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Life cycle assessment to demonstrate how automation improves the sustainability performance of an underground mining operation

Cover Page Footnote

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Life cycle assessment to demonstrate how automation improves the environmental performance of an underground mining operation

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Abstract

The worldwide move to introduce more automation into underground metal ore mining is currently aimed at improving both operational productivity and safety. A comparative life cycle assessment (LCA) was used as a novel approach to determine the beneficial impacts automation can also have on environmental performance, using data collected on mine site productivity and energy consumption. The LCA looked at four impact categories: global warming potential, acidification, eutrophication, and human toxicity. When comparing automated equipment to their traditional manual counterpart, all four impact categories experienced a reduction with automation and a subsequent improvement in sustainability performance. Global warming potential, for example, decreased by 18.3% over the mine life period, or 3.7 kg of carbon dioxide equivalent (CO₂ eq.) per tonne of ore extracted. Environmental impact reductions were due primarily to lower diesel fuel consumption in the loading and haulage processes as well as a 27% shorter operational mine life leading to less years of mine and mine camp maintenance.

Keywords: automation, energy reduction, environmental benefits, life cycle assessment, metals, underground mining

1. Introduction

Mining companies around the world continue to explore and assess new methods of extracting ore to improve safety and economic sustainability. Global concern of climate change and increasing restrictions on industrial emissions also obligates the mining and metallurgy industry to reduce their impacts on the environment. A life cycle assessment (LCA) technique can be used to gauge the environmental impacts of new extraction methods by quantifying the impacts of each process from raw material extraction through final use and ultimately disposal or recycling. However, while an LCA is one of the most popular methods used to quantify environmental performance, studies specifically

involving mining operations have increased but are still very limited [1].

Automation has become increasingly more popular in the mining industry as companies continue to experiment with automated equipment as a method of extracting ore more efficiently, in particular as they continue to develop deeper underground [2,3]. Automated technology has become a focus for three main reasons:

- (1) Safety – Automated equipment can be operated safely from the surface via remote control, removing personnel from hazards associated with the underground environment and areas with poor air quality and operating conditions such as high temperatures in deep mines [4,5].
- (2) Productivity – Productivity is increased through improved cycle times and operation of equipment from the surface during the blast window.

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Personnel are not permitted underground during large production blasts. On average, 4–5 h of production is lost during the blast window per day using current manual operated equipment [3], however, automated equipment can be operated from the surface during this time to boost productivity.

- (3) Maintenance – Manually operated equipment is subject to operator error, poor visibility and blind spots, leading to collisions with drift walls, excess tire wear and overwork engines [6,7]. Whereas, automated equipment is associated with fewer collisions, increased tire life, optimized driving and reduced consumption of spare parts [8].

Various LCA studies have previously been carried out to assess the environmental impacts from mining and mineral processing. A comparative LCA study was performed for three methods of tailings management for a copper zinc underground mine located in Canada. The authors reported that results from a specific site could be applied to other sites, but with caution due to differences in parameters such as ore grade, topography and other site-specific characteristics [9]. An LCA study of iron ore and bauxite mine sites concluded that loading and haulage operations were responsible for the highest greenhouse gas (GHG) emissions, while crushing and grinding operations were the largest contributors for copper production [10]. Another study reported that copper producing mines had a wide range of total GHG emissions (1–9 t CO₂ eq./t Cu.) due to differences in factors such as fuel sources, electrical energy sources and ore grade [11]. This supports the observation of Reid et al. [9], that varying mine site characteristics will have a significant impact on the total emissions produced on site.

There is, however, very limited available research on the environmental impact of autonomous equipment in the underground mining industry. This paper will focus, therefore, on comparing machine fuel efficiency, mine site energy consumption and length of mine-life for an underground metal mine operating with either manual or automated equipment to investigate their effects on the environment. This was done by using data collected from automation trials within a Canadian underground mine. The mine's use of automated Load-Haul-Dump (LHD) yielded positive results relating to increased productivity (35%) in removing ore from the stope, as well as improved fuel efficiency which led to lower overall CO₂ emissions from burning diesel fuel [12]. The environmental impacts

of these trials have been analyzed here using an LCA approach.

An LCA is a technique used to assess the environmental impacts of a product's processes from raw material extraction through final use and disposal or recycling. LCAs are used to analyze the environmental contribution of each life cycle stage with the goal of identifying areas for improvement and/or to compare different products/processes [13]. An LCA is carried out by defining the goal of scope, inventory analysis, impact assessments and interpretation as shown in Fig. 1. The ISO 14040:14,043 standards were created to for the evaluation of environmental performance of a product or service throughout its operational life cycle. The standards are listed below [13]:

- ISO 14040: Overall standard which includes all four phases of the LCA study.
- ISO 14041: Standards for goal and scope definition/inventory assessment.
- ISO 14042: Standards for life cycle impact assessment methods.
- ISO 14043: Standards for life cycle interpretation methods.

1.1. Goal and scope

This study analyzes an underground metal mine (zinc-copper-silver-gold) whose products from the extracted ore are a zinc concentrate (51% Zn.) and a copper concentrate (21% Cu.), with trace metals gold and silver found within the copper concentrate. Analyses of the ore and concentrate products are provided in Table 1 in terms of the defined functional unit for this LCA study (one tonne (t) of ore mined and processed).

