The effects of automation on the environmental impact of deep underground metal ore mining operations

by

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Abstract

The growing demand for increased production has resulted in the need to develop deeper underground mines to extract more resources. However, the mining process becomes less economically attractive as the ventilation and ore transportation costs drastically increase when operating at large depths. This has led to the industry investigating automated battery-electric and biodiesel fueled machinery instead of diesel machines to reduce emissions, and hence ventilation costs, as well improve productivity and thereby, the economic viability of deep mine projects.

A life cycle assessment (LCA) approach has been developed to evaluate the environmental impact from introducing automated equipment in underground copper mines. This is a novel application for an LCA, and as a gauge of model accuracy, it was found that calculated greenhouse gas (GHG) emissions for an underground mine site in Canada were within 5.6% of their reported emissions. The model was then expanded using data collected from automation trials at a Canadian mine to predict changes due to the introduction of various levels of automation with regards to the impact potentials of global warming, acidification, eutrophication and human toxicity. All impact levels were quantified and found to decrease due to automation. Data from this site study was then used to further develop the LCA model to predict changes in environmental impacts for underground copper mine sites in Australia, Canada, Poland, USA and Zambia. Site specific parameters and processes that contribute to their overall environmental impacts were identified, and the calculated CO_2 emissions were within 4.2-5.6% of the reported values.

The mining industry is moving toward introducing significantly more technology to enhance both productivity and safety. This thesis investigates using an LCA approach to add a third dimension; improved environmental impacts that contribute to more sustainable mining.

Keywords

Automated equipment, Battery-electric equipment, Energy Reduction, Life cycle assessment, Productivity, Sustainability, Underground metal mining

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Nomenclature

Symbol	Description
BEV	battery electric vehicle
CH_4	methane
CO_2	carbon dioxide
CO_2 eq.	carbon dioxide equivalent
CTUh	comparative toxic units (human)
Cu.	copper
DPM	diesel particulate matter
EC	elemental carbon
GHG	greenhouse gas
GHGRP	greenhouse gas reporting program
IP	internet protocol
LCA	life cycle assessment
LHD	load-haul-dump
N eq.	nitrogen equivalent
NO_x	nitrogen oxides
N_2O	nitrous oxide
O_3	ozone
SO_2 eq.	sulphur dioxide equivalent
TRACI	tool for the reduction and assessment of chemical and other environmental impacts
WiFi	wireless fidelity

List of Publications

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McLean, S.H., Chenier, J., Muinonen, S., Laamanen, C.A., **Moreau, K**., Scott, J.A., (Submitted). A comparative life-cycle assessment of a sulphuric acid plant with and without on-site low-grade heat recovery and repurposing. The International Journal of Life-Cycle Assessment.

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Chapter 1: Introduction

Technological advancements, increased complexity of new ore bodies, and the modifications to operations due to growing climate change concerns are the key challenges for the future sustainability for the underground mining industry (Littleboy et al., 2019). The complex ore bodies and changes to operations from environmental restrictions have created difficulties relating to operator productivity and high operating costs from increased energy demands. Various technologies have been studied to improve the productivity and energy consumption for deep underground mining operations, such as: automated equipment, battery-electric equipment and biodiesel fuels. However, research on the environmental impacts associated with the use of these technologies has been limited.

In 2010, the contribution of carbon dioxide emissions from the mining industry was calculated to be 1 Gt CO_2 eq. per year, which is about 2% of total global emissions (United Nations Framework Convention on Climate Change, 2018). As of 2020, the contribution of GHG emissions from the mining industry has risen to 4-7% of total global emissions (McKinsey & Company 2020). The suggested rise in emissions from the mining industry aligns with a 2020 report that mining companies have fallen short of the climate change goals set by the Paris Agreement in 2015. Mining companies have been setting low greenhouse gas (GHG) reduction targets (0-30%), while the Intergovernmental Panel on Climate Change suggests that the reduction from 2010 levels may need to be as high as 72% to limit a rise in global temperatures to $2^{o}C$ (Dempsey, 2020).

The use of automated equipment has been projected to increase productivity by 30% due to increased utilization by continually operating through the blast window, elimination of travel times underground, and decreased cycle times (Chadwick, 2010; Sandvik Mining, 2017). In addition, another major benefit of automated equipment that is important to the mining industry is the improved safety by operating equipment from the surface and removing personnel from underground workplace hazards (Paraszczak et al., 2015). The productivity and safety benefits of introducing automated equipment in underground mining operations have been well documented. However, literature searches on the environmental performance of automation in mining operations provide very limited results, and more specifically, life cycle assessments (LCA) within this area have not previously been performed.

This thesis focused on the effects of automated equipment within underground metal mines, and more specifically, underground copper mines. Copper ranks as the third most important metal for modern society, technology, and infrastructure, behind only iron and aluminum (Sverdrup et al.,2014). Previous studies have reported that greenhouse gas (GHG) emissions from underground copper operations were within a range of 1 to 9 t CO_2 eq./t Cu (Northey et al., 2016). The implementation of automated equipment within trials at an investigated mine site showed results of improved efficiency with regards to diesel fuel consumption, electricity consumption, as well as overall productivity, which could lead to a potential reduction in mine life. These efficiency gains were, therefore, evaluated using an LCA approach to compare the differences of emissions reported from previous underground mining LCA studies.

The use of battery electric equipment has been trialed in underground mine sites to reduce diesel fuel consumption, and thereby, ventilation requirements. Similarly, biodiesel has been used as a stop gap solution for transitioning to battery electric equipment as it has been shown, within underground mining operations, to reduce diesel particulate matter (DPM), nitrogen dioxide and total carbon emissions (Bugarski et al., 2014; Lutz et al., 2017). For underground mine sites, the ventilation process tends to be the highest consumer of electricity, responsible for up to 40-50% of electricity usage, and the ability to reduce the requirement for ventilation would have significant environmental and economic benefits (Vergne, 2008; Holmberg et al., 2017). There is a large capital cost associated with the substitution of battery-electric equipment, but with lower operating costs, and reduced costs for ventilation, and improved environmental performance, there are significant opportunities and benefits that have the potential to help the long-term sustainability of the mining industry.

1.1 Life cycle assessment applications in underground metal mining

Previous LCA studies have been performed to analyze various processes within the mining industry. These studies examine the environmental performance for the extraction, processing and waste management of a variety of metals of high economic value. Table 1.1 provides a summary of some of the past studies relating to LCA work in the mining industry that were used as a foundation for this thesis.

Table 1.1 Previous LCA studies within the mining and processing industry.

Title	Description
A global life cycle assessment for primary zinc production (Van Genderen et al., 2016).	An update on the average environmental impacts of global zinc production using an LCA approach. The study found that special high-grade zinc has a climate change impact of 2,600 kg CO_2 eq./t.
Comparative life cycle assessment of tailings management and energy scenarios for a copper ore mine: A case study in Northern Norway (Song et al., 2017).	An LCA of an underground copper ore mine that found electricity, diesel usage, blasting, and metals leaching form tailings as the primary factors of environmental performance. The study concluded that the electrification of diesel equipment would be beneficial depending on the electrical generation method used (clean energy).
Energy and greenhouse gas impact of mining and mineral processing operations (Norgate & Haque, 2010).	The extraction and processing of iron ore, bauxite and copper concentrate was examined using an LCA approach. The loading and hauling processes were found to have the largest contribution towards GHG emissions for iron and bauxite, while grinding and crushing were the main contributors for copper. Further research in available technologies for these operations should be investigated to improve environmental performance.
Life cycle assessment: a time-series analysis of copper (Memary et al., 2012).	Life cycle assessment to examine the historical environmental impacts of copper mining and smelting in Australia. The authors examine five different mine sites across Australia and incorporate the varying ore grades, technologies and regional energy sources.
Life cycle assessment of cobalt extraction process (Farjana et al., 2019)	An analysis of the cobalt extraction process using a life cycle assessment approach. Blasting and electricity consumption were the highest emitting processes, and the environment was affected the most through the global warming and eutrophication categories.
Life cycle assessment of mine tailings management in Canada (Reid et al., 2009).	Six tailings site management and closure scenarios were studied for a copper-zinc underground mine located in Canada. A higher impact on environment can be expected for scenarios that use tailings within backfill operations due to the high material and energy requirements for this process.
Life cycle assessment of nickel products (Mistry et al., 2016).	The Nickel Institute (NI) conducted a global LCA to evaluate the environmental impact from nickel and ferronickel mining and refining. The primary extraction and refining are the main consumers of energy and the main influencers of this energy demand were found to be ore grade and ore mineralogy.
Using sustainability reporting to assess the environmental footprint of copper mining (Northey et al., 2013).	Copper mining operations around the world were analyzed using an LCA approach. The range of GHG emissions was found to be between 1-9 t CO_2 eq./t Cu. (average 2.6 t CO_2 eq./t Cu). The large range was primarily due to the form of copper produced, ore grade, sources of fuel and electricity, and reporting methods.

The operations of metal ore extraction, processing and waste tailings disposal have previously been assessed throughout the LCA studies presented in Table 1.1, however, the comparative analysis of new technologies, specifically automated equipment, and traditional manual equipment have not been a topic of focus. Norgate & Haque (2010), suggested that the comparison of new technologies is an area of need to identify methods of reducing environmental impact from the high contributing processes, which supports the objective of this study; evaluating the use of automated equipment in underground copper mines for environmental performance, in addition to the productivity and safety benefits.

1.2 Objective

The objective of this thesis was to assess the environmental performance of underground copper mining operations by (a) identifying appropriate technologies for the comparison of emissions, productivity and safety with current mining operations/methods and (b) developing an LCA model that can be used to calculate the potentials of GHG emissions, acidification, eutrophication and human toxicity from mine sites around the world with varying characteristics, parameters and processes.

The thesis is organized such that Chapter Two provides a review of the use of automated equipment within the underground mining industry, as well as productivity and energy consumption data collected from an underground mine using both automated and manual equipment. Chapter Three evaluates the mine site using an LCA approach and assesses the impact potentials mentioned above. Chapter Four provides the details of the LCA model, which was developed from the single mine site in Chapter Three, and was used to analyze six underground copper mine sites from around the world. The results were then used to define the key parameters and operations that contribute to environmental performance, compare automated to manual equipment, and determine which sites/locations will have a greater positive environmental impact from implementing automated load-haul-dump (LHD) machines, haulage trucks and drill rigs.

The research project used productivity and energy consumption statistics from trial results and extrapolated them over the projected mine life. The productivity and energy consumption data associated with the various technologies were then used to perform a comparative LCA between traditional operations and operations using automated equipment. This assessment is the first step in enabling mining companies to maximize the performance of the equipment and justify the decision to use the technology with regards to safety, productivity and the environment, when developing new mines, or to transition to the appropriate technology within existing mine sites. The primary focus was on automated mining equipment, while battery-electric vehicles and alternative fuel sources, such as biodiesel, were also considered.

The study presented within this thesis was performed in the following three stages.

Stage 1: Data collection and bench marking

Collected data at various mine sites that currently use automated and battery electric technology to be able to evaluate the performance (operational, costs and environmental) and compare to operations without this technology.

Stage 2: Analysis of data, projecting and life cycle assessment

The collected data from Stage 1 was evaluated to determine the operational gains from the use of one of the mentioned technologies. A comparative LCA between the traditional underground mining operations and operations using automated equipment was performed. The potential impacts associated with the automated technology and how they relate to safety, productivity and the environment were analyzed.

Stage 3: Development of life cycle assessment model

An LCA model was developed by expanding on the methods used in the original LCA study, identifying the major variables that contribute to the environmental impacts from underground mining operations, and comparing the results to available reported emissions. The LCA model was used to calculate the potential impacts from six underground copper mine sites from around the world.

1.3 Methodology

Stage 1: Data collection and bench marking

a) Identified equipment suppliers and established an inventory list for available technology within the underground mining industry (Table A5. – Appendix 3).

b) Obtained permission for site access and design drawings at various mine sites.

c) Compared various mine operations based on production, costs, environmental impact and safety. This included a comparison of mine designs, mining methods, electricity generation methods, required equipment fleet, etc.

d) Qualitatively analysed the isolation of the automated work areas to ensure the continuous operation of automated processes and all other mine operations. Automated machines must be operated in the absence of human workers, and any contact between the two would result in production delays and safety concerns.

e) Studied specific interactions affected by autonomous and electric-powered operations such as fueling, preoperative evaluation, maintenance, battery swap, etc.

Stage 2: Analysis of data, projecting and life cycle assessment

a) Selected an appropriate mine site for the initial investigation of the effects of autonomous technology on the underground mining process. A mine in Manitoba, Canada was selected based on their ongoing trials of automated LHD machines.

b) Obtained permission for site access and access to automated productivity, utilization and fuel consumption data.

c) Production Analysis – Estimated the tonnes of ore per day and utilization hours using automated equipment. This data was tracked during the automation trial phases at the mine site and was compared with manual production rates.

d) Safety Analysis – Qualitatively analysed and discussed the safety improvements from automation.

e) Environmental Analysis – Compared the GHG emissions of existing operations to automated operations, that were characterized by a smaller equipment fleet, and decreased ventilation requirements, using a comparative life cycle assessment approach.

f) Modelling – Developed an LCA model that was used to estimate the impacts from implementing automated technologies in underground mines from all around the world.

Key processes and variables required for the inputs of the model were determined and the results from several sites from different geographical locations were evaluated.

Stage 3: Development of life cycle assessment model

a) Selected six underground copper mine sites from around the world (Australia, Canada, USA, Poland and Zambia) based on available data/reports, to comparatively assess the potential environmental impacts from using automated rather than manual equipment.

b) Developed an LCA model by expanding on the initial LCA study, identifying the major variables that impact the environment and adjusting for site specific processes.

c) Interpreted the results and discussed the processes that had the greatest influence on the potential impacts for automated vs. manual operations. The calculated results were also compared to the reported emissions from the mine sites with publicly available data.

Chapter 2: Review of automated and battery-electric equipment.

2.1 Introduction

As the mining industry continues to exhaust easily accessible ore bodies, the need for efficient deep mine operations, typically below 2500 m, increases (Atlas Copco, 2013a). However, the mining process can become economically infeasible as operation costs drastically increase at great depths (Neingo & Tholana, 2016). This has resulted in investigation into automating mining operations as the industry strives for improved productivity and operating costs (Schunnesson, Gustafson, & Kumar, 2009), whilst also removing personnel from hazardous work areas.

Advancements in autonomous mining equipment and information technology communication infrastructure has enabled the transition from manual operated equipment/line-of-sight remote control to semi-autonomous operations (Gustafson, 2011). Mine sites around the world are trialing and implementing automated drills, trucks and load-haul-dump (LHD) machines (Schunnesson et al., 2009; Chadwick, 2010; Paraszczak, Gustafson, & Schunnesson, 2015). The intent is to increase the efficiency of removing and transporting ore, whilst also providing safer working conditions (Chadwick, 2010).

Various reports have shown the potential to increase productivity and reduce energy usage with automation technology (Schunnesson et al., 2009; Chadwick, 2010; Paraszczak, Gustafson, & Schunnesson, 2015). In particular it has been found that operating autonomously from the surface between shifts provides an additional 3–4 hours per day of machine productivity (Schunnesson et al., 2009). However, there are complications with designing the mine layout in order to isolate automated areas during regular shift time with work personnel underground. Further research and trial studies are needed, therefore, to determine optimal mine layouts for isolation of automated equipment in a way that does not impact other underground operations.

The many benefits associated with automated mining can have a strong influence on the feasibility of deep mine projects. Glencore's Kidd Creek mine (Timmins, Canada), which extends 2,927 meters below the surface (Duddu, 2013), has operated with autonomous LHDs since 2012. The aim was to increase safety and productivity as the mine developed deeper underground (Kelly, 2017). Glencore has also announced their Onaping Depth Project (Sudbury, Canada), which will be over 2,500 m underground (White, 2018), compared to their current Nickel Rim South Mine, where operations extend from 1,100 to 1,800 m (Glencore, 2016; White, 2018). Glencore has committed to an all-electric fleet for Onaping Depth to allow for decreased ventilation requirements, and will also look to use automation technology to remove miners from underground hazards (Tollinsky, 2018). Automated and electric equipment have the capability to lower operating costs, increase productivity and provide a sustainable future through improved safety, decreased diesel usage and overall reduced energy consumption from lower ventilation demands.

2.2 Benefits from automated mining

2.2.1 Safety

When considering the transition from manual to automated mining equipment, a fundamental supporting argument is an increased level of safety and improved working conditions for operators (Paraszczak et al., 2015). Automation allows for operation of machines from a control station on surface, which alleviates the requirement for an operator to spend time underground in dangerous work areas with poor air quality (Chadwick, 2005).

Bugarski et al. (2004) reported that underground workers are exposed to the highest levels of diesel particulate matter (DPM) of all workers in the industrial sector. Diesel emissions control is primarily focused on regulating concentrations of nitrogen oxides (NO_x) and elemental carbon (EC), which is a basic fraction of DPM derived from fuel and lubricating oil (Majewski, 2016). Figure 2.1 shows elemental carbon and nitrogen oxides exposure in a variety of industrial sectors. Underground mining and maintenance workers, including tunnel workers, experience four to five times higher levels of EC and NO_x compared to workers in other industrial sectors, which is a major concern for mining companies and their employees (World Health Organization, 2014). In 2012, DPM was announced as a group 1 carcinogen by the World Health Organization due to evidence that exposure is linked to increased risk of developing lung cancer (World Health Organization, 2012).

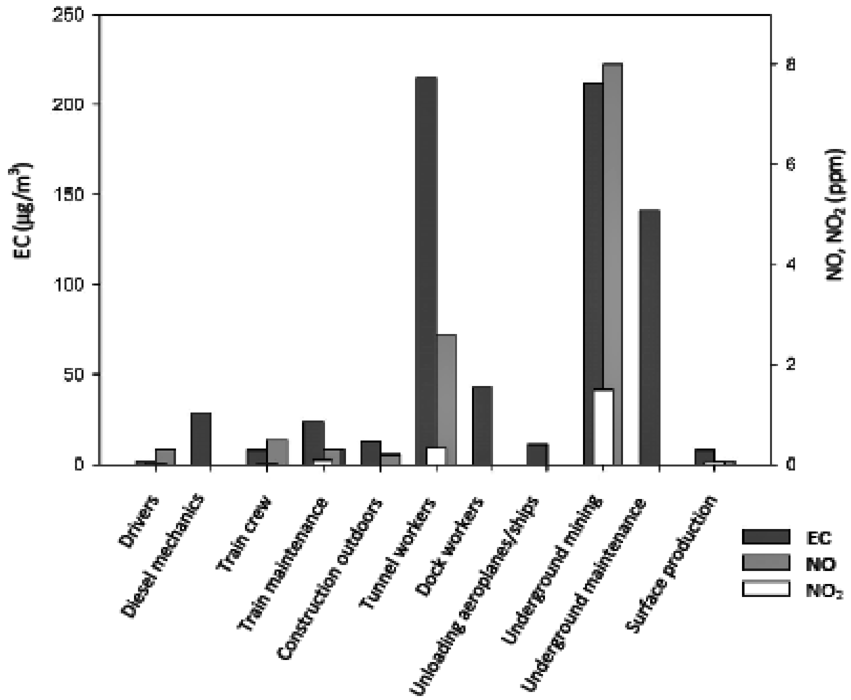

Figure 2.1 Average Diesel exhaust exposure in industry (International Agency for Research on Cancer (IARC) World Health Organization, 2014): EC elemental carbon.

