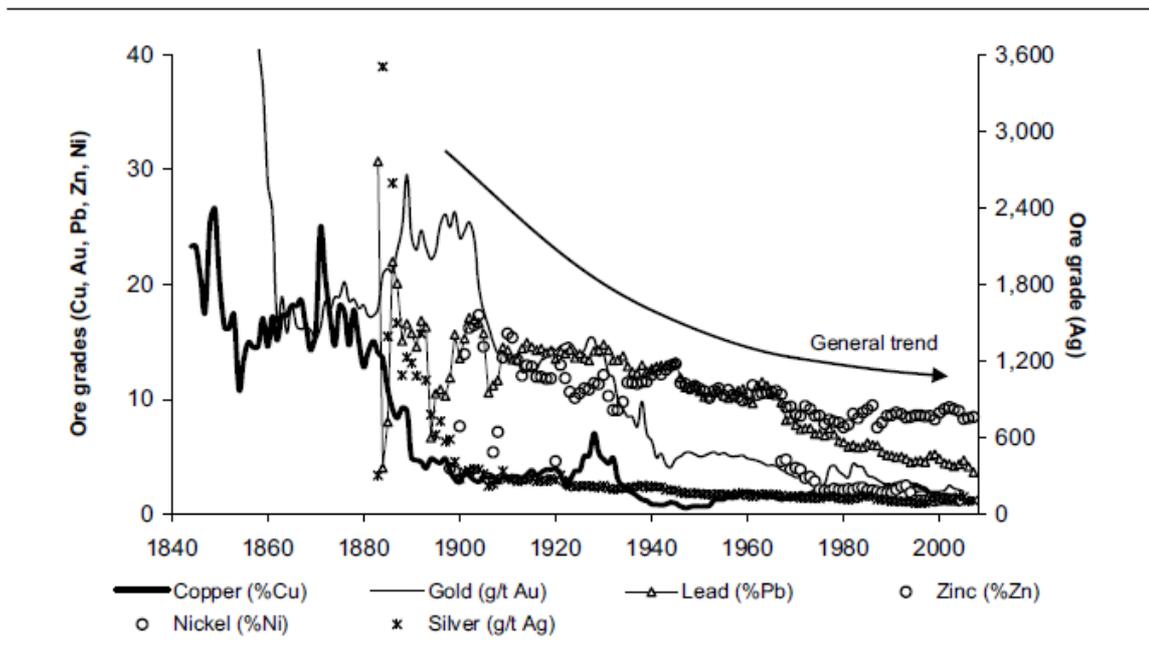
These trends were analysed in some detail in a 2008 analysis of the falling productivity of the Australian mining sector by the Productivity Commission (PC, 2008). The value of Australian minerals output has grown substantially in recent years, but output growth has remained relatively weak. While the mining sector has been characterised by a high level of labour productivity, in terms of output per hour worked, multifactor productivity (MFP) for the sector declined by 24 per cent between 2000-01 and 2006-07.[3] The mining sector makes up around 8.5 per cent of gross value added of the market sector, and the decline in MFP contributed substantially to a slowdown in productivity growth observed for the market sector as a whole.

The PC's analysis showed that the increasing difficulty of mining and processing minerals, as represented by an index of mining 'yield', was a key explanatory factor in the observed decline in MFP between 2000-01 and 2007-08 (Figure 2-4). The index was defined to represent a composite of features that characterise the quality of natural resource inputs used in mining, such as ore grade (metal per tonne of ore), ore quality (impurities, milling characteristics), reservoir pressure (flow rates of crude oil or gas), overburden ratio (waste material to ore or coal production), mine or well depth, distance from markets or key inputs and complexity of terrain/mine geology.

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[3] Multifactor productivity is the ratio of output to a combination of inputs used in the production of that output, such as labour and capital or capital, labour, energy, materials, and intermediate inputs.

Figure 2-4. Index of mining industry yield (1974-75 to 2006-07)
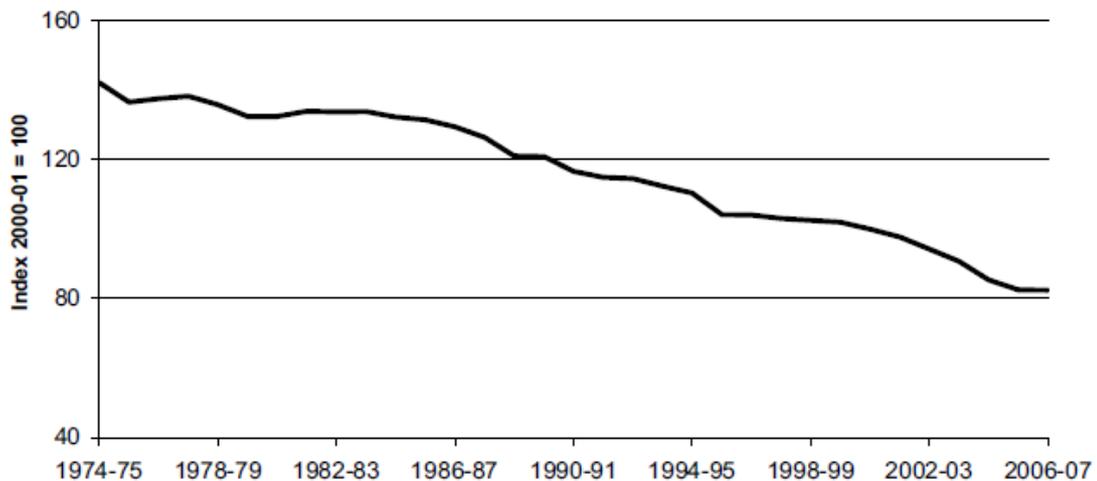
Source: Productivity Commission (2008).

It is clear from Figure 2-4 that the composite index of the average yield in mining has fallen significantly since the mid-1970s. Resource depletion in the form of yield declines is therefore estimated to have had a significant adverse impact on productivity in the mining industry over the past thirty-two years. Once the effect of yield changes is removed, mining MFP grew at an average rate of 2.5 per cent per year, compared with 0.01 per cent per year in conventionally measured mining MFP. The precise causes for the reduction in average yield depend on the mineral in question:

- for coal mining, relevant factors are an increase in the 'strip ratio' (the ratio of the volume of overburden moved to tonnes of saleable coal produced) due to the increased depth of open-cut mines, and greater depths required in underground coal mines; while

- for iron ore mining, the determinants were thought to be an increase in the production of overburden/waste rock per tonne of saleable iron ore and rising levels of impurities.

The most recent industry productivity estimates published by the ABS (2011) suggest that multifactor productivity in the mining sector has continued to decline in recent years. The gross value-added based multifactor productivity index for the sector as a whole declined from around 150 in 2000-01 to 111.5 in 2007-08 (the last year of the Productivity Commission study), to 87.9 in 2010-11. This represents a decline in productivity of more than 40 per cent over ten years.

Similar results have been reported for Canada where falling MFP productivity growth in the mining, oil and gas sector has also been attributed to lower resource yields, among other things (Arsenault and Sharpe 2008) and in the United States (Höök and Aleklett, 2009).

2.3.1.2   International trends

Declining ore yields have been reported in other established mining countries. Mudd (2009b) identified long-term declines in ore grade for mined copper in Canada and the United States. In the United States, mining has depleted the best coal seams, with coal reserves, for

instance in the Appalachian basin located in thinner, deeper coal beds than those currently being mined and a declining energy content of extracted coal (Höök and Aleklett, 2009). There is anecdotal evidence that exploration for many minerals is increasingly targeting zones for new deposits that are deeper than existing mines. Giurco et al. (2009) point to an increasing depth trend in copper, nickel and platinum metals mines, as well as in gold mines in South Africa and Canada, and for lead, zinc and silver in Australia. In solution mining, similar trends can be observed in the increasing depth of oil and gas fields for instance, the recent Tiber discovery in the Gulf of Mexico in 1,260 m of water depth with a further 9,430 m underground to the oil field.

These trends have significant implications for the mining industry. Quite apart from the technical and cost challenges of accessing deposits in more difficult ore bodies, they also raise new health and safety issues (Abrahamsson et al. 2009). Deeper underground mines increase the risks of overburden pressure with subsequent rock stability problems and risks for structural collapses. More generally, difficult to access orebodies in established mining locations reduce the attractiveness of countries such as Australia as a location for future mining investment. Bellamy and Pravica (2011) cite evidence that at the height of the recent mining boom, resource companies saw Australia as a mature mining region, as evidenced by a fall in capital investment in the gold and metals sector in West Australia in 2008. There was a notable trend to direct more investment to other regions where better mineral deposits were available, and labour costs, taxes and administration expenses were lower.

2.3.1.3   Example: Copper

Copper is a mineral that serves to illustrate all of the trends described above. Copper is an essential input in both building and construction (wiring and plumbing, heating and cooling, telecommunications), as well in the manufacture of cars and trucks (engines, wiring, radiators, brakes and bearings). The demand for copper is projected to rise substantially with increasing industrialisation and urbanisation, from around 20 million tonnes per annum (mtpa) today to approaching double that figure in 2030 (Figure 2-5).

Figure 2-5. World primary copper demand
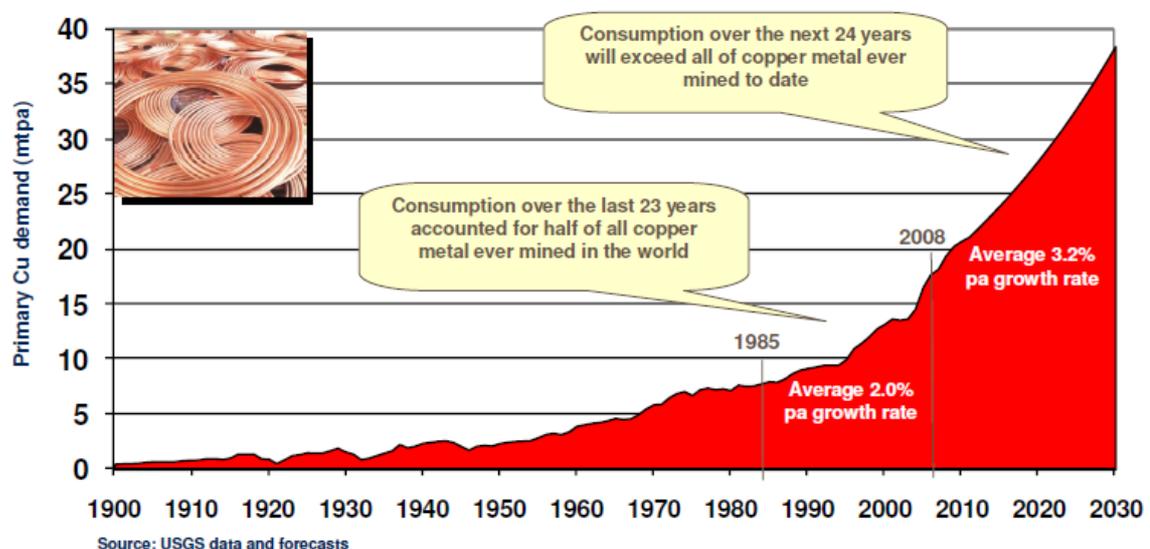
Source: McGagh (Rio Tinto), 2010.

Increased demand pressures have resulted in an intensified exploration effort for copper. This is reflected in rising global estimates of copper reserves, as reserve estimates are updated (

Figure 2-6). However, while reserve estimates overall have grown, the quality and accessibility of reserves declined:

- copper ore grades have declined, particularly in recent years (Figure 2-7); and
- the depths at which new copper discoveries are located and need to be mined have tended to become larger (Figure 2-9).

Figure 2-6. World copper reserves: 1900-2010
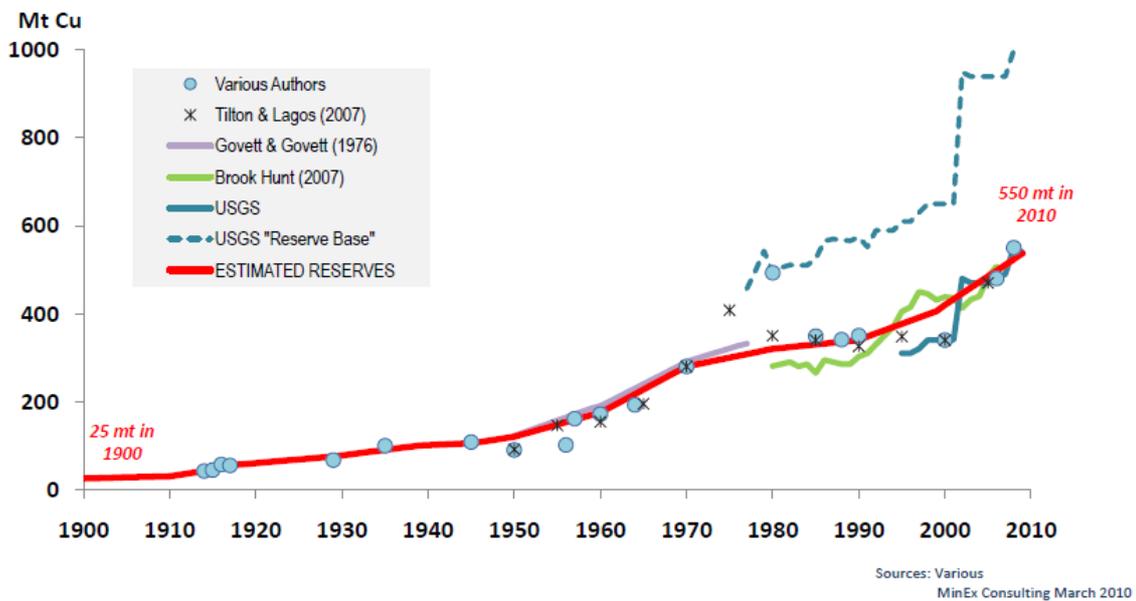
Source: Schodde (MinEx Consulting), 2010.

