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ORIGINAL PAPER

Mining productivity and the fourth industrial revolution

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Abstract
Rising productivity, alongside exploration, is the principal means by which mining can combat resource depletion. Over the past one hundred and fifty years, the mining industry has been remarkably successful in growing its productivity. However, since 2000, there are signs of a slowdown. Some aspects of this are clearly cyclical but there are increasing concerns that some of the underlying, longer term, factors which have kept productivity growing in the past are losing their force. Key amongst these factors are the physical contributions that the second industrial revolution, beginning in the late nineteenth century, brought to mining, most notably in the form of larger equipment operating in larger mines. There is much discussion in the industry around the arrival of a fourth industrial revolution and how this might 'disrupt' the sector and deliver a new boost to productivity through the promotion of intelligent mining but thus far there is little the evidence of such a boost. In its absence, the mining industry faces the prospect of rising costs as grades fall and waste volumes grow.

Keywords Mining · Fourth industrial revolution · Productivity · Depletion · Digitisation · Mining costs

Introduction

It can safely be said that nobody has contributed more towards the development of mineral economics in recent years than John Tilton. John combines an inquiring mind, a rigorous grasp of economic theory and the powers of a great communicator. He is also somebody I am pleased to call my friend these past thirty-five years, since we first met at a UN meeting on deep sea mining in New York in 1983.

In subsequent years, through various jobs, I have had the pleasure of undertaking several projects with John and sharing a number of adventures in places across the globe, including Sweden, France, Austria, Chile and Japan. I have learned an immense amount from him and, no less, have been a lucky beneficiary of his and Liz's generous hospitality.

One of the issues that has intrigued John over the years, and to which he has returned in his writings and speeches, is the issue of productivity in mining. In research published by Resources for the Future (RFF), John, along with Hans Landsberg, provided the definitive analysis of how the US copper industry saved itself by radically boosting its productivity in the 1980s (Tilton and Landsberg 1999). In later work, he addressed concerns that productivity in the mining industry might be in secular decline, demonstrating that productivity in mining is inherently cyclical, with high prices tending to suppress productivity as companies focus on volume, and with low prices tending to boost it as companies seek to reduce costs (Tilton 2014). He remained optimistic that, when the effects of the most recent boom had worked through, productivity growth in the industry would resume.

The purpose of this paper, as a tribute to John Tilton, is to take a very long-term look at productivity and to see what, cutting through the natural cyclical variations in productivity, the data tell us about past trends in mining productivity and where it might now be headed.

Productivity is, of course, key to all economic sectors as it central to a country's general economic well-being. John's chapter in the RFF study begins with the well-known quote by Paul Krugman that 'Productivity isn't everything, but in the long run it is almost everything. A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker'.

The notion of productivity, however, has particular significance in mining since mining operates in an industry with depleting assets. Productivity growth has first to overcome the effects of this before it can make any real headway. Although much discussion on depletion focuses on the issue of grade decline in the remaining available resources,

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depletion goes a bit wider than this. It can also take the form of higher stripping ratios (the need to remove more overburden), harder rock, more complex mineralogy and more impurities in the ore (necessitating more processing). Furthermore, it implies the need to safely dispose of—and pay for—increasing amounts of solid and liquid wastes. In the absence of a capacity for the positive contributors to productivity to outweigh the negative effects of depletion, then costs of mineral production must rise and so, eventually, must prices. Moreover, the nature of the commodity business hitherto, with its homogenised products, is such that producers can do little by way of branding or product differentiation to help boost the value of their output. It all comes down in the end to costs and, to a significant degree, this means productivity.

There have, in recent years, been some worrying developments in industry productivity. Since around the year 2000, productivity in mining across the globe appears to have declined, and declined significantly. Figure 1 shows indexes of labour productivity and multifactor productivity for mining in Australia and the USA since 1990. Labour productivity (LP) is a simple measure of output per worker in mining. Multifactor productivity (MFP) is a more comprehensive indicator of productivity, which seeks to measure the efficiency with which capital, labour and intermediate products are converted into outputs. It is sometimes also referred to as total factor productivity.

Whichever measure is used—and, as Fig. 1 shows, it is often the case that these measures broadly move together—the trend in recent years is clear. There are, it is true, some signs of a turnaround since 2012, consistent with John's view that productivity has a strong cyclical component and that much of the fall in productivity shown in the figure reflects the China-induced boom in prices that occurred from around 2004. However, it is also true that most readings on productivity are still a long way below their levels of 2000.

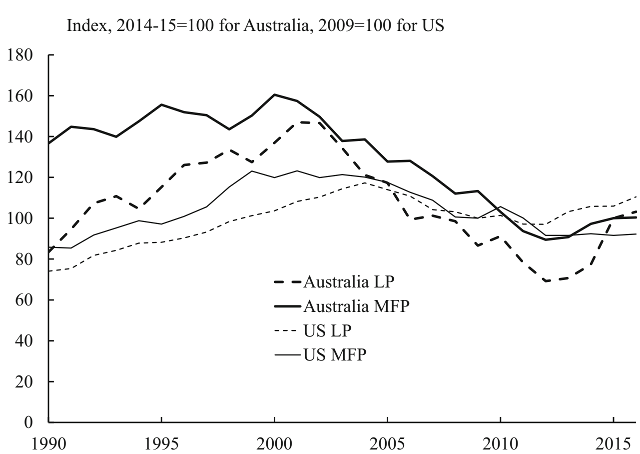

Fig. 1 Productivity in the Australian and US mining industries. Source: Australian Bureau of Statistics, Estimates of Industry Multifactor Productivity, https://www.abs.gov.au; Bureau of Labor Statistics, data for 'Mining, except Oil and Gas (NAICS 212)', https://www.bls.gov

Consistent with this observation, real terms operating costs for a number of major metals are still substantially higher than their pre-boom levels (Humphreys 2018). And then there is the rather awkward fact that the decline in productivity, in Australia at least, appears to have started before the boom got under way.

