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Viewpoint

Automation and robotics in mining: Jobs, income and inequality implications

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ABSTRACT

Although mining is a capital-intensive industry, its contribution to employment creation is generally praised as a leading local benefit to justify new or expanding extraction projects. However, labour substitution from automation and robotics is increasing in a wide range of modern mining processes. Such labour replacement is likely to intensify in the coming years due to advances and cost reductions in technology. Additionally, the COVID-19 pandemic also adds to the impetus of relying less on human interaction for critical operational processes. In this paper, we provide some insights on the global trends of automation/robotics in mining and discuss the main economic impacts that increasing human labour substitution could bring to mining communities, regions, and nations. We focus on mining automation/robotics impacts on jobs, income (including taxes), and regional inequality. We conclude by discussing policy options that governments could consider for mitigating these impacts, including the reskilling of miners and tax transfers.

1. Introduction

The COVID-19 pandemic has shown to multiple industries the benefits of increasing automation systems where human contagion risks are reduced in operations.[1] This benefit is especially noticeable across many mining operations that have seen just a few disruptions during the pandemic, thanks to automation processes (Australian Mining, 2020). Also, considerable technological improvements and reduced costs have provided new ways to process mining operations remotely, deepen the use of automation, and increasingly employ more robotic systems across different operations (East, 2019).

Mining is a capital-intensive activity, meaning that labour has historically and increasingly being substituted by machinery and automated processes. On this, Acemoglu and Restrepo (2019) show how in the US, the labour share in the value-added generated by mining has consistently decreased over the years, from around 40% in the mid-1990s to about 20% in recent years. Modern technology has promoted and speeded this decreased share, with mines becoming increasingly automated and operated from remote offices. Nowadays, it is common to have mine trucks drove and machines controlled by operators sitting in an office in Santiago, Sydney, or London – located thousands of miles away from operations. Although humans cannot be totally out of mines and operations (Lynas and Horberry, 2011), advances have reached such a point that the first 'self-proclaimed' fully automated mine is taking place in Mali (Mining Technology, 2018; East, 2019). These trends are just likely to keep expanding across operations. In early 2019, a worldwide survey asked more than 800 executives and representatives of 399 mining companies what technology areas will have the most significant impact on mining innovation over the next 15 years. Of those surveyed, 73% responded 'robotics and automation' (State of Play, 2019).

Increasing automation and employment of robots in mining can bring diverse social and economic impacts on mining communities, regions, and nations. These increasingly likely impacts are the focus of attention of this paper. In particular, we target our discussion on three main impact areas to understand better the trade-offs – benefits and negative consequences – that automation and robotics can bring to local and national economies.[2] The three main impact areas are:

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[1] Also reflected in online retail sales, with the shares of Amazon reaching a historic value during the pandemic (Neate, 2020).

[2] Hereafter, when we refer to 'automation', we are implying both automation *and* robotics.

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- Labour markets: An increase substitution of human labour by automation/robotics will cause a reduction of labour demand from mining activity, affecting labour markets in mining regions and labour mobility at the national level mainly due to a decrease in fly-in fly-out or drive-in drive-out (FIFO/DIDO) flows.
- Income: Lower labour demand will provide fewer jobs with high-earning salaries typical in mining. A decrease in local wages will subsequently reduce the disposable income available in mining regions, generating a diverse pool of indirect effects for mining communities and the rest of the communities who send mining workers. We also include some insights on the implications of this on income and sale taxes.
- Inequality across and between regions: A decrease of high-earning jobs will likely shift the median salary of mining regions to the left, narrowing the tail of high-income earners in mining regions while generating less wealth in these regions in contrast to non-mining areas. This last effect will be exacerbated by skilled labour employed in mining that will be able to operate remotely from cities and high amenity areas – an out-migration of high-salary earners out of mining regions.

We expand on these impacts and their implications for economic development below. After this, we provide a list of potential strategies that local and national governments could implement to reduce the incidence of negative impacts in the medium and long-terms. The analysis we provide here is also very relevant for the mining industry because it is widespread to observe new mining projects receiving political support and their social license to operate (SLO) based on the promise of job creation in new projects (Dumbrell et al., 2020; Nguyen, 2020). The potential new (generally well paid) jobs that mining projects bring to regions is the main benefit that mining companies typically bring to the negotiation table to seek support from local stakeholders when applying for new or expanding mine operations. With the 'rise of the machines,' the welfare-improving benefit of new jobs will fade over time as significant higher shares of operations functioning by automated processes, robots, or by human operators working remotely from distant cities are likely to materialize. A jeopardy to the SLO of mining companies.