Due to hazardous emissions from diesel engines, research into alternative fuel sources such as, biofuels and battery-electric vehicles (BEVs), has become a top priority for mining companies. There are high capital costs associated with implementing BEVs (20–30% higher than diesel equipment; Paraszczak, Laflamme, & Fytas, 2013); however, alternative fuels such as biodiesel can be used as an interim solution to improve air quality underground. While companies transition their existing diesel operated fleet to BEVs, they are also utilizing fuels with higher blends of biodiesel as a means of limiting total carbon emissions (Validakis, 2012). As of 2012, Macassa Mine (Kirkland Lake, Ontario, Canada) has been operating machines with biodiesel blended fuel (50 % blend in the summer, 20 % blend in the winter). Emissions tests performed on their equipment revealed CO and NO_x averages reduced from 2.36 to 1.85 ppm, and 0.15 to

0.085 ppm respectively, when compared to their diesel equipment counterpart (Kirkland Lake Gold Inc., 2015).

Workplace accidents are also a safety concern. Studies have shown there is a high number of pinch point and fall incidents when climbing in and out of equipment, as well as injuries resulting from collisions between heavy mobile machinery (Caterpillar Global Mining, 2008b). With automation the operator is not required to enter the machine, reducing the potential for these types of injuries. Automated mining equipment also travel designated pathways with higher accuracy, preventing inter-equipment collisions (Caterpillar Global Mining, 2008b).

To eliminate the possibility of autonomous vehicles coming into contact with other manual equipment or work personnel, automated equipment should be located within an isolated work area equipped with light barriers (Dragt, Camisani-Calzolari, & Craig, 2005; Caterpillar Global Mining, 2015). The intent of these barriers is that any object or person that crosses the barrier will cause the automated equipment to immediately shut down (Gustafson, 2011; Atlas Copco, 2015b).

2.2.2 Productivity and utilization

A four-month trial at BHP Billiton’s Olympic Dam Operation (South Australia, Australia) using Caterpillars MINEGEM automation technology, found that an autonomous LHD worked an additional 1.9 h/shift compared to a manually operated LHD (McHugh, 2004). Most of this utilization increase came from the ability to operate between shifts during the blast clearance window, and can lead to production increases of up to 30% according to Sandvik Mining (Sandvik Mining, 2017). Personnel are not permitted underground during large production blasts, therefore, a blast clearance time window is needed to perform this task, and to clear the work environment of the resulting smoke and emissions. On average, 4-5 hours of production is lost during the blast window per day using current manually operated equipment (Gustafson, 2011) There was also an increase in LHD utilization from eliminating the time it takes to travel to and from the surface, a factor of major significance in ultra-deep mines (Chadwick, 2010).

When tele-remote trams (remotely operated vehicles from a control station) were implemented in the early 1990's, tram speeds were lower compared to manual operations, resulting in increased cycle times (Roberts et al., 2000; Dragt et al., 2005). However, with advancements in automation technology this aspect has been greatly improved. In 2017, an operator of automated LHDs from a Canadian underground mine site reported that shorter cycle times contributed to increased production levels over a four-month period. Cycle times of automated mining equipment are now lower compared to manually operated machines due to optimum tram speeds and removing the need for climbing in and out of the machine at the entrance of a stope (Roberts et al., 2000; Schunnesson et al., 2009).

In 2017, a Canadian mine site began testing automated LHD machines with the goal of achieving production rates of 180 tonnes per haulage hour. During the trial, the haulage hours were increased from 13.4 hours/day to 15.1 hours/day which resulted in a higher average of tonnes moved per day. The hourly production rate was also increased from 102.4 tonnes per engine hour (tph) to 159.5 tph for the automated LHD (Appendix 1). The initial target of 180 tph was not, on average, achieved throughout the 13-day trial, but peak production on several occasions did surpass this target. The automation project team at the mine site expects that further familiarization with the technology will allow them to reach their target production on a more consistent basis.

2.2.3 Maintenance

To optimize an autonomous mine, there must be a strong focus on equipment maintenance. Work personnel are no longer located near the equipment to report the need for maintenance actions, therefore, a modified maintenance strategy is required to prevent breakdowns and lost production (Gustafson, 2013; Paraszczak et al., 2015). Automation requires more experienced and skilled personnel for proper maintenance, but it was found this cost was offset by decreased vehicle collisions, optimal driving parameters, increased tire life and reduced consumption of spare parts (Bellamy & Pravica, 2011).

Operations using autonomous vehicles are expected to experience reduced machine downtime and maintenance costs compared to manual operations. Equipment operated manually and through line-of-sight remote control are subject to more wear and tear from operator errors and poor visibility or blind spots leading to collisions with drift walls, excess tire wear and overworked engines (Dragt et al., 2005; Larsson, 2011; Gustafson, Schunnesson, & Kumar, 2013). Automation can help reduce the stresses put on working machines through optimized use. The precision of the navigation system allows the machine to follow an exact pathway through narrow mine drifts, avoiding damage from collisions with walls and other equipment (Gustafson, 2013; Paraszczak et al., 2015). Along with accurate navigation, the system can also respond precisely to the topography of the underground environment (Gustafson, 2011). In doing so, automated machines will shift gears at optimum times thereby improving fuel efficiency and extend the equipment life expectancy by ensuring engines are not over-revved or overheated (Gustafson, 2011; Gustafson et al., 2013).

2.2.4 Environmental impact

There has been pressure in recent years to create mining methods that result in a more sustainable operation (Caterpillar Global Mining, 2008c). In line with this, it is generally considered that automation will allow mines to operate with less equipment and burn less fuel, which will thereby help reduce both costs and environmental impact (Caterpillar Global Mining, 2008c).

With each machine operating at higher production rates, mine sites can reduce the amount of equipment they use, and ultimately reduce their greenhouse gas emissions (GHG) over the life-cycle of the mine (Paraszczak, 2014). The site's carbon footprint is also reduced by fuel efficiencies gained from optimized driving regimes (Bellamy & Pravica, 2011; McNab & Garcia-Vasquez, 2011). An improvement in efficiency is also economically significant as diesel fuel consumption can comprise up to 30% of total operating costs (Bellamy & Pravica, 2011).

During the automated LHD trial, at the previously mentioned Canadian mine site, the fuel effiency of the automated LHD was compared to manual equipment, with the goals of lowering costs and reducing CO_2 emissions. The improved utilization of equipment throughout the day resulted in an increased daily consumption of fuel and production of CO_2, but on a per tonne of ore basis, total CO_2 emissions should be lowered due to greater efficiency in ore production. Data monitoring technology, which was incorporated with the automation package was able to monitor fuel usage throughout the 13 days of use (Appendix 2). The recorded consumption of fuel per 100 tonnes of ore moved was 30% less on average throughout the trial for the autonomous LHD when compared to a manually operated LHD. Furthermore, CO_2 emissions were reduced by 32% per 100 tonnes of ore moved with autonomous operation. This trial is a small sample size and more extensive long-term data will be required for a more comprehensive analysis, but the initial findings demonstrated improved fuel use efficiency and reduced environmental impact, two key motivations behind implementing automated technology in underground mines.

Further improvements in GHG emissions may also arise from a shift to electrification (Ewing, 2016). Transitioning from diesel fuel to battery-electric equipment allows mine sites to operate equipment without contributing to mine air pollution, eliminate diesel particulate matter from the underground work environment (Jacobs et al., 2015), and to reduce costs from lowered ventilation demands (Jacobs, 2013; Ewing, 2016; Jaderblom, 2017). Goldcorp Inc. has projected that the shift from diesel to battery-electric equipment at Borden Lake (Chapleau, Ontario, Canada) will eliminate the need for 3 million litres of diesel fuel and 33,000 MWh of electricity per year, and reduce annual CO_2 emissions by 7,000 t (Braul, 2018).

The three current operating techniques for electrification in underground mining are battery-electric motors, overhead power lines, and umbilical trailing cables connected to the mine's electric infrastructure (Paraszczak et al., 2013; Jacobs et al., 2015). However, due to infrastructure costs and the limited range of trailing cables and installation of overhead power lines, battery-electric equipment provides the most flexibility for underground operations (Paraszczak et al., 2013). Battery-powered motors allow for travel throughout the entirety of the mine, but challenges with battery life and recharge times need to be overcome before optimal operation can be achieved (Jacobs et al., 2015). There is also the possibility of strategic implementation of multiple technologies in specific areas of the mine. Overhead power cables would be most effective for areas with frequent or repetitive activity such as within the ramp or on haulage levels, whereas battery-electric equipment would be more practical for temporary drift or stope operations (Paraszczak et al., 2013).

The Macassa Mine site, which implemented battery-electric equipment, found that their 20-ton haul trucks achieved a 1–2 hour (h) battery life and required 1.5–2 h to recharge, whereas 3-tonne capacity LHDs achieved a 1.5–2.5 h battery life and required 1.5–2 h to recharge (Ross, 2018). Therefore, revisions to procedures and mine designs may be required to allow the efficient change of batteries throughout work shifts, and additional batteries may need to be included within capital and maintenance costs. The composition of the equipment fleet at Macassa Mine is listed in Table 2.1, with the battery equipment listed as a horsepower equivalent to their diesel counterpart. Because ventilation regulations in Ontario (Canada) require supplying 100 cfm/HP of diesel-powered equipment, there is potential for a significant reduction in ventilation from the operation of battery-based equipment (Campbell, Seeber, & Wywrot, 2003).

Table 2.1 Composition of the equipment fleet in operation at Macassa Mine (Ross, 2018).

Equipment	Fuel type	HP (equivalent)	Percent of equipment fleet
LHDs	Electric	250	5
	Battery	3,455	63
	Diesel	1,805	33
	Total	**5,510**	
Haulage trucks	Battery	2,200	85
	Diesel	400	15
	Total	**2,600**	
Combined	Electric	250	3
	Battery	5655	70
	Diesel	2205	27
	Total	**8110**	

According to the United States Environmental Protection Agency (2018), CO_2 emissions can be as high as 1000 kg per MWh of electrical power consumed, depending on the method of generation, and 2.6 kg per litre of the diesel fuel used in underground heavy equipment. Energy consumption from underground mining totals 10^9 MWh/year, or 30% of the total energy consumed within the mining industry (Holmberg et al., 2017). With ventilation and haulage contributing up to 40 and 25% of total energy consumption respectively, there is potential for significant CO_2 emission reductions from utilizing automated and electric equipment underground (Vergne, 2008; Holmberg et al., 2017).

2.3 Navigation Techniques

According to one report, the successful navigation of fully autonomous vehicles is dependent on various navigation techniques to complete four main tasks (Dragt et al., 2005):

(i) Developing a map of the underground work area (absolute navigation).

(ii) Detecting the real-time working environment surrounding the vehicle through sensors located on the machine (reactive navigation).

(iii) Locating itself within the work area (absolute navigation and dead reckoning)

(iv) Navigating through the design pathway (reactive navigation and dead reckoning).

In terms of the various navigation techniques, absolute navigation uses a real-world coordinate system to determine the position of an autonomous vehicle in the underground work area (Dragt et al., 2005). An operator initially drives the vehicle along the desired route to “teach” the machine a predefined pathway to be followed (Makela, 2001b) and lasers mounted to the machine build a representation of the underground environment (Dragt et al., 2005). However, once operating, obstacles that were not present during the teaching phase will not be detected by the machine, which presents safety concerns and potential for machine damage (Gustafson, 2011).

Reactive navigation is used to detect the surrounding environment. Underground autonomous vehicles are equipped with lasers and cameras to identify drift walls, other vehicles and obstacles located within the vicinity of the machine (Gustafson, 2011). The technology allows the vehicle to react to its immediate environment and detect any physical changes from the time the machine was taught the route (Roberts et al., 2000).

The dead reckoning method measures the motion of the autonomous vehicle to determine its change in position from the initial starting point, estimating the speed vector based on wheel rotations, and determining the directional trajectory of the machine. (Makela, 2001a; Dragt et al., 2005). The most common instruments used for dead reckoning is the odometer, which is used to measure the rotation of the wheels to determine the distance travelled by the vehicle, and gyroscopes which measure the orientation of the vehicle (Makela, 2001b; Gustafson, 2011).

2.4 Network Infrastructure

The successful operation of autonomous equipment in underground mining also requires a specific standard of communication infrastructure. Autonomous technology provided by equipment suppliers can connect to the mine’s network backbone if it meets the performance requirements listed in Table 2.2.

Table 2.2. Backbone network performance requirements.

Parameter	Requirement	Notes
Latency	50 ms	Above 100 ms, video quality will degrade.
Jitter	± 20 ms	Delay can only vary a small amount.
Bandwidth	10 Mbits/s per loader	Includes two video streams, and control/safety signals

Collated data from Sandvik Mining & Construction, 2017 & Atlas Copco, 2017.

The mine site is responsible for the installation and configuration of the required backbone network, which includes fiber optic cable connecting the operator's station on surface to the autonomous work area underground (Sandvik Mining & Construction, 2017). Table 2.3 lists the minimum requirements which the network infrastructure should support.

Table 2.3. Minimum requirements for the standards and protocols, the network infrastructure shall support.

Standards & Protocols	Description	Application
IEEE 802.3u	10/100 Tx-Base Ethernet	LAN communications, control & safety
IEEE 802.1Q &p	VLAN, Layer-2 QoS	Network segmentation and traffic priority. Standard requirement for PROFINET and MODBUS/TCP
IEEE 802.11 a/b/g	Wireless LAN	Mobility; tele-remote control and autonomous operation
IEEE 802.1AB	LLDP	Layer-2 discovery; standard requirement for PROFINET and topology-aware systems
RFC 1441, 1452	SNMPv2	Network management. Standard requirement for PROFINET and network monitoring
IEC 61158, 61784	PROFINET-IO	Safety communications; safety barriers and loaders.
MODICON 1979	MODBUS TCP/IP (or UDP)	Safety communications, emergency system stop

Collated data from Sandvik Mining & Construction, 2017 & Atlas Copco, 2017.

Communication links between the automated machine and the control system are made via internet protocol (IP) based wireless (Wi-Fi) and non-wireless (Ethernet) communication (Sandvik Mining & Construction, 2017). Access points (Wi-Fi routers) should be installed in the autonomous work area in a manner that the autonomous vehicle remains in the line-of-sight of at least one access point at all times. Access points are connected via ethernet cable, and the wireless signal strength must be maintained above –60dBm (Atlas Copco, 2015a). Table 2.4 lists the design limitations for the autonomous work area.

Table 2.4. Cable and signal limitations for communication infrastructure (Atlas Copco, 2015a)

Component	Limitation (m)
Ethernet cable	< 90
Directional antenna	~100
Omnidirectional antenna	~40

There is also potential to utilize telecommunication, or long-term evolution (LTE) to implement automation technology. At Agnico Eagle's LaRonde mine (Quebec, Canada), an LTE network was installed to allow for high-speed wireless communication on mobile devices because it offered better coverage over a larger area compared to Wi-Fi, and is subject to less interference (Rolfe, 2018). The technology is being used for data sharing and communication amongst workers/supervisors, and in addition has the potential for future autonomous operations (Rolfe, 2018).

2.5 Advances in Mine Automation

Mining automation is undergoing rapid development with older technologies, such as line of sight remote control and tele-remote operations, being replaced with semi-autonomous technologies. This progression is discussed in the following sections.

2.5.1 Radio remote control (RRC)

The first level of automation introduced to the mining process was operating remotely while maintaining an open line of sight to the machine (Gustafson, 2011). This allowed for entrance into dangerous work areas with unsupported ground or poor ventilation (Poole, 1999). Radio remote control is typically used with LHD machines, but reduced productivity is expected due to poor visibility, and the operator continuously dismounting and mounting the machine (Roberts et al., 2000; Ghodratia et al., 2015).

2.5.2 Tele-remote operations

Tele-remote operation was the next advancement with machines operated from a control station on the surface with the use of cameras, sensors and positioning data software (McNab & Garcia-Vasquez, 2011; Ghodratia et al., 2015). The operator is in full command of the machine throughout the entirety of the process by using controls similar to those located on manual equipment (Gustafson, 2011; Ghodratia et al., 2015). Productivity is gained through the elimination of operator travel times and the ability to operate through the blast window (Chadwick, 2010; Sandvik Mining, 2017), but a worker can only operate one machine at a time (Gustafson, 2011).

2.5.3 Semi-autonomous operations

At most mine sites, semi-autonomous operation is the current level achieved in which some functions, such as drilling and loading, are controlled remotely from an operator’s station on the surface (Chadwick, 2010; Ghodratia et al., 2015). An example is operating an LHD where bucket loading is carried out by remote operation that requires operator intervention, but the machine is then fully automated throughout the haulage and dumping actions (Chadwick, 2010; Gustafson, 2011; Ghodratia et al., 2015). The typical operating station provided by Epiroc and Sandvik are shown in Figure 2.2.