Since the passing of the boom in 2012, mining companies have made growth in productivity a central plank of their efforts to boost their margins and recover the confidence of investors (BHP 2014). And yet accounting and consulting firm Deloitte was 2 years later still talking about 'sliding productivity and spiralling costs' in the mining industry (Deloitte 2014). The consulting group McKinsey's proprietary MineLens Productivity Index (MPI), which showed a more than 35% drop in global mining productivity between 2004 and 2012, has since begun to recover, but the recovery is weak and the index remains over 30% below the levels attained before the boom (Lala et al. 2016; Flesher et al. 2018). In Chile, an analysis of the country's copper industry showed at decline in MFP of between 68 and 85% between 2000 and 2009, although it has since recovered some ground (Solminihac et al. 2018). A more substantial recovery in mine productivity may come in time but, for the moment at least, there still seems to be a pretty major problem. Is depletion finally getting the upper hand?

Background

For something as fundamental to the functioning of the industry, and which companies talk about such a lot, it is surprising how little we know about the long-run drivers of mining productivity. Partly this is about data. Most of the detailed industry data available to us only really go back only to the 1970s. While this certainly provides interesting evidence of the cyclical character of productivity, as John Tilton has demonstrated in his work, it provides only limited insights into longer term trends, something which is rather important when we are talking about the relationship between productivity and depletion.

In their attempts to get an insight into this issue going back before the 1970s, some researchers have looked to long-run trends in mining costs and prices. Generally speaking, this research, in as far as it tends to show no clear evidence of a long-term rise in mining industry costs and prices when expressed in constant dollar terms, does provide strong circumstantial evidence that the positive, cost-reducing elements of productivity must, for the most part, have grown sufficiently strongly to have offset the negative, cost-increasing effects of depletion (Barnett & Morse 1963; Manthy 1978; Barnett 1979; Humphreys 2013).

Clearly, the absence of the data which would allow us to conduct a thorough analysis of long-run drivers of productivity is an insurmountable hurdle. We cannot invent data where none exist. Nonetheless, getting a firmer handle on long-term trends in mine productivity really matters. It is hard to see how it is possible to forecast the behaviour of productivity in the future if we do not know what drove it in the past. In the absence of an understanding of what lies behind trends in productivity, we are just extrapolating.

Broadly, we know the factors which shape changes in productivity. John provides a useful list of factors which drive change in MFP (Tilton 2014).

- Innovation and technological change
- Resource depletion and ore quality
- Government regulations
- Worker quality
- Investment lags
- Economies of scale
- Capacity utilisation
- Strikes, accidents and other unplanned production stoppages
- Other factors, e.g. management, organisation and market structure

For labour productivity, one needs also to add in variations in the quantity of capital and intermediate products used for production. For MFP, these are already accounted for.

The problem is that we do not know the precise role or the exact contribution of each of these factors. Moreover, it is evident that some of these factors, like capacity utilisation and strike action, while they may be important for year to year variations in productivity, are not particularly relevant to the longer term.

Other factors, however, would seem to be more obvious candidates as contributors to long-term productivity growth. It seems probable, for example that worker quality has improved over time as the work force has become better educated and as health care has improved. Economies of scale also seem, on the face of it, a likely candidate. And, perhaps most important of all, innovation and technology, as embodied in the equipment and techniques available to each succeeding generation of miners, must surely be a crucial contributor, as John acknowledges, even if it presents considerable problems of measurement.

In what follows, we attempt to dig back a bit further into history to see what evidence we can find to help us better understand longer term trends in mine productivity and the factors driving them. The objective is to identify the factors which have shaped the trend rather than those which have shaped variations around that trend. We will then, more speculatively, consider whether the factors which appear to have contributed to boosting productivity in the past have the capacity to continue to boost it into the future. We will also consider the role that newer, digital technologies associated with what is being called the fourth industrial revolution, might be able to play in sustaining productivity growth in mining at past levels.

Long-term trends

A few years ago, in the context of an investigation into the notion of sustainable development, I developed an analysis of labour productivity in US iron ore and copper mining going back over one hundred years, using data derived from the US Bureau of the Census (Humphreys 2001). These data have been updated and are presented in Figs. 2 and 3. A logarithmic scale has been used in the figures to emphasise trends and changes in trend.

These data are not without their limitations. The census data are irregular, in general available only at 5-year intervals and, in earlier times, are even more irregular still.[1] They are also data from only one country and two commodities and the data are only for labour productivity, not MFP.

Then again, on the positive side of the account, the USA is a very big country which has had a large and important mining industry throughout the period covered, and copper and iron ore are two of the most important commodities mined. Moreover, because of the open, competitive, nature of the US economy, the odds are good that developments in the USA are a broad reflection of trends in the industry globally. Most compelling of all, they are the only consistent data series we have!

The first thing to observe from the figures is that although there have certainly been variations over the period, the overall impression of productivity growth for both commodities is one of stability and continuity. For iron ore, the average annual growth in labour productivity over the period 1860–2010 is 2.4%. For copper, it is around 3% a year, although it should be noted that productivity for copper is measured in relation to copper in ore mined, not gross copper ore. Given that copper ore grades declined over this period, a fairer measure of productivity would be copper ore mined or milled per worker, rather than copper contained in the ore. It has not been possible to do this here but our earlier work, up to the 1997 survey, suggested that this would have pushed productivity about a

[1] Because of the irregularity of census surveys, adjustments have been made to the data to make them more manageable and to fill in some gaps. Thus, census data have been allocated to the nearest 5-year interval, so that they all appear to come at the beginning or in the middle of a decade (thus, 2012 survey data have been allocated to 2010), and gaps in the earlier years have been filled by interpolation on a straight line basis. In the most recent census surveys, production data have been withheld so these have had to come from other sources. With regard to employment, reported data on copper in the most recent surveys include also employment in nickel mining, but, since this is likely to be small in the USA, it has been disregarded. At the time of writing, results from the 2017 census had not been made publicly available.