2. The 'rise of the machines' and the economic outcome of mining activity

Discussions about the "rise of the machines" and their threat to human labour got a significant momentum in 2013, after a working paper coming from Oxford University (Frey and Osborne, 2013). The article, published in a peer-reviewed journal four years after its appearance (Frey and Osborne, 2017), assessed the automation potential of different jobs across sectors.[3] The authors claimed that 47 percent of all jobs in the USA are potentially automatable over some unspecified number of years –perhaps a decade or two (Frey and Osborne, 2013). Although the study has been lately refuted with claims that their estimates are overinflated and unnecessarily praised (e.g., Goos, 2018; Coelli and Borland, 2019), Frey and Osborne (2013) elevated the discussion of automation across the academic and public debate.

Following this debate in academia, many consultancy-sourced estimates have provided risk measures of labour displacement in recent years (e.g., CEDA, 2015; McKinsey Global Institute, 2017; Alphabeta, 2018), which have increased the public and policy attention to the topic. Although these estimates are generally questionable (and very uncertain), it is a fact that automation and robotics will eventually replace an important number of jobs in the future, especially in areas requiring low cognitive skills or that require scarce interaction with other humans.

Given its capital-intensive nature, even in large mining countries such as Canada, as seen in Table 1, the number of people employed by mining do not pass of the 2% of the total country employment. Chile did use a larger share, around 3% in 2013, but it also has a higher percentage of mining output in the total gross domestic product (GDP) of the country. To scrutinize whether an apparent decoupling from mining labour and mining out do exist – if there exists a clear substitution of labour with automation— it would have been interesting to observe labour/output variability across large mining countries (those with the largest mining sectors as contribution to national GDP). Alas, disaggregated mining labour data is only available only for select countries of the Organisation for Economic Co-operation and Development (OECD) group (such as the ones shown in Table 1), impeding such analysis. Using available data, we provide the closest possible analysis in Table A1 of Appendix 1. There we list the top countries in terms of mining contribution to GDP and their unemployment rates for two periods. As seen, in many cases, mineral rents have considerably increased between 2008 and 2018, but such positive change has not been in hand to a significant decrease in unemployment rates – in some countries such as Uzbekistan and Burkina Faso, the unemployment rate has notably increased. Although many factors explain such disparity, the case of a small economy such as Mongolia can be signalling the increasing capacity of the mining industry to raise rents without necessarily employing more people.

Of course, part of the variability of mining labour and rents across countries in Table 1 (and in Table A1, for rents) depends on the type of resources being extracted, the commodity cycle, and prices. For instance, the extraction of underground coal is more labour intensive than the extraction of oil, or the country can be in a mining boom given the high prices of an abundant commodity and therefore renting and employing more than others. Regardless of these considerations, the numbers in Table 1 help to understand the magnitude of the industry for particular countries and the low level of labour intensity in this economic sector.

Even though the mining industry employs a small share of the workforce of a country, the mining workforce does bring multiple benefits to different regions. Fleming and Measham (2014), for instance, estimate that for every additional ten jobs created in mining in a mining region in Australia, an additional four jobs are generated by spillover effects in the same region. This points out that employment generation in mining is not just crucial for miners, but for many local economies that sustain their activities on the disposable income of miners. The primary source of this spillover effect is given by the demand/consumption effect that higher disposable income generated by mining jobs produce in the region. On most occasions, the median income of a miner is considerably higher than national averages.

In highly geographically concentrated countries such as Chile (where one sizeable metropolitan area encompasses most of its population), the role of mining employment means the source of economic survival for many regional cities and towns. In the case of Chile, while most economic activity is based on its large metropolitan area (Santiago), for

Table 1
Mining employment and income generation across select mining countries.

Country	Year	Total mining employment (000′)	Share of total employment (%)	Mineral rents (in billion US $)	Share of national GDP (%)
Australia	2008	163.45	1.52	63.56	6.03
	2018	240.65	1.91	70.69	4.93
Canada	2008	265.80	1.45	13.01	0.84
	2018	272.30	1.46	8.07	0.47
Chile	2013	254.72	3.27	40.23	14.45
	2018	207.69	2.48	34.18	11.46
Mexico	2008	192.30	0.46	4.77	0.43
	2018	204.15	0.38	10.38	0.85

Sources: Employment data from OECD (2020) – data for Chile not available in 2008. Output data from World Bank (2020).