The LCA study performed incorporates drilling, blasting, hauling, hoisting, crushing, grinding,

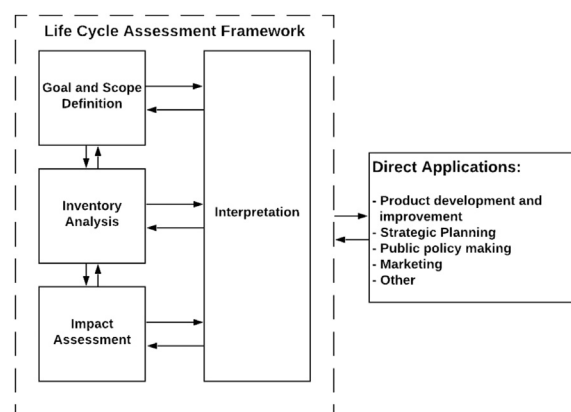


Fig. 1. Stages of an LCA study [13].

Table 1. Material analysis for the mined ore, zinc concentrate, and copper concentrate.

Material	Zinc	Copper	Silver	Gold
Ore				
Quantity	51.2 kg/t	6.9 kg/t	26.5 g/t	2.61 g/t
Recovery	92.5%	85%	50.9%	57.7%
Zinc Concentrate				
Quantity	51%	–	–	–
Contained Metal	47.3 kg	–	–	–
Copper Concentrate				
Quantity	–	21%	-0.05%	-0.005%
Contained Metal	–	5.87 kg	13.5 g	1.5 g

flotation, dewatering, and subsequent transportation of concentrated products to external refinery sites and disposal of waste tailings. Fig. 2 is a simplified process diagram showing the LCA boundaries.

The processes seen in the mining and milling sections of Fig. 1 are dependent on ore productivity, meaning as the productivity is increased from the use of automated equipment, the resources required for those processes (fuel, electricity, process water, compressed air, etc.) are also increased. However, improvements may still occur from efficiency gains of automated operations (e.g. fuel efficiency). Other processes, such as ventilation and the mine camp, remain constant when the productivity is increased, but these processes will experience significant overall reductions by eliminating approximately five years (27%) of total operation time (Table 2).

The data obtained was extrapolated over the mine's projected life based on fixed ore reserves of 20 million tonnes. The productivity measured at the mine site for both manual and automated LHD machines is listed in Table 2 along with calculated life-of-mine. The ability to extract ore at higher daily rate was estimated to decrease the mine life by 27%. It is generally expected that environmental benefits from automating underground equipment will be seen through improved fuel efficiency and energy consumption. Whereas, the effect of a reduced mine life is unknown, but may also prove to be significant in reducing overall environmental impacts. The outcomes arising from eliminating five years of mine and mill operations, mine camp related activities (water processing, landfill disposal, and energy consumption), and daily travel to and from the work site were, therefore, assessed within the LCA study.

The mine camp process considers the electricity, water and food requirement for the housing of work personnel and subsequently the wastes generated from daily living (garbage and wastewater). The mine camp process also includes emissions produced from burning gasoline for personal travel on

and off site by all workers required for mine and mill operation. The existing mine workforce is comprised of 340 employees with a mine camp capacity of 198 persons. The nearest town, along with mine camp, is located 16 km away from the mine site. The breakdown for workers' travel is shown in Table 3 and was used to calculate emissions from daily travel to and from the worksite.

The calculation for yearly distance from the various methods of travelling to and from the mine site takes into consideration the following:

- (1) As carpooling is a common method of travelling by work personnel, usually comprising of 2–4 people per car, an average of 3 was used for this study.
- (2) Personnel travelling from surrounding communities and long distances travel both ways once per week, as well as require travel from the mine camp daily.
- (3) The airport is located 208 km from the mine site, therefore personnel who require flights also include road transportation both ways, followed by travel from the mine camp each day. Personnel travelling by air are typically members of senior management and therefore are expected to travel sporadically.

Items included within the mine and mill miscellaneous processes shown in Fig. 2 are also not affected by an increase in ore production. Operating equipment such as boom-trucks, mincats, forklifts, personnel carriers are all included within this process as well as electric energy consumption for operations unrelated to the movement of ore, which will experience a decrease of five years due to the reduction of mine life. A list of the electric utilities included within the mine and mill miscellaneous sections is provided in Table 4.

2. Materials and methods

The LCA study is an analysis of inputs and outputs for all the processes within the defined boundaries,

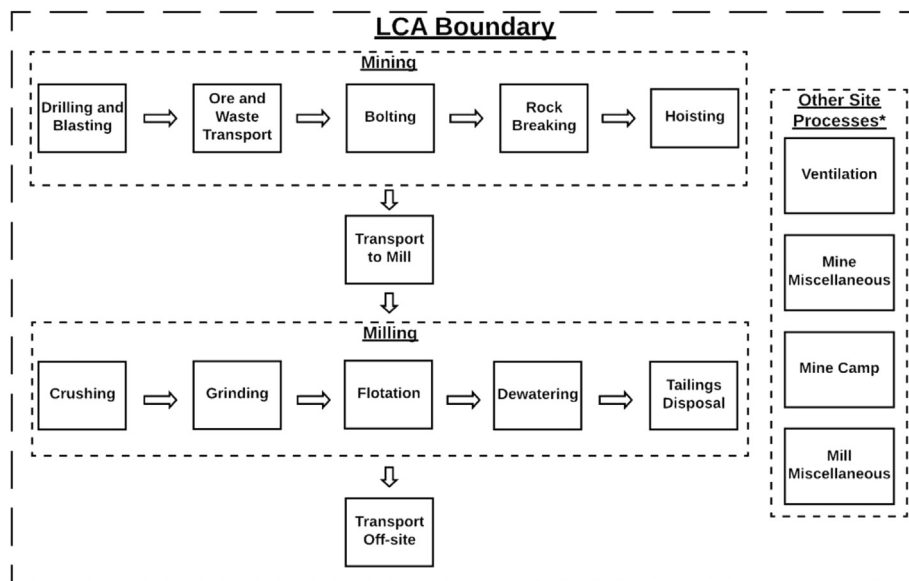


Fig. 2. Boundary for the LCA study of the investigated mine site. *Not included within the flow of ore (time-dependent).