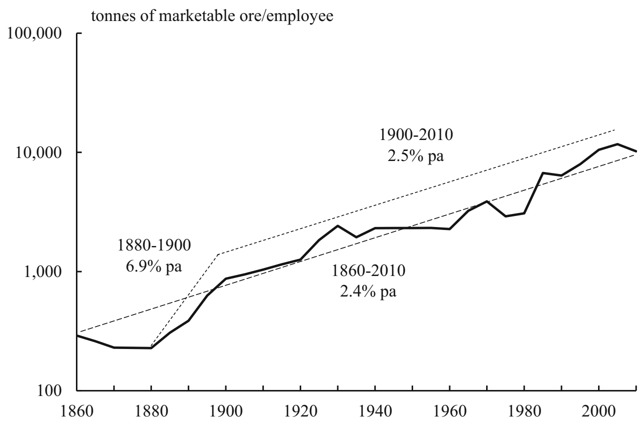

Fig. 2 Productivity growth in US iron ore mining. Source: US Bureau of the Census, USGS

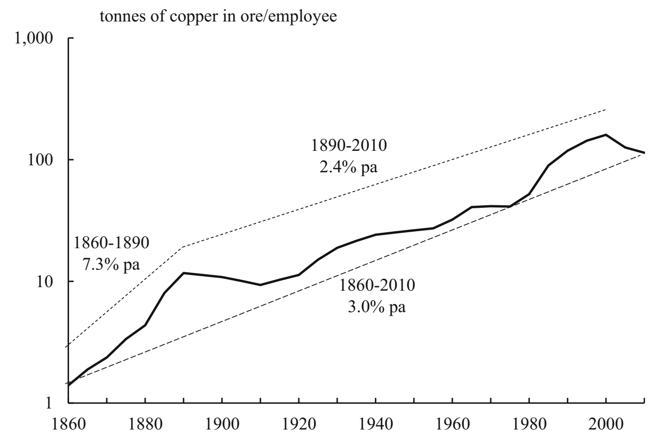

Fig. 3 Productivity growth in US copper ore mining. Source: US Bureau of the Census, USGS

percentage point higher still, i.e. nearer 4%. This is a pretty impressive achievement.

The second thing to observe is that, notwithstanding the consistency of productivity growth over most of the period covered by the figures, there does appear to have been something of an acceleration in the rate of productivity growth during the late nineteenth century, between 1860 and 1890 for copper (when labour productivity grew at slightly over 7% a year) and between 1880 and 1900 for iron ore (when it grew at almost 7%).

The reason for this is not hard to find. The latter part of the nineteenth century was the launch pad for the second industrial revolution, a revolution rooted in electrification, motorisation and the beginnings of mass industrial production.[2] Mining, with its need to drill, to dig and to haul could have been made for this revolution, and gradually the industry figured out how best to use the technologies and equipment becoming available to it.

Steam shovels were introduced in 1892 to mine iron ore in the Mesabi Range in Minnesota and in the following years, they began to be adopted more widely across the US mining industry, notably in copper and in coal. They were also exported from the USA to copper mines in Spain (Rio Tinto), Chile (Chuquicamata) and the Congo (Kambove in Katanga). Most famously, they were deployed at Utah Copper's Bingham Canyon's mine, which started up in 1906. This was a landmark development which demonstrated how technology could be harnessed to mine and process, on a large scale, low grade porphyry copper ores which had not until then been deemed economic to work (Marsh 1920; Lynch 2002). Combined with powerful new crushers and grinders to break down the ores, Wilfley tables (invented in 1895) to perform gravity separation, and froth flotation (introduced in 1910) to concentrate the copper, this heralded a revolution in the mining industry and a quantum leap in mine productivity (Lynch 2002). During the same period, the mining of gold was being transformed by the introduction of bucket dredges.

The third thing to observe is that there is the suggestion in the last few years of a slowdown in productivity growth. This is consistent with the data trends shown in Fig. 1, although, given the irregular nature of the census data, it cannot be considered conclusive. In my earlier paper, before this slowdown showed, I took the view that, on the basis of the data then available, there was no reason to suppose that productivity growth in the industry would not continue to follow the same trajectory it had for the preceding one hundred years.

Developments in mining equipment

Industrial revolutions do not come about overnight. It often takes many years for the technological breakthroughs that such revolutions make possible to be properly understood and their attributes exploited.

The longer term impact of the second industrial revolution on mining and mining productivity can perhaps be appreciated in part by looking at developments in mining equipment. Mention has already been made of the introduction of power shovels in the 1890s (steam was replaced in later years by diesel power). In this section, we look at trucks and drills.

After mineral ores have been broken out of the surrounding rock using explosives and scraped up by power shovels, then the key challenge is to get them to the crushers and thence to the mill. For this, one needs a fleet of trucks.

Early trucks were very small by today's standards. A breakthrough in truck technology came in 1915 with the introduction of the Mack Model AC 'Bulldog', a truck with a carrying capacity of 6.8 t (7.5 short tons). This became the workhorse

[2] The first industrial revolution, based largely on developments in coal, iron and textiles, launched in the second half of the eighteenth century. Mining in this era was essentially a manual activity with transport provided by animals and, later, canals and railways. Vestiges of this sort of mining persist amongst artisanal and small-scale miners (ASMs).

of the mining industry and was produced until the end of the 1930s, albeit that by then Mack had introduced (in 1932) the Model AP which could carry up to 22.7 t (25 short tons) (Haddock 1998).

