PGM mining and processing in the circular economy: A framework towards circularity

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Platinum group metals, or PGMs, are useful materials which end up as unintended waste of the platinum mining industry, due to these metals being dumped among tons of mining waste. Waste storage and treatment facilities end up collecting vast reserves of solid and liquid waste which is both highly dangerous and unprofitable, due to these valuable PGMs being lost in the process. Improving the extraction, reuse and reclamation of these materials from ore bodies and waste can push the sector to a true system of sustainability and increased profitability with zero health hazards to communities and nature. Water is another valuable resource in the PGM mining industry. Through sustainable usage and recycling of water the industry can benefit greatly.

The circular economy (CE) can aid the PGM mining and processing industry to promote environmental, social and governance (ESG) principles by implementing a system of increased resource utilisation through the reuse and recycling of waste created in its value chain. Implementing a system of value retention within an organisation can be a valuable driver for future growth, both for continued investment and sustainability. ESG scoring has become an important measure for companies to position themselves in the global market, but unfortunately there exists no mechanism to measure value retention and how different ESG value drivers impact an organisations' ESG performance and investment opportunities when comparing it with other companies in the same industry. This is especially seen in mining companies (of different sizes) having various ESG commitments, for example one company focusing on lowering emission and another company focusing on recycling.

This paper aims to investigate a framework on how the PGM mining and processing industry can move towards sustainable development by adopting a circular economy within its operating model. Methods towards circularity were researched and set out in a framework of circularity, and not a detailed investigation into the technical or metallurgical processes of each method. Relating to ESG, this paper will focus solely on the environmental element.

Keywords: Platinum group metals, circular economy, value retention, value drivers, environmental impact, sustainability, waste generation, resource management

INTRODUCTION

The past decade has seen a worldwide push for a transition to sustainable development in the industrial sectors due to increased pressure on our Earth's natural resources. The impact of global mining activities on the environment and its consumption of valuable resources has contributed greatly to this increased need for sustainable development.

It is therefore important that the use of energy resources and raw materials is done smartly, to bring down the excessive production of waste and depletion of natural resources, especially in the mining industry.

The mining industry is under more pressure to commit to environmental, social and governance (ESG) policies within its operations. This form of corporate responsibility aims to ensure that businesses operate ethically with regards to the natural environment and resources, communities and workforce, by adhering to legal obligations and guidelines. As South Africa is the dominant producer of PGMs globally, with an estimated 88% of global resources, the need to decrease the environmental impact and costs associated with energy consumption, greenhouse gas emissions, pollution, waste dumps and water and land usage should be prioritised, together with the impact on communities and socio-economic factors (Glaister and Mudd, 2020). A resource challenge therefore exists within South Africa due to the basis of development and creation of wealth relying heavily on the extraction of resources. Without it there can be no basic functions of society such as food, transportation, communication and housing. As a nation strives towards economic development, the resources required per person also increase, which in turn requires development in technology.

PGMs can be seen as important minerals due to their having a leading role in the advancement and production of new technologies in the Fourth Industrial Revolution (4IR) sphere, such as automated robots, electronic vehicles, hydrogen fuel cells and smartphones, with demand predicted to increase steadily over the coming years (Glaister and Mudd, 2020). This increased demand also poses various challenges to the industry as natural resources are finite, and negative environmental impacts are felt heavily due to excessive waste creation from mining and mineral processing practices. The various sustainability challenges faced by the mining industry can be increasingly mitigated through the adoption of a circular economy (CE) model within its operations, as well as including accurate metrics of ESG impact and performance, benchmarking across similar industries, and defining how different value levers relate to each other and drive the organisations' ESG performance and its overall system performance. The various sustainability challenges faced by the mining industry can be increasingly mitigated through the adoption of a CE model within its operations.

The aim of the CE is to increase economic growth through a sustainable system of production, consumption and recycling, without increasing the need to extract more resources and create more waste (Granados-Fernández, 2021). This is a move away from the traditional linear economy model of extraction, production, consumption and finally disposal. The difference between the two models is illustrated in Figure 1. The CE model can be achieved by turning waste from one industry into resources for other industries, therefore creating closed loops in industrial ecosystems which result in zero waste, zero harm to the environment and overall sustainable methods of development (Granados-Fernández, 2021).