Table 2. Operational data for manual and automated LHD operation at studied mine site.

LHD operations	Ore reserves	Production rate	Life of mine
Manual	20,000,000 t	3000 t/day	18.3 years
Automated	20,000,000 t	4050 t/day	13.5 years

which include environmental inputs/outputs and those related to the Technosphere (the environment that is made or modified by humans). Table 5 provides the list of inputs/outputs for both the manual and automated operations that were examined in this LCA study with respect to the defined functional unit of mining and processing one tonne of ore. Scenario 1 contains the data obtained for entirely manual operations at the mine site. Scenario 2 analyzes the process using automated LHDs, with productivity and fuel consumption statistics taken from the trial results. Scenario 3 includes projections for additionally including automated haulage trucks and drill rigs.

2.1. Productivity analysis

Productivity fluctuation can be expected, especially during mine start-up and closure. Metal prices will also have an impact on the rate of mining but projecting metal prices into the future is a difficult

Table 4. Electricity requirements for operations included in the miscellaneous sections of the LCA.

Description	Electricity (kWh/t)
Mine	
Underground lighting	0.38
Underground maintenance shop	0.08
Refuge stations	0.02
Welder	0.02
Exploration	0.67
Surface lighting	0.15
Surface maintenance shop	0.06
Hot water heaters	1.38
Parking lot (plug ins)	0.27
Offices	0.03
Heating	0.28
Mill	
Lighting	0.22
Hot water heaters	0.55
Parking lot (plug ins)	0.11
Offices	0.01
Heating	0.28

task. External demand leading to fluctuations in a mine's required production levels will be the same irrespective of the level of automation and so the average production rates were used to compare the various scenarios. In 2017, the mine reported non-

Table 3. Breakdown of travel distances for worksite personnel.

Travel type	Distance (one-way)	Personnel (%)	Yearly travel
Surrounding Communities	230 km	163 (48%)	1.29×10^6 km
Town	16 km	136 (40%)	2.65×10^5 km
Long distance	700 km	34 (10%)	6.87×10^5 km
Flights	908 km	7 (2%)	1.60×10^5 km

Table 5. Inventory analysis for one tonne of ore mined and processed at investigated mine site.

Category	Object	Scenario 1 Manual operations	Scenario 2 Automated LHDs	Scenario 3 Automated operations	Units
Underground operations					
Inputs from nature	Zinc	51.2	51.2	51.2	kg
	Copper	6.9	6.9	6.9	kg
	Gold	26.5	26.5	26.5	g
	Silver	2.61	2.61	2.61	g
	Fresh water	0.2	0.2	0.2	m ³
	Fresh air (ventilation)	4.58×10^5	4.58×10^5	4.32×10^5	m ³
	Compressed air	31.2	31.2	31.2	m ³
Materials and fuel	Diesel fuel	4.71	4.07	3.53	L
	Electricity (Grid)	85.3	85.3	82.0	kWh
	Explosives	1.15	1.15	1.15	kg
	Steel	0.44	0.44	0.41	kg
	Tires	0.05	0.05	0.047	kg
Mill operations					
Inputs from nature	Fresh water	0.86	0.86	0.86	m ³
Materials and fuel	Diesel fuel	2.09	2.09	2.09	L
	Electricity (Grid)	39.3	39.3	38.2	kWh
	Lime	2.5	2.5	2.5	kg
	Methyl Isobutyl Carbinol	0.06	0.06	0.06	kg
	Copper sulfate	0.25	0.25	0.25	kg
	Flotation chemical 3418A	0.285	0.285	0.285	kg
Mine camp					
Inputs from nature	Fresh water	9.33×10^{-3}	9.17×10^{-3}	8.76×10^{-3}	m ³
Materials and fuel	Gasoline	0.243	0.239	0.225	L
	Electricity	1.21	1.19	1.14	kWh
	Food and grocery	0.042	0.041	0.039	kg
Air emissions					
	Carbon dioxide	19.7	17.6	16.2	kg
	Sulphur dioxide	30.1	26.7	24.3	g
	Nitrogen oxides	354	316	287	g
Water emissions					
	Zinc	3.09	3.09	3.09	kg
	Copper	0.68	0.68	0.68	kg
	Gold	0.77	0.77	0.77	g
	Silver	150	150	150	g
Waste					
	Tailings	1.66	1.66	1.66	t
	Scrap steel	0.045	0.045	0.042	kg
	Scrap tires	0.033	0.033	0.032	kg
	Landfill (Mine camp)	0.02	0.019	0.018	kg
	Sewage (Mine camp)	0.059	0.058	0.055	kg
Final product					
	Zinc concentrate	92.8	92.8	92.8	kg
	Copper concentrate	27.9	27.9	27.9	kg

automated productivity rates of 3000 t/day and this was been used as the base productivity rate for the manual operations (scenario 1). The data gathered from the trials conducted at the mine site showed a 35% increase in productivity (4050 t/day) from LHD automation, which was consistent with other reports [12] and was used for the productivity rate of automated equipment in this study.