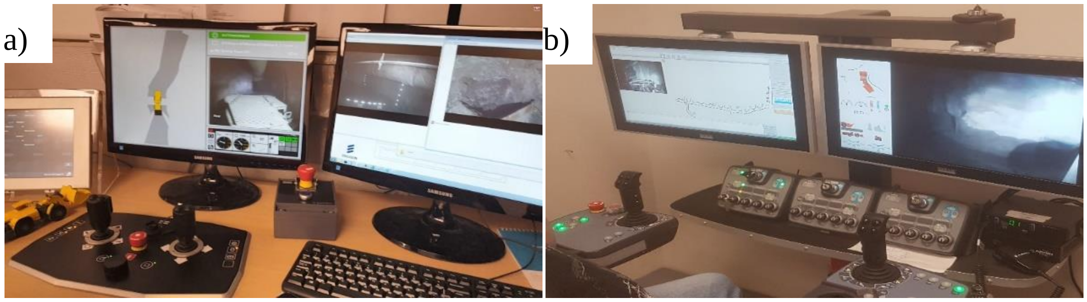

Figure 2.2. An LHD autonomous operating station on surface; a) Epiroc product; b) Sandvik product (Courtesy of Hudbay Minerals)

2.5.4 Full autonomous operations

The step to achieve fully autonomous operations is to develop technology to carry out drilling and loading functions, and thereby remove the need for any direct operator interaction (Gustafson, 2011; Ghodratia et al., 2015). Loading assistance technology has been developed by several equipment manufacturers for LHDs, resulting in fully automated cycles that eliminate the need for remote-control operation (Sandvik Mining, 2016). These advancements also allow one operator to oversee multiple machines from the surface, whilst monitoring overall productivity (Gustafson, 2011; Ghodratia et al., 2015; Sandvik Mining, 2016).

2.6 Available technology

Underground mining equipment is supplied by a variety of companies that have developed technologies to improve safety and production. Komatsu, for example, announced their project to retrofit the Komatsu 930E mining truck for autonomous driving with Caterpillar's MineStar^{TM} Command technology (Caterpillar, 2018). Hard-Line Solutions claim to be able to configure their automation technology to any make or model of machine within a mine's existing fleet (Hard-Line Solutions, n.d.). Table 2.5 summarises five major companies offering automation technology for LHD equipment, with a more detailed description of equipment and sizes given in Table A5. in Appendix 3.

Table 2.5. Mining equipment suppliers currently offering automation technology.

Company	Automation technology	Headquarters
Caterpillar (Caterpillar, 2018)	MineStar^{TM} Command	Illinois, U.S.
Epiroc (Epiroc, 2018)	Scooptram Automation Rig Control System	Nacka, Sweden
Hard-Line Solutions (Hard-Line, 2018)	Teleop^{TM}	Ontario, Canada
Komatsu Limited (Komatsu, 2018)	Autonomous Haulage Vehicle MineStar^{TM} Command	Tokyo, Japan
Sandvik (Sandvik 2018)	AutoMine®	Stockholm, Sweden

2.7 Case studies

Numerous case studies and trials with automated equipment have been performed at mine sites around the world. This section will discuss some of the operations that include LHD, haulage truck and drilling automated processes, as they will be the focus of the LCA studies within this thesis.

2.7.1 Automated LHD operations

In 2007, LKAB's Malmberget iron ore mine (Malmberget, Sweden) partnered with Caterpillar to automate the R2900G LHD in their underground operations and it was reported that there was a 10–20% increase in production (tph) after transitioning to automation (Caterpillar Global Mining, 2008a; Schunnesson et al., 2009). This production increase was partially attributed to the sub-level caving mining method. The large, slightly inclined ore body is considered to be an ideal condition for automated LHD operations due to the designed repetitiveness and low variability of the layout and activities associated with sub-level cave mines (Caterpillar Global Mining, 2008a; Gustafson, 2011; The Redpath Group, 2012).

Codelco's Andina copper mine (Santiago, Chile) used Epiroc's ST-14 scooptram over a one-year period (Atlas Copco, 2013a). The average ore production using manually operated LHDs was 44,850 tonnes per month, during the trial, the average rate increased to 80,000 tonnes per month and reached a peak of 133,000 tonnes in one month (Atlas Copco, 2013a). This with the operators located 80 km away and far from dangerous work conditions (Atlas Copco, 2013a).

2.7.2 Automated haulage trucks

From September 2015 to January 2017, Fortescue Metals Group's 54 autonomous trucks safely hauled 240 million tons of ore at their Solomon Hub iron ore mine (Mount Sheila, Australia) (Brown, 2017)—a 20% increase in productivity (tph) compared to their manual operations. There are similar reports from other mining companies utilizing autonomous vehicles, including Rio Tinto and BHP Billiton (Brown, 2017).

In 2008, Rio Tinto began trialing Komatsu's autonomous haulage system (AHS) technology in five sites across Pilbara, Australia (The Mining Journal, 2018) and by 2017, the autonomous fleet had expanded to 80 haul trucks and is expected to grow to over 140 by the year 2020 (The Mining Journal, 2018). Rio Tinto stated that in 2017, each truck operated an average of 700 more hours than manually operated trucks, and unit costs were lowered by approximately 15% (The Mining Journal, 2018).

2.7.3 Automated drilling operations

A 10–20% increase in productivity, which for drilling is measured as meters drilled per hour (m/hour), was reported at the Malmberget mine as a result of automated Caterpillar and Epiroc drill rigs (Caterpillar Global Mining, 2008a; Atlas Copco, 2013b). Caterpillar deployed five electric-powered automated production rigs that each drilled 10,000 m of 11.5 cm diameter holes at an average depth of 50 m (Caterpillar Global Mining, 2008a). In 2013, the mine introduced six of Epiroc's Simba WL6 C rigs for upward drilling with full automation (Atlas Copco, 2013b). They drilled holes with a depth of 30–47 m and a diameter of 115 mm and it is expected that the new automated fleet will lead to a 20% increase in productivity (m/hour) (Atlas Copco, 2013b).

BHP Billiton has been utilizing Epiroc's rig control system within their Yandi mine since 2015. As of November 2017, a Pit Viper 271 drill had operated autonomously for 15,000 h and drilled over one million metres (Turner, 2017). The mine reported a 20% increase in productivity (m/hour) of their drilling operations due to a 16% speed increase per drill cycle, as well as improved deviation metrics through drilling, leveling, tramming and de-leveling operations (Turner, 2017). The rigs were also capable of working 11.5 h out of a 12-h shift as compared to 8.5 h with a manually operated drill (Turner, 2017).

2.8 Challenges for automated mining

There are many benefits associated with the introduction of automated vehicles and equipment within the underground workplace, but to optimize autonomous operations to its full potential there are challenges to overcome. The condition of haulage roads is one of the most important factors associated with production (Caterpillar Global Mining, 2008d). An operator from a

Canadian underground mine site claimed that when roadways were not maintained, the autonomous vehicle was not able to travel at peak velocity, and, therefore, beneficial cycle time efficiencies from using them was not achieved. They acknowledged that because the operator is located on the surface, there is an absence of work personnel underground to perform roadway maintenance and work procedures need to be developed to address this issue (Hudbay Minerals operator, personal communication, 2017).

With less personnel underground and the equipment operator located on the surface, a new challenge is the requirement to maintain equipment, which will require additional maintenance personnel with specialized technical expertise (Gustafson et al., 2013). The reliability of mining equipment has historically been low and the time between equipment failures will need to be improved to accomplish desired production increases (Schunnesson et al., 2009). An important component of developing automated technology will, therefore, be to reduce the frequency of scheduled maintenance. This may be helped by less wear and tear through use of automation, but scheduling corrective maintenance appropriately to limit equipment downtime and maintain high production rates will be vital (Gustafson et al., 2013; Paraszczak et al., 2015).

The infrastructure within a mine and its design layout can affect the performance of automated equipment in the underground mine environment, but the required infrastructure may not coincide well with the mine's existing infrastructure and layout (Ghodratia et al., 2015). It is also important to design the autonomous work area properly (Ghodratia et al., 2015) to isolate autonomous operations from other areas of the mine, without hindering the productivity of operations that have yet to be automated (Gustafson, 2013).

2.9 Conclusions

From improved utilization of equipment, and the ability to operate between shifts, mine sites have the opportunity to increase machine productivity with near real-time data reporting. To obtain the maximum potential of utilizing autonomous technology, the challenges of mine design, maintenance planning and scheduled roadway maintenance will, however, need to be addressed through the innovation of mine engineers.

Table 2.6 provides a summary of the productivity and utilization gains from LHDs, haulage trucks and drills mentioned throughout this chapter.

Table 2.6. Summary of automated case studies.

Equipment	Productivity change	Utilization change
LHDs		
Jundee mine (Schunnesson et al., 2009)	-	+ 3 hours/day
Olympic Dam mine (Schunnesson et al., 2009)	~40%	+ 4 hours/day
Malmberget mine (Caterpillar Global Mining, 2008a; Schunnesson et al., 2009)	~10-20%	-
Andina mine (Atlas Copco, 2013a)	~25%	12 hour shifts
Haulage operation		
Solomon Hub mine (Brown, 2017)	~20%	-
Rio Tinto mine (The Mining Journal, 2018)	-	+2 hours/day
Drilling operation		
Malmberget mine (Caterpillar Global Mining, 2008a; Atlas Copco, 2013b)	~20%	-
Yandi mine (Turner, 2017)	~20%	+ 6 hours/day

There is also potential to further research and quantify the environmental impact of autonomous operations in underground mines. Past automation trials have shown promising higher efficiencies, lower fuel consumption and lower energy consumption from decreased ventilation demands. An improved impact on the environment will be an important justification for the transition to autonomous vehicles and the sustainability of the mining industry.

2.10 Continuation of literature review (updated for 2019-2020)

There has been additional research into automated, battery-electric, and other technologies for underground mine operations, since the submission of the review paper that was presented within Chapter. This section will present the publications that have been added to the research field, and discuss how they relate to the studies within this thesis. Table 2.7 provides the list and summaries of the new studies (post 2018) that were not included earlier in this chapter.

Table 2.7 Further review of relevant research articles.

Title	Description
Artificial intelligence, machine learning and process automation: existing knowledge frontier and way forward for mining sector (Ali & Frimpong, 2020).	A review to analyze all the recent automation related work in all aspects of the mining industry, including; exploration, mine planning, equipment selection, and underground/surface equipment operation. LHDs are the most advanced automated equipment within underground mine sites, while further development is still needed for other equipment types.
Automation in the Mining Industry: Review of Technology, Systems, Human Factors, and Political Risk (Rogers et al., 2019).	A review of the state of automation in the mining industry focused on the automation technology, system's engineering and management process, and human factors engineering. The authors state that automated processes will require continuous feedback and analytics using the feedback mechanism – internet of things (IoT). IoT is the interconnectivity of devices within a process allowing them to send a receive real time data.
Increased safety in deep mining with IoT and autonomous robots (Günther et al., 2019).	This paper analyzes the development and application of mobile autonomous vehicles and IoT within underground mining. The focus of the research is on mine safety, with discussion on the benefits and limitations with regards to mine operators.
Innovation in the Mining Industry: Technological Trends and a Case Study of the Challenges of Disruptive Innovation (Sánchez & Hartlieb, 2020)	A discussion and review of the importance of innovation within the mining industry and the required mechanisms. Technological progress is important for the extraction of new ore deposits with added complexities such as deeper deposits, lower ore grades, extreme weather conditions and harder rock masses with high stress conditions. Automation, IoT and analytics are the primary focus of this research paper.
Investigation of fast charging and battery swap options for electric haul trucks in underground mines (Rafi et al., 2020).	An investigation on the processes and operations required for battery swapping and fast charging specifically for underground haul trucks. The research focuses on productivity and costs comparisons for the available equipment offered within the industry, and different battery size/charging options.
Performance evaluation of tele-remote underground drilling for sublevel caving (Gromov et al., 2020).	Analysis of the global experiences with tele-remote longhole production drilling within underground mines. It was shown that tele-remote drilling had a 15-31% increase in utilization and drilling performance and reduced stope excavation costs by 7.9%.

The previous research papers provided in Table 2.7 presented adequate information on the required innovation within the underground mining industry. The focus of the more recent papers has been mostly on reviewing the available technologies such as automation, IoT, and battery-electric equipment, with provided case studies. The research has still only considered the productivity, safety and economical factors for the transition of manual to automated underground mining equipment, and there remains a gap for the comparative assessment of environmental performance. As previously mentioned, LCA tools and techniques have not been used as a method of assessing the impacts on environment from implementation automated equipment within the underground environment, therefore, the methodologies and work presented throughout this thesis are novel to the industry.

Chapter 3: Life cycle assessment to demonstrate how automation improves the environmental performance of an underground mining operation

3.1 Introduction

Mining companies around the world continue to explore and assess new methods of extracting ore to improve safety and economic sustainability (Chadwick, 2010). 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 (McNab & Garcia-Vasquez, 2011; Vintro et al., 2014; Braul, 2018). 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 underground metal ore mining operations but are limited due to difficulties with quantifying the various inputs and outputs required within mining processes (Ferreira and Leite, 2015).

Automation has become increasingly 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 (Chadwick, 2010; Gustafson, 2011). Automated technology has become a focus for three main reasons:

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 (Chadwick, 2005; McNab & Garcia-Vasquez, 2011).

Productivity – Productivity is increased through improved cycle times and operation of equipment from the surface during the blast window. Personnel are not permitted underground during large production blasts. On average, 4-5 hours of production is lost during the blast window per day using current manually operated equipment (Gustafson, 2011). However, automated equipment can be operated from the surface during this time to boost productivity.

Maintenance – Manually operated equipment is subject to operator error, poor visibility and blind spots, leading to collisions with drift walls, excess tire wear and overworked engines (Dragt et al., 2005; Gustafson et al., 2013). In contrast, automated equipment is associated with fewer collisions, increased tire life, optimized driving and reduced consumption of spare parts (Bellamy & Pravica, 2011).

Since 2005, the mining industry has experienced a 28% (3.5% per year) decrease in productivity worldwide (McKinsey & Company, 2015). Labour productivity (output per unit labour such as each hour worked) in the Canadian, American and Australian mining industries decreased between 2000-2007 due to declining capital, resource yield decline, production lagging, labour skills shortages and increasing regulations (Matysek & Fisher, 2016). Statistics Canada reported a decline of 2.21% in labour productivity during this same time period (Sharpe & Bradley, 2009). A visual of the labour productivity decline for the mining sectors within Canada, USA and Australia is provided in Figure 3.1 (Sánchez & Hartlieb, 2020). The Chamber of Mines of South Africa reported a decline in productivity over the past ten years within their mining industry. Technical challenges with deep-level mining were listed as reasons for this decline in productivity, and the long-term success of the mining industry will rely heavily on companies to develop innovative methods of addressing these challenges (Neingo & Tholana, 2016).

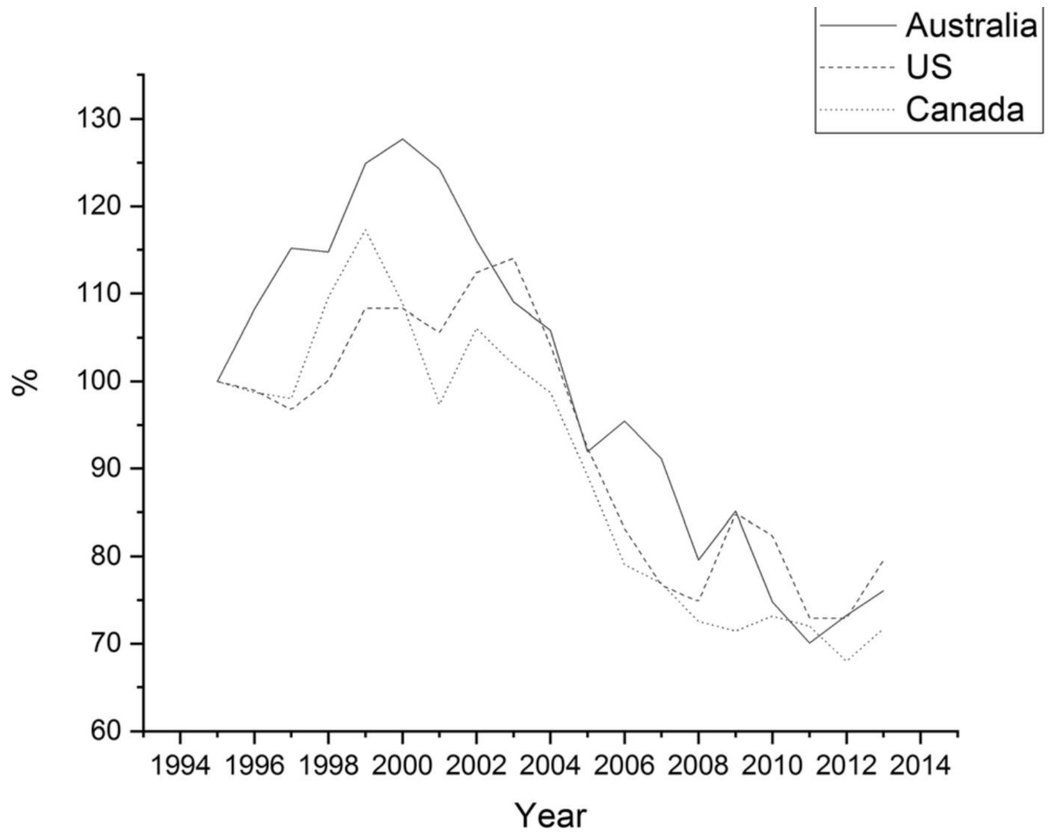

Figure 3.1: Labour productivity (tonne/worker-hour) of the Canadian, USA and Australian mining sectors presented as a percentage of 1995 levels (100%) (Sánchez & Hartlieb, 2020).

While research in the area of mining LCAs has been reported as limited, a few studies have previously been carried out to assess the environmental impacts from mining and mineral processing. Reid et al. (2009), performed a comparative LCA study of 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 (Reid et al, 2009). 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 (Norgate and Haque, 2010). Another study reported that copper producing mines had a wide range of total GHG emissions (1-9 t CO_2 eq./ t Cu.) due to differences in factors such as fuel sources, electrical energy sources and ore grade (Northey et al., 2013). This supports the observation of Reid et al, (2009), that varying mine site characteristics will have a significant impact on the total emissions produced on site.

There is limited available research on the environmental impact of autonomous equipment in the underground mining industry. This chapter focuses, 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 comparison was done by using data collected from automation trials, performed in 2017, within an underground mine in Mantioba, Canada. The details of these trials are provided in Appendices 1 and 2. The mine's use of automated Load-Haul-Dump (LHD) equipment 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 CO_2 emissions from burning diesel fuel (Moreau et al, 2019). 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 (ISO 14040, 2006). An LCA is carried out by defining the goal and scope, inventory analysis (compilation and quantification of inputs and outputs for a given product system throughout its life cycle), impact assessments and interpretation as shown in Figure 3.2. The ISO 14040:14043 standards were created for the evaluation of environmental performance of a product or service throughout its operational life cycle. The standards are listed below (ISO 14040, 2006):

- 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.