Although truck capacity continued gradually to improve, at the start of the 1960s, the largest truck available to miners was still only 27.2 t (30 short tonnes), i.e. four times the size of the Mack Bulldog. From here on, however, as Fig. 4 illustrates, the pace of truck development increased dramatically, so that today the largest truck available has a carrying capacity of almost 500 t. This is eighteen times the size of the largest truck available at the start of the 1960s, potentially representing a substantial increase in mine productivity.

A similarly dramatic evolution appears to have taken place in drilling technologies, as Fig. 5, based on an analysis by Epiroc (formerly Atlas Copco) illustrates. Over the one hundred years (1907–2005) covered by the figure, drilling rates increased from 3 to 5 m per hour to 450 m per hour, an increase of one hundred fold. By comparison with the growth of truck size, the developments in drilling appear to have been a bit more even through time, although there is still evidence of an acceleration during the second half of the period. While drilling rates increased ninefold between 1907 and the early 1960s, they increased 13-fold between 1962 and 2005.

Economies of scale

Going hand in hand with the increasing size and quality of equipment has been an increase in the size of mines. This permitted the deployment of larger and more productive equipment as well as helping to reduce unit costs of production by helping to spread fixed costs over larger tonnages. Scale in mining is, in effect, the equivalent of mass production in manufacturing.

Although there can be little doubt that mines have generally got bigger over time, the evidence to illustrate and quantify this across the industry is hard to come by. Databases characterising the production and costs of the mining industry only really started to become available in the 1970s and industry-level data before this is patchy. Given, however, that some of the biggest gains from scaling up appear to have come in the post–World War II period, this may not be too serious a constraint.

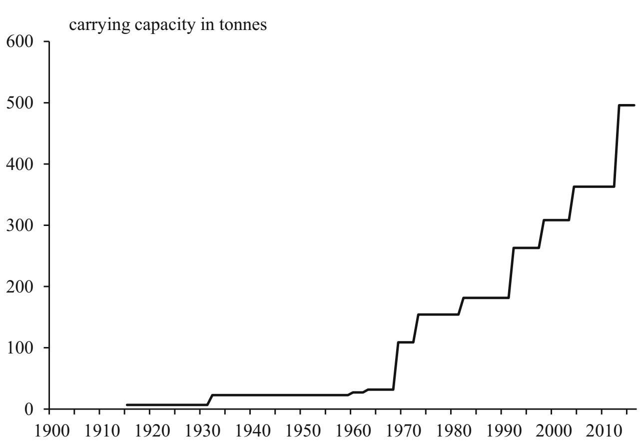

Fig. 4 Mine truck capacity: introduction date of largest haul truck on the market. Source: Industry sources

Figure 6 shows that large copper mines, defined here as those producing over 10 million tonnes of ore a year, increased their share of global copper output from 20% in 1970 to 80% in 2000.[3] Other data sources confirm this trend. Crowson (2003) found that between 1976 and 2000, the mean size of the world's copper mines grew 182% and the size of the median copper mine grew 252%. The comparable numbers for zinc mines over 1980–2000 were 117% and 133% respectively. The picture for gold was a little different. Mean mine size went down 2% but the median went up 131% between 1975 and 2000. This pattern probably reflected the closure of large South African mines during this period.

Imperfect as these data are, they are sufficient to make the point that mine size increased dramatically over the twentieth century, being both facilitated by, as well as creating opportunities for, the deployment of larger and larger equipment. Almost certainly, it was a major contributor to improvements in mine productivity.

It is unclear whether this trend has continued into the twenty-first century but is it possible that it has not. In the case of copper, the twenty-first century has not yet seen the opening of any new mega mines on the scale of Grasberg (started 1973), Escondida (1990) or Collahuasi (1999). Moreover, there is some evidence from exploration data that copper discoveries are getting smaller. Research by SLN Metals Economics Group (since incorporated into S&P Global Market Intelligence) revealed that the average size of copper deposits found declined from 5.8 million tonnes of ore in the period 1990–1994 to 3.8 million tonnes of ore during the period 2005–2011 (Chender 2012). The same research revealed that gold found in major discoveries fell steeply between the mid-1990s and the late 2000s. More recent research from S&P Global Market Intelligence confirms that these trends continued through to 2017 (Mining Journal 2018b).

Other factors

The increasing scale of mines and of the equipment used in them are fairly obvious contributors to productivity. Developments in transportation have also made an important contribution, especially for the bulk commodities like coal and iron ore. The cost of rail freight has fallen

[3] The data in this figure came from the Rio Tinto Mine Information System. It could not be updated since the system no longer exists.