[3] The journal version of the paper has over 6,000 citations in Google Scholar.

Table A1
Mining output and unemployment rate across countries with the largest contribution of mining to GDP (ranked as values in 2018).

Country	Mineral rents (in billion US$) 2008	Share of national GDP (%)	Unemployment rate	Mineral rents (in billion US$) 2018	Share of national GDP (%)	Unemployment rate
Mongolia	1.13	20.08	5.57	3.79	28.88	6.25
Congo, Dem. Rep.	1.52	7.67	3.26	7.57	16.17	4.19
Mauritania	1.80	35.02	9.40	1.05	14.88	9.46
Zambia	2.61	14.55	7.93	3.95	14.62	11.50
Papua New Guinea	2.39	20.47	1.98	3.00	12.79	2.42
Sudan	0.12	0.21	14.80	3.31	12.70	16.90
Chile	33.87	18.86	9.28	34.19	11.46	7.23
Guinea	0.49	7.01	4.20	1.18	9.68	4.25
Burkina Faso	0.10	1.07	3.61	1.56	9.64	6.09
Peru	11.05	9.17	4.06	18.23	8.21	3.39
Mali	0.68	6.96	10.21	1.41	8.19	7.11
Uzbekistan	2.02	6.84	4.89	3.71	7.37	5.74
Ghana	1.13	3.97	4.76	3.71	5.65	4.16
Australia	63.53	6.03	4.23	70.70	4.93	5.30

Sources: Data from World Bank (2020). We only report here countries with over 1 billion dollars in minerals rents in 2018.

several regions, mining is the main sustention of economic activity (Paredes, 2013). The region of Antofagasta, the most important mining region in the country and principal copper region in the world, had in 2016 43,354 people directly employed by mining, while unofficial estimations quadruple this number when outsourcing activities are included. The median monthly salary of a miner in Chile in 2019 was around $700,000 Chilean pesos, which was two times higher than the median wage in the country.[4]

In addition, to bring indirect economic spillovers by demand for goods and services, the salaries perceived by miners are also an important source of tax revenue. In addition to income tax, the higher disposable income of miners also means higher tax revenues from the consumption of goods and services and property taxes. This last one is generally very relevant for local economies, as they directly support local government budgets and real estate market activity.

An increasing mining automatization and the employment of robots will affect job trends, salaries, and income tax revenue in mining countries. The relevant question is, how much will automation affect these economic indicators? An exact answer to such question is practically impossible to determine as the substitution of human labour will be conditioned by many aspects, including policy regulation, across countries. However, regardless of the final impact of automation on these areas, it is clear that the level of these indicators will likely decrease over time if new automation-intensive mines are not able to absorb the workforces of future mine closures.

3. Mining automation impacts on employment

Given its capital-intensive nature, a large number of routine job processes, and the hazards that many job activities possess, mining operations are generally a fertile ground for the application of automated processes and robotics. For instance, in the case of the large coal mining industry in Queensland, Australia, using labour replacement estimates from Alphabeta (2018), Fleming-Muñoz et al. (2020) state that automation could see around 10,000 coal mining jobs being replaced in the near future – or approximately 40% of the current Queensland's coal mining labour force. The authors argue that such a reduction in numbers can be mitigated by proposed new coal mining projects in the State. However, Fleming-Muñoz et al. (2020) also state that all new mining projects will likely demand much less human labour than in the past, reducing the potential benefit of employing an increasing number of displaced miners.

One crucial issue to fully understand the impact of automation in employment is the lack of reliable data for mining employment over time. At a country level, for instance, as we discuss above, we only found data from a select group of countries in the OECD, while for most countries, such information is not available. Data on employment by mine site is generally hard to track over time as the industry many times fluctuate operations by commodity cycles or after price signals. In addition, the wide use of subcontractors employed by the mining sector in some countries makes the tracking of the number of mining jobs even harder –people can be directly working in mine sites, but their source of employment can be listed in a non-mining company. This problem is most evident for less developed mining countries such as Perú, Mexico, and Chile.

This lack of reliable employment data is a double edge sword because it also affects economic modelling to estimate job spillover effects. This is key because the typical input-output models used by mining companies and planners to justify mining projects generally tend to overestimate the potential number of new (direct and indirect) jobs to be created – see, for instance, criticizing the I-O jobs figure of different reports used to justify shale gas extraction in the USA. Thus, if such figures have tended to be overestimated in the past, with the increasing wave of automation and the lack of consistent data, job numbers provided by I-O tables or similar models will need to be increasingly scrutinized.