Figure 2-7. Average feed grades of copper
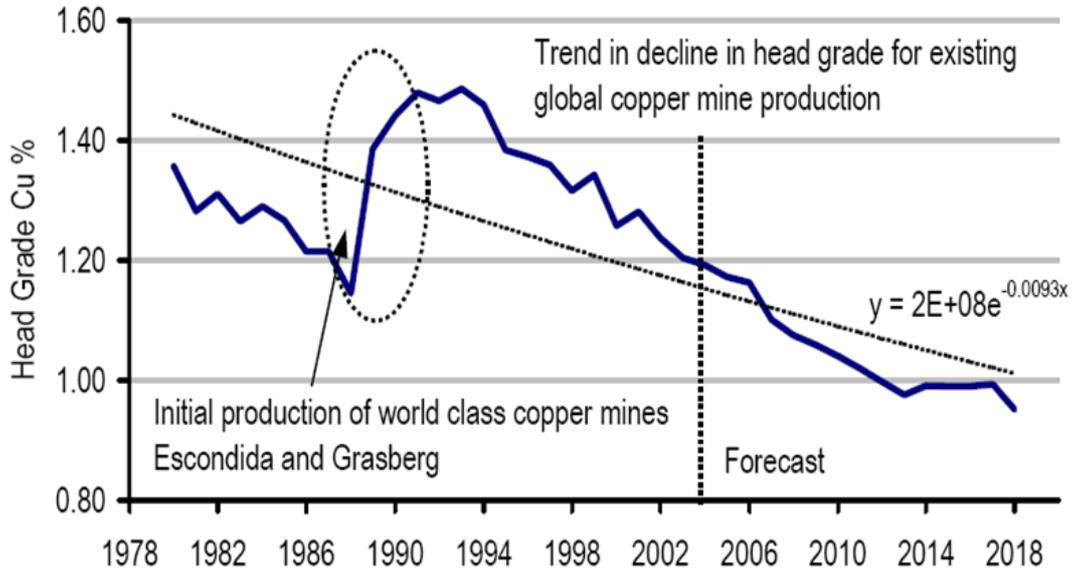
Source: Goodes (Rio Tinto), 2010, citing Brooke Hunt, 2010.

Figure 2-8. Copper discoveries showing depth of deposits with greater than 4 Mt contained copper
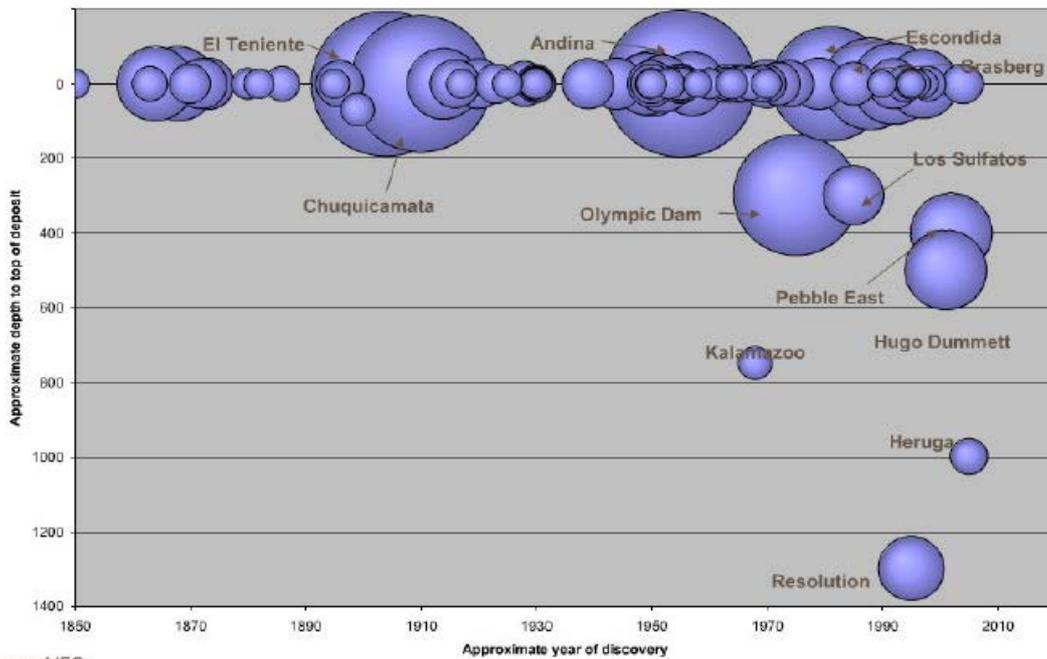
Source: McGagh (Rio Tinto), 2010.

Overall, and while new copper discoveries have kept pace with rising demand, there appears to be a clear trade-off between the volume of copper resources discovered and the grades of

these resources (Figure 2-9). Schodde (2010) estimates that most of the growth in known copper resources over the past 70 years can be attributed to a reduction in cut-off grades.

Figure 2-9. Copper grades versus size of resource (grade data for 48 copper deposits)
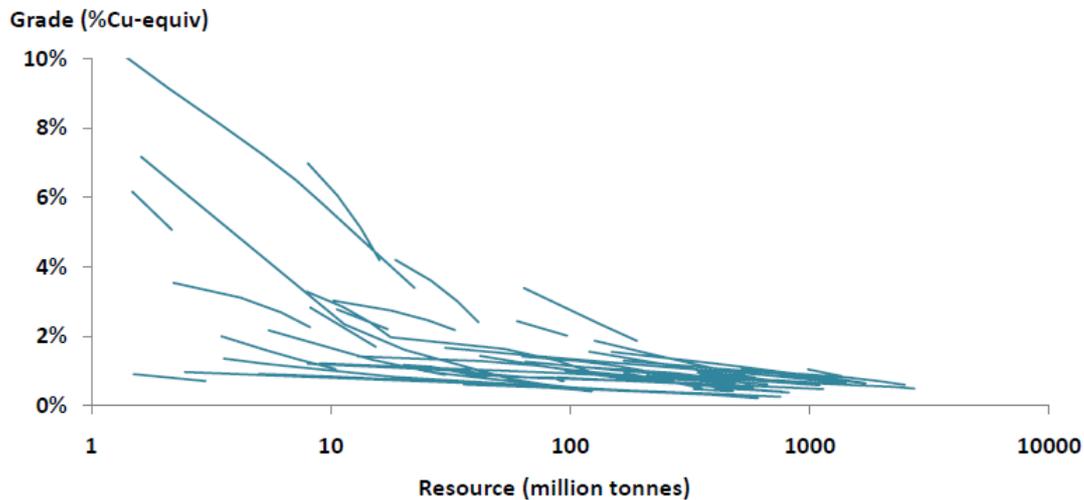
Source: MinEx Consulting March 2010

Source: Schodde (MinEx Consulting), 2010.

Irrespective of the growing demand for copper and declining quality of deposits, copper prices have declined significantly in real terms. While copper prices (like those of many other commodities) exhibit significant volatility, Schodde (2010) estimates that in real terms, the delivered price of copper (including mining, transportation, smelting and refining, as well as marketing costs) has roughly halved between 1900 and 2010. This is a reflection of two factors:

- intense competition to find and develop new resources around the globe; and
- an ongoing process of technical innovation and search for scale economies that have significantly reduced the operating and associated processing costs of mines (Figure 2-10).

Figure 2-10. Key technical innovations and implications for average operating costs for copper mines

Source: Schodde (MinEx Consulting), 2010.

2.3.2   Health and safety issues

While there has been a process of continuous innovation and modernisation in the industry, mining fundamentally takes place in a harsh and often hostile environment. Miners work in conditions that are dirty, noisy, sometimes in confined spaces and often in remote locations. All aspects of mining and related activities that take place around mining processes are hazardous (NRC 2002):

- In open pit mines, rock falls and slope failures can create significant hazards. Large surface mines are effectively giant industrial sites in which humans interact with very large and moving equipment. Hazards to humans arise from:
    - limited visibility/blind spots of personnel from the vantage of very large haulage vehicles;
    - irregular road designs, blind intersections and obstructions;
    - factors such as fatigue, boredom and complacency; and/or
    - speed of moving equipment.

- Dangers encountered in underground mines include massive failures of pillars, severe coal and rock bursts and roof and side falls, as well as explosions and fires. Additionally, large and moving industrial equipment in confined spaces are a significant hazard in underground mines.

- Across all mining activities, hazards are posed by gases, dusts, chemicals and noise in the work environment, as well from working in extreme temperatures.[4] As

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[4] Silicosis, pneumoconiosis (black lung disease), occupational hearing loss, and other medical problems have long been associated with mining operations.

processing technologies move toward finer and finer particle sizes, the health effects on workers of these particles (but also resulting environmental concerns) are becoming increasingly important. Additional health hazards arise from chemicals used in mining or in the processing of ores.

Figure 2-11 shows a breakdown of fatalities in the Australian mining sector between 2000 and 2008 based on data collected by the New South Wales Department of Primary Industries (NSW DPI, 2008).

Figure 2-11. Fatalities in the Australian mining sector (2000 to 2008)
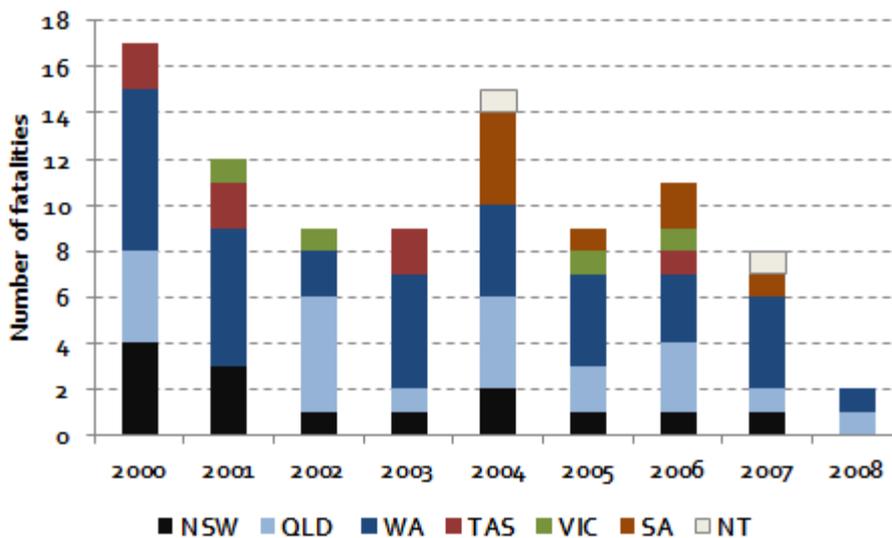
Source: NSW Department of Primary Industries 2008 data.

Since 2000, the great majority of mining fatalities have occurred in New South Wales, Queensland and West Australia. Most coal mining fatalities have occurred in New South Wales and Queensland; fatalities in other mining sectors have predominantly occurred in West Australia. Many more incidents (around 80 per cent) occurred in open-cut, non-coal mines than in underground mines. While many fatalities happened in the actual mining area, they also occurred in processing plant, workshops, on roads and roadways, and in yards. Most fatalities occurred during the operation of trucks and load-haul-dump vehicles (LHDs),[5] with the leading identified causes of deaths being the unintended operation of equipment, contact with moving or rotating plant, drowning, falls from heights and tyre explosions.

Figure 2-12 shows a comparison of mining fatalities in Australia, Canada and the United States for open cut (o/c) and underground (u/g) mines. Internationally, a comparison of mining accidents in the developed world shows that the main causes of deaths were roof, side or highwall collapses, the unintended operation of equipment, contact with moving/rotating

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[5] LHDs commonly used in underground mines for the loading and transportation of ore and minerals. These machines weigh 20 to 75 tonnes and they run on electrical or diesel power at a speed of about 20-30 km/h. LHDs consist of two parts connected by an articulation point to give the machine a high level of manoeuvrability in narrow tunnels.

plant, falls from heights and gas explosions (NSW DPI, 2008). As is the case in Australia, the key sources of equipment danger originates from trucks, LHDs and continuous miners. The number of deaths reported in developed countries pale in comparison with those reported in China. It is estimated that between 2000 and 2009, more than 51,000 miners died in coal mining accidents alone (Wei 2011).