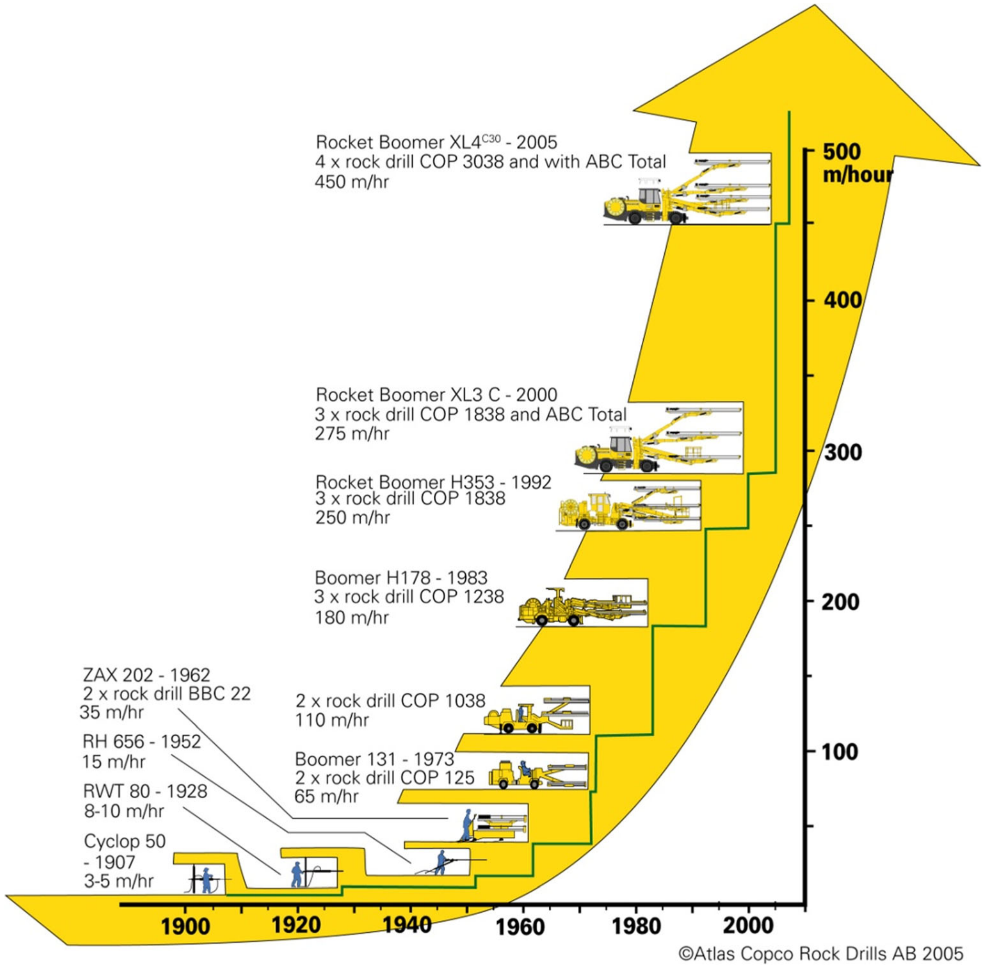

Fig. 5 Growth in drill capacity over one hundred years. Source: Epiroc/Atlas Copco

substantially over the years. According to the OECD, the cost of maritime freight in real terms halved between 1870 and 1930 and fell another 80% between the 1930s and 2000, this largely because of the growth in ship size and in particular the widespread use in recent years of Capesize vessels for dry bulk commodities (Huwart and Verdier 2013). These developments in transportation have in turn facilitated the opening up of rich but remote mineral deposits which it might not otherwise have been economic to develop. The iron ore deposits of the Pilbara in Western Australia and those in Amazonia in Brazil stand as examples of this.

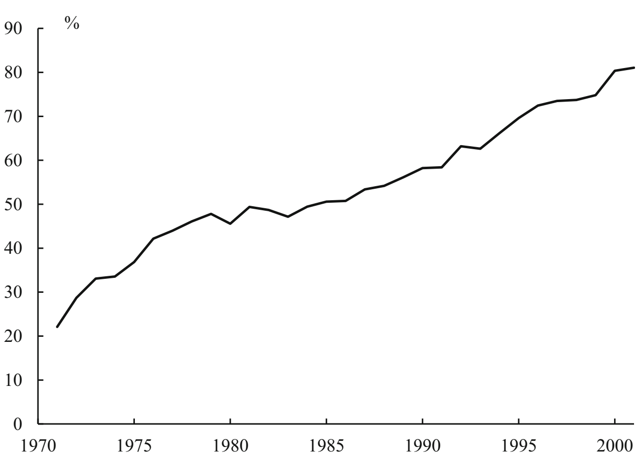

Fig. 6 Share of world copper produced by mines mining 10 million tonnes a year. Source: Humphreys 2001

But there are other factors which are harder to pin down and to measure. A major input cost to mining, often the second most important after labour, is the supplies a mine buys in. These can range from tyres, machine spares and explosives to construction raw materials and chemicals. In as far as the sectors that produce and sell these things strive to boost their own productivity, there is the potential for increases in the performance of these bought-in products, arising from innovation and technological change in those sectors, to flow through into an increase in mine productivity. Although it is true that changes in the quantity of intermediate inputs to mining are taken into account in calculating MFP, it may well be that such calculations do not fully capture changes in the quality of inputs or, therefore, the lift that they can give to mine productivity.

There is also the issue that contributions to productivity can be overlapping. We have already noted that larger mines and larger equipment are, in a sense, two sides of the same coin. Some improvements in productivity which one might put down to the exertions and ingenuity of the miners may in fact reflect the effects of increased competition stemming from globalisation or from changes in government regulations. Also to be factored is the inertia which arises from the fact that high quality, low-cost resources endow their owners with an enduring competitive advantage. (Explaining why, in stark contrast to many industrial sectors, the same companies, BHP, Rio Tinto and Anglo American, have been leaders in the industry for generations.)

Perhaps most problematic of all is the contribution of management to productivity. Intuitively, it seems highly probable that a key element in boosting productivity lies in the ability of management to pull all the various factors of production, capital, labour and intermediate products together in an effective and disciplined fashion. Moreover, the data systems that they use to monitor what is going on and to assist with decision-making must also play a part in this process, perhaps an increasing one. Unfortunately, we can only infer this from the progress of productivity; it is almost impossible to measure directly. Indeed, most of the factors which contribute towards changes in MFP report collectively in what is known statistically as the 'Solow residual', after all the directly measurable inputs like labour and capital have been taken into account, and are not easily disentangled (Solow 1957).