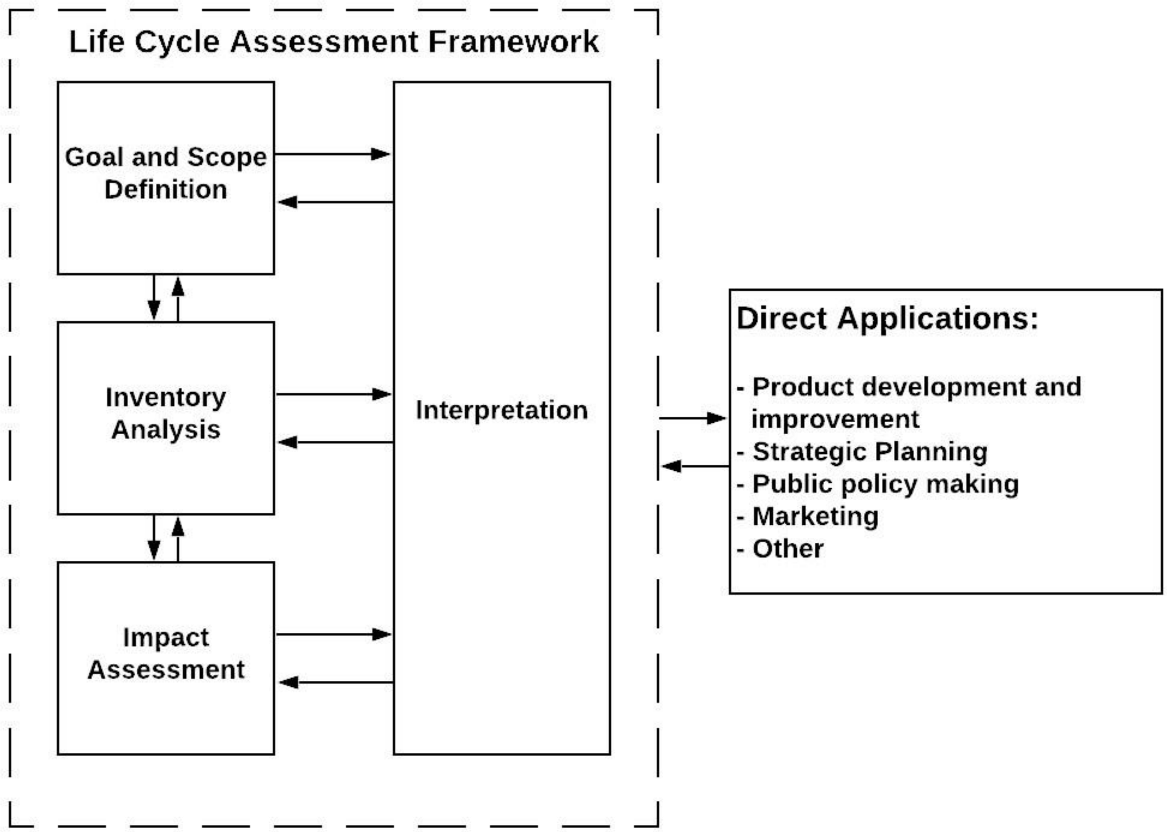

Figure 3.2: Stages of an LCA study (ISO 14040, 2006).

3.2 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, from the mine site's annual technical report, are provided in Table 3.1 in terms of the defined functional unit for this LCA study (one tonne (t) of ore mined and processed).

Table 3.1. 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

The LCA study performed incorporates drilling, blasting, hauling, hoisting, crushing, grinding, flotation, dewatering, and subsequent transportation of concentrated products to external refinery sites and disposal of waste tailings. Figure 3.3 is a simplified process diagram showing the LCA boundaries, while Table 3.2 provides a description of the processes included within the boundary.

Table 3.2. Underground mine and mill process descriptions (Vergne, 2008; Darling, 2011; Hudbay Minerals, 2017).

Process	Description
Drilling	Drilling has been separated into two sections; development drilling and production drilling. Development drilling uses a hydraulic drill (jumbo drill) to further develop the drifts (tunnels) horizontally throughout the mine. Drifts are advanced by approximately 3m at a time. For hard rock mining, production drilling typically uses a percussion drill (In-the-hole hammer drill) to drill vertical holes up to 25m in depth.
Blasting	Drill holes are filled with explosives and detonated between shifts when workers are not present. The resulting rock (muck) pile is primarily classified as waste rock, for development drilled areas, and valuable ore for production drilled areas.
Ore transport (loading and hauling)	Ore transportation is performed using an LHD machine to pick up ore from either the drift muck pile, or from the bottom of the open void (stope) created during the production drilling and blasting processes. The bottom of the stope is accessed via drift development, and ore is transported via LHDs and haulage trucks down the mine through vertical raises (voids) to the loading pocket to be hoisted. Alternatively, ore can be transported to surface via haulage truck.
Waste transport (backfill)	Waste rock is the rock determined to be low grade, and primarily is a result of development drilling and blasting. Typically, waste rock is deposited (backfilled) into empty stopes from previously worked areas of the mine. The waste can be combined with paste fill made from waste tailings, sand fill or others.
Bolting	Bolting is the process of supporting the exposed rock on the walls and back (roof) of the drift from blasting. Bolting requires a handheld percussion drill (jackleg or stoper) and typically drills rock bolts into the rock for support. Other methods can also be used such as cable bolts, shotcrete and mesh/screens.
Rock breaking	Rockbreakers are used to initiate the size reduction process required to further transport the ore. Hydraulic or pneumatic rockbreakers can be used with a grating (steel rails) placed over an open hole. The resulting ore is reduced to a size acceptable for hoisting or further crushing.
Hoisting	Hoisting systems are comprised of hoists, cables/wires, cages/skips, shafts and headframes. The ore is loaded into cages or skips and hoisted up the mine through a vertical tunnel (shaft) to the headframe (physical structure at the entrance to the mine).
Ventilation	Ventilation is the process of providing sufficient air of high quality to the underground workings to replace the oxygen consumed by the miners and dilute contaminants produced during operation.
Mine auxiliaries	Any operation that is not affected by the productivity rate of the mine (e.g. lighting, heating, welding, office electricity consumption, etc.)
Crushing	Ore enters the concentrator at a size of approximately 0.55m. The concentrator utilizes a jaw crusher, cone discharger and vibrating screens to produce a particle size of 19mm.
Grinding	The product from crushing is grinded with a combination of rod and ball mills in a circuit. The ore passes through the rod mill to create a reduced course particle, then proceeds through the ball mill to produce a particle of 150 microns. The process requires 3 tonnes of water for each tonne of ore processed.
Flotation	Using flotation cells, the 150-micron particles float to the top of the solution using the appropriate reagents. The product is treated by cleaning cells and the concentrate is pumped to the thickener. The remaining liquid is the final plant tailings.
Dewatering	The concentrated product is pumped to thickeners where it is dewatered to a target moisture content (9%). The dewatered concentrate is then transported to refinery sites for further concentrating.
Tailings disposal	Waste tailings from the flotation process are pumped to the tailings pond for sedimentation. A portion of the tailings can be used for paste fill purposes in underground open voids.
Mill auxiliaries	Any operation that is not affected by the productivity rate of the mill (e.g. lighting, heating, office electricity consumption, etc.)
Mine camp	Processes include; electricity consumption, water and solids disposal, employee transportation.

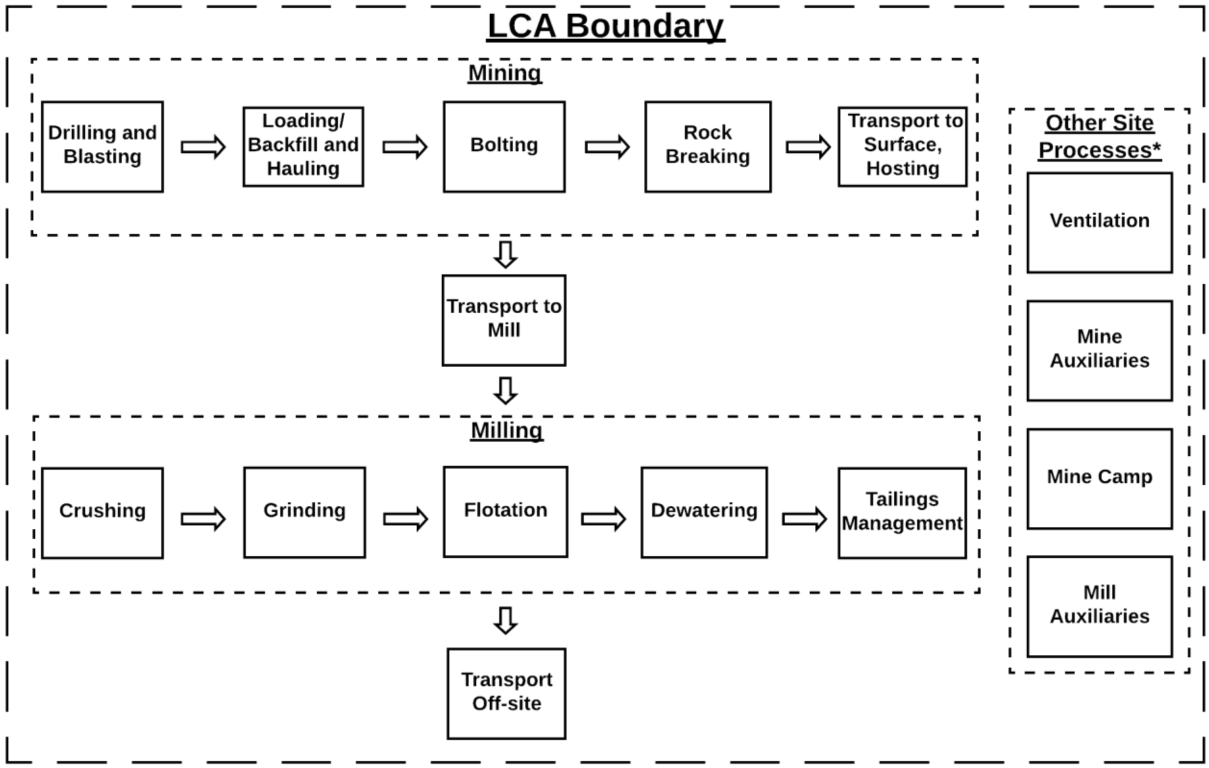

Figure 3.3: Boundary for the LCA study of the investigated mine site. *Not included within the flow of ore (time-dependent).

The processes seen in the mining and milling sections of Figure 3.3 are dependent on ore productivity (tonne/day), 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 that were not impacted by the movement of ore, 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 3.3).

The operational data obtained from the mine site 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 3.3 along with calculated life-of-mine. The ability to extract ore at a 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 environmental impacts 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.

Table 3.3. Operational data for manual and automated LHD operation at the studied mine site, and the expected life of mine.

LHD Operations	Ore Reserves	Production Rate	Expected Life of Mine
Manual	20,000,000 t	3,000 t/day	18.3 years
Automated	20,000,000 t	4,050 t/day	13.5 years

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 3.4 and was used to calculate emissions from daily travel to and from the worksite.

Table 3.4. Estimated 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

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 auxiliary processes shown in Figure 3.3 are also not affected by an increase in ore production. Equipment such as boom-trucks, minecats, forklifts, and personnel carriers are all included within this process, as well as the 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 requirements included within the mine and mill auxiliary sections is provided in Table 3.5.

Table 3.5. Electricity requirements for operations included in the auxiliary processes of the LCA (adapted from Vergne, 2008).

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

3.3 LCA Inventory Analysis and Interpretation

The LCA inventory analysis is an analysis of the material and energy inputs and outputs of all the processes within the defined boundaries, which include environmental inputs/outputs and those related to the technosphere (the environment that is made or modified by humans), such as energy consumption and materials processing. Table 3.6 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 represents entirely manual operations at the mine site. scenario 2 analyzes the mining and milling processes using automated LHDs, with productivity and fuel consumption data obtained from the trial results. scenario 3 includes projections for additionally including automated haulage trucks and drill rigs.

Table 3.6. Inventory analysis for one tonne of ore mined and processed at the 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	21	18.8	17.3	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

3.3.1 Productivity Analysis

Productivity fluctuation can be expected, especially during mine start-up and closure, but the average daily rate has been used to analyze total emissions over a large period of time. In 2017, the mine reported non-automated productivity rates of 3,000 t/day and this was used as the basis for the manual operation productivity rate (scenario 1). The data gathered from the trials conducted at the mine site showed a 35% increase in productivity (4,050 t/day) from LHD automation, which was consistent with the companies' other reports and well within the ranges stated from other sources (10% - 60%) (Schunnesson et al., 2009; Gustafsson, 2011; Brown, 2017; Sandvik Mining, 2017). Therefore, the 4,050 t/day rate was used as the productivity rate of automated equipment in this study. Metal prices will certainly have an impact on the rate of mining but projecting metal prices into the future is a difficult task. External demand leading to fluctuations in a mine's production levels will be the same irrespective of the level of automation and so the average production rates detailed above were used to compare the various scenarios.

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 (Moreau et al, 2019).

Productivity increases from improved cycle times and operation during the blast window would allow the mine to operate with less equipment while maintaining the 4,050 t/day production rate. With less equipment and a projected improvement in required maintenance of 15 to 30% (from less accident related damage) for automated equipment (Darling, 2011; Paraszczak et al., 2015), it is also expected that there will be a reduction in replacement parts and scrap tire disposal throughout mine-life operations.

3.3.2 Fuel Consumption Analysis

The manual and automated LHDs were found to consume fuel at a rate of 0.27 and 0.18 L/t of ore mined respectively (Appendix 2). 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 3.7 below.

Table 3.7. List of equipment used at investigated 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
Underground auxiliaries (minecats, forklifts, etc.)	19
Surface auxiliaries (trucks, loader, pickups, etc.)	22

The CO_2 emission factor used for diesel burned in heavy-duty equipment was 2,681 g/L of diesel fuel (Government of Canada, 2019a). The reduction of underground diesel usage (4.71 L/t for scenario 1) could have a large impact on the environmental footprint over the entire mine life, especially when projecting automated fuel consumption reductions for other machines and equipment (3.53 L/t for scenario 3).

3.3.3 Ventilation Analysis

Ventilation at the mine site is responsible for 32.3% of electric power consumption (the next highest consumption activities are grinding at 11%, ore and waste transport at 9.9%, flotation at 7.3%, hoisting at 7% 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 CO_2 emitted and the environmental footprint of mining operations. Table 3.8 lists the global average GHG intensity factors of various electricity generation methods for comparison (World Nuclear Association, 2011).

Table 3.8. GHG emission intensity factors of various electricity generation sources (World Nuclear Association, 2011).

Source	Mean	Low	High
	g CO_2 eq./kWh		
Lignite	1,054	790	1,372
Coal	888	756	1,310
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

Regulations stipulate that mines supply 100 cubic feet per m,.inute (cfm) of fresh air per horsepower of diesel equipment in operation, which is consistent across various regions (Campbell et al., 2003; Vergne, 2008). The ventilation requirements for the three scenarios are presented in Table 3.6, with reductions seen for scenario 3. The increased productivity projected for individual automated haulage trucks and drills reduces the number of equipment needed to maintain production rates, and the resulting environmental impacts were analyzed.

3.3.4 Methodology and Software

For this study, Thinkstep's GaBi Solutions software (Thinkstep, 2019) 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. The processes within this extension had various metals production operations, which included the impacts from mining, milling, smelting and recycling for 1 kg of metal produced. However, the specific operations used for mining and milling, that are analyzed in this study, were not included as processes within the software. These processes were developed in the software for the first time, specifically for this mine site study. The required equipment (e.g. heavy-duty diesel truck, industrial loader, etc.) and 23 major inputs/materials were provided within software's extension package, and were used to construct the new processes. Further details for these processes are provided in Table A6. Of Appendix 3.

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, (Canadian Industry Program for Energy Conservation, 2005; Vergne, 2008)). The data was entered into 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 t.

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. The impact assessment method that was used for this study was TRACI version 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts), which was developed by the U.S. Environmental Protection Agency (Bare, 2011). TRACI's 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 (Menoufi et al., 2011).

3.4 Results and Discussion

3.4.1 Global warming potential

As previously mentioned, the contribution of carbon dioxide emissions from the mining industry, in 2010, was calculated to be 1 Gt CO_2 eq. per year, which is about 2% of total global emissions (United Nations Framework Convention on Climate Change, 2018). As of 2020, the contribution of GHG emissions from the mining industry increased to 4-7% of total global emissions (McKinsey & Company 2020). Global warming potential was developed to compare the impacts of different GHGs emitted to air (e.g., CO_2, CH_4, N_2O) and is measured as equivalency to carbon dioxide (kg CO_2 eq.) (United States Environmental Protection Agency, 2017). 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 IPPC'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 (Intergovernmental Panel on Climate Change, 2007). Table 3.9 contains the reporting criteria required by the Canadian Greenhouse Gas Reporting Program (GHGRP) under which the studied mine falls.

Table 3.9. GHGRP requirements for reporting selected GHGs (Canada Gazette, 2019).

	Emissions Source								
Greenhouse Gas	Stationary Fuel Combustion	Industrial Process	Industrial Product Use	Fugitive: Venting	Fugitive: Flaring	Fugitive: Leakage	On-site Transport-ation	Waste	Wastewater
Carbon dioxide	✓	✓	X	✓	✓	✓	✓	✓	✓
Methane	✓	✓	X	✓	✓	✓	✓	✓	✓
Nitrous oxide	✓	✓	X	✓	✓	✓	✓	✓	✓
Sulphur hexafluoride	x	✓	✓	x	x	x	x	x	x
Hydroflurocarbons	x	by species	by species	x	x	x	x	x	x
Perflurocarbons	x	by species	by species	x	x	x	x	x	x

In 2017, the site reported 19,260 t of CO_2 eq. were emitted from their operations (Government of Canada, 2019b), whereas the LCA software calculated 23,740 t of CO_2 eq. production per year. The 21.3% increase was mainly 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 1,430 and 2,100 t CO_2 eq. respectively, which taken out would reduce the LCA calculated value to 20,210 t of CO_2 eq., which is only a 4.8% 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. The results from the mining processes studied in the three investigated scenarios are presented in Table 3.10.

Table 3.10. Global warming potential results from investigated mine site.

Scenario	kg CO_2 eq./t	% decrease (from scenario 1)
1	21.8	-
2	19.4	11.1%
3	17.9	17.9%

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 (Figure 3.4). As LHD machines are primarily used within these operations they were expected to have the largest impact on CO_2 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 CO_2 emissions and other impacts from the mine camp by eliminating years of on-site energy consumption, daily travel to and from the workplace, as well as landfill solid waste 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, based on recommendations from the automation team at the mine site and their future implementation plans, that the mine site will utilize two machines per operator for LHDs, haulage trucks and drills, while also requiring additional specialized personnel for maintenance, 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 Figure 3.4.