Figure 2-12. Comparison of fatalities in Australia, Canada and the United States (2000 to 2007)
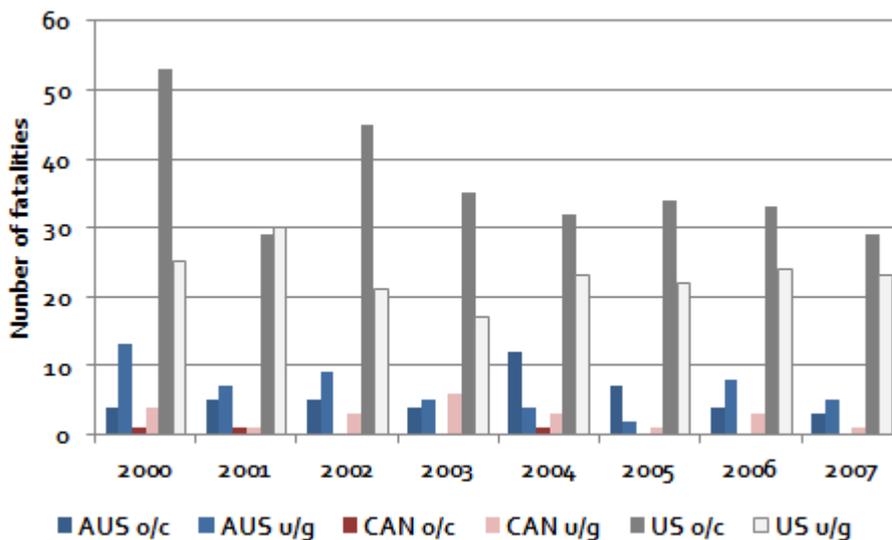
Source: NSW Department of Primary Industries 2008.

2.3.3   Shortages of skilled workers

The recent resources boom has created a shortage of skilled workers in mining industries around the world (Johansson et al. 2010). Modern mines are technically advanced, but are also often located in remote and unattractive locations. The ability to recruit highly skilled workers therefore represents a real challenge to miners' efforts to expand production. Large mining companies operate and compete globally, and must also attract the staff that can operate in several countries. One of the key means of attracting skilled staff, including women, is therefore to increase the attractiveness of working in the mining industry.

Existing and projected skills shortages affecting the Australian mining sector have similarly been identified in a number of different studies. Lowry et al. (2006) considered the labour needs by the mineral resources sector across occupational groups between 2006 to 2015, and compared these with the capacity of the economy to meet this demand. As of 2005, around 73 per cent of employees in the sector were semi-skilled workers and tradespersons. A comparison of future labour requirements based on output projections for eight major commodities (coal, iron ore, gold, bauxite, copper, nickel, zinc, lead and uranium) with supply projections (reflecting factors such as demographic and labour force participation trends) highlighted:

- significantly increased demand for labour in the resources sector leading up to 2015 with annual growth rates in the range of 4 to 5 per cent;

- declining growth rates in numbers in key occupations from around 2 per cent in 2005 and approaching 1 per cent by 2015 (including growth in semi-skilled workers close to zero); and therefore
- a widening gap between the projected demand and supply for labour in the mineral sector.

By 2015, this gap was projected at around 70,000 workers, with the largest shortages projected in the non-professional occupations such as tradespersons (around 27,000) and semi-skilled workers (around 22,000). The most affected sectors are copper, nickel, bauxite and potentially uranium mining; and the greatest shortages are projected in Western Australia (42,000) and Queensland (15,000). Overall, labour shortages were expected to be a major constraint on the growth of the mineral sector over the next decade, emphasising a need to:

- put in place appropriate training systems for semi-skilled workers, in particular for on-the-job training;
- target new labour reservoirs, including from the manufacturing sector, from immigration, and in particular by attracting women into the mining workforce.

More recent labour demand projections suggest that the demand-supply gap has widened (Molloy and Tan, 2008). That study considered labour requirements by the coal, bauxite/alumina, copper, gold, iron ore, lead, zinc, nickel and uranium sectors,[6] and concluded that the mining sector will need to employ 86,000 additional workers between 2008 and 2020. The largest projected increases in demand were expected to occur:

- on a regional basis, by a significant margin, in Western Australia (around 48,000);
- by mineral commodity, for iron ore (around 48,000); and
- by occupation, for tradespersons and semi-skilled worker (around 61,400 in total).

Molloy and Tan (2008) conclude that two approaches to achieving productivity improvement should be pursued by the minerals industry:

- emphasising labour saving technology as mine investment is undertaken, to minimise both ongoing labour costs as well as the risk of disruptions to operations because of the scarcity of labour; and
- further focusing on already high levels of training and upskilling of new employees from outside the mining industry.

The most recent study undertaken considered the skills needs of major new energy (in particular natural gas), mining and minerals processing projects announced in recent years (Australian Government, 2010). That study identified a projected shortfall of tradespeople (required for construction, mining operations and gas operations) of 35,800 by 2015.

2.3.4   The environment and possible carbon constraints

The potentially adverse environmental impacts of many types of mining operations are well known and have led to significant changes in how the industry operates and is regulated. Depending on the type of mineral extracted and the size of the mine, mining often involves

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[6] The study did not consider the possible commissioning of BHPB's Olympic Dam project, however.

the production of large quantities of waste. These impacts are often more pronounced for open-pit than for underground mines, and can potentially degrade aquatic ecosystems and water bodies as a result of sedimentation, acid drainage and metals deposition. Metals production processes, for instance, result in a range of emissions during mining and processing, and indirectly via the consumption of raw materials and utilities (Norgate et al. 2007). The beneficiation and chemical transformation of ores to extract metals and produce industrial materials requires significant amounts of energy, as well as reagents, water and fuel. Many factors influence the environmental impacts of such processes, including ore grade, electricity energy source, fuel type, material transport, as well as process technology. Mining operations may more broadly affect biodiversity, as well as plant and animal habitats, most obviously when vegetation and surface soil is removed.

In recent years, given significant public concern over the environmental impacts of mining, governments as well as the mining industry itself have made significant efforts to move toward a more sustainable approach (Azapagic 2003). Relevant initiatives at an industry level include the Global Mining Initiative, the US-based Sustainable Minerals Roundtable, the Canadian Minerals and Metals initiative and the work of the European Industrial Minerals Association. In Australia, sustainability reporting has become the norm for large mining businesses, but individual corporate initiatives also play an important role. Examples include:

- the Rio Tinto Foundation set up with $35 million in funding to support research and technical development into sustainable solutions for environmental challenges for the mining industry (CSIRO, 2005);

- new technology initiatives aimed at waste minimisation, pollution prevention and cleaner production processes instituted by companies such as Newmont Australia, Alcoa and Tiwest (van Berkel 2007); and.

- the Woodside Energy Limited sponsorship of the study by the Australian Institute of Marine Science (AIMS, 2009) of ecosystem processes on the Scott Reef in the Indian Ocean.

Significant challenges to the mining industry arise as a result of growing pressures on countries and businesses to reduce carbon emissions. Mineral resource extraction and processing are energy intensive and a significant source of greenhouse gas emissions. These vary greatly by type of mineral and even on a mine by mine basis, for instance:

- for LNG production, it is estimated that stationary energy and fugitive emissions amount to between 0.32 and 0.63 tonne of CO_2 per tonne of LNG (Grattan Institute, 2010);

- in coal mining, fugitive emissions from methane trapped within coal seams are estimated to amount to between close to zero to 0.7 t CO_2-e per tonne of coal (Commonwealth of Australia, 2008);

- copper ore processing is estimated to produce around 0.63 tonnes of CO_2 per tonne of concentrate, most of which occurs during the crushing and grinding processes to process ore into concentrate (CSIRO 2011); while

- the production of bauxite and iron ore is estimated to produce around 4.9 kg of CO_2 per tonne and 11.9 kg CO_2 per tonne, respectively, about half of which occurs in the course of the loading and hauling operations that are necessary to transport ores from deposits to mineral processing facilities.

The imperative is therefore to improve on the energy efficiency of mining and associated processes. This task is all the more pressing because of falling ore grades and the need to access deeper deposits. These trends will require increasing volumes of material to be handled in more difficult environments to produce the same quantity of mineral.

Another environmental challenge facing the mining industry is the requirement for water. CSIRO (2011) estimates that the Australian mining industry's use of water increased by around 29 per cent between 2000–01 and 2004–05. In future, the resulting challenges for the mining industry are likely to increase, reflecting expanding hydrometallurgical operations, declining ore grades, escalating production pressures and water scarcity.

3 Innovation and autonomous technologies in the mining industry

Given rising demand, competitive pressures and a range of other challenges facing the industry, mining companies have increasingly focused on a process of ongoing innovation and the deployment of new technologies. A number of large mining businesses around the world are known to be investing in and trialling automated technologies, although much of this effort remains commercial-in-confidence and is therefore not in the public domain. Rio Tinto has adopted the most high profile strategy geared toward increased mine automation, and many of the innovations described below are based on reports about or by that company.

3.1 Historical innovation trends in the mining industry

The process of introducing new technologies and innovations in underground and surface mining, as well as in associated processes for treating the raw product, such as in milling, separation and refining has a long history. The mining industry has evolved from a labour intensive to a highly mechanised one (Peterson et al. 2001, Bellamy et al. 2011). Mining was largely a manual production process until the middle of the 20th century when mechanised production became increasingly important.

In underground mining, unmanned mining rail carriages were first deployed in the 1960s, followed by automated drills, and remote controlled underground ore cutting machines in the 1970s. The most recent innovations relate to the remote operation of underground LHDs that use scanning lasers to see tunnel walls and can navigate autonomously from ore face to a haul truck (Bellamy et al. 2011), as well as automated shotcreting and rockbolting devices.

In surface mining, an increased capacity of machinery dramatically reduced the 'cycle time' required for the equipment to perform its assigned task, such as with the use of bucketwheel excavators in large open pit coal mines, and advances in rubber technology that allowed for longer and moulded belts (Craig 1992). Significant increases in productivity were achieved as a result of increasing truck sizes from a 25 tonne payload to some 400 tonnes today (along with dramatically improved energy efficiency) and the use of safer and cheaper explosives (Giurco et al. 2009). The slower uptake of new technologies in surface mining may reflect the complexity of open-pit environments and the associated technological hurdles in implementing effective automation (Bellamy et al., 2011). Innovation is harder for a variety of reasons, including the fact that many more vehicles and other objects share the same work space, that these operate at higher speeds, and that open pits are subject to changing environmental and weather conditions.

3.2 Recent innovation trends

Mining innovation today is driven by the need to find and access new resources to meet rapidly growing demand, often in complex and difficult to mine environments. The effort ranges from incremental improvements in existing technologies and processes aimed at gradually improving the efficiency of operations, to significant innovation that deliver a step change in productivity, to the development of entirely new approaches focusing on large-scale automation of mining and other processes.

3.2.1 Incremental innovations

Although the distinction is not necessarily clear-cut, incremental innovation delivers gradual improvements in the efficiency, safety or other aspects of mining processes, but imply only limited changes to business-as-usual operations. These types of innovations may imply some technological advances developed over a medium-term timeframe and at relatively modest development cost. Research and development (R&D) and implementation risks therefore tend to be moderate to medium. Some recent examples of these types of innovations are summarised in Table 3-1 and described in more detail below. These innovations deliver a range of benefits, including enhanced employee health and safety, technical efficiencies that make better use of equipment and cut down on materials and energy use, and improved environmental outcomes.

3.2.1.1 'Asset Health' system

Systems that monitor the real-time performance of valuable equipment have been in operation at three of Rio Tinto's mines since 2008. The MineCare® 'Asset Health' system deployed by Rio Tinto is a supporting function designed to optimise the life cycle of equipment by monitoring performance in real time. Data generated on board the equipment is streamed wirelessly to evaluators based at the company's Operations Centre (OC) in Perth, who analyse and take steps to maximise the operational effectiveness of individual pieces of equipment. In this way, 87 heavy mobile equipment assets are continuously monitored. Rio Tinto estimates that, during the first three months of 2010, Asset Health delivered maintenance cost savings of more than $1 million. The system additionally:

- improved equipment availability;
- reduced unplanned maintenance by avoiding component failures;
- improved maintenance planning; and
- extended the life of equipment components.

3.2.1.2 Miner Assist Technical Equipment (MATE™)

Rio Tinto's operations in the Pilbara are geographically isolated. In the event of significant breakdowns or equipment failures, Rio Tinto has traditionally had to rely on flying experts to the site with associated production delays, safety risks and cost overruns (Rio Tinto, n.d.). The Miner Assist Technical Equipment (MATE™) pack comprises a headset, microphone, camera, video display and microcomputer, as a means of instantly transmitting information to staff at the OC. Personnel at the mine site can communicate with central support teams via two-way video, voice and data communications. Successful trials of this technology at two mine sites have demonstrated the system is an effective support tool in a variety of scenarios.