The 35% increase in productivity was also applied to haulage trucks and drill rigs, which are the next steps to be automated at this mine site. As ore handling from the stope using LHDs is the bottleneck within this mine's production process, daily

ore tonnage would be dependent on LHD productivity and not haulage trucks or drill rigs [12]. However, productivity increases from improved cycle times and operation during the blast window would allow the mine to operate with less equipment while maintaining the 4050 t/day production rate. With less equipment and a projected improvement in required maintenance of 15–30% (from less accident related damage) for automated equipment [14,15], it is also expected that there will be a reduction in replacement parts and scrap tire disposal throughout mine-life operations.

Table 6. List of equipment used at investigate mine site.

Description	Fleet
Underground trucks	8
LHD	10
Jumbo drill	4
Longhole drill	3
Bolter	8
Scissor lift trucks	8
Powder trucks	3
Boom trucks	2
Grader	1
Shotcrete sprayer	1
Trans-mixers	2
Personnel carriers	26
Miscellaneous underground (minecats, forklifts, etc.)	19
Miscellaneous surface (trucks, loader, pickups, etc.)	22

2.2. Fuel consumption analysis

The manual and automated LHDs were found to consume fuel at a rate of 0.27 and 0.19 L/t of ore mined respectively (Moreau et al., 2019). By applying this 30% decrease to other pieces of equipment, such as haulage trucks and drill rigs, further emissions reductions can be expected. The complete list of LHDs, haulage trucks, drills and all other site equipment is provided in Table 6 below.

The CO₂ emission factor used for diesel burned in heavy-duty equipment was 2681 g/L of diesel fuel [16]. The reduction of underground diesel usage listed previously in Table 5 (4.71 L/t for scenario 1) could have a large impact on the environmental footprint over the entire mine life, especially when projecting automation statistics to other machines and equipment (3.53 L/t for scenario 3).

2.3. Ventilation analysis

Ventilation at the mine site contributes 32.3% of electric power consumption (the next highest consumption activities are grinding at 11%, haulage and mucking at 9.9%, flotation at 7.3%, hoisting at 7%

Table 7. GHG emission intensity factors of various electricity generation sources [17].

Source	g CO ₂ eq./kWh		
	Mean	Low	High
Lignite	1054	790	1372
Coal	888	756	1310
Oil	733	547	935
Natural gas	499	362	891
Solar PV	85	13	731
Biomass	48	10	101
Nuclear	29	2	130
Hydropower	26	2	237
Wind	26	6	124

and others, e.g. drilling, crushing, dewatering, etc., at 32.5%). Depending on the electric power generation methods used in the area of the mine site, decreased ventilation demands could have a significant impact on CO₂ emitted and the environmental footprint of mining operations. Table 7 lists the global average GHG intensity factors of various electricity generation methods for comparison [17].

Regulations stipulate that mines supply 100 cubic feet per minute (cfm) of air per horsepower of diesel equipment in operation, which is consistent across various regions [18,19]. This is reflected in the reduced ventilation requirements in Table 5 for scenario 3. The increased productivity projected for individual automated haulage trucks and drills reduces the number needed to maintain production rates, and the resulting environmental impacts were analyzed.

2.4. Methodology and software

Sphera's GaBi Solutions software [20] was used to compare the environmental impacts of extracting ore from an underground mine using both automated and manually operated equipment. The LCA software contains about 32,000 datasets developed from working globally with companies, associations and public bodies. It also offers a "Precious Metals" extension equipped with 28 processes, which was used in this study.

The required operating statistics were obtained from the mine's technical report forms, which provide material and technical information relating to activities occurring on the property. Resources containing statistical guides were also used when specific information was not provided within the technical report (e.g., power consumption for a mine hoist is 1 kWh/t for each 367 m of hoisting distance [19,21]). The data was inputted to the LCA software for specified operations on-site for a production period of one day. The results were extrapolated from mine life calculations of 18.3 and 13.5 years for manual and automated operations respectively, based on ore reserve estimates of 20 million tonnes.

Numerous methods are available for assessing the environmental impact of a project using the LCA output. Each method contains a variety of impact categories such as global warming potential, acidification, eutrophication and human toxicity. These four impact categories were selected to be studied based on their popularity within various LCA studies in the industry as well as the recommendations within the software itself. The method that was used for this study was TRACI version 2.1 (Tool for the Reduction and Assessment of Chemical and

Table 8. GHGRP requirements for reporting selected GHGs by source [25].

Greenhouse gas	Emissions Source								
	Stationary fuel combustion	Industrial process	Industrial product use	Fugitive			On-site transport-ation	Waste	Wastewater
				Venting	Flaring	Leakage			
Carbon dioxide	✓	✓	x	✓	✓	✓	✓	✓	✓
Methane	✓	✓	x	✓	✓	✓	✓	✓	✓
Nitrous oxide	✓	✓	x	✓	✓	✓	✓	✓	✓
Sulphur hexafluoride	x	✓	✓	x	x	x	x	x	x
Hydrofluorocarbons	x	by species by species		x	x	x	x	x	x
Perfluorocarbons	x	by species by species		x	x	x	x	x	x

Other Environmental Impacts), which was developed by the U.S. Environmental Protection Agency [22]. The TRACI method enables impact assessment for sustainability, life cycle assessment, industrial ecology, process design, and pollution prevention [23]. The methodology impact categories are said to be more suited to the USA, therefore it was chosen to assess the investigated mine site (Canada) rather than other methodologies that were European based [23].