When projecting the productivity gains and fuel efficiency from automated LHDs to haulage trucks and drills, a 17.9% reduction in kg CO_2 eq./t of ore was projected for the tested mine site operations. As seen in Figure 3.4, a substantial portion of this reduction was contributed from the haulage and mucking operations. Drilling operations provided a reduction of 0.03 kg of CO_2 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.

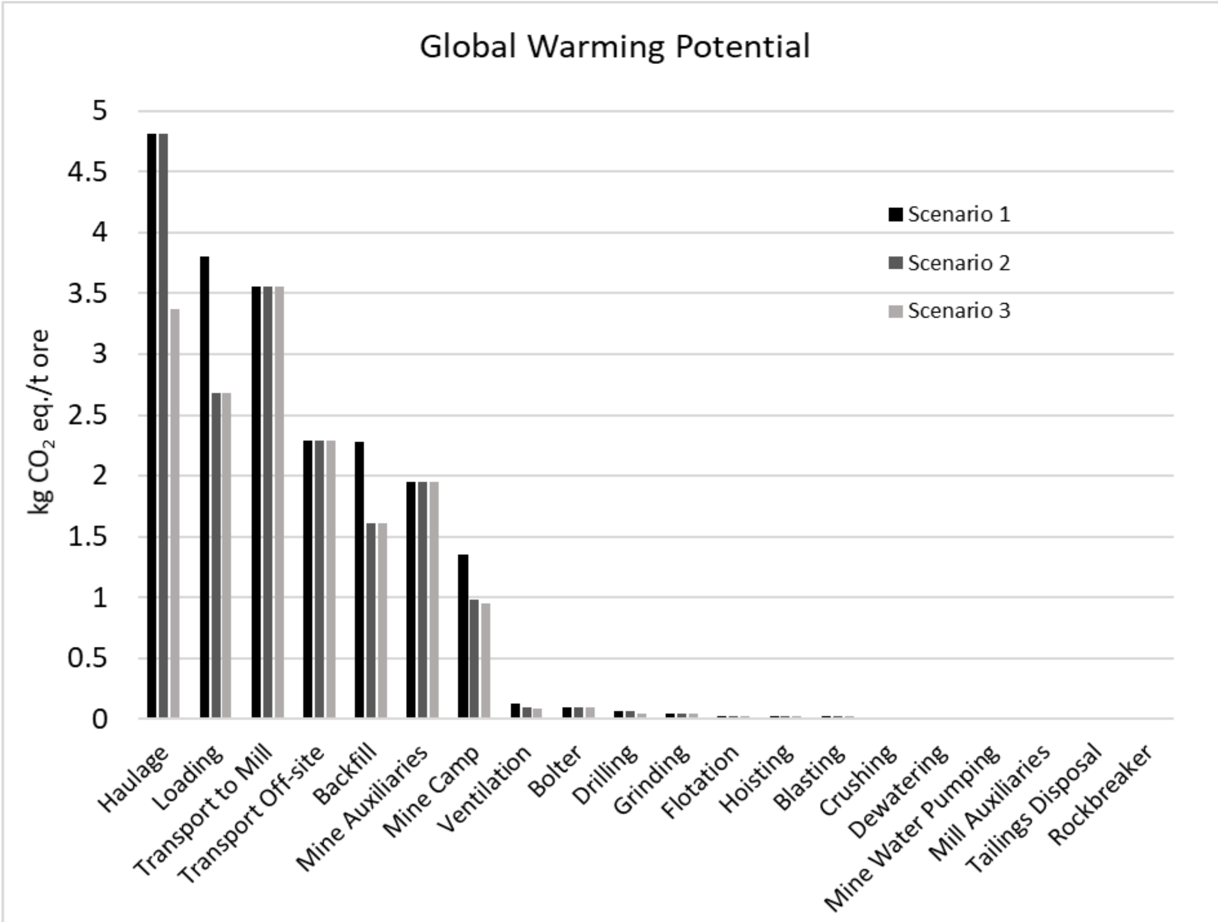

Figure 3.4: Global warming potential of individual mining operations.

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. Renewable hydropower accounts for 98% of the electricity generation in this area, which produces the lowest GHG emissions during operation as seen in Table 3.8 (World Nuclear Association, 2011). The remaining 2% is generated from natural gas resources and the average intensity factor was reported to be 3.4 g

CO_2 eq./kWh in the region where the mine is located (Government of Canada, 2017). 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 CO_2/kWh), whereas areas using fossil fuels to generate electricity have GHG intensities as high as 790g CO_2/kWh (Alberta) (Government of Canada, 2017). 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.

3.4.2 Acidification and eutrophication potentials

When analyzing environmental impacts of an operation or industry, the main focus is often on GHG emissions (CO_2 eq.), but the purpose of the 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 (H_2SO_4 and HNO_3) in surface soils and waters (Pacheco-Torgal, 2016). In 2018, the ore and mineral industries contributed 32% of the sulphur oxide emissions in Canada (259 kt), which is the second largest source of sulphur emissions behind only the oil and gas industry (261 kt). 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 (Guinée & Lindeijer, 2002).

Eutrophication potential is an increase in nutrient concentration, primarily phosphorus and nitrogen, resulting from the deposition of nutrients to aquatic or terrestrial areas from human activities, such as chemical fertilizer application or wastewater discharges (Kim & Chae, 2016).

The enhancement of nutrient richness may result in a shift in species composition and increased biomass production in both aquatic and terrestrial ecosystems. In aquatic quatic ecosystems, this leads to depressed oxygen levels and poor drinking water quality (Guinée & Lindeijer, 2002). 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 the explosives used in the underground mining process. A study estimated that 50 kt of nitrogen are emitted per year from explosive blasting agents used in the mining industry, which is relatively minor compared to the global emissions of 41,300 kt of nitrogen per year (Oluwoye et al., 2017). However, these mine blasts can contain large concentrations of NO_x (500ppm), which is 3,000 times the international standard, and leads to significant impacts at mining sites and the immediate surrounding environment (Oluwoye et al., 2017).

The acidification potential for each scenario was estimated based on mass of SO_2 eq. and presented in Table 3.11. The data obtained from the automation trial period indicated a 9.8% decrease in calculated SO_2 equivalent (scenario 2), while a 17.3% decrease was projected when also including automated haulage trucks and drills (scenario 3). In comparison, the use of automated equipment resulted in a decrease in eutrophication potential of 4.8% and 8.5% for scenarios 2 and 3, respectively.

Table 3.11. 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%

Tables 3.12 and 3.13 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, where haulage and mucking processes are large contributors and are affected by automation technology.

Table 3.12. Process analysis for acidification potential.

Operation	Acidification Potential (kg SO_2 eq./tonne)		
	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}

Table 3.13. Process analysis for eutrophication potential.

Operation	Eutrophication Potential (kg N eq./tonne)		
	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}

3.4.3 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 (Hertwich et al., 2001). Mining activities and fossil fuel combustion are major sources of diesel particulate emissions, as well as global mercury pollution, which are two examples of the emissions included within this impact category (Bugarski et al., 2004; United States Environmental Protection Agency, 2020b). The LCA software calculates human toxicity using the USEtox® scientific consensus model which calculates characterization factors (link between chemical emissions and impacts on humans based on environmental fate, exposure and effects) for human toxicity by assessing the toxicological effects of a chemical emitted into the environment through environmental fate, exposure and effects (Rosenbaum et al, 2008). Human toxicity is measured in Comparative Toxic Units (CTUh), which is an estimation of increased morbidity per unit mass of chemical emissions (Rosenbaum et al, 2008). The results for scenarios 1-3 are listed in Table 3.14.

Table 3.14. Human toxicity potential comparison using USEtox® scientific consensus model.

Scenario	CTUh/t	% decrease (from scenario 1)
1	2.97×10^{-6}	-
2	2.64×10^{-6}	11.2%
3	2.40×10^{-6}	19.2%

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 (Rosenbaum et al, 2008).

3.4 Practical implications of the present study

The implementation of automation was found to have a significant impact on all the investigated impact categories. Previously reported GHG emissions from underground copper operations had a range of 1-9 t CO_2/t Cu. metal (Northey et al., 2013). The results from the current study for the global warming potential of the mine site under current manual operations (scenario 1: 21.8 kg CO_2/t ore) is, based on actual copper metal production (6,400 t/a), 3.73 t CO_2/t Cu., which falls within the lower half of the range suggested by Northey et al, (2013). Whereas, with the use of automated LHDs, haulage trucks and drills (scenario 3: 17.9 kg CO_2/t ore) it is equivalent to 3.06 t CO_2/t Cu. This 18% reduction in GHG emissions was primarily from operations that use diesel fuel as an energy source (Figure 3.4). Mucking, haulage, and backfill were responsible for 84.1% 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 (10.6%), ventilation (4.5%), and drilling (0.8%), which are a result of lower energy consumption and less employee travel due to the 27% decrease in operational mine life.

The mine site operations were also examined as if the mine 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 3.15, the GHG emissions factor for electricity generation in Nevada, USA, was estimated to be 421.4 g CO_2 eq. per kWh compared to 3.4 g CO_2 eq. per kWh at the mine studied.

Table 3.15. 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

Operations relying on electricity as an energy source, including ventilation and grinding, become some of the highest contributors to CO_2 eq./t of ore in this situation. Ventilation is the highest contributor, compared to eighth highest in the original anylsis, but also experiences the largest reduction when automation is introduced, as seen in Figure 3.5. The total reduction from scenario 1 to 3 was calculated as 9.7 kg CO_2 eq./t, whereas the reduction from ventilation was calculated to be 5.3 kg CO_2 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.

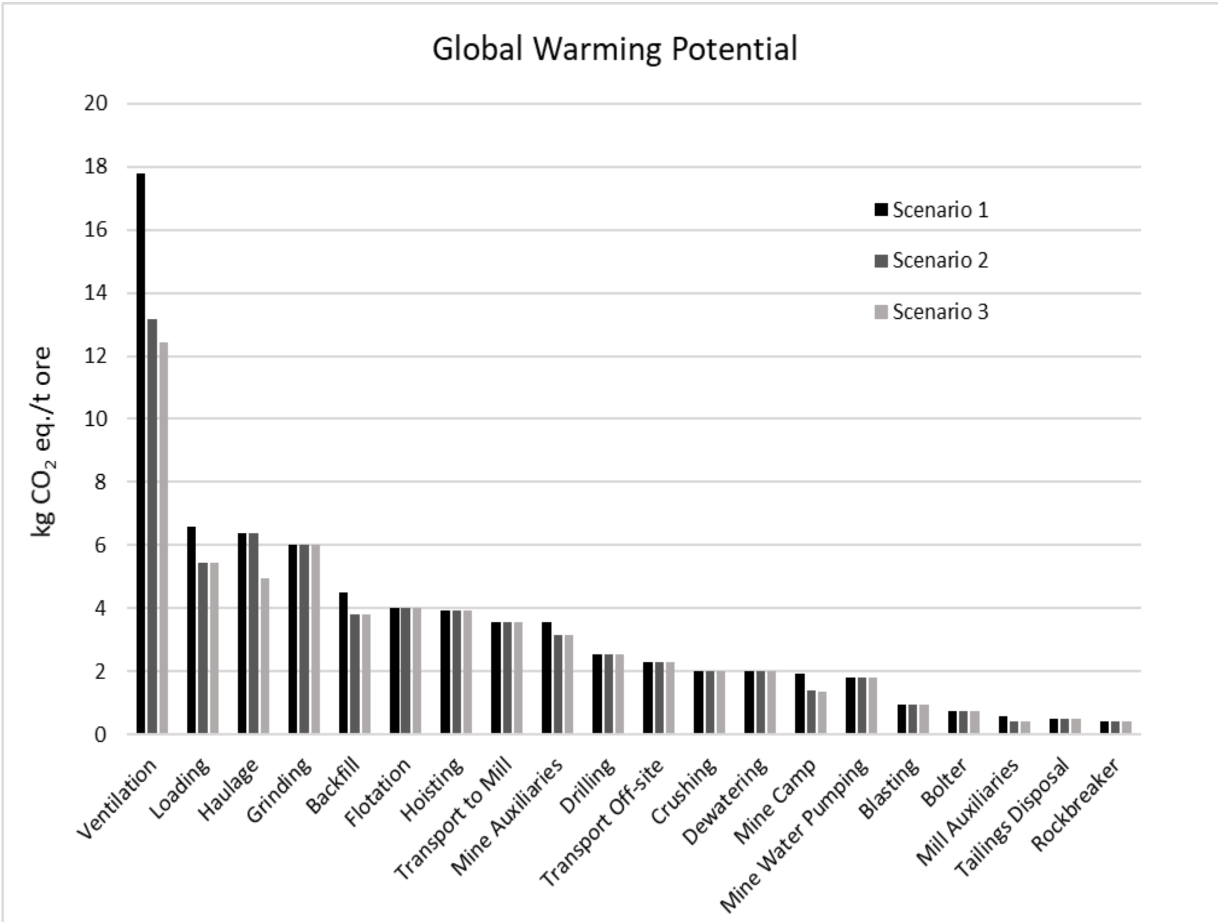

Figure 3.5: Global warming potential breakdown of specified operations with an electric energy generation GHG intensity factor of 421.4g CO_2 eq. per kWh.

The sensitivity of the LCA results in this study, with regards to the method of electricity generation, was analyzed further for all three investigated scenarios. The LCA study was performed repeatedly for coal, wind, natural gas, solar, biomass, and nuclear electricity generation and compared to the actual mine site (98% renewable hydropower). The results for the life of mine (20 million tonnes of ore) are presented in Table 3.16 below. The total emissions from mine site operations, along with the potential reductions from the use of automated equipment, varies significantly depending on the electricity generation method, and should be considered a key parameter for future comparative LCA studies involving manual and automated equipment in underground metal ore mine sites.

Table 3.16. Sensitivity of CO_2 eq. emissions with various electricity generation methods.

Electricity generation method	Scenario 1	Scenario 2	Scenario 3
		tonne CO_2 eq.	
Coal	2,585,000	2,310,000	2,248,000
Natural gas	1,895,000	1,693,000	1,641,000
Solar	536,000	477,000	446,000
Biomass	498,000	443,000	412,000
Wind	419,000	372,000	342,000
Nuclear	413,000	368,000	338,000
Studied mine site (98% hydropower)	**403,000**	**359,000**	**329,000**

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 addressed in this study (Figure 3.6), provide a more comprehensive site-specific analysis of environmental benefits, or otherwise, from introducing automation.

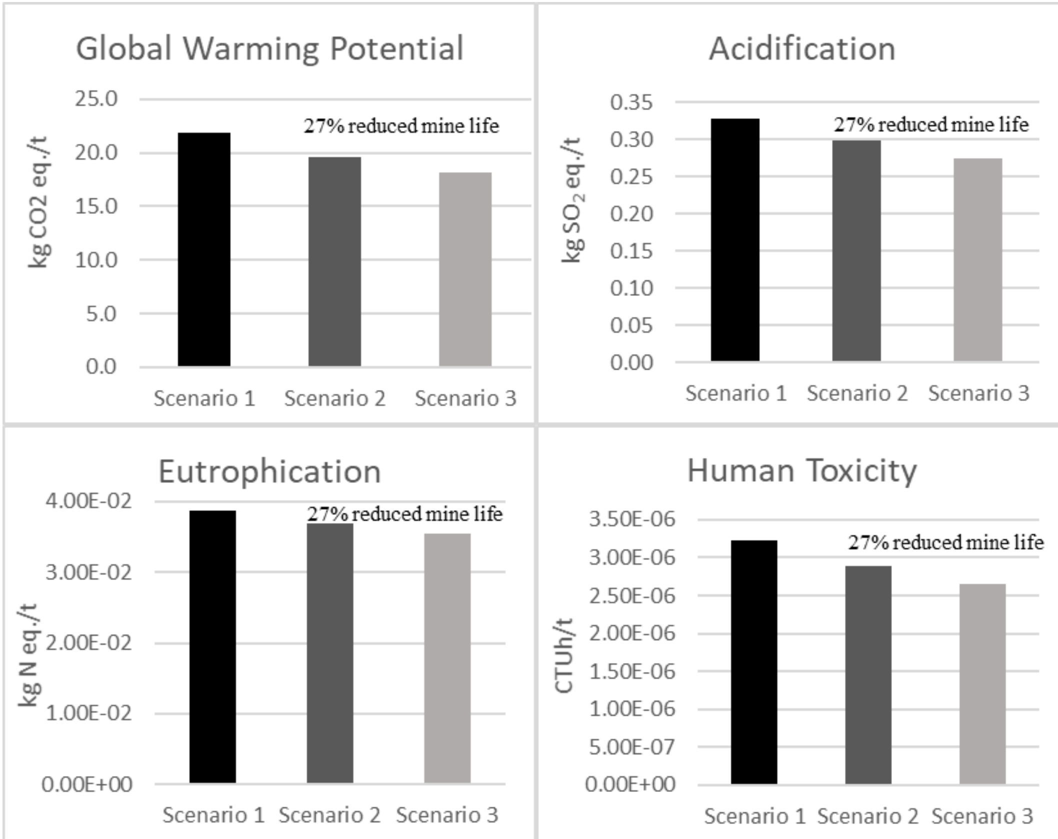

Figure 3.6: Impact category results for investigated scenarios calculated using the LCA software (scenarios 2 and 3 reflect the impact of a reduction in the required operational life of the mine due to automation).

3.5 Conclusion

Mining companies are carrying out economic evaluations of introducing automation 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 provides a range of environmental benefits. For the mine studied, overall global warming potential was decreased by 11.1% when utilizing automated LHD machines, and by 17.9% when extrapolating 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 decreases mine life by 27% or 5 years. This is very significant not just in reducing environmental impacts, but also on the economics of mine investment and payback.

The results for the studied mine site displayed the reductions with processes relying on diesel fuel for operations. However, the automation of processes that primarily use electrical energy as a fuel source did not significantly reduce CO_2 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 world-wide locations that use other types of electricity generation (e.g. using coal or natural gas) GHG emissions due to ventilation, grinding, drilling and mine camp operations will be much more significant. There is potential to further research the varying parameters across multiple underground metal mines such as; electricity GHG intensity factor, mine depth, ore grade, and geographical location, that will have an impact on emissions to the environment. The results from this paper, along with the analysis of these parameters can be used to model the impacts from mine sites looking to implement automated technology to improve safety, productivity and environmental performance.