Within labour markets, the effect of automation and robots is a tale of winners and losers. While low-skill routine jobs are more in jeopardy, demand for high-skill workers will tend to keep increasing as automation technology would require a workforce capable of operating sophisticated machinery and computer coding. However, this disbalance of labour demand has two clear outcomes: (1) the increase in demand of skilled workers will never provide the number of jobs to be lost for automation as economy of scales will tend to decrease employment needs; and (2) most of the high-skill labour is likely to operate automated machinery or manage robots from high-amenity regions (such as large cities or coastal towns), resulting in low or negligible economic spillover to regions hosting mining activities or their nearby small cities (Frank et al., 2018). This last effect will add out-migration pressure to mining regions over what FIFO/DIDO labour schemes have already produced to local mining economies (Paredes et al., 2018; Palomino and Sarrias 2019).

On the other hand, the benefit of automation in mining is the increased safety and efficiency that this can bring to mine sites. Many mining jobs are deployed in hazardous environments, so the replacement of human labour by machinery is a positive step for safety and health outcomes. With the increasing use of robots, mining will be a safer activity requiring lower levels of investments in human safety.

[4] Derived from the 'Encuesta Suplementaria de Ingresos (ESI)' from the 'Instituto Nacional de Estadísticas' of Chile.

However, here an important economic trade-off is likely to materialize, especially in developed nations: increased security could mean lower salaries, as mining companies will no longer need to pay premiums for hazard exposure. This is another implication of automation on income and taxes.

Another benefit of automation and remote operations is the increasing diversity in the labour workforce. Given that now operators can locate in cities, the participation of women in the mining workforce is facilitated, providing increasing opportunities for a large segment of the workforce that in the past had not much chance to locate in remote mining locations. Finally, important to consider too that in many cases new or expanding mine operations would not be viable without higher levels of automation, so the resources and royalties generated by these would be a positive impacts that otherwise (without automation) might have not been materialised.

4. Income (and taxes) impacts

The immediate expected economic effect of lower labour demand as a consequence of automation is a decline of wages in low-skill workers. On the contrary, it can be expected that high-skilled workers will see their wages increase. These effects can have general equilibrium effects in other industries because if the mining industry has considerable monopsony power in a particular region, the changes in wages can also affect the salaries offered by other sectors (Modrego et al., 2017). Thus, if wages in mining decline, it can be the case that wages in other non-mining industries will also decline in the community.

In addition to a potential decrease in wages for the average low-skilled miner, there will be a total accumulated effect of less disposable income in mining regions as consequence of a lower number of mining jobs. This is not a new effect perceived in mining regions, as FIFO/DIDO employment move most of the miners' disposable income to the places where they reside. However, the rise of automation is just likely to increment the FIFO/DIDO effect, but without the wage, premium effect paid to miners that engage in long commuting efforts (Paredes et al., 2018).

As aforementioned, a decrease of both mining wages and the number of mining jobs will have a direct effect on income tax revenues, but also an impact on property value tax collection as lower disposable income will likely also affect the housing market of mining communities, decreasing house values and therefore the taxes they collect as well as with direct consequences on local public goods in mining communities (Oyarzo and Paredes, 2018).[5] For the immediate effect on income tax revenue, even assuming that substituted miners and the reduction of future job opportunities in mining can be absorbed by employment demand from other industries, it is improbable that the level of wages will equate to that paid by mining.

5. Inequality between and among regions

Potential higher wages of a few numbers of high-skill workers in contrast with lower or stagnant wages of low-skilled workers will tend to increase inequality within a society if non-skilled workers are considerably more than skilled ones. Automation tasks favour high-skill workers who tend to have a comparative advantage in new and complex tasks, while automation substitutes capital for labour in lower-indexed jobs where low-skill workers have their comparative advantage (Acemoglu and Restrepo, 2018). This is a potential consequence of mining automation in mining regions, which can bring further challenges to the SLO of mining operations, given that as inequality increases, so can social discontent (Lopez and Miller, 2008).