3. Results and discussion

3.1. Global warming potential

Table 8 contains the reporting criteria required by the Canadian Greenhouse Gas Reporting Program (GHGRP) under which the studied mine falls. In 2017, the site reported 19,260 t of CO₂ eq. were emitted from their operations [24], whereas the LCA software calculated 22,437 t of CO₂ eq. production per year. The 15.2% increase was due to including mine camp related activities, employee travel to and from the workplace, and electrical energy consumption, within the LCA, none of which are included within the GHGRP. But for the purposes of a study which analyzes the mine's whole life span, these processes need to be included. The GHG emissions from the mine camp and electric energy consumption were calculated to be 1590 and 470 t CO₂ eq. respectively, which taken out would reduce the LCA calculated value to 20,377 t of CO₂ eq., which is only a 5.6% difference from the GHGRP reported emissions. The similarity of reported values and LCA results confirmed that reasonable operational data was gathered for this study and can be used for projecting long-term environmental

impacts by operations utilizing automated mining equipment.

Global warming potential was developed to compare the impacts of different GHGs emitted to air (e.g., CO₂, CH₄, N₂O, O₃) and is measured as equivalency to carbon dioxide (kg CO₂ eq.) [26]. The TRACI 2.1 assessment method uses Assessment Report 4 from the International Panel on Climate Change (IPCC) to measure global warming potential from GHG production. The IPCC's assessment report provides a current and comprehensive assessment of causes, impacts and response strategies to climate change and form a worldwide standard reference for academia, government and industry [27]. The results from the mining processes studied in the three investigated scenarios are presented in Table 9.

The transition to automated LHDs in scenario 2 resulted in an 11.1% decrease in global warming potential due to the mucking and backfill operations (Fig. 3). As LHD machines are primarily used within these operations they were expected to have the largest impact on CO₂ emission reductions. The remaining contribution is primarily a result of the mine camp operations and decreased ventilation requirements.

The increase in productivity from using automated LHD equipment will lead to a shorter mine life when analyzing a project with a fixed amount of ore reserves. A shorter mine life reduces overall CO₂ emissions and other impacts from the mine camp by eliminating years of on-site energy consumption, daily travel to and from the workplace, and also reduces landfill and wastewater. Automation is also expected to have an effect on the workforce required for operations. When the mine site becomes more experienced with the technology, a single operator can remotely control multiple machines at once from the surface.

For this study, it has been assumed that the mine site will utilize two machines per operator for LHDs, haulage trucks and drills, while also requiring additional specialized personnel for maintenance,

Table 9. Global warming potential results from investigated mine site.

Scenario	kg CO ₂ eq./t	% decrease (from scenario 1)
1	20.5	–
2	18.3	11.1%
3	16.8	18.3%

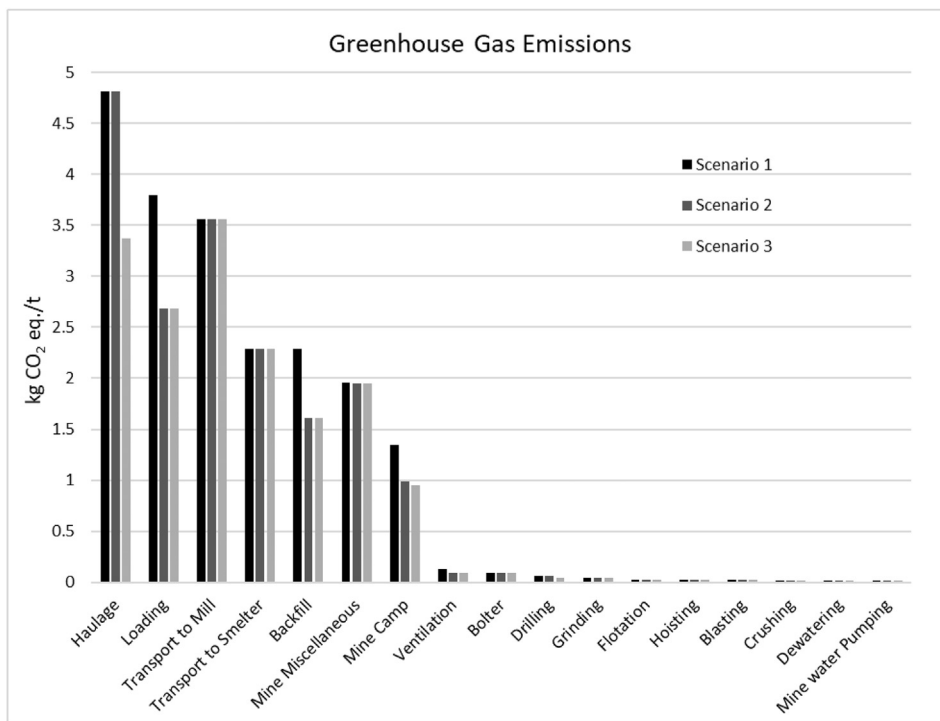


Fig. 3. Global warming potential breakdown of specified operations.

IT communication and project management relating to automated operations. This adjustment in workforce will further affect the travel to/from work as well as electricity consumption and waste disposal at the mine camp, all of which have been reflected within the mine camp process in Fig. 3.