Chapter 4: Modelling the environmental impact of introducing automation into underground copper mines using a life cycle assessment approach

4.1 Introduction

Copper ranks as the third most important metal for modern society, technology and infrastructure, behind only iron and aluminum (Sverdrup et al., 2013). As of 2020, the annual global production of copper metal was estimated to be 21 million tonnes, a 1.9% increase from 2019, but below the forecasted growth-rate of 3.4% due to the covid-19 pandemic (Mining, 2020). The United States Geological Survey (USGS) has estimated that known global copper reserves are 790 million tonnes, resulting in at least 27 years of copper production (USGS, 2020). In 2014, the USGS also claimed that identified resources are upwards of 1.9 billion tonnes of copper and unidentified resources, which are resources that are only suggested or assumed based on a level of geologic certainty, were estimated as 3.2 billion tonnes of copper (USGS, 2020).

With copper extraction expected to continue for many years, there will be significant environmental impacts from operations, including greenhouse gas (GHG) emissions due to high energy consumption and diesel fuel usage. The sustainability of future mining operations will be heavily dependent on the industry's response to technological advancements, increased ore body complexity (depth, grade), and climate change (Odell et al., 2018; Littleboy et al., 2019). The range of GHG emissions from various copper mines around the world is 1 to 9 t CO_2 eq./t Cu, with an average of 2.6 t CO_2 eq./t Cu (Northey et al., 2012). The range of GHG emissions can be impacted by the methods of extraction (open pit or underground), electricity generation methods, ore grade, and many other factors. A growing demand for metals has led to the depletion of ore reserves classified as high-grade and easily accessible which leads to increased energy requirements for processes involved with ore extraction in less readily accessible sites (e.g., ventilation, haulage and hoisting) (Harmsen et al., 2012). As a response, mining companies have been investigating the use of automated underground equipment to increase productivity and lower energy requirements to economically mine ore bodies that are at greater depths and/or defined as lower quality (Moreau et al., 2019).

A previous life-cycle assessment (LCA) performed on an underground mine which had trialed automated load-haul-dump machines (LHDs) indicated that productivity and energy consumption improvements projected over the mine's estimated operating life would result in a 17.9% decrease in CO_2 eq. emissions (Moreau et al., 2020). This LCA model has been developed further to analyze the comparative environmental impacts from six different underground copper mine sites from a wide range of environments implementing automation. The results of the model show comparative decreases in the environmental impact potentials of global warming (CO_2 eq.), acidification (kg SO_2 eq.), eutrophication (kg N eq.) and human toxicity (CTUh).

Goal and Scope

An LCA model has been developed to analyze the environmental impacts, with respect to the defined functional unit of mining and processing one tonne of ore, from all the core processes involved through ore extraction and mineral processing stages up to transportation of concentrates to off-site refining facilities (Figure 4.1).

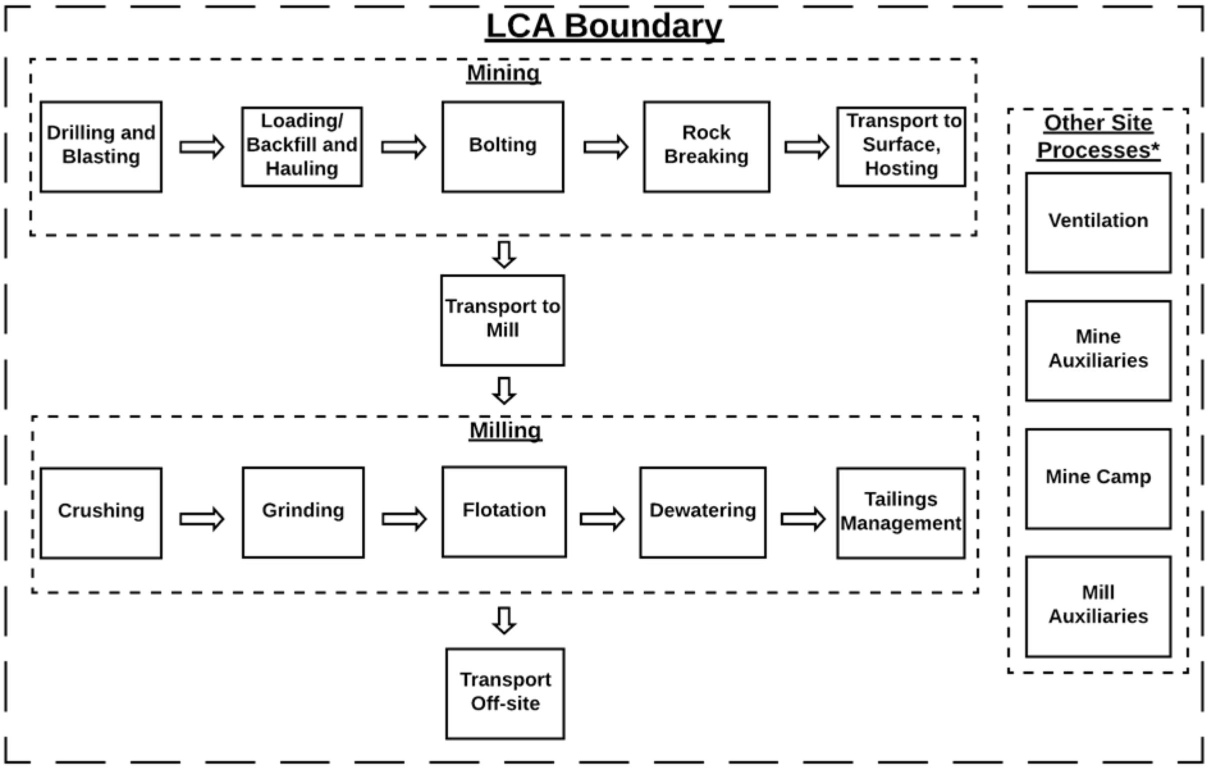

Figure 4.1: Boundary of the designed LCA model. *Not included within the flow of ore (time-dependent).

The LCA model must be flexible to accommodate site specific processes, as for example, different methods of filling underground open voids (waste transport) including waste rock, paste fill, and sand fill. Similarly, it may be necessary to remove a process from the model's boundaries when the site does not use it, such as hoisting the ore up a shaft as some sites may truck ore from underground to the surface. The different operations and climates associated with the six investigated mine sites are summarized in Table 4.1.

Table 4.1. Location, production, and key notes of the selected mine sites.

Mine Site	Location	Production (Cu. tpa)	Average Ambient Temperature (High/Low)	Notes
A	Manitoba, Canada	6,400	24°C / -23°C	The only mine with on-site mine camp facilities. Uses waste rock for backfill. Benchmark of study. Ore is hoisted to surface. Main electricity generation (98%) is from renewable hydropower.
B	New South Wales, Australia	53,000	35°C / 5°C	Waste rock and paste backfill, requires paste fill plant. Ore is hoisted to surface. Main electricity generation (80.8%) uses coal.
C	Copperbelt Province, Zambia	18,000	34°C / 10°C	Waste rock backfill. Ore is hoisted to surface. Main electricity generation (85%) uses renewable hydropower.
D	Lower Silesia, Poland	74,000	25°C / -3°C	Waste rock and sand fill combination. Use of rail car and conveyor haulage system, requires approximately 11 kWh of electricity per tonne of ore. Ore is hoisted to surface. Main electricity generation (80%) uses coal.
E	Nevada, USA	23,000	40°C / 3°C	Waste rock and paste backfill, requires paste fill plant. Ore is hoisted to surface. Main electricity generation (70%) uses natural gas.
F	Michigan, USA	19,000	28°C / -8°C	Combination of waste rock and cemented backfill. Ore is transported to surface via haulage rather than hoisting. Electricity generation is diverse, with the primary sources being coal (37%), nuclear (27%) and natural gas (27%).

4.2 Methodologies

In addition to the outlined processes and scope boundaries, the LCA model required key operational variables. These variables would change from site to site, but their values could be easily entered into the model and used to calculate the impacts on the environment from each site using manual equipment, or projecting the impacts if automated equipment were to be implemented. The key variables identified for this study are:

Productivity Rate - The rate of production is the amount of ore that moves through each process per day.

Ore Reserves –The ore reserve and previous tonnage mined along with the productivity rate determines the operating life of each mine studied within the model, or essentially, the length of time emissions should be calculated for.

Diesel GHG Intensity Factor – Heavy equipment, such as LHDs and haulage trucks, underground and on the surface, are continuously operated throughout the day using diesel fuel. The GHG intensity for the six geographical locations used within this study are listed below in Table 4.2 (Centre for Energy, Environment & Engineering Zambia Limited, 1999; Commonwealth of Australia, 2017; United States Environmental Protection Agency, 2018; Government of Canada, 2019; National Centre for Emissions Management, 2019).

Table 4.2. Listed diesel GHG intensity factors for investigated mine sites.

Mine Site	Diesel GHG Intensity Factor (g CO_2/L)
A	2,681
B	2,740
C	2,700
D	2,712
E	2,697
F	2,697

Electricity GHG Intensity Factor – The electricity GHG intensity factor depends on the generation methods used in the region where the mine is located. Electricity generation methods are expected to change in the future, and a comprehensive view of how the global energy system could develop in the coming decades is provided by the International Energy Agency (2020). However, the future electricity generation analysis is provided on a global scale, while specific data for each area analyzed in this study would be required. Therefore, the most current generation method breakdown for each site has been assumed over the projected mine life. The electricity processes were developed for each mine site in the LCA software, for the first time, with the electricity generation breakdown percentages as listed in Table 4.3 below.

Table 4.3. Breakdown of electricity generation methods for studied mine sites.

Generation Method	Mine Site					
	A[1]	B[2]	C[3]	D[4]	E[5]	F[6]
Coal	-	81%	8%	80%	7%	37%
Natural Gas	-	2%	7%	7%	70%	27%
Hydropower	97%	5%	85%	-	4%	1%
Nuclear	-	-	-	-	-	27%
Solar	-	5.1%	-	-	-	4%
Wind	3%	5.3%	-	13%	-	4%
Biomass	-	1.6%	-	-	19%	-

[1](Government of Canada, 2017); [2](State of New South Wales, 2019); [3](USAID, 2020); [4](U.S. Energy Information Administration, 2016b); [5](U.S. Energy Information Administration, 2020); [6](U.S. Energy Information Administration, 2019).

Ventilation Requirements – Ventilation depends on the size and depth of the mine, and equipment fleet, but can contribute up to 40% of an underground mine's total power consumption (Chatterjee et al., 2015). Mine ventilation will vary based on the size of the diesel equipment fleet present and can be calculated using a multiplier of 0.047 m^3/s per horsepower equivalent of diesel equipment as determined by empirical data (Campbell et al., 2003; Vergne, 2008; Wallace et al., 2015).

Mine Depth – The depth of a mine can have an impact on many processes involved with the extraction of ore, such as power consumption required to transport ore to the surface and ventilation and cooling demands (Wallace et al., 2015).

Employees – Water usage and sewage are influenced by the number of people on site on a daily basis, as well as the emissions produced commuting to and from the mine. Commute distance was calculated by averaging the distance from the mine site to surrounding communities, while also factoring in carpooling and shuttle services offered when specified.

Mineral processing – Four out of the six sites evaluated have mill processing operations on-site, whilst the other two require transportation. The subsequent distance to the smelter or transportation off-site, is the last process step considered within the LCA model. The travel distance and method of transportation (truck, rail or ship) differs depending upon on the mine's on-site ore processing infrastructure and geographical location.

Equipment Inventory - The equipment inventory is used to calculate emissions from their operation. Equipment lists found in the mine site annual technical reports are summarized in Table 4.4.

Table 4.4. Equipment inventories used in the LCA model.

Equipment	Mine Site					
	A	B	C	D	E	F
Haulage Truck	8	10	10	30	8	9
LHD	10	13	12	43	15	5
Drills	7	4	5	24	11	9
Bolters	8	5	6	33	7	3
Explosives Vehicle	3	4	4	19	2	3
Personnel Carrier	26	50	15	54	10	7
Auxiliary	55	30	50	83	16	20

When provided with the information necessary to calculate the variables defined above, the environmental impacts from each site can be estimated using LCA software. Table 4.5 lists the values which were entered to the model for calculating emissions from operations with the manual equipment currently used at each mine site.

Table 4.5. Listed values for the LCA model variables of investigated mine sites.

Parameter	Mine Site					
	A	B	C	D	E	F
Mining						
Productivity rate (tpd)	3,000	2,750	2,630	22,000	5,000	2,000
Average copper %	0.69 %	5.7 %	2.2 %	0.95 %	1.5 %	2.7 %
Ore reserves + previous mined (Mt)	20	26	41	336	24	9
Calculated mine life	18.3	26	42.7	42	13.1	13.3
Diesel GHG intensity Factor (g CO_2/L)	2,681	2,740	2,700	2,712	2,697	2,697
Electricity GHG intensity factor (g CO_2/kWh)	3.4	734.7	128.1	801.8	421.4	449.1
Ventilation (m^3/s)	450.7	625.5	394.1	1,520	237.4	207.7
Depth (m)	1,500	2,100	1,100	910	670	500
Employees						
Number	340	361	250	3,100	320	189
Average driving distance (km)	42	29	16	18	35	58
Mineral processing						
Mill distance (km)	20	On-site	On-site	On-site	On-site	105
Smelter distance (km)	210	670	75	25	450	1,000

A comparative analysis was then performed by using and extrapolating the automated trial data (productivity and fuel consumption rates) obtained from mine site A (Moreau et al., 2020). The productivity and fuel consumption rates would be applicable because the sites selected for this study are all underground copper mine sites, with similar equipment types and operations and any differences in operations/parameters were all accounted for in Tables 4.1 - 4.5. This provided the following modifications to performance metrics of the existing (non-automated) practices if they become automated:

1. Productivity rate was increased by 35% with the use of automated LHDs.
2. The required equipment fleet of haulage trucks and production/development drills was reduced by 35%, due to the mucking operations (use of LHDs) being the operational rate limiting step.
3. Decreased ventilation requirements resulting from a reduced equipment fleet
4. Fuel efficiency was increased by 30% for automated machinery.
5. Reduced workforce as a single operator can control two automated machines.
6. Adjustments to values for processes and resources affected by the reduction in mine life (e.g., daily personnel travel to/from site, office usage (heating and cooling), water, sewage, underground lighting, etc.).

The consequence of a reduced mine life and resulting workforce can be viewed as a negative social impact from loss of potential jobs (Haikola & Anshelm, 2016, Littleboy et al., 2019). However, the increased productivity and decreased energy consumption associated with automated operations allows for safe and economic extraction of ore that was determined to be infeasible in the past (deep and/or low-grade ore bodies) (Matysek & Fisher, 2016; Sánchez & Hartlieb, 2020). The ability to expand the definition of an economical ore body will allow for the opening of new projects in the future, as well as the possibility to further operations at current sites, thereby potentially safeguarding or improving employment prospects.

The adjusted variables for automated operations are listed in Table 4.6. All other variables remain as previously listed.

Table 4.6. Adjusted values for the LCA model variables for automation case.

Parameter	Mine Site					
	A	B	C	D	E	F
Productivity Rate (tpd)	4,050	3,712	3,550	29,700	6,750	2,700
Calculated Mine Life (years)	13.5	19.3	31.6	31.1	9.6	9.9
Ventilation (m^3/s)	403.5	581.5	347	1,350	177.6	151
Number of Employees	318	337	243	3,006	289	169

4.3 Results

The investigated mine sites were analyzed for the following impact categories using the GaBi LCA software: global warming potential; acidification potential; eutrophication potential; and human toxicity (Sphera, 2020). However, as a first step it is essential to first determine the accuracy of the constructed LCA model with current reported impact data before using it to predict any changes in emissions from automated operations. GHG reporting methods and availability can vary from company to company, but reported emissions values were only available for three of the mine sites and these were compared to the calculated values generated by the LCA model in Table 4.7 below.

Table 4.7. Comparison of reported and calculated CO_2 emissions form current operations.

Mine Site	Reported CO_2 emissions (kg CO_2 eq./t ore)	LCA calculated CO_2 emissions (kg CO_2 eq./t ore)	Difference (%)
A	17.59	18.61*	+5.6%
D	68.03	65.26	-4.2%
F	80.68	84.71	+4.9%

* Total CO_2 emissions for mine site A were estimated to be 21.9 t CO_2 eq./t ore., however, the reported value had not taken into account emissions from electricity consumption, therefore the calculated value was adjusted for this comparison.

It was found that the model averaged a 4.9% difference from that reported, a variation which could be due to differences in calculation methods (i.e., differences in assessment methods, such as TRACI 2.1, CML 2001, ReCiPe, and USEtox), changes made since the last GHG emissions report, as well as the reporting criteria for industrial processes determined by their governing bodies (Dragomir, 2012). The developed LCA model was considered, therefore, to be acceptable for estimating the emissions before and after implementation of automated underground machinery.

4.3.1 Global Warming Potential

On-site CO_2 emissions are defined under three main scope classifications (Shan et al., 2015; United States Environmental Protection Agency, 2020a):

Scope 1 - direct emissions produced on site from sources that are owned or controlled by the company (e.g., fossil fuel consumption).

Scope 2 – indirect emissions produced from sources that are owned or controlled by the company (e.g., purchased electricity consumption).

Scope 3 – emissions produced from sources related to site operations but not directly owned by the company (e.g., employee travel to work, solid waste and wastewater disposal, etc.).

All three scopes were included within the LCA model and it was found that the majority of CO_2 eq. emissions were produced from diesel fuel and electric energy consumption. The emissions within scope 3 that were evaluated within the LCA were from employee travel, wastewater disposal, and landfill. The overall global warming potential results for each mine are presented in Figure 4.2, where it can be seen that the decreases in CO_2 eq. emissions per tonne of copper metal ranged from 11.4–18.0%.