Table 3-1. Selected recent mining industry innovations

Innovation	Description	Purpose	Outcomes
Underground mining			
Improved rock bolts	New rock bolt design to absorb energy and control rock mass deformation while providing containment of materials	Human safety	Improved control of rock failures, collapses of stopes and drifts
			Reduced risk of rock bursts at increased mining depths and mining scales
Collision avoidance system	Personnel and vehicle tags communicate wirelessly with moving vehicles Driver alert and vehicle unit display of number of people and other vehicles in proximity	Human safety	Vehicle operators are alerted to the presence of personnel or other vehicles in the vicinity
Trapped miner location system/ paging system	Very Low Frequency (VLF) signal can penetrate through earth over large distances	Human safety	Reliable means of quickly locating trapped miners
			Reliable means of transmitting alert, warning and evacuation messages
Intelligent drill rigs	Intelligent drill rigs: - drill according to drill and bolt plan design - ongoing measurement and reporting on tunnel profile - remote access to program new drill plans - ongoing monitoring of status of drill rigs and remote diagnostics	Process/efficiency improvements	Improved/more precise tunnel drilling
			More rapid response/navigation of drill
			Eliminates the need for surveyors
			Enables remote evaluation of drill profile
Extra low profile (XLP) mining equipment	Track mounted XLP dozer, bolter and drill rig capable of operating in a 'narrow reef' (<1.2 m height) and undulating mining environment	Improved access/efficiency improvement	Reduced waste rock/increased useful excavation
			More accurate drilling and higher face advance
Surface mining			
Collision avoidance	Various technologies, including:	Human safety	Reduced risk of vehicle collisions

Innovation	Description	Purpose	Outcomes
systems	- blind spot elimination via video cameras - sensing technologies (infrared, ultra-sound, radio frequency tagging (RFID),radar) - visual and audible alarms - identification of objects through vehicle IDs - two-way alarming for both the primary vehicle and the vehicle at risk - audit trail data logging	Protection of mining equipment	Third party monitoring enabled
Electric rope shovel enhancements	Replacement of mechanical (rope) crowd with hydraulic crowd: - enhanced shock absorption - fewer misalignment issues - less mechanical stress	Improved machine availability/utilisation Improved safety of mine maintenance personnel	Reduction in planned and unplanned maintenance/outages Reduced wear and tear on machine and boom Real-time diagnostic and troubleshooting information
Universal Dig & Dump System	Computer assisted and more flexible drag lines for use in surface coal mining	Operational efficiency	13-21 per cent productivity improvement
Pulsed water jet technology	3.4mm diameter water jet able to split blocks of very strong rock in a few seconds	Rock breaking process improvements	Improved energy efficiency, reduced use of explosives and less collateral damage to surrounding rock
Mobile equipment interfacing	Sensors used to measure real-time equipment health and performance in real time, including: - engine degradation - truck hydraulics and payload - tyre pressure and temperature - braking patterns - oil and fuel analysis - road conditions and road events - driver handling events	Equipment utilisation and life Efficiency of operations Operator safety	Immediate identification of safety issues Diagnosis of equipment degradation Warning of imminent catastrophic failure Real time planning and ordering of parts Improved fuel efficiency and equipment performance

Innovation	Description	Purpose	Outcomes
Fleet and operator optimisation tools	Sensors provide real time vehicle fleet information on: - vehicle productivity - cycle time performance - fault patterns and frequency of fault events - troubleshooting	Efficiency of vehicle fleet operations	Productivity and fault diagnostics Rapid diagnosis of complex problems Reduced unplanned downtime Reduced operations and maintenance costs
Drilling technologies	Drill design to eliminate bending in the drilling process	Drilling improvements for subsequent optimisation of load, haulage and crushing operations	Controlled blast event/minimised use of explosives Uniformity of cut surface for stability Controlled rock fragmentation (eliminate oversize, maximised fragmentation) Overall 17-31 per cent reduction in net cost per tonne
Tyre pressure monitoring systems	Standard monitors installed in cabs to provide real time and remote tyre pressure monitoring readings and alerts	Improved equipment utilisation Cost reductions Operator safety	Increased fuel efficiency Extended tread life Decreased maintenance costs Reduced downtime Enhanced operator safety Enhanced vehicle handing, stability and braking

Source: Advanced Mining Technologies Mining Magazine Congress 2009: Capehart, John, 2009, "Collision Avoidance System Technology for Surface Mine Operations"; Haws, Ruth, 2009, "Electric Rope Shovel Productivity Enhancements"; Lopez, Jennifer, 2009, "Modular MineCare® System, Mobile Equipment Interfacing"; Hicks, Bob, 2009, "Remote Health Monitoring"; Wu, Rocky, 2009, "Development of Yield-Lok® Yielding Rock Bolts"; Hissem, William, D., "Improving Hole Straightness/Quality and the Impact on Mining Operations"; Farjow, Wisam, 2009, "Technological Advancements for Safety In Confined Spaces". Advanced Mining Technologies Mining Magazine Congress 2010: Lourel, Ivy, "Truckless MiningTechnology – Delivery for Outcomes"; Topalovic, Stevan, "Advanced Technologies in Underground Mining". Harrison, G.A, 2008, "Anglo Platinum extra low profile (XLP) mechanized equipment implementation—an update"; Third International Platinum Conference 'Platinum in Transformation'. Bigby, David, Keith MacAndrew, Ken Hurt, 2010, "Innovations in mine roadway stability monitoring using dual height and remote reading electronic telltales", Underground Coal Operators' Conference 2010. CRCMining (2010). Mining & Technology Australia (2010).

3.2.1.3   Water and environmental process improvements

The range of innovations encompasses all aspects of mining and associated processes, and for a range of purposes. CSIRO is in the process of developing a number of innovations to address more stringent environmental and related constraints applying to mining and processing operations (CSIRO, 2011). These initiatives include:

- Methods for using saline water in minerals processes such as crushing, grinding, flotation, as well as magnetic and gravity separation. The research is concentrated on using seawater and saline underground water without pre-treatment, and recycling available water as much as possible. Initial trials at a South Australian copper concentrate-producing company found that bore water and associated energy consumption could be reduced by 260 tonnes per hour through recycling saline water from processing.

- New capabilities for more effectively separating solids and liquids to improve the storage and disposal of tailings, in collaboration with R&D company AMIRA International. Applied at AngloGold Ashanti's Sunrise Dam Gold Mine, improved water use efficiency and reduced cyanide levels in tailings storage facilities were estimated to have saved over $100,000 a year in operating costs.

- New fluid injection technologies to reduce water and energy use in minerals processing by improving the transport of concentrated tailings suspensions. The thicker the slurry, the more likely it is to require energy intensive high-pressure pumps. CSIRO's technology introduces lubricating fluid to reduce the friction between the flowing slurry and the pipe wall, allowing the amount of process water to be reduced. Other potential uses for the fluid injection device include providing an anticorrosive film along the inside of a pipe wall.

3.2.2   Step-change innovations

Other innovations involve a step change in R&D effort to develop complex solutions in order to overcome significant technical challenges. Step-change innovation generally implies a significant departure from business-as-usual processes. Such innovation takes place over far longer time horizons and requires a very substantial upfront investment with an uncertain outcome. Innovations of this type go through a number of stages:

- from an initial idea to the 'proof of concept' stage, to demonstrate the potential feasibility of the project;

- to the pilot project stage for an initial limited roll-out of a system as an initial test;

- to the demonstration stage where an innovation is trialled at a commercially significant scale; and

- through to the full-scale roll-out and commercialisation of a technology where it becomes an integrated part of a wider process.

Innovations that are unsuccessful at any point in the trial chain will be discarded, and typically very few succeed to the commercialisation stage. Step-change innovations rely on significant technological advances and are therefore high-risk, both in terms of the financial investment they require and the fundamental uncertainty that remains about the success of the technology.

3.2.2.1 Airborne exploration technologies

An example of a step-change innovation that will be applied in an exploration context is the development of the VK1 system, developed by Rio Tinto in collaboration with the University of West Australia (McGagh, 2010). This is a highly sensitive airborne gravity measurement system to detect subtle density differences in the earth's crust, and thereby identify the potential location of mineral resources.

3.2.2.2 Minerals processing

Rio Tinto has expended significant research effort on developing new ways of improving the amount of minerals that can be recovered in the course of ore processes (McGagh, 2011). A number of separate processes have been developed under the 'Excite Detect Separate (eXDS™) platform :

- IronX™ is a process for upgrading marginal iron ore or waste material while at the same time reducing energy consumption; and

- Copper-NuWave® similarly upgrades marginal copper ore or waste material at reduced energy requirements.

All eXDS™ platforms share a common capability of enabling the upgrade of marginal quality ores, including the ability to reclaim ore from current waste piles, and the upgrade of current ore feeds to produce a better product. They also have in common a reduced energy requirement and therefore improved process efficiencies.

3.3 Automation

Most innovations developed over the past century were reliant on guidance by a human operator, but this is rapidly changing with the development of remotely operated and autonomous mining equipment. Today, automation is widely seen as a major step change that must be achieved by the mining industry in order to meet the many and various challenges described above. These technologies represent a broad class of innovations that involve a step-change in the R&D effort and are likely to profoundly change how minerals are mined and processed in the future.

Automation can be broadly defined as the intelligent management of a system using appropriate technology so that its operation can occur without direct human involvement (Lynas et al. 2011). Remote or teleoperation technologies such as LHDs allow humans to communicate with and control machinery remotely and are increasingly used in underground mine sites, and in toxic and other hazardous environments.[7] Such machines are semi-autonomous rather than fully automated in the sense that they cannot handle all exceptions that are presented to the machine where humans must step in. These machines remove humans from hazardous areas, but also increase productivity as mining equipment moves faster and covers longer distances, and requires fewer operators to control machines.

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[7] Teleoperation uses a combination of radio communication, TV cables and fibre optics, and guidance systems based on optical systems or lasers (DeGaspari 2003). First attempts at teleoperation in the mid-1990s, using a standard television signal, were plagued by poor image quality and the need to remain in close proximity to vehicles. By the end of the decade, dedicated communication lines for television and data improved communication between the vehicles and control rooms. Today, digital communications are the norm.

Until recently, progress in automation in the mining industry was piecemeal and focused on technologies to improve the 'manned mining system' (Noort and McCarthy 2008). Automated production drills have been available since the mid-1980s. Automated LHDs are now commercially available, although automation of the dig cycle is problematic in anything but very well broken rock.[8] Automated trucks have operated reliably at the Finsch mine in South Africa for some time. Longwall coal mines have achieved partial automation of a relatively repetitive (continuous) mining system by automating one easily defined machine operation or task while the rest of the operations remained manual. In Australia, equipment suppliers such as Komatsu initially began to develop surface automation technology, but early attempts to introduce the technology were not taken up.

Up until now most automation effort is concentrated on the component or subsystem level, and at a relatively small scale relative to the number of mines, processing plants and export facilities in Australia. Innovations in mining automation include automated surface haul trucks, automated underground LHDs, and autonomous blast-hole drilling equipment. In some cases, only automated components have been developed, for example, automatic swing controls for drag-lines, heading controls for coal shearers, or proximity warning and safety systems for trucks.

The focus today has shifted to building the 'autonomous mining system' that can carry out tasks automatically or with a minimum of external control (Lynas et al. 2011). Under full automation, a machine controls all aspects of its functions, including monitoring and correcting for defects. CSIRO quote Rio Tinto's Head of Innovation John McGagh to highlight the advances that can be achieved from increased mine automation (CSIRO 2009c, p.3):

> *Automation increases the level of control in what is inherently a chaotic process. It gains control by applying more stringent rules to decision-making processes, and removing the randomness inherent in isolated decision making. It is about applying a controlled process to variable mine geology and ever-changing topography.*

> *Automation allows for the management of disparate information flows in new ways to deliver unified end-to-end interlinked processes. Mining processes have traditionally been viewed as being standalone but much theoretical work has been done on how the processes should interact. Also, removing human intervention and running end-to-end with machine control allows for unparalleled levels of efficiency and repeatability: true process quality.*

The ultimate goal in automation is robotics – machines that sense and reason about their environment (Durrant-Whyte, 2010; Lynas et al. 2011). Automating mining processes remains a formidable task, however. While robots used in other industrial processes generally remain stationary and perform tasks on products or components conveyed to them, mining robots must move around, often in complex underground or surface environments. Automated technologies are therefore only made possible by increased computing power; new algorithms for signal processing, perception and control; and new sensing technology for monitoring mine geometry, including GPS, radar and laser systems. The requirements to develop and operate these technologies are correspondingly complex and rely on high-level interdisciplinary skills. Additionally, automation technologies are difficult to retrofit to

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[8] At Olympic Dam in South Australia, the implementation of automation technology in LHD applications resulted in a benefit of an additional two available production hours per 12-hour shift by operating the loaders manually and swapping to automated mode during shift changes.

existing equipment, and significant practical problems remain in making all the pieces of equipment and software fit together or work with each other.

3.4 Case studies of remote and autonomous systems

The following sections describe applications of automation technologies that are currently being trialled or have already been implemented. They span the range from automated sub-systems of broader processes, such as sampling, rockbreaking, ship loading and transportation activities, to mines with a significant degree of remote control and automation, such as the Kiruna and El Teniente mines, to highly automated and integrated systems such as Rio Tinto's 'Mine of the Future'.

3.4.1 Automated subsystems and processes

3.4.1.1 Underground mining: Rapid Underground Development

Rio Tinto is working with machine manufacturers to develop a new class of tunnelling machine (Smith 2010, 2011). These machines are designed to extract 75,000 to 100,000 tonnes per day of deep lying ores in a block caving system where a grid of tunnels is created beneath an ore body.[9] Conventional ways of forming shafts and drifts through rock via drilling and blasting is inherently slow, may make the orebody unstable, and give rise to a number of safety risks.

The need for these machines arises because of the tremendous effort involved in bringing such mines to operation. Around three to four kilometres of vertical shafts and 50 to 75 km of tunnels must often be developed before large block cave mines start production. The life of such mines can range from 20 to 40 years, and may require a further 100 to 250 km of tunnels to sustain production. An increase in the development rates for sinking vertical shafts and developing horizontal passages can then significantly reduce costs. A further consideration is the depth and associated risks to personnel of such mines, so that remote and autonomous operations increasingly become a necessity. Three prototypes are currently under development:

- Herrenknecht's Shaft Boring System for sinking large diameter shafts. This machine will carry out tunnelling and supporting operations simultaneously and will create shafts at twice or three times the rate of conventional drill and blast techniques.