Tentative conclusions from the long-term history

From the data presented, it is evident that the mining industry has been remarkably successful over the last one hundred and fifty years in raising its productivity. And the fact that productivity growth has been net positive throughout almost all of this period implies that the industry has done an effective job in offsetting the tyranny of depletion. At the heart of this success, as John acknowledges in his work, has been the advancement and application of technology.

The journey through time has, however, been an uneven one. The data on US mining suggests that the initial adoption of second industrial revolution technologies resulted in a surge in industry productivity. In today's parlance, one might call this the expression of 'disruptive' development. The subsequent, slower, trend in productivity growth (particularly slow in the case of the US iron ore industry through the 1940s to the 1970s it might be noted) points to a more gradual absorption of new technologies and a multiplicity of contributing factors. Unpublished research conducted in Rio Tinto in 2000 suggested that a key driver for this trend was the gradual displacement of labour by capital and energy, this in turn reflecting a sustained shift in relative factor prices, the falling price of machinery and of energy on the one hand and rising real incomes on the other.

The variation around the trend in productivity growth since its initial surge seems, as John has demonstrated, been significantly shaped by commodity price cycles. Periods of acute price pressure have stimulated sharp increases in productivity, such as those in US copper in the 1980s and in iron ore mining pretty much everywhere during the same decade (Tilton 2014; Topp et al. 2008). This is down to a raft of factors ranging from worker layoffs, operational improvements and the lagged effects of earlier investment. During periods of high prices, by contrast, when mining companies have a tendency to focus on volume growth rather than unit efficiency, productivity has a tendency to decline.

In assessing what is driving current productivity performance and determining where things are likely to be headed in the future, it is necessary to separate out secular and cyclical influences. Is the recent apparent decline in productivity simply a cyclical phenomenon which will in time reverse or might it herald a break in the secular trend? The answer to this is rather important since it potentially has implications for the industry's capacity to offset the effects of depletion in future. We need, in effect, to try to look through the cyclical variations.

If we focus down on the things which we have identified as key drivers of the long-term, secular, trend in productivity, there are some worrying indications that they may be losing their force.

First, the increasing scale of mines along with the deployment of ever larger machinery have played what is surely an indisputable role in boosting industry productivity. But, it is hard to see these factors playing the same role in the future. The industry is simply not finding and bringing on the large mines that could take this to a whole new level. For some niche commodities important to modern technologies, large-scale deposits may simply not exist. While we can doubtless expect improvement in truck technology in the future, it is hard to believe that truck carrying capacity will, or indeed could, increase eighteen times over the next fifty years. The same consideration applies to advances in shipping. Eventually, with any given technology, one runs up against the constraints of immutable physical laws. In addition, as already indicated, the information we have available to us suggests that exploration discoveries are generally getting smaller and the cost of finding a unit of economically recoverable mineral is increasing (Koch et al. 2015).

Second, it has been suggested that an important factor driving productivity increases in the past has been capital-labour substitution, a tendency supported by the declining costs of capital and energy relative to labour. It is, of course, hard to know how the costs of these factors will develop in the future. The expectation (or, at any rate, hope) must be that labour costs will continue to rise as standards of living increase. However, the situation for energy is very unclear. It is entirely possible that energy prices will have to rise in future to reflect the cost of carbon emissions resulting from the use of hydrocarbons and to incentivise investment in carbon-free power generation.

A third concern is that the global economy has been subject to some essentially non-repeatable events which have fostered and reinforced productivity growth in the mining industry and other industrial sectors but which, having happened once, cannot happen again. Here, I am thinking of the opening up of investment opportunities which have followed on from economic globalisation, as well as the intense competition which flows from more open global markets. Transactional costs of international trade have fallen dramatically in the post–World War II era (Huwart and Verdier 2013). I am also thinking of the dramatic changes in global financial markets which have permitted the financing of very large capital-intensive projects, such as mines, even in quite high-risk countries. In short, a geopolitical environment characterised by greater nationalism and protectionism may not be as conducive to the growth of mining industry productivity as have been the conditions experienced over the past half century.

Impacts of the third and fourth industrial revolutions

Of course, we cannot rule out that, as the old drivers of productivity weaken and play out, so new ones will emerge to take up the baton of productivity growth in mining.

We talked earlier about the dramatic effect that the advent of the second industrial revolution had on productivity in mining. Conventional wisdom has it that since the ructions of the second industrial revolution, there have been two further revolutions. The third industrial revolution was a digital revolution and is generally viewed as having been launched in the 1960s or 1970s. This revolution marked the transition from analogue, electrical and mechanical devices to digital technologies. It is associated with personal computing, the Internet and advances in information and communications technologies (ICTs) (Table 1).

More recently, a view has formed that we may be entering a fourth industrial revolution, sometimes referred to as Industry 4.0 (Schwab 2017). This builds on the third revolution and is characterised by technologies which integrate the physical, digital and biological spheres. Features of the new revolution are robotics, artificial intelligence, blockchain, nanotechnology, quantum computing, biotechnology, the Internet of Things (IoTs), 3D printing and autonomous vehicles. Its impacts on production, management and society are commonly talked about in terms of their capacity to ‘disrupt’ existing practices and behaviours.

That these more recent revolutions will have, indeed already have had, an impact on the mining industry is not in doubt. The crucial question though is not whether they will have an impact but whether they will have the same kind of impact on the industry as the second revolution and have sufficient force to keep productivity on an upward path in the face of countervailing pressures from depletion.