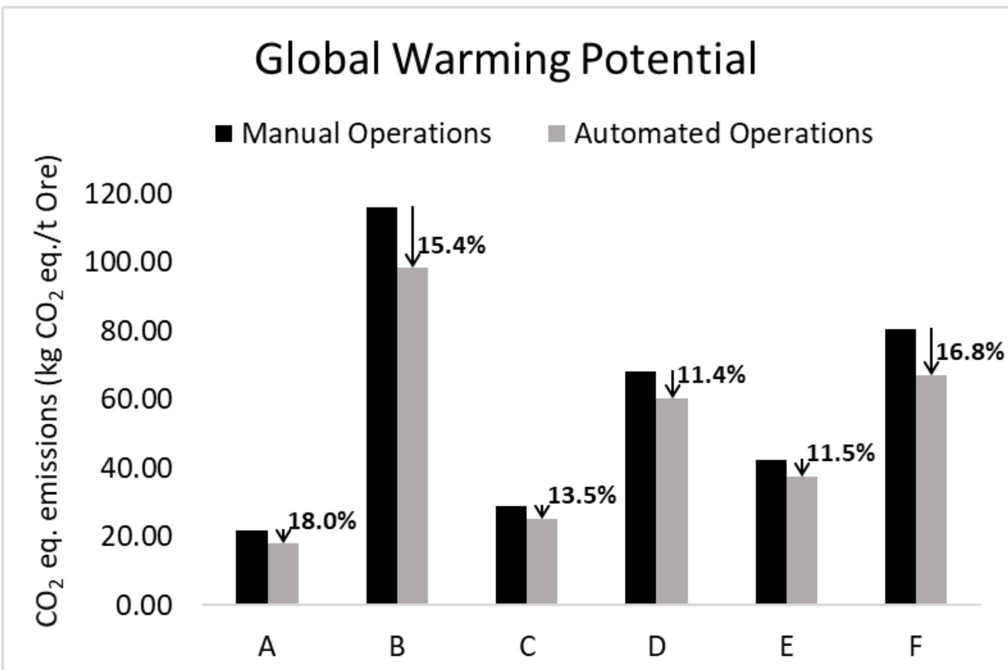

Figure 4.2: Global warming potential of the investigated mine sites before and after automation.

4.3.2 Acidification Potential

Acidification is considered to be an important impact category to assess due to its contribution to air, water and soil pollution, and ability to form acid rain (Kim and Chae, 2016; Zheng et al., 2018). Major sources of acidification are sulphur dioxide (SO_2) and nitrous oxides (NO_x) produced by burning fossil fuels. It has been predicted by the year 2100 that global surface pH will decrease by approximately 0.3-0.5 units and continue to reduce by 0.8-1.4 units by the year 2300 due to atmospheric emissions (Caldeira and Wickett, 2005).

Acid mine drainage (AMD) is also a significant environmental concern and is triggered by the output of sulphides in air and water from mine processes (Martinez et al., 2019). AMD leads to increased acidity in bodies of water and is a growing concern in areas with active and abandon mine sites (Martinez et al., 2019). Acidification potential is the measure of the mass of sulphide equivalent (SO_2 eq.) produced from a process. The calculated acidification potentials for both manual and automated operations of the six investigated mine sites are given in Figure 4.3.

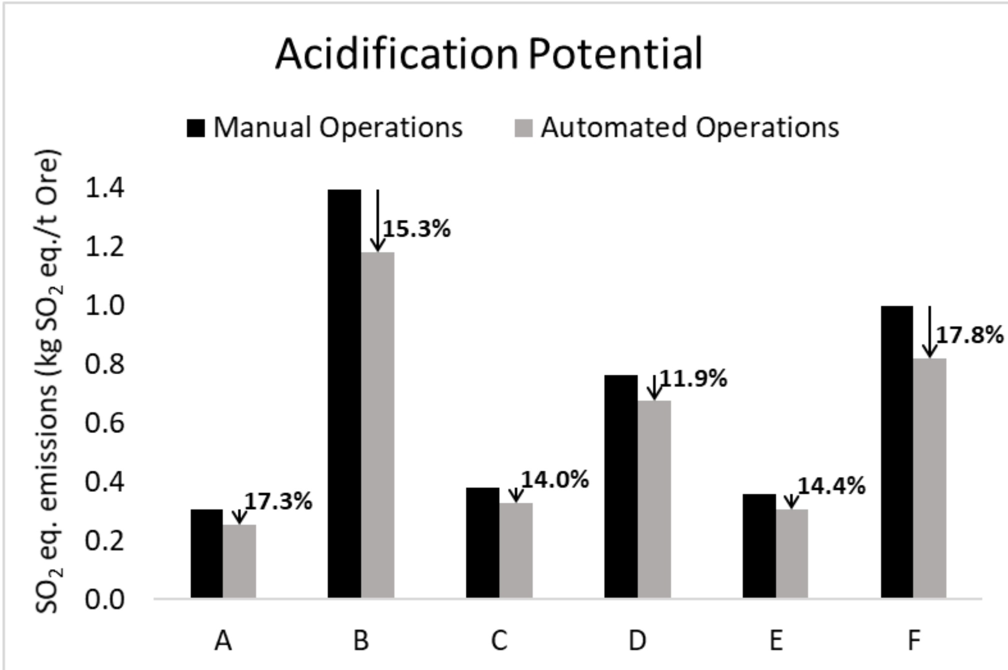

Figure 4.3: Acidification potential of the investigated mine sites before and after automation.

4.3.3 Eutrophication Potential

Globally, ining operations are one of the major contributors towards surface water pollution (Millogo et mal., 2018), which can lead to excessive growth of algae in water bodies. Eutrophication is assessed within an LCA as eutrophication potential (Pacheco-Torgal, 2016), which is a measure of the macronutrients nitrogen (N) and phosphorus (P) (Payen and Ledgard, 2017). Algal buildup on the surface of water causes high turbidity, decreased dissolved oxygen levels and increased hypoxia conditions from plant decay, which can lead to unsatisfactory sources of drinking water as well as die-off of fish and other aquatic life (Hupfer & Hilt 2008; Goel & Motlagh, 2014). The calculated eutrophication potentials for the investigated mine sites are shown in Figure 4.4.

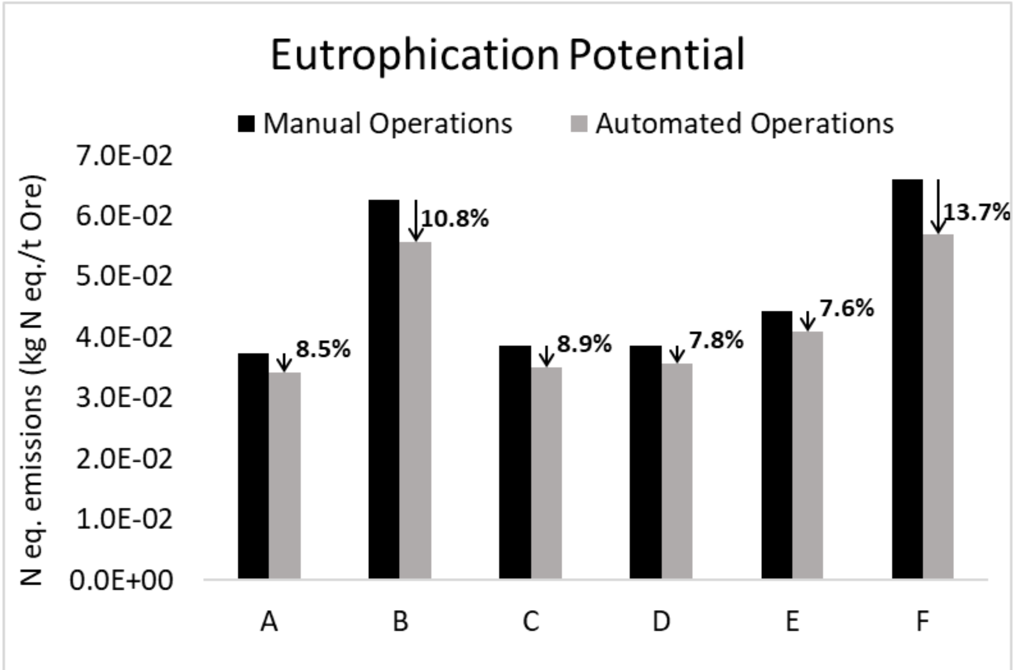

Figure 4.4: Eutrophication potential of the investigated mine sites before and after automation.

4.3.4 Human Toxicity Potential

Safety is a primary motive for using automated equipment in underground workplaces. Not only are operators able to control machines from the surface rather than in dangerous work zones (Chadwick, 2005). Furthermore, emissions harmful to human health are also lowered due to the reduced emissions associated with automated operations and increased productivity. Diesel particulate matter (DPM), a Group 1 carcinogen, is an emission of major concern for human health and it has been reported that underground workers are exposed to the highest DPM levels of any industry (Chang & Xu, 2017).

The LCA impact category, human toxicity potential, measures all potentially harmful chemical emissions released to the environment from a given process (Oliveira et al., 2017). The measurement is expressed in terms of comparative toxic units (CTUh), which is an estimation of the morbidity of the human population per unit mass of chemical emissions (Rosenbaum et al, 2008). The estimated impacts of manual and automated underground copper operations on human toxicity, which includes both cancerous and non-cancerous effects, are given in Figure 4.5.

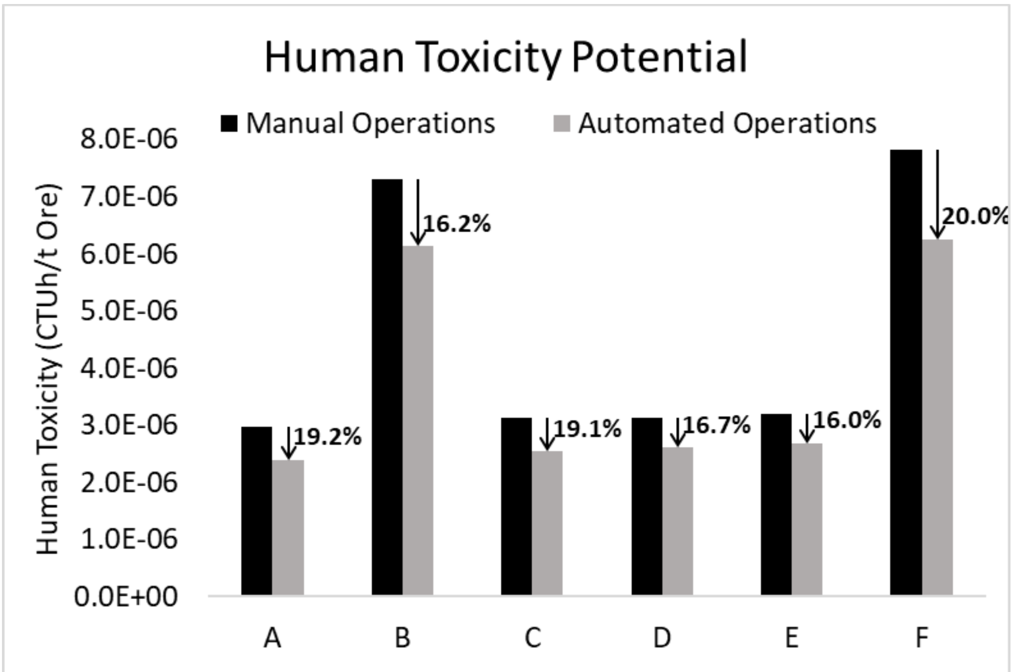

Figure 4.5: Human toxicity potential of the investigated mine sites before and after automation.

4.4 Discussion

The environmental impacts that were analyzed experienced varying reductions depending on the specific operations used at each site, the geographical location, electricity generation methods and all other key variables identified in Section 4.2. For example, when introducing automated underground equipment, the global warming potential was reduced by a ranged of 11.4-18.0%

compared to the current operations utilizing manual equipment. It was previously mentioned that underground copper mine sites were found to produce GHG emissions between 1 to 9 t CO_2 eq./t Cu metal. The LCA model calculated a range of 2.08-7.35 t CO_2 eq./t Cu metal for current operations and was reduced to a range of 1.80-6.52 t CO_2 eq./t Cu metal for automated operations. A summary of the calculated global warming potentials from each site is provided in Table 4.8 with reduction estimates in Table 4.9.

Table 4.8. Summary of global warming potentials of investigated mine sites.

Mine Site	Manual Operations				Automated Operations			
	Mine life	t CO_2/year	kg CO_2/t ore	t CO_2/t Cu	Mine life	t CO_2/year	kg CO_2/t ore	t CO_2/t Cu
A	18.3	23,900	21.8	3.73	13.6	26,900	17.9	3.06
B	26	116,000	116.2	2.19	19.3	133,000	98.3	1.86
C	42.7	28,000	29.0	2.08	31.6	32,500	25.1	1.80
D	42	543,900	68.0	7.35	31.1	651,000	60.3	6.52
E	13.1	77,500	42.4	3.37	9.6	92,500	37.5	2.98
F	13.3	58,800	80.7	3.10	9.9	66,100	67.1	2.58

Table 4.9. Calculated CO_2 eq. reductions from utilizing automated heavy-duty equipment.

Mine Site	Mine Life Reduction (yr)	Total CO_2 eq. Emission Savings (t)	CO_2 Reduction (%)	kg CO_2/t ore Savings	t CO_2/t Cu Savings
A	4.7	71,530	18.0	3.9	0.67
B	6.7	449,100	15.4	17.9	0.33
C	11.1	168,600	13.5	3.9	0.28
D	10.9	2,594,700	11.4	7.7	0.83
E	3.4	127,250	11.5	4.9	0.39
F	3.5	127,650	16.8	13.6	0.52

Mine site D was found to have the lowest CO_2 reductions (11.4%). It was previously mentioned a conveyor and rail car system was used for haulage, which means the automation of haulage trucks would have less of an impact on emissions compared to sites that rely heavily on trucks for ore transportation. For example, mine site F has a higher percentage of site emissions reductions (16.8%) due to the use of trucks for ore transportation throughout the mine, as well as transportation to the surface, rather than a hoisting process. The highest CO_2 reduction percentage was measured at mine site A (18.0%). Mine site A has the lowest GHG intensity factors from electricity generation due to the high usage of renewable hydropower in this area (98%). This means a higher percentage of the mine's GHG emissions are generated from the burning of diesel fuel, which is reduced with improved fuel efficiency of automated equipment. From analyzing the mine sites with the highest reduction in CO_2 emissions, mine sites A and F, it can be seen that the sites that rely more on diesel consuming operations, or have a low emissions factor from electricity generation, will have the greatest positive impact from introducing automated equipment within their underground operations.

The use of automated equipment reduced acidification and eutrophication potentials by 11.9-17.8% and 7.6-13.7% respectively. The results for acidification mimic those of the estimated global warming potential, however, eutrophication experienced a lower reduction from automated equipment than the other investigated impact categories. The highest contributor to eutrophication potential comes from explosives residue (ammonia, nitrate, and nitrites) in wastewater streams. The required quantity of explosives per tonne of ore processed remains unchanged when transitioning from manual to automated equipment, justifying the lower effect this transition will have on the measured eutrophication potential. The measured human toxicity potential reduction range was found to be between 16.0-20.0%. The large reduction seen in this impact category could be associated with the reduction in scope 1 emissions (burning of diesel fuel) and thereby the decreased DPM emitted. Scope 2 emissions, such as the emissions from electricity generation, would vary from site to site depending on the methods of generation (eg. coal vs. hydropower).

Further emission reductions will require the continual research and development of other innovative technologies. The use of battery-electric equipment was previously mentioned in this thesis as an alternative to diesel fuel. This would eliminate scope 1 diesel emissions from the underground mine site, and limit emissions relating to the loading and haulage processes to the electricity required for the charging of batteries, which hopefully, in the future, is from low emissions generation sources.

4.5 Conclusion

The developed LCA model successfully calculated CO_2 eq. emissions from underground copper mine sites within an average of only 4.9% variation with reported values. The model was used to estimate potential environmental impacts from introducing automated equipment into underground copper operations and compare the results to the mine sites current operations. The reductions in all impact categories, along with the increased interest in automating underground equipment for safety and productivity purposes, also bodes well for the environmental impacts from the underground copper mining industry for the current and future years of operation.

The underground mine sites in this study were responsible for emissions between 21.8-116.2 kg CO_2/t ore, and the introduction of automated LHDs, haulage trucks and production/development drills were shown to have the potential to considerably reduce the level of greenhouse gas emissions. The implementation of automated equipment provided a reduction of 3.9-17.9 kg CO_2 eq./t ore, reducing the site ranges to 17.9-98.3 kg CO_2 eq./t ore from lowered diesel emissions associated with the haulage and loading operations, fewer years of operation and daily employee travel, and potentially further reductions based on lower ventilation requirements. By taking into consideration the world's identified and unidentified copper resources of 1.9 and 3.8 billion tonnes respectively, the reductions in CO_2 eq emissions from using automated equipment could, therefore, have a significant and positive global impact on the environment.

Automation of underground equipment also provided reductions in acidification potential (11.9-17.8%), eutrophication potential (7.6-13.7%) and human toxicity (16.0-20.0%). The lowered impact from operations on these categories will reduce soil and water degradation in the surrounding area, alleviate the risk of deterioration of structural buildings, and decrease the health risks to employees and nearby communities associated with the mine and mill operations. The net outcome from implementing automation is, therefore, the potential for a mine to have a lower operational environmental impact and also leave a less impacted environment post closure.

Chapter 5: Conclusions

5.1 Conclusion

The global GHG emissions from the mining industry have continued to rise, and fossil fuel combustion, off-road vehicles/mobile equipment, electric utilities and the ore and minerals industry is considered to be a top contributor of SO_2, NO_x, DPM and mercury pollution. Restrictions on emissions have been created in order to reduce the impact from mining processes, but the targets from most of the industry have not been met. The use of new technologies such as automated, battery-electric and biodiesel fueled equipment in underground metal mine operations, have shown many benefits throughout trial experiments. However, research has been focused on the safety, productivity, and costs reduction aspects associated with these technologies, while environmental impacts have not significantly been discussed. This thesis provided a novel study on the environmental impacts of implementing automation technology in underground metal ore mine sites using a comparative LCA approach and operational data, collected on site, from a mine currently using the technology.

Automation trials within a Canadian underground mine site recorded productivity increases of up to 35%, as well as a decrease in fuel consumption by 30%. The automation trials were further used to perform a life cycle assessment (LCA) on underground metal mines to compare emissions from traditional manual operations and future automated operations. The designed LCA model calculated CO_2 eq. emission reductions of 3.9-17.9 kg CO_2 eq./t ore (11.4-18.0%) across six investigated mine sites. The comparative LCA also included reductions in acidification potential (11.9%-17.8%), eutrophication potential (7.6-13.7%, and human toxicity potential (16.0-20.0%). Automated technology has previously been advertised as a solution towards safer, high production operations. With this research, improved sustainability and reduced impact on the environment can also be included as characteristics for the use of automated equipment in underground metal mines.

5.2 Future Work

There are multiple directions in which this research can be continued, including but not limited to:

- Continued development of an LCA model for underground automated equipment.

  The novel LCA model presented in Chapters 3 and 4 of this thesis showed encouraging results across all environmental impact categories that were included within this study. However, the basis of the model was created off a single site and their specified operations, and furthermore, adapted to project environmental emissions for underground copper metal mines. Further research and development could be directed towards the adaptation of the model to allow for the projection of environmental emissions from underground metal mines of various metal production and processes.