When projecting the productivity gains and fuel efficiency from automated LHDs to haulage trucks and drills, a 18.3% reduction in kg CO₂ eq./t of ore was projected for the tested mine site operations. As seen in Fig. 3, a substantial portion of this reduction was contributed from the haulage and mucking operations. Drilling operations provided a reduction of 0.03 kg of CO₂ eq./t of ore mined which represents less than 1% of the overall reduction in global warming potential from scenarios 1, 2 and 3. Drilling operations consist of minimal travel during shift time compared to haulage trucks and LHDs and are operated through the mine's electrical infrastructure

when drilling. Therefore, as expected emissions from burning diesel fuel is significantly less for drilling operations compared to the continuous operation of haulage trucks and LHDs.

The results from the LCA confirmed the expectations of reducing the environmental impact from mine site operations that were heavily reliant on diesel fuel consumption. However, the impact was minimal when analyzing process operations that require electricity as their primary energy source, such as drilling and ventilation. Their impact is a factor of the electric energy generation methods used in the specific area where the mine is located. 98% of the electricity generated for the area is from renewable hydropower, which produces the lowest GHG emissions during operation as seen in Table 7 [17]. The remaining 2% is generated from natural gas resources and the average intensity factor was reported to be 3.4 g CO₂ eq./kWh in the

Table 10. Estimated GHG emission factor for electricity generation in Nevada, USA.

Source	Monthly electricity generation (kWh)	% Generation	g CO ₂ eq./kWh
Oil	1.00 × 10 ⁶	0.02%	733
Natural gas	3.09 × 10 ⁹	69.83%	499
Coal	3.08 × 10 ⁸	6.95%	888
Hydroelectric	1.77 × 10 ⁸	3.99%	26
Renewables (non-hydroelectric)	8.51 × 10 ⁸	19.21%	52

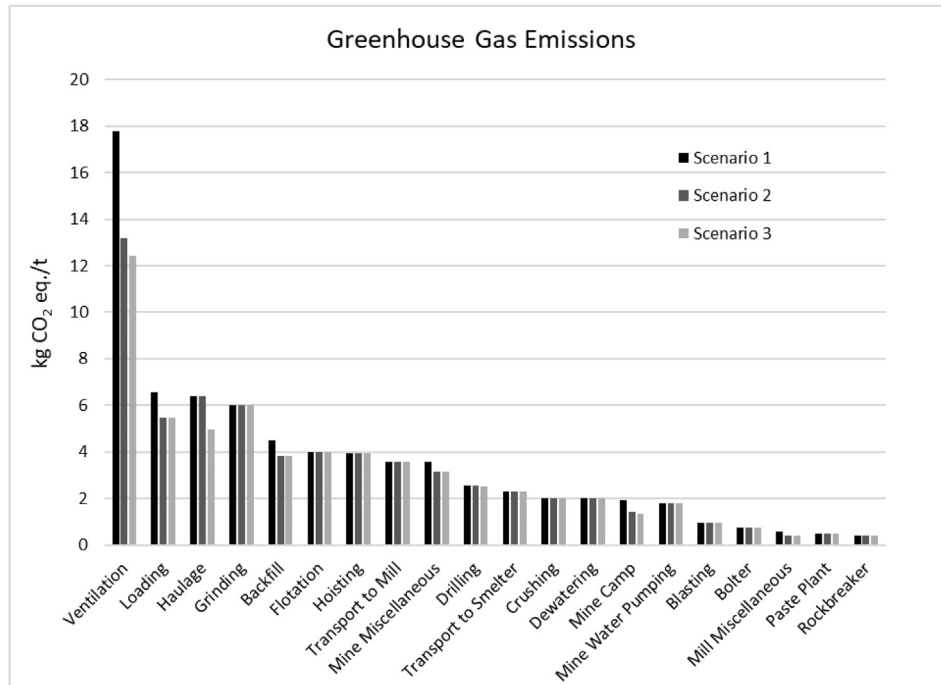


Fig. 4. Global warming potential breakdown of specified operations with an electric energy generation GHG intensity factor of 421.4 g CO₂ eq./kWh.

region of the mine's location [28]. The GHG intensity factor can vary depending on the method used for electricity generation in that area. For example, in Canada, areas that primarily utilize hydropower have lower GHG intensities (Quebec 1.2 g CO₂/kWh), whereas areas using fossil fuels to generate electricity have GHG intensities as high as 790g CO₂/kWh (Alberta) [28]. Future studies could involve a comparison of GHG intensity factors from different methods of electric energy generation and how this would affect ventilation, drilling and mine camp operations when using automated underground equipment.

The mine site operations were also examined as if it was located in a different area in the world, where it is assumed the main change is the type of electric energy generation. For example, based on the information provided in Table 10, the GHG emissions factor for electricity generation in Nevada, USA, was estimated to be 421.4 g CO₂ eq. per kWh compared to 3.4 g CO₂ eq. per kWh at the mine studied.

Operations relying on electricity as an energy source, such as ventilation and grinding, become

some of the highest contributors to CO₂ eq./t of ore in this situation. Ventilation is the highest contributor but also experiences the largest reduction when automation is introduced, as seen in Fig. 4. The total reduction from scenario 1 to 3 was calculated as 9.7 kg CO₂ eq./t, whereas the reduction from ventilation was calculated to be 5.3 kg CO₂ eq./t, representing 55% of the total. This study shows that areas with high GHG intensity factors from electricity generation benefit more from limiting ventilation requirements compared to haulage or mucking. Further improvements can be made from other technologies such as battery-electric vehicles, which significantly reduce ventilation requirements, whereas areas with low GHG intensity factors from electricity generation should focus on automated technology and improving diesel fuel consumption.

3.2. Acidification and eutrophication potential

When analyzing environmental impacts of an operation or industry, the main focus is often on GHG emissions (CO₂ eq.), but the purpose of the

Table 11. Acidification and eutrophication potential results from investigated mine site.