- Two advanced tunnelling machines. Aker Wirth's Mobile Tunnel Miner can excavate rectangular, circular or horseshoe cross-sections using around half the energy per excavated cubic metre of rock compared to conventional cutters. The machine additionally undertakes required supporting activities such as shotcreting and rockbolting, meshing, laying a second layer of concrete, and then directing the excavated material to the mouth of the conveyor. Atlas Copco's Modular Mobile Mining Machine can advance at a rate of at least 12 m per day, compared to rates achieved with conventional equipment of 83 m per month. This machine similarly carries out the range of supporting activities.

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[9] Block caving is a mining technique that drives mine shafts below the ore body to create a void into which the fractured ore body is collapsed for removal. This technique precisely targets the ore body and eliminates the substantial cost of removing the overburden, but also requires an advanced understanding of rock mechanics.

3.4.1.2   Drilling and blasting: Semi-autonomous drills and 'smart' explosives trucks

Rio Tinto operates three largely autonomous drills at the West Angelas mine site in late stage pilots (Hooper, 2010). Drills are directed to the bench where blasting will take place from operators located in an automation control vehicle a distance away. The drills then switch to autonomous mode to drill the blast holes, and collect real-time data to generate an enhanced map of the bench. These drills can accurately pinpoint each drill location, and use automated levelling technologies to enable true vertical holes to be drilled. Optimised blasting is subsequently achieved using an intelligent explosives loader. These technologies reduce health and safety concerns and combine several advantages that improve the efficiency of drilling and blasting operations:

- a more efficient recovery of the orebody by reducing the amount of waste that is created and greater fragmentation of the blasted rock;

- more consistent and predictable outcomes from precision drilling and blasting, requiring no redrills and lowering the use of consumables such as explosives; and

- a more productive workforce as a result of the remote operation of several drills simultaneously.

3.4.1.3   Ore hauling: Autonomous trucks

Rio Tinto currently operates five autonomous trucks developed in partnership with Komatsu, also at the West Angelas mine (Hooper, 2010). These trucks (as well as all other vehicles at the site) have on-board computers that inform them of the position of other vehicles and communicate with the computer systems at the OC. Trucks are fitted with radars, lasers, communication antennas and high precision GPS to operate communications, guidance and avoidance systems. These systems enable trucks to use pre-defined GPS courses to automatically:

- navigate haul roads and intersections;

- move within the loading and dumping areas;

- enter the tie-down area for refuelling; and

- interact with manned equipment such as excavators, graders, bulldozers and light vehicles.

Rio Tinto plans to increase its autonomous truck fleet to 150 by 1015 (Freed (AFR), 2011). Driverless trucks are also being tested by BHP Billiton at its New Mexico coal operations, while FMG reportedly plans to use driverless trucks at its Solomon mine.

3.4.1.4   Ore processing: Remote controlled rock breaker and run-of-mine bin

This is a collaborative research project undertaken by Rio Tinto, CSIRO and equipment manufacturer Transmin to established the feasibility of a remote controlled rock breaker at the West Angelas iron ore mine (CSIRO 2009). The rock breaker is used to smash oversized rocks, which are prevented from entering the crusher because of their size, and are dumped into the ore receptacle or 'run-of-mine bin'. In conventional operations, an on-site operator identifies an oversize rock with the naked eye and uses a wireless remote-control pack to determine the most effective way to break the rock.

The new remotely controlled technology enables the operator to be based at Rio Tinto's OC in Perth. The remote rock breaker system combines virtual reality and actual reality images,

which the operator can access as required to direct the operations of the machine. The choice of interface was determined by conducting a number of human factor studies to find the most acceptable and productive. Remote operation of this process has a number of advantages:

- relocating operators to the OC and away from the mine site enables them to perform their work in a safer and cleaner environment;
- instead of requiring a dedicated operator per rock breaker, operators can operate one or more rock breakers simultaneously;
- the technology reduces the number of workers on site and thereby the number of fly-in fly-out personnel and associated pressures on site accommodation; and
- reduced crusher downtime resulting from delays in deploying plant operators to the rock breaker area.

3.4.1.5   Product handling: Remote ship loading

The difficult and necessarily precise process of loading bulk carriers with iron ore is currently controlled by an operator from a cabin located at the end of the shiploader's boom. A joint Rio Tinto/CSIRO team is currently developing the requisite technology for 'extended' teleoperation of the loading infrastructure (CSIRO 2009). Teleoperation of loading processes will then result in the operator working from a place beyond line-of-sight with video images of the operating area and access to additional sensors to monitor the process. These sensors deliver graphical displays of models of the loader that is synchronised with the real-time movement of the machine, information on proximity to the ship and other critical infrastructure, and profiles of the load in the hold.

Fully operational, this technology will deliver significant benefits in a range of areas; chief among these is the removal of human operators from a hazardous environment. The current location of operators potentially exposes them to a range of risks to human health and life, including as a result of exaggerated boom movements, accidents traversing the boom, unsecured movement of the moving platform, working at heights suspended over ship or water, collisions between the boom and other infrastructure on the port or ship, as well as exposure to wind gusts, heavy rain and dust. In addition, the technology overcomes a number of difficulties that currently limit productivity in manual operations:

- the current inability of operators to see a hold's interior;
- the need to make stop/start decisions in the course of loading hatches to distribute the cargo correctly;
- difficulties in moving the loading boom to the desired location over the hatch; and
- the current inability of operators to measure a vessel's trim directly.

Other benefits arise from improved reliability /sustainability of the operations. They include an extended machine lifespan as a result of smoother movements, reduced wear-and-tear associated with manual handling of equipment, and the benefits of boom 'auto-positioning' to compensate for any tidal drift in the ship and thereby maintain the correct over-hatch location.

3.4.2　Automated mining operations

Future mines will evolve around remote operations centres, and make extensive use of sophisticated technologies and intelligent systems to communicate with, monitor, direct and coordinate operations a long distance away (Bassan et al. 2008). Technology assisted workers will perform the jobs of two or three traditional roles, with only a skeleton workforce remaining on site. This vision is gradually being implemented as mines are being developed.

3.4.2.1　El Teniente New Mine Level Project

At the El Teniente copper mine in Chile, the New Mine Level Project (NMLP) is being developed by Codelco Chile at an estimated cost of $3 billion in order to mine deposits located under the current operational orebody (Revuelta et al., 2008; International Mining, 2010). Start-up is planned for 2017. El Teniente sits at an altitude of 2,500 m above sea level and is currently the largest underground mine in the world. Mining originally began in 1905, and the mine consists of more than 2,400 km of old passages and six mining sectors located at different elevations. Access to the existing mine is via a narrow mountain road and is difficult.

The NMLP essentially consists of developing a new underground mine, on average at 350 m below the existing undercut levels. The new mine design will use extensive remote control and automated processes to mitigate against risks from increases in rock mass stresses in this environment, such as rock bursts, collapses, rock falls, water inundation, hazards from mobile equipment, as well as diesel equipment or conveyor belt fires. Additional complexities in underground mining, transportation and crushing processes arise because the materials mined will contain steel and wood scrap originating from old support structures.

Codelco is using custom-built drills to reduce power requirements, speed up the mining process and improve the safety of operations. A number of processes within the existing mine are already automated or operated remotely, but the extent of automation is being expanded in the course of the development of the mine. New mine control rooms will be located close to the nearest city, some 50 km from the mine. The mine design encompasses:

- ore extraction using remotely controlled LHDs (three per remote operator), which subsequently move autonomously to an underground crusher, dump the load and autonomous move to the next allocated load point;

- underground haulage by means of automated trucks at a new intermediate haulage level;

- remote operation of rock breakers and secondary fragmentation machines installed at LHD dumping points;

- remote operation of loading chutes and crushers;

- an automated ore transportation system with a 10,000 tonnes/hour conveyor belt system that provides real-time operational data;

- ventilation through an intelligent system based on the current requirements of personnel and equipment; and

- gas and heat sensors, as well as additional sensors to enable real-time monitoring of rock mass behaviour for safety and improved production planning.

Remote controlled and automation will significantly reduce the number of personnel in the mine, improve working conditions, as well as reducing labour costs. In addition the mine design is intended to achieve:

- increased productivity and equipment usage with longer effective working hours;
- lower maintenance requirements;
- process optimisation with the assistance of real-time and online information;
- lower fuel and energy costs, for instance as a result of the intelligent ventilation system; and
- a decrease in reaction time to unforeseen events, due to the availability of real-time information.

Other planned innovations include the introduction of electric trucks and LHDs to save on fuel and reduce ventilation requirements, automated blasting procedures to improve the safety of personnel and the introduction of advanced tunnel boring machines (TBMs). TBMs will be able to simultaneously excavate and ground-support the working section while advancing at a rate of 12 to 15 m/day. These machines will also eliminate risks associated with explosives handling.

3.4.2.2   Kiruna iron ore mine

LKAB's Kiruna iron ore mine in Sweden, considered to be the world's largest, most modern underground iron ore mine, has used driverless underground trains since the 1970s (mining-technology.com, 2011; Arvidsson, 2005; International Mining, 2008 and 2010). Kiruna is located in the extreme north of Sweden, far north of the Arctic circle, and has been mined both above- and below ground for more than a century.

Current mining operations take place at a depth of 1,045 m. The mine operates in a mixture of autonomous and remote control modes that rely on sensors and wireless communications throughout the mine and fibre optic cables connecting operators that are either located at a level of 775 m underground, some distance from the drilling surface, or in a control centre located in LKAB's main office in the town of Kiruna:

- electric-powered, drilling rigs and ore handling equipment are remote controlled;
- remote controlled and in some cases autonomous LHDs carry the run-of-mine ore to the nearest ore pass, from which it is loaded automatically on a train;
- seven remote controlled 500t-capacity shuttle trains collect ore from ten groups of ore passes and deliver it to one of four crushing stations; and
- crushing, weighing, skip loading and hoisting are entirely automated.

The entire process is monitored and controlled from the central control centre in Kiruna, with some 15,000 measurement points covering everything from underground operations to ship loading in port. Operators can compare actual performance with production plans at any time. These arrangements have led to substantial labour cost savings, from 3,000 workers in 1983 to 1,800 staff in 2003, of which only around 400 were located in the mine itself.

The mine is currently undergoing expansion to a depth of 1,365 m, the seventh rail haulage level since late 1950 (Chadwick 2010). This new level will incorporate new advances in technology and automation, including:

- automated drilling equipment with automated hammer and drill bit changes;

- integrated monitoring and diagnostic systems for maintenance purposes;
- the use of robots to charge explosives; and
- automated electric LHDs.

Other innovations that have been introduced are equipment specifically designed and manufactured to resist wear and the impact of heavy iron ore materials for a minimum of 25 years. The loading chute has been made to extend the life of the structure and to enable the system to handle sticky/wet muck or large boulders. Similarly, rail cars are made from abrasion-resistant steel.

3.4.2.3 Rio Tinto's Mine of the Future™ program

The most ambitious plan for automation that has been announced publicly relates to Rio Tinto's 'Mine of the Future' program (CSIRO, 2009; Delabbio, 2011). The Mine of the Future project represents a concerted effort to automate all aspects of a mine, and is the result of a long process of collaboration between Rio Tinto, research centres around the world and key equipment suppliers. It follows full-scale trials of autonomous and remotely operated equipment such as autonomous haulage and drill systems at Rio Tinto's 'A Pit' trial mine in 2009-10 and subsequently at West Angelas.

The Mine of the Future will combine the various innovations to deliver autonomous but fully integrated processes that are coordinated from a remote location. The application of these new technologies will enable a holistic view of all operations from mine to port and provide near real-time information as a basis for improved decision-making. Rio Tinto's vision encompasses:

- automated blast-hole drill rigs that will perfectly position every hole, conduct analysis during drilling, and dictate to the explosives delivery vehicle the explosives load and blend to be charged for each hole;
- an excavator that can 'see' the difference between ore and waste in the muckpile, can separate the two, and will automatically load a driverless haul truck before dispatching it;
- driverless haul trucks that safely navigate around the mine landscape to move waste and ore in a precisely optimised manner without human intervention, and that automatically report to workshops when maintenance is due;
- remotely operated rock-breakers;
- the use of advanced sorting machines that are capable of upgrading low grade ores and significantly extending mine life;
- the incorporation of autonomous sensing equipment to fine-tune beneficiation and other processes so as to maximise recovery and save on energy and water;
- the operation of driverless trains that can 'see' beyond the horizon and deliver product to automated train load-outs;
- ongoing coordination all mine operations from mine to port so that quality controlled, correctly-blended product arrives at port ready for shipment to customers;
- on-site employees that undertake essential service and maintenance and are assisted remotely by experts a long distance away; and

- a remote operations centre that oversees the entire integrated operation of the mine while experts constantly analyse and fine-tune processes and that enables the ongoing real-time update of knowledge about the orebody.

Rio Tinto is now in the process of rolling out its Mine of the Future. At its core is the OC located in Perth, which has been operational since 2009-10. The centre currently undertakes the remote monitoring of a number of significant assets and oversees full-scale trials of autonomous trucks, drills and ship and train loading operations. It operates 24 hours a day, 365 days a year and is staffed with 200 controllers and schedulers, as well as more than 230 technical, planning and support staff (Rio Tinto, n.d.). The centre has been designed to control and monitor on a real-time basis Rio Tinto's entire operations across the Pilbara, including (currently) 14 mines, 1,400 km of rail, three ports and power generation facilities at Dampier and Paraburdoo.