- Continued development of and LCA model for biodiesel production and use in underground mining.

  The LCA model presented in Chapter 5 of this thesis showed greater reductions in emissions, relative to the mine's original carbon footprint, for regions with "green" methods of electricity generation (renewable hydropower, wind solar) and increased emissions in areas that use methods such as coal and natural gas. Further research into the energy efficiency of large-scale methods of the harvesting biomass and lipid extraction processes could yield positive results for the latter operations. Currently the methods used for biodiesel production from harvested microalgae require significant energy, and therefore, can be investigated for improvements in future studies. The current model has implemented biodiesel at a 20% blend in diesel fuel required for operations. It is possible to implement biodiesel at higher blends if production can be increased through efficiency gains in the proposed methods, algae selectivity, and temperature control for year-round production.

- Development of an LCA model for battery electric equipment in underground mining.

Battery electric equipment will be an important technology for the sustainability of the underground mining industry because it allows for significant ventilation reductions, which leads to reduced costs, energy consumption, diesel emissions, and therefore, greenhouse gas emissions. An LCA model can be developed if the available information is available from sites currently using the technology. The required information from mine sites would be the following:

1. Ventilation reductions from battery electric vehicle implementation.
2. Energy consumption from charging of batteries.
3. Cycle time differences between battery and diesel equipment.
4. Time lost during battery exchanges.

5. Other considerations for diffrences in productivity or energy consumption.

- Inclusion of economic evaluations within the LCA model.

  LCA softwares, such as the GaBi Solutions software used for several mine site studies within this thesis, is also capable of performing an economic analysis. If the data on costs were made available for all the required inputs and outputs (waste disposal costs) then the cost comparison for automated and manual equipment could be an additional study that would be valued by mining companies considering automated equipment for future operations.

- Various LCA models for technologies of interest for deep underground mining operations.

  Automated, battery electric and biodiesel equipment were the focus of this thesis, but there are various technologies that could improve the sustainability of underground metal mine operations. Hydrogen fuel cell technology has also been considered to replace heavy-duty diesel equipment. Ventilation on demand systems have been under consideration to control and monitor ventilation to specific areas of the mine and reduce requirements in areas that are not in use for extended periods of time. Both of these technologies are related to potential diesel emission reductions and/or reduced energy consumption, and therefore, are suitable for environmental investigation using an LCA approach.

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Appendix 1: Productivity Analysis

A primary focus for research into automated mining equipment is the potential increase in productivity due to the efficiency of the operations, as well as the increased utilization from eliminating travel times and ability to work through the blast window. In August of 2017, a mine site in Manitoba, Canada, began trialing automated LHD machines with the goal of achieving productions rates of 180 tonnes per hour (tph). The trial was split into three phases with one stope (excavation in a mine from which ore is, or has been, extracted) mined per phase. The first phase consisted of determining whether the automated system would run effectively within the mine's current fibre backbone, connection tests from surface and training of operators. The introductory tasks associated with implementing a new system limited the relevance and quality of data obtained during phase one. During phases two and three, the automated LHD began operating for 24 hours per day and utilized a 14 tonne and 18 tonne LHD machine respectively. The automation technology provided by Epiroc (formerly Atlas Copco) tracks productivity, utilization and fuel consumption statistics of the tested machines and uploads the information to online spreadsheets. The spreadsheets were accessible during the mine site visit for collection and analysis for the purposes of this study Production results from phase two are shown in Table A1. below and compared with the same LHD operated manually.

Table A1. Automated and manual production statistics for a 14 tonne LHD at a Canadian mine site.

	Manual Operations			Automated Operations		
Day	Total Tonnes	Engine Hours	Tonnes/ Hour	Total Tonnes	Engine Hours	Tonnes/ Hour
1	2419.6	16.3	208.6	2736.0	10.4	304.0
2	1066.1	9.7	166.6	3273.9	14.1	287.2
3	1938.2	11.1	251.7	1458.7	8	194.5
4	2368.8	12.3	254.7	2855.0	17.6	219.6
5	1948.5	12.7	211.8	2122.6	14.2	202.1
6	2204.6	14.5	208.0	1713.6	10.4	214.2
7	1919.5	15.7	160.0	2438.0	15.1	217.7
8	2873.4	15.8	254.3	860.4	9.1	148.3
9	2498.5	14.5	240.2	630.0	6	157.5
10	1947.6	15.5	192.8	528.5	10.7	88.1
11	1733.9	15.3	160.5	719.6	5.3	159.9
Average	2083.5	13.9	149.5	1757.8	11.0	159.9

The average total tonnes moved per day was higher for the manually operated LHD due to the difference in utilization. The manually operated LHD was operating 13.9 hours per day on average compared to 11.0 hours for the automated LHD. However, with automation, the productivity on a per hour basis was higher throughout the 11-day trial, moving approximately 10.4 more tonnes of ore per hour. The data from phase two demonstrates the importance of improving the utilization of equipment. Implementing new procedures and operations introduces many challenges that must be solved in order to achieve the maximum potential of the technology.

Phase three consisted of transitioning the automated package from the 14-tonne LHD to the 18-tonne LHD. The smaller LHD was hit by falling oversize (large rock/ore that needs further blasting in order to transport) at the end of phase two causing significant damage to the machine. This allowed the mine site to expand the trial and test how automation would affect production for larger equipment within their operations. The results from phase three are shown in Table A2. below and compared with the same LHD operated manually.

Table A2. Automated and manual production statistics for an 18 tonne LHD at a Canadian mine site.

	Manual Operations			Automated Operations		
Day	Total Tonnes	Engine Hours	tph	Total Tonnes	Engine Hours	tph
1	1,550	13.8	112.3	1,714	11.8	145.3
2	1,376	16.3	84.4	1,379	14.9	92.6
3	1,258	16.9	74.4	3,365	17.8	189.0
4	1,467	17.7	82.9	3,428	19	180.4
5	1,664	16.8	99.0	2,345	10.7	219.2
6	968	13.5	71.7	1,440	8	180.0
7	1,751	12.5	140.1	1,238	6	206.3
8	1,180	11.5	102.6	1,653	14.6	113.2
9	1,940	16.8	115.5	2,075	21.4	97.0
10	1,112	13.1	84.9	2,000	9.7	206.2
11	1,076	10.8	99.6	3,578	18.6	192.4
12	915	10	91.5	3,010	21.6	139.4
13	878	5.1	172.2	2,443	21.8	112.1
Average	1,318	13.4	102.4	2,282	15.1	159.5

The data above shows an improved utilization for the automated LHD during phase three. The engine hours were increased from 13.4 hours/day to 15.1 hours/day and resulted in a much higher average tonnes moved per day. Alternatively, the transmission hours for the manually operated LHD were lower during phase three, possibly due to unpredictable delays and difficulty operating larger equipment within the same mine infrastructure. The hourly production rate was also increased from 102.4 tph to 159.5 tph for the automated LHD. The initial target of 250 tph (haulage hours) was not achieved on average throughout the 13-day trial of phase three, but peak production on several occasions did surpass this target.

Appendix 2: Fuel Consumption Analysis

Automated technology has been projected to have a positive impact on mine productivity throughout various literatures, but there is also the added benefit of improving fuel efficiency in order to further lower costs and reduce carbon dioxide (CO_2) production from continuous operation of diesel equipment. Data monitoring technology, which was incorporated with the automation package during the three-phase trial described in section 2.5, was able to collect the fuel usage throughout the trial and the data from phase two is provided in Table A3. below.

Table A3. Automated and manual fuel consumption statistics for a 14 tonne LHD at a Canadian mine site.

	Manual Operations				Automated Operations			
Day	Engine Hour	Litres/ Engine Hour	Liters/100 Tonnes	kg CO_2/100 Tonnes	Engine Hour	Liters/ Engine Hour	Liters/100 Tonnes	kg CO_2/100 Tonnes
1	16.3	34.1	23	67.5	10.4	32.0	12	35.1
2	9.7	24.3	22	64.6	14.1	27.7	12	47.1
3	11.1	27.9	16	47.2	8	11.1	6	19.3
4	12.3	29.0	15	43.9	17.6	17.2	11	48.4
5	12.7	24.6	16	48.6	14.2	19.9	13	61.1
6	14.5	25.9	17	49.8	10.4	16.1	10	37.7
7	15.7	30.6	25	73.8	15.1	23.1	14	68.8
8	15.8	29.1	16	46.5	9.1	20.0	21	109.9
9	14.5	27.5	16	48.6	6	1.1	1	4.7
10	15.5	25.2	20	60.5	10.7	14.7	30	177.1
11	15.3	28.3	25	75.7	5.3	20.0	15	51.7
Average	13.9	27.9	19	57.0	11.0	18.4	13	60.1

Phase two had various delays and challenges from implementing the new technology which led to lowered productivity and utilization statistics. From the fuel consumption data collected during phase two, it is evident that these challenges have also had a negative effect on liters of fuel and kg of CO_2 produced on a per tonne basis. There were also errors with the data gathering technology throughout phase two. Specifically, when analyzing day 9 of the 11-day trial, 1 liter of fuel was burned per 100 tonnes of ore moved during a 4-hour production period, resulting in 630 tonnes of ore being handled. Similar production was seen on day 11 (719 tonnes, 4.5 hours), but more accurately, 15 liters of fuel was burned per 100 tonnes. The accuracy and consistency should be improved through familiarity with the technology and a larger sample size, removing anomalies like the one above. The fuel consumption results from phase three are shown in Table A4. below, with improved data monitoring.

Table A4. Automated and manual fuel consumption statistics for an 18 tonne LHD at a Canadian mine site.

	Manual Operations				Automated Operations			
Day	Engine Hour	Litres/ Engine Hour	Litres/100 Tonnes	kg CO_2/100 Tonnes	Engine Hour	Litres/ Engine Hour	Litres/100 Tonnes	kg CO_2/100 Tonnes
1	13.8	29.2	26	77.9	11.8	26.1	18	53.5
2	16.3	24.5	29	86.6	14.9	20.5	22	66.0
3	16.9	24.6	33	98.0	17.8	25.1	13	39.6
4	17.7	23.2	28	82.0	19.0	28.1	16	46.6
5	16.8	27.7	28	83.4	10.7	22.3	10	30.2
6	13.5	29.3	41	121.4	8.0	24.4	14	82.5
7	12.5	29.8	21	63.5	6.0	13.9	6	15.0
8	11.5	30.7	30	89.3	14.6	28.5	25	75.3
9	16.8	26.7	23	68.7	21.4	27.4	28	84.2
10	13.1	22	26	76.9	9.7	26.9	13	38.7
11	10.8	20.2	20	60.6	18.6	30.6	16	47.3
12	10	32	15	43.3	21.6	27.7	20	59.4
13	5.1	26.2	36	108.5	21.8	29.4	26	78.3
Average	13.4	26.6	27	81.5	15.1	25.1	18	55.1

Phase three presented more consisted data with the elimination of any obscure results throughout the 13-day trial. The consumption of fuel per 100 tonnes of ore moved was 30% less on average throughout the 13-days for the autonomous LHD compared to manually operated LHD. Furthermore, CO_2 emissions were reduced by 32% per 100 tonnes for the autonomous operations. It is expected that increased utilization of equipment will result in an increased daily consumption of fuel and production of CO_2, however, when analyzing on a per tonne basis, the total amount will be lowered through the entirety of the mine life through the improved production efficiencies. Phase three is a small sample size and further supporting data will be required from the mine site as well as other locations, but the initial findings have supported the motivations for implementing automated technology in underground mines.

Appendix 3: Additional Tables

Table A5. Automated equipment currently available from various equipment suppliers. Information obtained from suppliers' websites (Hard-Line Solutions, n.d.; Caterpillar Inc., 2018; Epiroc, 2018; Sandvik Group, 2018; Komatsu Limited, 2018)

Supplier	Equipment	Name	Size	Description
Caterpillar	Dozer	D11T	229800 lbs	Semi-autonomous technology, one operator can control up to three machines at one time
Caterpillar	Loader	988K	4.7–13 m^3 bucket size	Semi-autonomous technology, move material safely and efficiently
Caterpillar	Loader	R1600H	4.2–5.9 m^3	Semi-autonomous technology, move material safely and efficiently
Caterpillar	Loader	R1700G	4.6–8.8 m^3	Semi-autonomous technology, move material safely and efficiently
Caterpillar	Loader	R2900G	6.3–8.9 m^3	Semi-autonomous technology, move material safely and efficiently
Caterpillar	Haulage Truck	793F	250 ton (US)	Autonomous haulage to dump points and reports maintenance issues
Caterpillar	Haulage Truck	789D	200 ton (US)	Autonomous haulage to dump points and reports maintenance issues
Caterpillar	Drills	MD6250	152-250 mm hole diameter	Autonomous drill, more accuracy and operate up to three drills at one time
Epiroc	LHD	ST-7	7 tonne load capacity	Loaders capable of equiping scooptram automation, a semi-autonomous technology improving safety and performance
Epiroc	LHD	ST-14	14 tonne	Loaders capable of equiping scooptram automation, a semi-autonomous technology improving safety and performance
Epiroc	LHD	ST-18	18 tonne	Loaders capable of equiping scooptram automation, a semi-autonomous technology improving safety and performance
Epiroc	Haulage Truck	MT-42	42 tonne	To be automated in the near future
Epiroc	Haulage Truck	MT-65	65 tonne	To be automated in the near future
Epiroc	Drills	PV-235	12 m hole depth	Hole diameter 171–270 mm, Automated rotary blasthole drill
Epiroc	Drills	PV-271	19.2 m	Hole diameter 171–270 mm, Automated rotary blasthole drill
Epiroc	Drills	PV-275	59.4 m	Hole diameter 171–270 mm, Automated rotary blasthole drill
Epiroc	Drills	PV-311	19.8 m	Hole diameter 270–311 mm. Automated rotary blasthole drill
Epiroc	Drills	PV-316	91.4 m	Hole diameter 270–311 mm. Automated rotary blasthole drill
Epiroc	Drills	PV-351	19.8 m	Hole diameter 207–406 mm, Automated rotary blasthole drill
Epiroc	Drills	Simba S7	51–89 mm hole diameter	High precision automated long-hole drill
Epiroc	Drills	Simba M4	51–178 mm	Automated hydraulic production drill rig
Epiroc	Drills	Simba E6-W	89–254 mm	Automated longhole production drill for large size drift
Epiroc	Drills	Boomer S2	43–64 mm	Automated two-boom face drilling rig
Komatsu	Haulage Truck	830E-1AC	245 ton (US)	Autonomous Haulage Vehicle design by Komatsu
Komatsu	Haulage Truck	930E-4SE	320 ton (US)	Automation system to be design by Caterpillar
Sandvik	LHD	LH-410	10 tonne	Mass mining loaders, AutoMine Onboard Package, AutoMine Loading readiness
Sandvik	LHD	LH-514	14 tonne	Mass mining loaders, AutoMine Onboard Package, AutoMine Loading readiness
Sandvik	LHD	LH-517	17 tonne	Mass mining loaders, AutoMine Onboard Package, AutoMine Loading readiness
Sandvik	LHD	LH-621	21 tonne	Mass mining loaders, AutoMine Onboard Package, AutoMine Loading readiness
Sandvik	Haulage Truck	TH-551i	51 tonne	Articulated underground dump trucks. AutoMine trucking onboard option allows autonomous haulage for both transfer level and decline ramp application.
Sandvik	Haulage Truck	TH-663i	63 tonne	Articulated underground dump trucks. AutoMine trucking onboard option allows autonomous haulage for both transfer level and decline ramp application.
Sandvik	Drills	DR-412i	216–311 mm	Rotary blasthole surface drilling rig
Sandvik	Drills	DU-412i	89–216 mm	Articulated ITH longhole production drill
Sandvik	Drills	DD-422i	43–64 mm	Development drill rig
Sandvik	Drills	DT-1121i	43–64 mm	Tunneling jumbo drill, two-boom
Sandvik	Drills	DT-1131i	45–64 mm	Tunneling jumbo drill, three-boom, 183 m^2 coverage
Sandvik	Drills	DT-1231i	45–64 mm	Tunneling jumbo drill, three-boom, 211 m^2 coverage
Sandvik	Drills	DT-1331i	45–64 mm	Tunneling jumbo drill, three-boom, 232 m^2 coverage

Table A6. LCA processes and major inputs and outputs.

Process	Software inputs	Software outputs
Mining		
Drilling	Compressed air (7 bar), electricity mix, diesel (regional), process water.	Groundwater, diesel emissions, dust particulates.
Blasting	Compressed air (7 bar), electricity mix, diesel (regional), explosives.	Ore (inert rock, copper, zinc, trace gold, trace silver), diesel emissions, ammonia, nitrate, nitrite.
Loading	Ore (copper, zinc, gold, silver), diesel (regional), electricity mix, compressed air (7 bar), process water.	Ore, diesel emissions, groundwater.
Haulage	Ore, diesel (regional), electricity mix.	Ore, diesel emissions.
Backfill	Ore, diesel (regional), electricity mix. compressed air (7 bar), process water.	Ore, diesel emissions, groundwater.
Bolting	Compressed air (7 bar), electricity mix, diesel (regional), process water.	Groundwater, diesel emissions, dust particulates.
Rockbreaking	Ore, Compressed air (7 bar), electricity mix.	Ore, dust particulates.
Hoisting	Ore, electricity mix.	Ore.
Ventilation	Fresh air, electricity mix.	Used air, water in air (evaporation/condensation)
Mine auxiliaries	Electricity mix, diesel (regional)	Diesel emissions.
Transport to mill	Ore, diesel (regional)	Diesel emissions.
Milling		
Crushing	Ore, electricity mix.	Fine ore (19 mm).
Grinding	Fine ore (19 mm), electricity mix, process water, fresh water, lime.	Fine ore and water mixture.
Flotation	Fine ore and water, electricity mix, copper sulphate, flotation reagent (3418A), methyl isobutyl carbinol.	Flocculated copper concentrate, flocculated zinc concentrate, mine tailings.
Dewatering	Flocculated copper concentrate, flocculated zinc concentrate, electricity mix.	Copper concentrate (9% moisture), Zinc concentrate (9% moisture).
Tailings disposal	Mine tailings, electricity mix,	Tailings disposal to pond.
Transport to smelter	Copper concentrate, zinc concentrate, diesel (regional)	Diesel emissions.
Mine Camp		
Facility	Groceries, fresh water, electricity mix, diesel (regional)	Diesel emissions, solid waste (landfill), wastewater.
Employee travel	Gasoline, diesel, aviation fuel.	Fuel emissions.