Scenario	kg SO ₂ eq./t	% decrease (from scenario 1)	kg N eq./t	% decrease (from scenario 1)
1	0.307	–	3.74×10^{-2}	–
2	0.277	9.8%	3.56×10^{-2}	4.8%
3	0.254	17.3%	3.42×10^{-2}	8.5%

Table 12. Process analysis for acidification potential.

Operation	Acidification Potential (kg SO ₂ eq./t)		
	Scenario 1	Scenario 2	Scenario 3
Haulage	7.5×10^{-2}	7.5×10^{-2}	5.3×10^{-2}
Mucking	5.9×10^{-2}	4.2×10^{-2}	4.2×10^{-2}
Backfill	3.6×10^{-2}	2.5×10^{-2}	2.5×10^{-2}
Mine water pumping	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}
Mine camp	8.1×10^{-3}	6.0×10^{-3}	6.0×10^{-3}
Drilling	1.6×10^{-3}	1.6×10^{-3}	1.1×10^{-3}

LCA we have developed is to provide the analysis for several environmental impacts (i.e., acidification, eutrophication and human health). Acidification potential is a measurement of air pollutants, sulfur dioxide and nitrogen oxide, transmitted to the atmosphere and deposited as acids (H₂SO₄ and HNO₃) in surface soils and waters [29]. Acidification impacts the environment through rainwater, soil, groundwater, surface water, and biological organisms leading to fish mortality, forest dieback, and the deterioration of building materials [30].

Eutrophication potential is an increase in nutrient concentration, primarily phosphorus and nitrogen, deposited to aquatic or terrestrial areas from human activities, such as chemical fertilizer application or wastewater discharges [31]. Nutrient richness may result in a shift in species composition and increased biomass production in both aquatic and terrestrial ecosystems, leading to depressed oxygen levels and unsatisfactory sources of drinking water [30]. Typically, phosphorus is used to measure eutrophication, but for the purposes of this study nitrogen equivalents will be used due to the higher concentration of nitrogen, compared to phosphorus, in discharge water from explosives used in the underground mining process.

The acidification potential for each scenario was measured based on mass of SO₂ eq. and presented in Table 11. The data obtained from the automation trial period resulted in 9.8% decrease in calculated SO₂ equivalent, while projecting the automation statistics for haulage trucks and drills, a decrease of 17.3% was estimated.

The use of automated equipment resulted in a decrease of 4.8% and 8.5% for scenarios 2 and 3 respectively. Tables 12 and 13 list some of the key operations at the mine site and it can be seen that the main contribution towards eutrophication potential is mine water pumping, and more specifically the disposal of wastewater containing ammonia, nitrate, and nitrites. This is unchanged throughout scenarios 1–3 and, therefore, the implementation of automated equipment did not have as significant of an impact compared to acidification potential,

Table 13. Process analysis for Eutrophication potential.

Operation	Eutrophication Potential (kg N eq./t)		
	Scenario 1	Scenario 2	Scenario 3
Mine water pumping	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}
Haulage	4.5×10^{-3}	4.5×10^{-3}	3.1×10^{-3}
Mucking	3.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
Backfill	2.1×10^{-3}	1.5×10^{-3}	1.5×10^{-3}
Mine camp	4.9×10^{-4}	3.6×10^{-4}	3.6×10^{-4}
Drilling	9.6×10^{-5}	9.6×10^{-5}	6.8×10^{-5}

where haulage and mucking processes are large contributors and are affected by automation technology.

3.3. Human toxicity

An additional aspect of an LCA is to relate environmental impacts to human health. For this, human toxicity potential is used as a measure of impacts from chemical emissions released into the environment [32]. The LCA software calculates human toxicity using the USEtox® scientific consensus model which calculates characterization factors for human toxicity by assessing the toxicological effects of a chemical emitted into the environment through environmental fate, exposure and effects [33]. Human toxicity is measured in Comparative Toxic Units (CTUh), which is an estimation of increased morbidity per unit mass of chemical emissions [33]. The results for scenarios 1–3 are listed in Table 14.

The CTUh decreased 19.2% when implementing automated LHDs and projecting the productivity and fuel consumption statistics to haulage trucks and drills. This means over the entire mine life it is expected to experience approximately 11 fewer disease cases amongst humans from chemicals emitted from the mining processes used in scenarios 1 and 3. The calculation is based on both cancerous and non-cancerous effects derived from laboratory studies [33].

3.4. Discussion

The implementation of automation was found to have a significant impact on all the investigated

Table 14. Human toxicity potential comparison using USEtox® scientific consensus model.

Scenario	CTUh/t	Mine life disease cases (20 million tonnes of ore)	% decrease (from scenario 1)
1	2.96×10^{-6}	59.2	–
2	2.63×10^{-6}	52.6	11.2%
3	2.39×10^{-6}	47.8	19.2%

impact categories. Previously reported GHG emissions from underground copper operations had a range of 1–9 t CO₂/t Cu. metal [11]. The results from the current study for the global warming potential of the mines site under current manual operations (scenario 1: 20.5 kg CO₂/t ore) is, based on actual copper metal production (6400 t/a), 3.51 t CO₂/t Cu., which falls within the range suggest by Northey et al., (2013). Whereas, with the use of automated LHDs, haulage trucks and drills (scenario 3; 16.8 kg CO₂/t ore) it is equivalent to 2.88 t CO₂/t Cu. This 18% reduction in GHG emissions was primarily from operations that use diesel fuel as an energy source (Fig. 3). Mucking, haulage, and backfill were responsible for 87.6% of total emission reductions due to an increase in fuel efficiency and the ability to operate with fewer machines while maintaining desired productivity levels. The remaining reductions were from the mine camp facilities (10.9%), ventilation (1.1%), and drilling (0.4%), which are a result of lower energy consumption and less employee travel due to the 27% decrease in operational mine life.