A number of advanced technologies enable the many monitoring, operational and planning processes undertaken by the centre, including the MATE™ technology described. A different but equally powerful technology, referred to as 'VirtualEYES' is a system that generates a virtual representation of operations on the ground in real time (Rio Tinto, n.d.). This system combines survey and weather data, aerial photos and vehicle telemetry, with information on mine design, geological models and infrastructure plans to simulate an accurate three dimensional representation of events at the site. VirtualEYES will enable the sharing of real-time information to improve problem solving and collaboration.

3.5 Research and investment in mining automation

Today, Australia is a global leader in research into mining automation (Durrant-Whyte 2010). Three main research centres currently undertake work in this area in Australia:[10]

- CSIRO (the Commonwealth Scientific and Industrial Research Organisation) is Australia's national science agency. It undertakes research across the range of activities in the minerals sector, including minerals exploration, mining, minerals processing and metal production.

- CRCMining (the Cooperative Research Centre for Mining) is a research centre established by the Commonwealth Government with links to the University of Newcastle, the University of Queensland, the University of Western Australia and Curtin University, and supported by a number of mining businesses and equipment makers.[11] The centre was established in 2003 with an initial $27 million in government funding, and subsequent funding of $12 million in 2009, and an estimated $100 million in funding from industry and university partners. CRCMining focuses on automation, equipment and power management, drilling processes to manage fugitive emissions in coal mining and rock fragmentation and handling.

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[10] Internationally, Natural Resources Canada is similarly investing in research into mining automation in collaboration with the mining industry and equipment suppliers (Natural Resources Canada 2011). That research is particularly focused on narrow-vein and deep mining operations, much of which is undertaken at the CANMET-MMSL Experimental Mine, an underground facility for in-situ testing and research in a mining environment.

[11] Anglo American, AngloGold Ashanti, BHP Billiton, Caterpillar Elphinstone, Computer Sciences Corporation, Herrenknecht Tunnelling Systems, Newcrest Mining, Newmont Mining, P&H MinePro Services, Peabody Energy, Sandvik, Wellard and Xstrata.

- The Rio Tinto Centre for Mine Automation (RTCMA), established at the University of Sydney in 2007 and funded by Rio Tinto with $21 million for an initial period of five years. It focuses on robotics, sensing technologies, data fusion and systems engineering. RTCMA is one of a number of research centres with links to universities funded by Rio Tinto (Roberts,2011):
    - the Rio Tinto Centre For Underground Mine Construction in Canada, which focuses on rock mechanics, geotechnical rock mass modelling, mechanical excavation and underground construction techniques;
    - the Rio Tinto Centre for Materials & Sensing, based at Curtin University in West Australia;
    - the Rio Tinto Centre for Advanced Mineral Sorting at the University of Queensland, which undertakes research in the areas of mineral excitation, non-destructive sensing, mineral sorting classification and orebody classification; and
    - the Rio Tinto Centre for Advanced Mineral Recovery at Imperial College (London), where research focuses on the fundamentals of rock fracture and processes to improve the efficiency of mineral extraction.

While Rio Tinto and some other international mining businesses provide information about ongoing innovation and automation efforts, most, including most Australian businesses do not. It is therefore difficult to gauge overall trends in automation. What is clear however, is that information and communications technology (ICT) expenditure in the mining industry has increased rapidly in recent years, along with record levels of investment (Topp et al. (PC), 2008). ICT is important in all stages of mining activity, especially in the field of exploration and three-dimensional seismic surveys, but is also an essential requirement for the automation of many mining processes.

Whereas ICT expenditures have increased relatively slowly when investment has picked up in the past, ICT expenditures have grown rapidly over the past ten years (Figure 3-1). This trend is expected to continue with the increasing importance of automation and remote control in the mining industry together with other developments in telecommunications in the Australian economy in the future.

Figure 3-1. Gross fixed capital formation in the Australian mining sector – Aggregate and ICT expenditure ($ nominal)
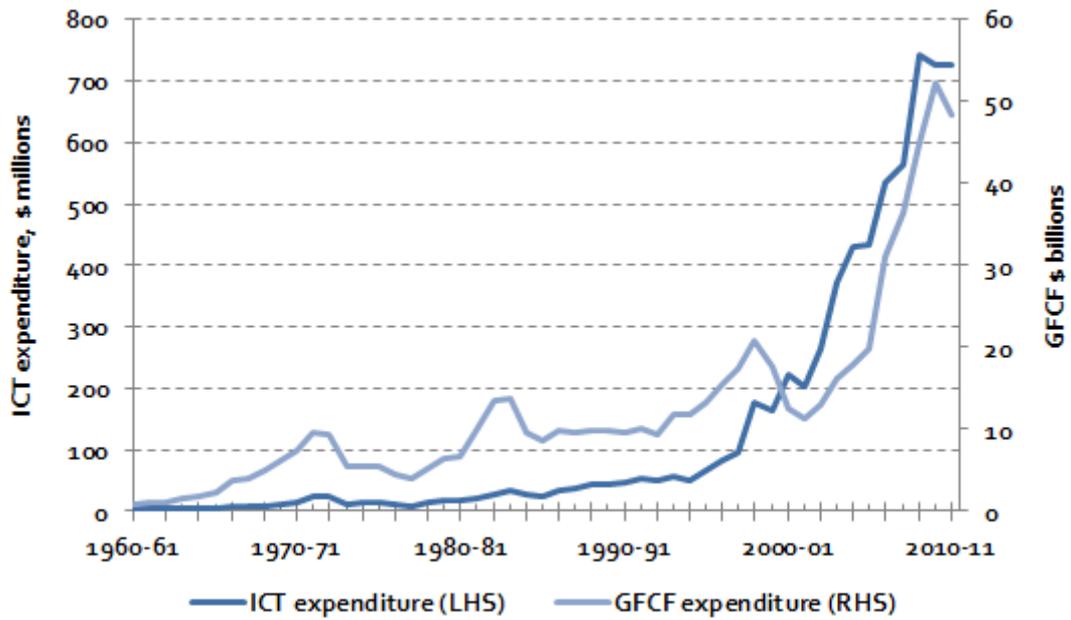
Notes: Chain volume measures. ICT refers to expenditure on computers and peripherals, computer software, electronics and electrical equipment.

Source: ABS, 5204.0 Australian System of National Accounts; Adapted from Topp et al. (PC), 2008.

4 Benefits and costs of remote and autonomous mining technologies

An economic assessment of the implications of remote and autonomous mining technologies must consider not only the most immediate cost and benefits, for instance in terms of safety and improved efficiencies, but also the economy-wide 'knock-on' effects that such innovations can deliver. Given intense competition and other challenges facing the Australian mining sector today, the application of these technologies may be critical to supporting the ongoing growth of the sector.

4.1 Economic framework

Most businesses contemplating a significant investment such as automating some aspects of their operations will undertake an internal appraisal to establish whether the corresponding outlays are justified in commercial terms. An economic (cost-benefit) appraisal takes a broader perspective, focusing instead on the overall implications for society, rather than just on the (private) gains and costs to certain businesses or individuals (see for example Mishan 1975, Department of Finance 1991). An economic assessment of the implications of automation and other innovations in the mining industry is therefore fundamentally concerned with the efficient allocation of resources; that is, making the most of the limited resources that are available to society. Such an assessment is structured around comparing the benefits and costs of increased automation with the benefits and costs that would arise under a 'business-as-usual' scenario. The general decision rule that is applied to all economic assessments is that a project adds value to society if its net present value (NPV) is positive; that is, if the difference between the benefits and costs of a project – properly valued over the life of the project and discounted to a common point in time – is positive. A positive NPV means that by redirecting resources to a particular project, society gains overall.

Economic project assessments are then forward looking and focus only on incremental benefits and costs relative to a business-as-usual scenario. Applying such a framework in practice is not necessarily straightforward, however. In some instances, benefits and costs may be difficult to express in monetary terms. This can be the case for environmental benefits and costs, for less tangible benefits such as improved health and lives saved, but also in circumstances where market prices are not a good reflection of social costs and values, for instance for wages when unemployment is high. Uncertainty about the future can also introduce some complications, as may interactions between a (large) project and other parts of the economy. Finally, and as is likely to be the case here, where a project can potentially deliver a step change in efficiency in a key sector of the Australian economy with associated impacts on domestic employment and trade, wider economic effects need to be considered. A variety of techniques have been developed over the years to handle all of these issues, including the use of general equilibrium (GE) models to capture sectoral trends, balance of trade impacts and the consequences for overall economic growth.

4.2 Direct benefits and costs

The key direct benefits of increased automation arise from the improved health and safety of the workforce and from efficiency improvements so that the same output can be generated with fewer resources. In many instances, efficiency improvements translate into reduced requirements for energy and consumables, as well as less waste, and therefore better

environmental outcomes. Efficiency benefits take many different forms, however, and are highly specific to the innovation in question and the context in which automation is applied.

4.2.1   Health and safety benefits

As set out in Section 2.3, mining can impose a substantial cost on the workforce , not just in terms of injuries and possible lives lost, but also in terms of a range of broader health risks that are common in a mining environment. The mining industry has, over the years, introduced many incremental innovations that have improved the safety of personnel working in inherently hazardous environments, both above and below ground. Such improvements have taken the form of rigorous processes and procedures to eliminate common sources of accidents, but also new inventions such as the 'telltales' introduced in the early 1990s to alert personnel to impending roof falls, and significant improvements in roof bolting and stabilisation technologies. In recent years, assistive technologies such as automated collision detection devices have been introduced, both in underground and in surface mining, to protect personnel from moving equipment (as well as to safeguard these high value assets themselves).

The introduction of remotely controlled and autonomous technologies, however, represents a major advance in terms of its potential to significantly reduce the risks to humans of working in a hazardous environment. Automation will minimise the number of human operators that will need to be located on site or in close proximity to operations. This applies across different types of mines:

- in underground mine sites where heavy moving equipment is operated in confined places, and where serious risks arise from explosions and rock falls; and

- in surface mines where operators undertake repetitive and potentially hazardous activities such as truck driving and drilling, explosives must be handled as a matter of routine, and where industrial type accidents are relatively common.

In the absence of automation, these risks will increase in future as mines expand on the surface and deeper underground. The need to access ore deposits in deeper and increasingly complex environments heightens safety risks, and accounts for the heavy emphasis on automation in modern mines being commissioned today.

Beyond the immediate concerns for human health and safety, other factors are also relevant. Mines are fundamentally dusty and dirty industrial sites, frequently wet in the case of underground mines, and often located in remote and difficult to access areas with few amenities. There is additionally a significant shortage of skilled workers, which is projected to become an increasing constraint in future. These difficulties are already apparent in Australia today (Minerals Council, 2011):

- Women comprise only around 18 per cent of the minerals industry workforce, compared to a national participation rate of 46 per cent. Only three per cent of employees at mine sites and minerals processing operations are women.

- The indications are that employee turnover in the minerals sector is high. Employee turnover at fly-in fly-out sites was estimated to have reached 30 per cent in 2008, and Australian Bureau of Statistics (ABS) figures suggest that 12 per cent of mining workers in February 2008 had changed their employer in the previous 12 months.

The need to attract new employees, including women, in an environment where skilled labour is in short supply will therefore further reinforce the trend toward automation, which places workers in a safe environment close to their communities.

There are some challenges, however, that will need to be addressed before the full benefits of automation for the workforce can be achieved. Increased automation requires changes in the qualifications, knowledge and skills required of modern mineworkers. Traditional craftsman-like skills are being replaced by more technical qualifications that are necessary to operate new advanced technologies and to understand integrated process flows. New forms of knowledge and skills require concentration and tactile ability, for instance to drive a truck via monitor and joystick, rather than physical strength, manual skills or tacit knowledge.

It is also the case that automating previously manually controlled systems creates some specific risks arising from 'human factors'. These issues have been well studied in aviation, transport and other industries were automation is common (Parasuraman and Riley 1997). They include circumstances where there is an overreliance on automation, when monitoring errors occur, when warning systems are ignored or turned off, or when complex systems cause operators to be overloaded. Similar challenges must therefore also be addressed in the course of introducing greater automation in the mining industry, for instance in the design of user-friendly equipment interfaces and the integration of multiple warnings and alarms without overloading the operator. Other challenges arise because the nature of mine workers' jobs change in remotely controlled and automated mines (Lynas et al. 2010, 2011):

- a 'passive operator' of an automated system may lose situational awareness and over time becomes deskilled, and may be unable to take appropriate corrective action in the event of equipment malfunction or unusual events;

- greater automation can lead to boredom and complacency on the part of operators with what then becomes a vigilance task and deskilling, which in turn increases risk;

- alternatively, automated systems can overload, confuse and distract rather than assist the operator; and

- more generally, poor operator acceptance of new technologies/automation can be an issue.

These issues are well-recognised, however, and typically form an integral part of the development of automated technologies. Extensive testing and operator feedback, for instance, has been an integral component in the piloting of remotely controlled machinery at trials undertaken at Rio Tinto's mines.