The third revolution has been with us some time. Advances in computing have, without doubt, played a useful role in improving mine planning, truck scheduling, maintenance efficiency, process control, cost monitoring and project assessment amongst other things, while developments in communications technologies have facilitated management oversight, helped improve safety and assisted with procurement and sales. However, it would be hard to maintain that there was anything truly transformational about these changes. They would appear to have made a useful contribution to the ongoing incremental improvement in productivity which the industry experienced through the 1980s and 1990s but they do not appear to have had sufficient force to prevent the subsequent decline in productivity. Certainly, there is nothing in the data we have on productivity to suggest an impact of the sort delivered by the onset of the second industrial revolution in the late nineteenth century. The third revolution seems to have been more about the optimisation of existing technologies than about technological breakthrough.

There is currently much hope vested in the possible impacts on mining industry productivity of the fourth industrial revolution. A recent survey of CEO opinion on drivers of future industry transformation indicated that industry leaders expect digitisation to be the principal driver of future change. Third

Table 1 Four industrial revolutions

	Approximate start date	Features	Key industries
1	1760	Coal, steam, power, iron	Textiles, railways, construction
2	1870	Electrification, steel, mechanisation, oil	Cars, telephones, power, generation, electrical appliances
3	1970	Digitisation, electronics, semiconductors	Computers, Internet, media, ICT, aerospace, chemicals
4	Now	Fusion of physical, digital and biological technologies	Robotics, AI, biotech, IoTs, 3D printing, nanotech, green energy

Source: Author, based on a variety of sources on the list of drivers was falling ore grades (Mining Journal 2018a). The perspective of the CEOs appears to be rooted in the potential that the new technologies could have on enabling mines to work more intelligently, from the deployment of autonomous machinery to the wholesale networking of mines into single, interconnected and optimised entities. 'Smart', it has been said, 'is the new big'.

In 2016, the trade journal *Mining Magazine* conducted an extensive survey on the specific technologies which mining companies believe will have most impact on the industry—its profitability, productivity and safety—in the future. More than 120 mining companies responded to the survey. The results are summarised in Table 2.

Leading the list of technologies expected to have a major impact on the industry over a 5- to 10-year horizon were those related to improvements in remote geological surveying using satellites and drones, together with improved imaging. (HP is 'high powered'.)

The biggest contributions to increased performance on the production side of the business were expected to come from the application of high powered computing and big data - a shift to 'intelligent mining'. The key here is the generation of real-time information on every conceivable aspect of mining operations and the use of these data to bring about lean, factory-style production, reducing downtime, saving energy, increasing safety and boosting output.

A second cluster of technologies—the Internet of Things and operating technology-information technology (OT-IT) integration—is focused on linking all aspects of a business together into a seamless whole, collaborative IT as it is sometimes called. Unlike factories, conditions in a mine are shaped by nature and are constantly changing, so information and management systems have to be continuously adapting. Better integrated, real-time systems are seen as potentially unlocking large productivity gains by improving maintenance, mine planning and asset utilisation.

Interestingly, some of the more visible technologies, including automation and remote mining, appear further down the list, as do such physical technologies as pre-concentration, in-pit crushing and conveying systems, and improved blasting techniques.

Table 2 Mining technologies of the future: response to the question 'Which technologies will have the most impact on a 5-10 year horizon?'

Rank	Technology	% responding
1	HP satellite/drones/laser survey/imaging	97.4
2	Big data/predictive analytics	95.7
3	High powered computing/cloud	92.2
4	Internet of Things/connectivity	69.8
5	Operating technologies-IT integration	53.4
6	High precision guidance/control	53.4
7	Remote/teleremote control	50.0
8	Automation/robotics	35.3
9	Ore sorting/pre-concentration	28.4
10	Gaming type visualisation/software	25.0

Source: Mining Magazine 2016

Commenting on such developments, the head of growth and innovation at one of the world's largest mining companies is quoted as saying, 'Data is the new oil … . As an industry we have achieved incredible things through scaling and ever refining known technologies. The Tech 4.0 digital disruption is now starting to manifest in a significant way upon our industry. From cloud computing, to new sensors, to drones, to ever more automation and now the rise of machine learning and AI. This is all being fused together through data science to generate new insights' (Roberts 2018a).

Collectively, these technologies hold considerable promise and some of them are already being operationalised. Autonomous trucks and driverless trains are already a reality in the industry. However, their full potential has yet to be realised and their capacity to contribute a significant boost to productivity is unproven. In addition, they raise some awkward structural questions about the mining industry. Many of the groundbreaking technologies being developed are not the products of the mining industry itself but of the Mining Equipment and Technology Services (METS) sector. This makes mining companies increasingly dependent of the efforts of others for their success, forcing a reassessment of what constitutes their core skills set and competitive advantage (Buia et al. 2018).

Future directions

There is little question that the second industrial revolution brought about massive improvements in mining industry productivity. Later revolutions have supported these developments but, despite the rhetoric of 'disruption' which accompanies the most recent revolution, they have not, or at least have not yet, proved transformative in the same way or to the same degree. It is possible that this is simply a matter of time. Many of the benefits of the second revolution took years to come through, during which there were sustained periods of low (and negative) productivity growth (for example in US copper in the 1890s and 1900s and in US iron ore in the 1940s and 1950s). But, then again, it is also possible that the mechanical basis of the second industrial revolution gave it a special relevance to, and impact on, mining because of the industry's essential nature as a physical, earth-moving and processing, activity.