The current study was extended to analyze how the GHG intensity factor for electricity generation would affect the results. The mine site examined is located in a region that generates electricity with

a low level of GHG emissions (3.4 g CO₂/kWh), and the developed LCA model was modified to include a GHG intensity factor of 421.4 g CO₂/kWh. This was estimated based on the electricity generation methods used in a different region (Nevada) and was studied because of the diversity of methods (oil, natural gas, coal, hydropower and other renewables) compared to the actual region of the mine which was heavily dominated by hydropower electricity generation (98%). The results shown in Fig. 4 indicate that operations that use electricity as a fuel source, such as ventilation, grinding, floatation and hoisting, surpass some of the diesel operations (haulage, loading, and backfill) with regards to CO₂ emissions. Therefore, operations that contribute the most to GHG emissions will depend on the GHG intensity factor for electricity generation.

The intensity factor for electricity generation is one parameter that could influence the total GHG emissions produced from an underground metal mine, as well as influence which operations should be targeted for potential reductions through the use of technologies such as automated vehicles. But the results of all LCA impact categories (Fig. 5), provide a more comprehensive site-specific analysis of environmental benefits, or otherwise, from introducing automation.

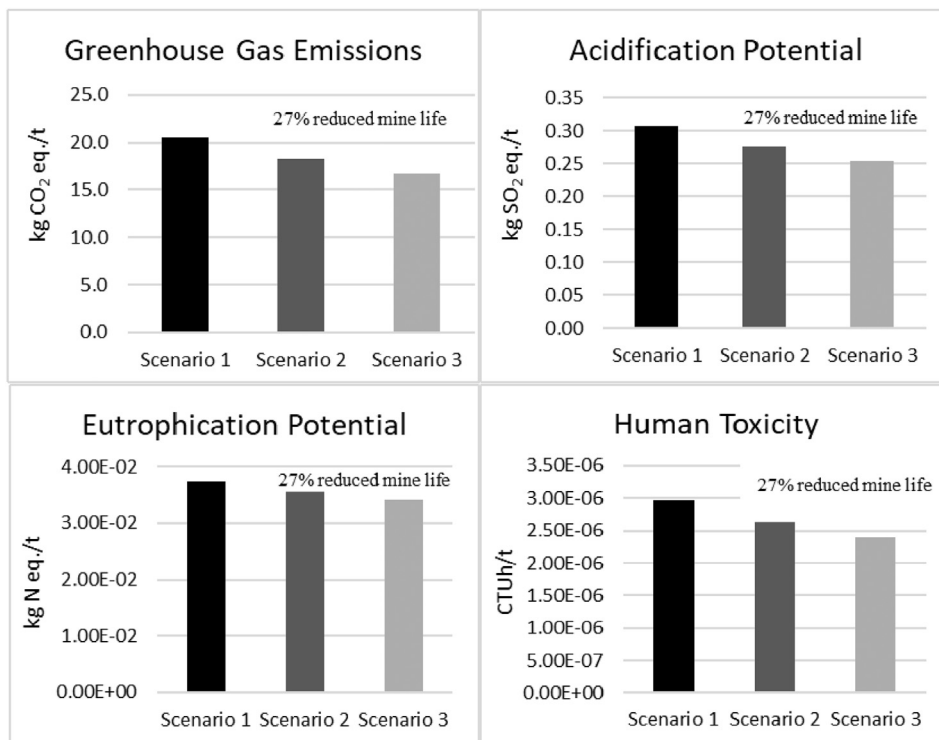


Fig. 5. Impact category results for investigated scenarios calculated using the LCA software (scenarios 2 and 3 reflect the impact of a reduction in the required operational life of the mine due to automation).

4. Conclusions

Mining companies worldwide are carrying out economic evaluations of introducing automation, not least as they continue to search for more profitable methods of extracting ore at great depths. What is less considered are any impacts on the environment from increasing the level of automation. This can be addressed by using a life cycle assessment (LCA) approach, which shows that implementation of automated equipment reduces a range of environmental benefits. For the mine studied, overall global warming potential was decreased by 11.1% with automated LHD machines and by 18.3% when projecting LHD productivity and fuel efficiency data to other machines, such as haul trucks and drills. Utilizing automated equipment, the ore body can be extracted at a higher daily rate, which decreased mine life by 27% or 5 years. This is very significant not just in improved environmental impacts, but also for the economics of mine investment and payback.

For the site investigated, the results displayed significant environmental impact reductions with processes relying on diesel fuel for operations. Whereas, processes that primarily used electrical energy did not contribute a significant reduction in CO₂ emissions due to the low GHG intensity of the main electricity generation method (hydropower) used by power plants that supplied the mine. However, by applying the developed LCA approach to worldwide locations that use other types of electricity generation (e.g., coal or natural gas) the introduction of automation will have an even greater impact on GHG emissions due to ventilation, grinding, drilling and mine camp operations. The results from this paper along with the analysis of these parameters can be used, therefore, to model the impacts from mine sites in general looking to implement automated technology to improve safety, productivity and environmental performance.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflict of interest

None declared.

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