4.2.2 Efficiency benefits

Automation essentially substitutes capital for labour and other inputs to achieve the same or a better production outcome. The automation of mine sites will move mine workers to a safer environment, but it will also reduce overall employee numbers and labour costs as operators undertake multiple tasks at the same time and require less time for shift changes. Relatedly, automation will reduce the cost of transporting and housing employees at remote mine sites, and related environmental and social impacts.

The various technical efficiencies that can be achieved are multifaceted and interrelated, and arise both at the process level and at the wider system level if processes are better

integrated. The nature of these efficiencies differs by type of innovation, but there are some common themes:

- Equipment that is controlled remotely or automated can be better utilised. Its operation generally does not depend on a worker being on-site and available. In underground mining, autonomous machines can operate in situations, for instance, following blasting, where there are normally significant delays before humans can approach a site. Mining is capital intensive; capital costs make up around 42 per cent of total costs for iron ore mining and 43 per cent for coal mining (PC, 2008). The ability to make better use of very costly (fixed) capital can therefore deliver significant economies.

- Remote controlled and automated equipment operates in a more predictable, controlled and precise manner. This eliminates a range of inefficiencies, for instance:
  - unnecessary wear and tear or fuel consumption on the part of equipment such as automated trucks and LHDs, which operate at efficient speeds, or for automated trains, which brake in a controlled manner;
  - the need to repeat tasks such as redrilling blast holes that do not meet specifications;
  - unnecessary movements to place equipment in precisely the right position, for instance in the manual operation of ship loaders;
  - a reduction in the use of energy and consumables, for instance because automated processes measure and adjust input requirements in real time.

- Automated equipment can be better maintained, and is at less risk of catastrophic failure. Traditional equipment maintenance takes place in fixed cycles or once an asset has failed. With greater automation, including the use of sensor and other data transmitted remotely, equipment comes in for maintenance when a part is reliably observed to be approaching failure. Diagnostic tools that are incorporated in automated equipment allow faults to be identified more quickly, and also reduce equipment downtime. More generally, remote monitoring of equipment can extend the life of assets, and save on consumables and fuel, for instance because tyre pressures are maintained at the right level.

Many of these efficiencies are clearly interrelated, and there are often beneficial knock-on effects. For instance, precisely drilled blast holes in combination with the optimal use of explosives improve the efficiency of all subsequent mining and processing activities.

The counterpart of efficiency improvements at the individual process level is improvements at the system level. Businesses can take a holistic view of their operations with the help of integrated real-time information. Staff located in a central control centre are able to analyse and coordinate operations across multiple sites and at all points in the value chain. More informed decisions can be made on the basis of up-to-date data, for instance about the geology of the mine. As sensor and data analysis capabilities have advanced, mine planning has become considerably more sophisticated so that mining can take place more selectively and with lesser environmental impacts.

These benefits must be assessed not just in the near term but also in the future in the context of more difficult and complex mining environments. With greater automation, mining in areas that would otherwise not be accessible can be developed. New processing

technologies may enable historical mine waste to be reprocessed, resulting in significant energy and other savings.

4.2.3 Benefits from reduced environmental impacts

Many of the environmental benefits from automation have already been described above. They generally arise because machines are operated in a more precise and efficient manner so that fewer consumables and less energy are used in the process. Environmental benefits therefore arise in a wide array of applications. Intelligent ventilation systems can adjust requirements depending on the number and location of personnel. In some instances, the ability to reprocess existing waste piles from past operations can substitute for new blasting and mining operations and therefore reduce the environmental footprint of an expanding mine. Finally, significant process innovations such as Rio Tinto's eXDS™ platform significantly reduce energy requirements.

4.2.4 Costs

Information about the cost of developing and installing remotely controlled and autonomous technologies is not in the public domain, but these costs are understood to be substantial. As described in Section 3.2, creating step-change innovation is a long, complex, and costly process that stretches from R&D undertaken in research centres to multiple intermediate stages until the full-scale roll-out and commercial use of technologies. Rates of failures along the way are very high. The funding costs of Rio Tinto's research centres alone, for instance, amount to several tens of millions of dollars. Expensive prototypes of complex large machines such as Rio Tinto's underground drills must be designed, built, tested in an appropriate environment, and further refined in an intensive process involving multiple partners and many different types of expertise.

Installing remotely controlled and autonomous equipment in mines is also complicated because of the unique character of each mine operation. These systems are highly customised (Peterson et al. 2001). Requirements vary by type of mine, and considerable testing and investment in equipment such as control rooms and mobile assets, but also in ancillary services such as sensing and communications technologies, as well as signal processing and computing power must be undertaken.

As mining technologies become more complex and mining processes become more tightly integrated, the need for sustained, strategic alliances between equipment developers and mine operators becomes more critical. Few organisations have the capability to combine metallurgy with machine design to develop advanced technologies. Similarly, the development of automated equipment requires coordination and collaboration among producers of machinery, communications and GPS, sensors and imaging technologies and control algorithms.

Equipment manufacturers have identified the need for a standardised approach to automation and data exchange (Noort and McCarthy 2008). At the same time, the proliferation of equipment suppliers that only specialise in certain aspects of mining operations means that assembling one integrated solution from diverse hardware and software is difficult and costly. Additionally, the protection of intellectual property and similar considerations means that collaborative approaches by equipment manufacturers or mining companies can be an issue.

4.3   Broader economic effects

While many economic assessments consider an individual project in isolation, given the importance of the mining sector to the Australian economy, broader economy wide knock-on effects from automation are likely to be substantial and cannot be ignored. This issue goes to the counterfactual that must be considered in any economic assessment – how Australia's mining industry would evolve if mining operations were not increasingly automated. More specifically, the question arises as to the implications for the Australian economy if, in the absence of greater automation and associated efficiencies, the minerals sector gradually declines in competitiveness relative to the rest of the world.

Australia is only one of many countries that are rich in natural resources, and that compete in global commodities markets to supply the raw material needs of developing economies. As Australian resources become progressively more difficult to mine, mining companies must continue to innovate to remain competitive. At the same time, the Australian mining sector suffers from a sustained shortage of staff who are both skilled and willing to work in an inhospitable environment, and must more generally comply with increasingly stringent environmental and other regulations. This context contrasts with that in many other resource rich countries with significant untapped deposits that have only recently begun to develop their own mining industries. While non-traditional producers face a number of hurdles in bringing their mines to full production, it is clear that a significant development effort with associated large capital flows is directed toward emerging mining industries in these countries. Unless Australian producers remain competitive, future production is likely to shift to those countries that are today catching up rapidly.

4.3.1   Direct and indirect effects of the resources sector on the national economy

While the effects on different sectors of the Australian economy have varied, to date, there is no doubt that the Australian economy has benefited greatly from the recent natural resources export boom to mainly Asian economies. Resources exports (including oil and gas) account for 55 per cent of total exports compared to 35 per cent ten years ago (Figure 4-1). The current resources boom continues to have a far greater impact on the Australian economy than has historically been the case (Connolly and Orsmond (RBA), 2011). Between 2000 and 2010:

- mining revenue increased from 6 per cent of GDP in 2000 to 14 per cent;
- mining investment rose from 1.5 per cent of GDP to over 4 per cent; and
- mining employment increased from under 1 per cent of total employment in 2000 to 1.7 per cent.

Figure 4-1. Selected minerals exports – shares of total export values
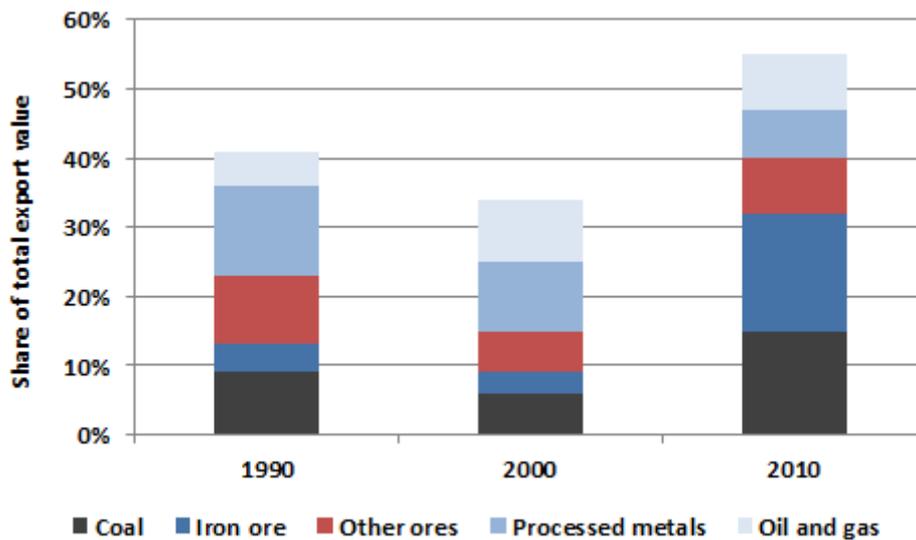
Source: Connolly and Orsmond (RBA), 2011.

The direct effects of the expansion of the mining sector over the past decade on the national economy can be broken down into a number of components (Connolly and Orsmond (RBA), 2011):

- Although mining is very capital intensive and employs relatively few people, employment in the mining industry grew at a rate of around 10 per cent per year, compared with employment growth in the national economy of 2 per cent.

- The costs of intermediate inputs used in the mining sector (goods and materials used in mining operations, and services) grew rapidly at an annual average rate of 15 per cent. Around a third of goods and materials were direct imports, but services, which make up around 66 per cent of intermediate inputs were provided locally. These services include mining support; finance, insurance, property and business; transport and storage; wholesale and retail trade; utilities; accommodation; and construction services.

- Royalties and company income taxes paid by the mining industry increased from around 0.5 per cent of GDP in 2000 to around 2 per cent of GDP in 2008-09.

- After deducting royalties and other taxes, the gross operating surplus of the industry rose from around $15 billion in 1999-2000 (2 per cent of GDP) to around $65 billion in 2008-09 (5.2 per cent of GDP).

- The mining industry boosted spending in the Australian economy through large-scale investment activity, which increased from $10 billion (1.4 per cent of GDP) in 2000 to most recent estimates of around $58 billion (4.2 per cent of GDP). It is estimated that, in broad terms, and over the life of a project, the domestically contracted share of mining investment averages around 70-80 per cent for iron ore and coal projects.

Overall, the increase in mining revenues in the 2000s made a significant direct contribution to economic activity, and it is estimated that Australian residents received around half of the total receipts earned from mining operations.

The direct effects described above have had a number of wider consequences for the economy. Australia's terms of trade rose significantly, as did real incomes. Generally speaking, and although there is significant regional and inter-industry variability, the pace of growth of exports for manufactured goods and tourism services slowed concurrently, while import growth picked up. Overall, however, and perhaps reflecting large variations in how local sectors were affected, aggregate output and employment shares between industries have not changed significantly since the mid-1990s.[12] Similar effects occurred at the state level. While resource endowments and associated growth of the mining industry have varied significantly across states, growth in overall demand and output across the states has become more similar. The implication is that the distribution of mining receipts – for instance through dividends and tax receipts – is relatively evenly dispersed across the country.

4.3.2   Sector-specific benefits

One key consequence of Australia's position at the forefront of mining innovation, which also illustrates the longer-term potential for growth in specific sectors, is the emergence of an Australian mining technology services and equipment (MTSE) sector (Tedesco and Haseltine (ABARE), 2010). This sector mainly consists of small to medium-sized businesses employing 50 or fewer people and specialising in:

- technology applications for exploration, mine development, mining, minerals processing, minerals handling and transport, and mining maintenance technologies; they include remote sensing, airborne and ground exploration technologies, exploration and mine planning software, remote control systems, protection systems and communications systems ;

- equipment and machinery manufacture and supply, including of scientific and electronic equipment, but also heavy plant, machinery and equipment;

- consulting services, such as surveying, geological, mining, geotechnical engineering, scientific research, laboratory and testing, environmental management, training and other services; and

- contract services, including specialist on- and off-site service contractors.

The Australian MTSE sector is now a dominant presence in the global market for the supply and development of technology goods and services for the minerals industry. As technologies have progressed, the range of applications has also widened and a number of companies now supply industries beyond mining.

Table 4-1 provides an overview of the broad characteristics of the MTSE sector in terms of global and export sales revenues, labour force and R&D expenditures. While the sector has historically grown at a similar pace as Australian minerals exports, the MTSE sector appears to have been relatively insulated from the effects of the GFC.

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[12] For instance, activity at hotels servicing capital cities and fly-in/fly-out operations has been strong, while hotel bookings and flight reservations elsewhere has often declined. Similarly, different parts of the manufacturing and construction sectors have benefitted, depending on sales to the mining industry.

Table 4-1. Comparison of selected MTSE sector estimates, Australia

Year	Global sales revenue		Export sales revenue		Size of labour force	R&D expenditure
	$ million	Av. annual growth rate (per cent)	$ million	Av. annual growth rate (per cent)	Full-time-equivalents	$ million
2000-01	3,120	20	611	6	17,300	382
2003-04	4,750	n/a	1,110	n/a	16,800	339
2008-09	8,710	20	2,490	25	31,300	985

Notes: Selected years from three ABARE studies; estimates may not be directly comparable across studies. Labour force is measured in full-time equivalents.

Source: Tedesco and Haseltine (2010).