To put it in another way, while mining, along with manufacturing, may have been a particular beneficiary of the second industrial revolution, it may be that the primary benefits of the other industrial revolutions lie elsewhere. The first industrial revolution wholly transformed man's power to lift and to move things by harnessing the power of coal to replace animal muscle in transport and construction. The primary value of the third and fourth revolutions, which transform our capacity to compute and communicate, may lie in other economic sectors, for example in medicine, in design, in social media, in travel and in biotechnology. It is perhaps significant that, in the Mining Magazine survey shown above, the area where the industry expects the fourth revolution to have its greatest impact is not actually in mining but in exploration, a fundamentally more knowledge-based activity. In this context, it is interesting to note that, in recent years, the patenting of exploration technologies has, along with the patenting of environmental technologies, grown faster than any other mining-related technologies (Fig. 7). As for the business of mining itself, it may turn out that the fourth industrial revolution will deliver some useful general purpose technologies, like AI (patents for which have grown rapidly in recent years but are not included in Fig. 7), but may not be transformative in the way that the second revolution was.

Concerns about productivity are not, of course, confined to the mining industry. Slowing productivity is a widespread feature in many advanced economies (OECD 2014; Economist 2016). Moreover, economists have for some time raised questions about the impact of developments in ICT on economic productivity, with Robert Solow famously quipping about being 'able to see the computer age everywhere but in the statistics' (Solow 1987). It is unclear where the explanation for this lies, whether the problem is real and the performance of new technologies simply are not what they are claimed to be (particularly when compared to the transformative ones of earlier eras), whether we have a problem with measurement of outputs in economies with a high intangible component, or whether the introduction of new technologies works with very long lags and that we are experiencing the lull before the storm (Wolf 2018).

The objective of this article is not to argue that productivity growth in mining is in terminal decline and that commodity prices must therefore rise. Rather, it is to investigate the longer term technological drivers of productivity in the industry and to point up the scale of the challenge the industry faces in reversing the recent decline in productivity. It is also to question whether the succeeding waves of technological change represented by the four industrial revolutions have similar relevance to this particular economic sector. My conclusion is that they probably do not and that the more recent revolutions, while they will be supportive of productivity developments, may struggle to deliver the same quantum improvements that the industry was able to extract from the earlier ones.

We cannot say for sure where future changes in the industry will come from and the form they will take. It is true that, over the years, the industry has had an impressive track record of finding ways to defy the odds and combat the tyranny of depletion. And, for most of history, it has not done to bet against the ingenuity of the human race. However, it is also true that mining is an industry which suffers from considerable inertia because of its capital-intensive nature and because of the inbuilt competitive advantage which resides in certain high-quality resources. It has been suggested that the impact of the fourth revolution may be incremental at large existing mines with their sunk capital and given footprints, but may have more scope for application in smaller, more flexible, more selective, automated mines that exploit variability and have a much lower social and environmental impact. There may also be scope for technological breakthroughs in directly disintegrating mineral grains in rocks to reduce energy inputs and waste, in advanced fragmentation using new blasting techniques and in bulk sorting to eliminate waste earlier in the production process (Roberts 2018b).

While such developments may be disruptive in the sense that they change the modus operandi of the industry, shift its policy focus or lead it to supply new, more technologically, sophisticated markets, it is far from clear how they could disrupt, or transform, industry productivity. True disruption is about innovations which create new markets and value networks and displace existing markets and networks. It involves, in effect, a new value proposition for customers and investors. One can see the effects of this clearly enough in areas like retail and media (and even in oil where the advent of fracking has shaken up the global industry) but the application of the idea to mining requires a bit more imagination.

Disruption for mining productivity has to be about a fundamental step change in the relationship between inputs and outputs. In the past, the value proposition of miners has typically been found in the delivery of cheaper raw materials achieved through a relentless focus on the efficient management of inputs. It would be wrong to suppose that we have exhausted the scope for doing this. However, if, as seems possible, the ability to achieve substantial new gains in this area is diminishing, then the industry may have to explore other avenues to extract value. It might, for example point to mining companies seeking, and being able, to secure premiums for their products by branding based on the responsible and sustainable manner of their production. Or it might involve companies 'renting out' their products for the life of the goods into which they are incorporated rather than selling them, thereby positioning themselves as pivotal players in the circular economy. In other

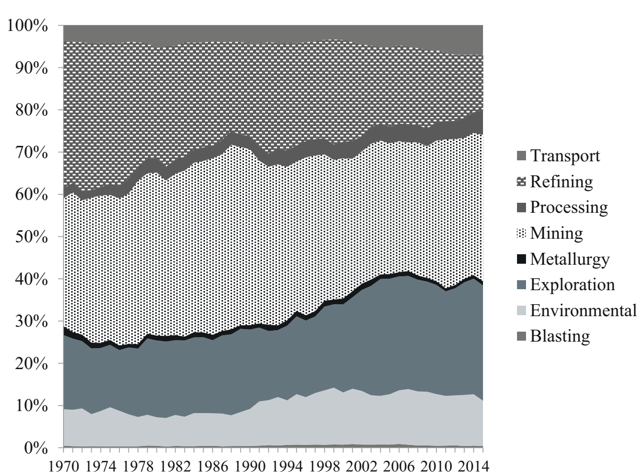

Fig. 7 Composition of mining innovation, measured by patents filed. Source: Daly et al. 2019

words, it may lie not in increasing the efficiency of use of inputs but discovering ways to promote the value of outputs.

The outcome matters. While the scale of the challenge will vary amongst commodities, pressures from depletion are unlikely to abate and may well intensity. Although it goes beyond the scope of this article, there is some evidence that depletion may be non-linear and that the challenges faced by productivity in offsetting depletion are set to get materially harder (Mitra 2018). If productivity in the mining industry does not increase to meet it, then mineral prices must rise. This is not a matter about whether one is an optimist or a pessimist. Rather, it is about having an appreciation of how things worked in the past and adopting a hard-nosed view about whether it is reasonable to assume that what applied in the past is likely to apply in the future. What cannot be doubted is that the mining industry is going to have to work very hard and to be very creative to maintain the momentum of its past productivity performance.

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