[5] This is particularly important for countries like Chile, where around 40% of local government budgets come from property taxes (Oyarzo and Paredes, 2018)

On the other hand, cross-regional inequality is also likely to increase between mining and non-mining regions. As automation allows high-skill operators to work from remote offices in high-amenity regions, out-migration of high-skill workers from mining regions is likely to continue happening. This will bring high disparities in the disposable income of regions, increasing between region inequalities. An increase in the inequalities that FIFO/DIDO labour systems have already produced (Perez-Trujillo, Oyarzo, and Paredes, 2020). In addition, as discussed extensively by Piketty (2014), the marginal return of capital is more considerable than labour, which produces an increase in income and wealth inequality. As the owners of capital tend to live in cities, automated mining operations will generate wealth for their owners, increasing the disparity between cities and regions. This concern is even more relevant for those mining countries already characterized by sizeable spatial inequality, such as the case of Chile (Atienza et al., 2020)

Given these points, the substitution of labour from automation will very likely increase both within and between regions inequality.

6. What can be done to address socioeconomic negative impacts?

Although human labour has been increasingly substituted by modern technology across all industries in the last century, the fast track of automation and robotics in capital intensive sectors such as mining (likely to speed up given events such as the COVID-19 pandemic) brings a complex and challenging scenario for regional prosperity. What can regions and countries do to avoid the consequences of lower labour demand from mining activity? And what about lost governmental revenue from lower income taxes? If inequality is likely to increase between and among cities, are there ways to control these increasing disparities? The solutions to these wicked problems are not easy and require robust research and debate. Here we point to some options that can, in theory, address some of the potential negative impacts discussed in this paper. We do not claim these are the best solutions but are starting points of discussion.

4- *Learning and adapting from 'Just transition' programs*. In recent years the notion of 'just transition' has importantly emerged as countries moving away from fossil fuel can see many workers negatively impacted (Jakob et al., 2020). Regarding this, we can learn from the just transition literature and ensure that governments plan a transition process that could allow miners to move to a different industry or opt to achieve a high-skilled position in mining after proper training. among actions related to just transition, we can mention
   - Skill transitions should take full place in mining regions
   - Reinforce the role of local universities to orient the academic structure towards those skill areas with potential growth over the standard mining industry
   - Economic support packages to substituted miners

4- *Management of community expectations*. Expectations regarding new job opportunities in future mining projects should be critically managed. Misleading expectations on the number of jobs promised by new mining projects can jeopardize the local SLO of mining companies. To reduce this risk, it is important to be upfront and transparent with local stakeholders with respect to the number of local jobs new projects will generate versus the number of remote operators.

4- *Improve mining labour data to estimate potential lost tax revenue*. In direct relation to the previous point, if governments want to estimate potential losses in tax revenues from the lower prospects of employment generation in new automated mining operations, it is important to evaluate and contrast job numbers to historic mining employment trends. With reliable data, governments can better estimate average historical ratios workers/mining output so that future projects can be contrasted to such ratios and the impact of automation assessed. This point resembles the discussion of 'robot taxes' raised by some economists (e.g., Zhang, 2019; Gasteiger and Prettner, 2020) but focusing on mining outputs obtained without the incidence of labour operation.

7. Conclusion

The rise of automation and robots are already creating a significant disruption in labour markets, essentially turning the production into more capital-intensive processes. Mining activity has always been a capital-intensive economic process; however, this tendency is just likely to exacerbate in the coming future. It is not hard to find nowadays several automated mining trucks operated by one person sitting in a city office. Given this rapid evolution of technology, it is not a stretch to think that in the medium-term, mining activity will be operated and managed by fewer humans and by multiple machines and algorithms. This trend will produce real-life implications for many mining countries and regions. Our intention with this paper is to bring a discussion on the topic by providing insights mostly on the likely socioeconomic negative impacts that automation can bring to mining communities and countries, although we also outline some of the positive benefits that this change is bringing such as increased safety and work force diversification. Focusing on the negative implications, we briefly discuss potential options to mitigate some of the described impacts. Further research is desperately needed to start evaluating the current implications of automation and robotics and better plan strategies for a transition that could allow a Pareto optimal rate of resource extraction.

Finally, something that we do not discuss here is the intergeneration issues that automation in mining can bring. As Sachs et al. (2015) point out, a rise in robotic productivity is more likely to lower the welfare of young workers and future generations than the current workforce. It is the incoming new mining operations the ones that will increasingly employ fewer people, proving lower employment opportunities to new generations. This intergenerational impact points alarms to the future of mining regions. Are there going to be enough future miners to sustain mining towns or regions? Nowadays, it is hard and in the future will be practically impossible to have new human settlements occurring because of the opening of a mine, such as were the cases of Calama in Chile or Denver in the USA. A modern mining industry requires serious social, urban, and regional planning based on research, political deliberation, and stakeholder consultation.

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Appendix 1. Mining output and unemployment

Table A1.

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