MTSE businesses' domestic sales were greatest in Western Australia (1.1 per cent as a share of state GDP), Queensland (1.1 per cent) and New South Wales (0.6 per cent). Over the past three years, exports were a main source of revenues for MTSE businesses in Queensland and South Australia; West Australian businesses mainly sold their products and services domestically. Major export destinations include Oceania, Africa, North Asia and Europe; less important destinations are North America, Latin America and the Caribbean.

Although the sector definitions used in individual studies differ, Tedesco and Haseltine (2010) cite a number of other sources that point to the growing contribution of the MTSE sector to the Australian economy:

- Austrade (2008) estimated that in 2007-08 the sector generated $12 billion in annual sales, with $2.5 billion in export sales;

- a study commissioned by Invest Brisbane (2008) estimated that the Queensland mining technology and services (MTS) sector generated $1.1 billion in sales revenue since 2006, accounting for a 26 per cent share of the Australian MTS sector;

- HighGrade (2010) estimated that in 2008-09 the MTS sector generated $27.5 billion in annual sales and employed 82,725 people.

4.4   Implications for the benefits and costs of automation

The preceding discussion shows that, while the costs and associated wider challenges of automation in the mining sector are substantial, they are potentially far outweighed by the benefits they can deliver. Considered in isolation, step-change innovations can significantly reduce the risks to human health and safety, as well as delivering process and systems efficiencies, and environmental benefits. These benefits may help to counteract a number of the challenges currently facing the industry, including persistent skills and labour shortages, declining ore grades and more complex mining environments, and environmental challenges arising from the need to reduce emissions and impacts on natural resources. On a broader perspective, increased automation may sustain Australia's longer-term competitiveness compared to a situation where Australia's resource exports decline in importance relative to those from competitor nations with equally good or better resource endowments but fewer constraints.

On this longer-term view, economic growth and income in Australia may decline in a business-as-usual world relative to a situation where Australia maintains and strengthens its competitive position. As discussed above, the economic benefits of the present resources boom have been distributed widely across the economy, both in terms of employment and incomes. A decline in resources exports would then equally be expected to slow employment and income growth across Australian states and territories, as well as sectors, in particular the services sector.

From this perspective, concerns about a reduction in employment in the mining industry as a result of automation are misplaced. While some specific roles are likely to disappear over time, employment overall would be expected to grow faster while Australia maintains its competitive position. Relocating challenging new jobs to more desirable locations will furthermore broaden employment opportunities and attract more talent in addition to easing overall labour constraints in the Australian economy.

References

Abrahamsson, L, Johansson, B and Johansson, J. (2009), 'Future of metal mining: sixteen predictions', *International Journal of Mining and Mineral Engineering*, 1(3).

Arsenault, J-F. and Sharpe, A. (2008), 'An analysis of the causes of weak labour productivity growth in Canada since 2000', *International Productivity Monitor*, Centre for the Study of Living Standards, 16, pp.14-39.

Arvidsson, S. (2005), *'Remote control and automation in Swedish iron ore mining'*, *Géosciences*, numéro 1, January.

Austrade (2008), at: www.austrade.gov.au/Mining-Equipment-Technology-Services-overview/default.aspx, New South Wales, accessed on 11 October 2011.

Australian Bureau of Statistics (ABS) (2011), 5260.0.55.002 – Experimental estimates of industry multifactor productivity, 2010-11, 11.30am Canberra time), 7 December.

Australian Government (2010), *Resourcing the Future*, National Resources Sector Employment Taskforce, July.

Australian Institute of Marine Science (2009), *Annual Report 08-09*, AIMS, Townsville.

Bellamy, D. and Pravica, L. (2011), 'Assessing the impact of driverless haul trucks in Australian surface mining', *Resources Policy*, 36(2), p. 149-58.

Chadwick, J. (2010), 'Ironclad Kiruna', *International Mining*.

Commonwealth of Australia (2008), *Carbon Pollution Reduction Scheme, Australia's Low Pollution Future*, White Paper, Volume 2, Canberra.

Connolly, E. and Orsmond D. (2011), 'The mining industry: from bust to boom', Paper prepared for the Reserve Bank of Australia Conference on 'Australia in the 2000s', H.C. Coombs Centre for Financial Studies, Kirribilli 15–16 August.

CRCMining (2010), *CRCMining News*, July.

CSIRO (2005), 'Rio Tinto's approach', ECOS Magazine, Issue 126, August-September.

CSIRO (2009a), 'Breaking rocks goes hi-tech', *Earthmatters*, Automating the mine, Issue 19, March/April.

CSIRO (2009b), 'Gently does it', *Earthmatters*, Automating the mine, Issue 19, March/April.

CSIRO (2009c), 'Get set!', *Earthmatters*, Automating the mine, Issue 19, March/April.

CSIRO (2011), 'Process', CSIRO research in minerals processing and metal production, February.

DeGaspari, J. (2003), 'Automated controls – armchair mining' [online], *Mechanical Engineering*, The American Society of Mechanical Engineers, at: http://www.memagazine.org/contents current/features/armchair/armchair.html; accessed on 12 October 2011.

Delabbio, F. (2011), 'The future is now', *World Coal*, November.

Department of Finance (1991), *Handbook of Cost-benefit Analysis*, Australian Government Publishing Service, Canberra.

Durrant-Whyte, H. (2010), Transforming [sic] mining industry globally', Australian Centre for Field Robotics, The Warren Centre, February; at: http://sydney.edu.au/warrencentre/bulletin/NO61/ed61art1.htm, accessed on 10 October 2011.

Eslake, S. (2011), Commodity Prices, Paper presented to the International Conference of Commercial Bank Economists Amsterdam, the Netherlands, 23rd June.

Freed, J. (2011), 'Rio to extend driverless fleet', *Australian Financial Review*, 3 November.

Geoscience Australia 2008, 'Sustaining the mineral resources industry – overcoming the tyranny of depth', in ABS (Australian Bureau of Statistics), *Year Book Australia 2008*, catalogue no. 1301.0.

Goodes, C. (2010), 'Innovation - from ideas to implementation', IMPC Conference, September.

Giurco, D., Prior, T., Mudd, G., Mason, L. and Behrisch, J. (2010), 'Peak minerals in Australia: a review of changing impacts and benefits', prepared for CSIRO Minerals Down Under Flagship, by the Institute for Sustainable Futures (University of Technology, Sydney) and Department of Civil Engineering (Monash University), March.

Grattan Institute (2010),' Restructuring the Australian economy to emit less carbon: detailed analysis', April.

Harberger, A. C. (1997), 'New frontiers in project evaluation? A comment on Devarajan, Squire, and Suthiwart-Narueput', *World Bank Research Observer*, Oxford University Press, 12(1).

Höök, M. and Aleklett, K. (2009), 'Historical trends in American coal production and a possible future outlook', *International Journal of Coal Geology*, 78(3).

Hooper, M. (2010), 'Automation paving the way forward', *Australian Mining Review*, November.

Huang, Y., and Wang, B. (2011), 'From the Asian miracle to an Asian century?, Economic transformation in the 2000s and prospects for the 2010s", Draft paper prepared for the RBA Conference, 15-16 August.

International Longwall News (2008.),'Beltana sets new national record', http://www.longwalls.com/storyview.asp?StoryID=169803, accessed on 10 October 2011.

International Mining (2008), 'Kiruna grows', June.

International Mining (2010), 'El Teniente goes deeper', October.

International Mining (2010), 'Ironclad Kiruna', July.

Johansson, B., Johansson, J. and Abrahamsson, L. (2010), 'Attractive workplaces in the mine of the future: 26 statements', *International Journal of Mining and Mineral Engineering*, 2(3).

Kearns, J. and Lowe, P. (2011), 'Australia's Prosperous 2000s: Housing and the Mining Boom', paper prepared for the Reserve Bank of Australia Conference on 'Australia in the 2000s' at the H.C. Coombs Centre for Financial Studies, Kirribilli, 15–16 August.

Lowry, D., Molloy, S. and Tan, Y. (2006), *The Labour Force Outlook in the Minerals Resources Sector 2005-2015*, Report prepared for the Minerals Industry National Skills Shortage Strategy, National Institute of Labour Studies, Flinders University, May.

Lynas, D. and Horberry, T. (2010), 'Exploring the human factors challenges of automated mining equipment', Proceedings of the 46th Annual Conference of the Human Factors and Ergonomics Society of Australia, 31 October - 2 November 2010.

___ (2011) 'Human factor issues with automated mining equipment' *The Ergonomics Open Journal*, 4 S2-M3: 74-80.

Mining Industry Skills Centre (2010), 'Automation for success', May.

Mining-technology.com (2011), at: http://www.mining-technology.com/projects/kiruna/, accessed on 12 October 2011.

MEi Online (2009), 'State-of-the-art Courier® Analyser and Sampling System for Olympic Dam, January; http://www.min-eng.com/appliedmineralogy/131.html, accessed on 10 October 2011.

McGagh, J. (2010), 'Rio Tinto and step-change innovation drivers and progress', ASEG Conference, 22-26 August.

___ (2011), 'Financial community visit to the Pilbara: Rio Tinto Innovation, Rio Tinto, June 10.

Minerals Council of Australia (2011), 'A sustainable population strategy for Australia', Submission to the Australian Government's Issues Paper, March.

Mishan, E.J. (1975), *Cost-Benefit Analysis: An Informal Introduction*, George Allen & Unwin Ltd, London.

Molloy, S. and Tan Y. (2008), 'The labour force outlook in the Australian minerals sector: 2008 to 2020', Report prepared for the Minerals Council of Australia, June.

Mudd, G. M. (2009a), 'The sustainability of mining in Australia : key production trends and their environmental implications for the future, *Research Report No RR5*, Department of Civil Engineering, Monash University and Mineral Policy Institute, Revised April.

___ , (2009b), 'Historical trends in base metal mining: backcasting to understand the sustainability of mining, Proc. 48th Annual Conference of Metallurgists, Canadian Metallurgical Society, Sudbury, Ontario, Canada, August.

National Research Council (2002), *Evolutionary and Revolutionary Technologies for Mining*, Committee on Technologies for the Mining Industry, Committee on Earth Resources, National Academies Press.

Natural Resources Canada (2011), 'Mine mechanization and automation', http://www.nrcan.gc.ca/mms-smm/tect-tech/sat-set/mec-mec-eng.htm, accessed on 11 October 2011.

Noort D. and McCarthy, P. (2008), 'The critical path to automated underground mining', paper presented at The First International Future Mining Conference, Sydney November.

Norgate, T.E., S. Jahanshahi and Rankin, W.J. (2007), 'Assessing the environmental impact of metal production processes', *Journal of Cleaner Production*, 15(8-9).

NSW Department of Primary Industries (2008), International-Mining-Fatality-Review-database.xls.

Parasuraman, R. and Riley, V. (1997), 'Humans and automation: use, misuse, disuse, abuse', *The Journal of the Human Factors and Ergonomics Society*, 39(2).

Peterson, D.J., LaTourrette, T. and Bartis, J.T. (2001), 'New forces at work in mining: industry views of critical technologies', RAND Science and Technology Policy Institute.

Petty, J. (2011), 'Financial community visit: unparalleled sector leadership, West Angelas', Rio Tinto, 8 June.

Port Jackson Partners (2011), *ANZ insight, Earth, Fire, Wind and Water: Economic Opportunities and the Australian Commodities Cycle*, Report commissioned by ANZ, Issue 1, August.

Revuelta, J., Reyes, F. and Pozo, R. (2008), El Teniente New Mine Level Project , First International Future Mining Conference Sydney, NSW, 19 - 21 November.

Rio Tinto, n.d. *Operations Centre.*

Rio Tinto, n.d. *Mine of the Future™, Asset Health.*

Rio Tinto, n.d. *Mine of the Future™, Miner Assist Technical Equipment (MATE™).*

Rio Tinto, n.d. Mine of the Future™, *VirtualEYES.*

Roberts, P., (2011), 'Rio Tinto leads in mineral innovation', *Australian Financial Review*, 9 May.

Sandu, S. and Petchey, R. (2009), 'End use energy intensity in the Australian economy', *ABARE Research Report* 09.17, Canberra, November.

Schodde, R. (2010), 'The key drivers behind resource growth: an analysis of the copper industry over the last 100 years', MEMS Conference, Mineral and Metal Markets over the Long Term, Phoenix March 3.

Smith, K. (2010/11), 'Mining – a new future for tunnelling?', *Tunnelling Journal*, December/January.

Steinberg, J.G., and De Tomi, G. (2010), 'Lean mining: principles for modelling and improving processes of mineral value chains', *International Journal for Logistics Systems and Management*, 6(3).

Tedesco, L. and Haseltine, C. (2010), 'An economic survey of companies in the Australian mining technology services and equipment sector, 2006-07 to 2008-09', *ABARE–BRS research report 10.07*, Canberra, July.

Topp, V., Soames, L., Parham, D. and Bloch, H. (2008), 'Productivity in the mining industry: measurement and interpretation, Productivity Commission Staff Working Paper, December.

United Nations, Department of Economic and Social Affairs, Population Division (2007), 'World population prospects: the 2006 revision, highlights', Working Paper No. ESA/P/WP.202.

van Berkel, R. (2007), 'Eco-efficiency in the Australian minerals processing sector', *Journal of Cleaner Production* 15.

Wei, G., 2011, 'Statistical analysis of Sino-U.S. coal mining industry accidents', *International Journal of Business Administration*, 2(2).

Woodford, G. (2010), 'How reliable are your assets?', *CIM Magazine*, 5(4).