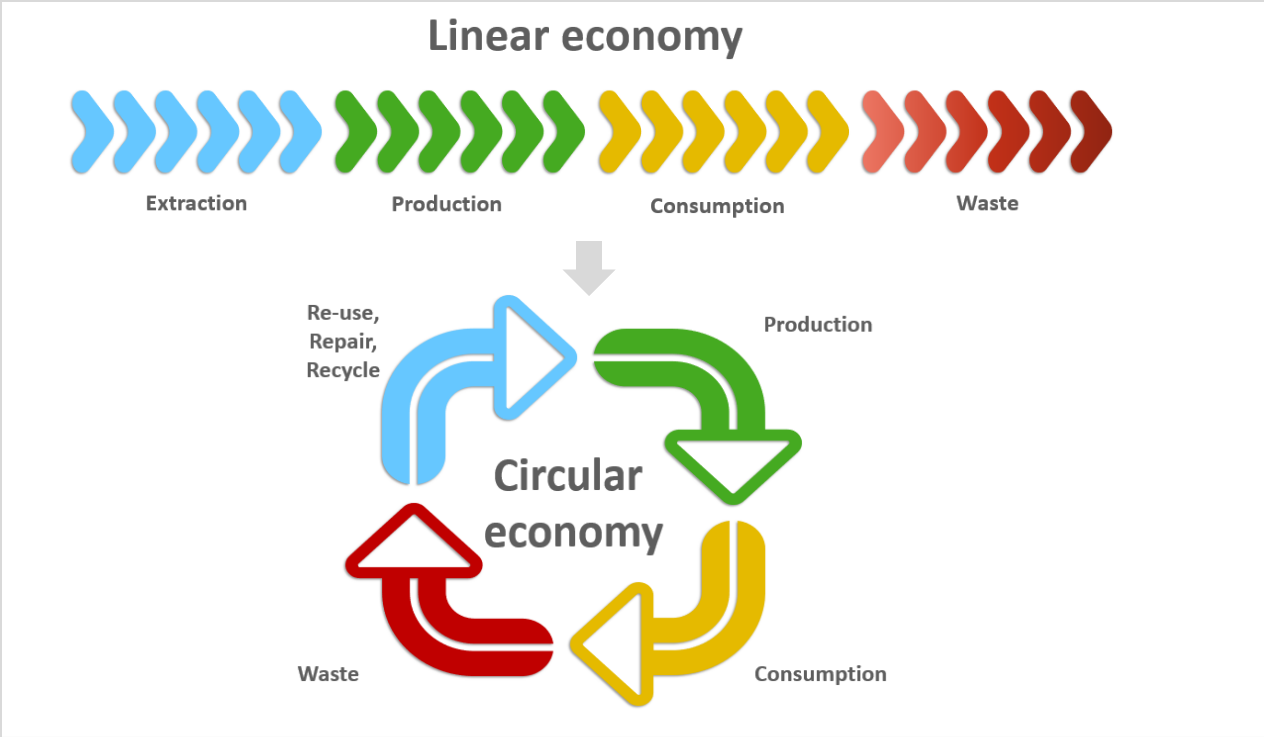

Figure 1. Linear economy vs circular economy.

CE and the mining industry
As the demand for the exploitation of mineral resources such as PGMs increases globally, there is a massive decrease in the concentration of these valuable minerals and therefore creates a need to extract and process far more quantities of ore, resulting in a higher consumption of water and energy and the generation of more waste (Mudd, 2021).

Whilst the traditional approach of a linear economy is to extract, produce, consume and dispose of a product, the CE model, as illustrated in Figure 2, aims to close the loop by implementing sustainable processes in an organisations' value chain (Granados-Fernández, 2021). The CE model therefore goes beyond the concept of recycling, as it requires fundamental changes in how production stages are designed and how resources are consumed. Fundamental changes within the PGM industry and the mines' operating models will however be necessary if true sustainability is desired. The focus will therefore have to be on how the raw materials are extracted, how products are designed and produced, and how end-of-life products are recycled.

Figure 2. An overview of the circular economy (Joslyn Institute for Sustainable Communities).

CE can be defined as a model which allows business strategies to be systematic in their approach to sustainability by resembling an industrial ecosystem. This ecosystem of integrated processes is governed by the idea that broader operations occur in a circular loop where waste does not exist, but rather functions as a resource for other industries. The industrial ecosystem and the concept of circular loops can be seen Figure 3, illustrated as a “butterfly diagram” by the Ellen McArthur Foundation.

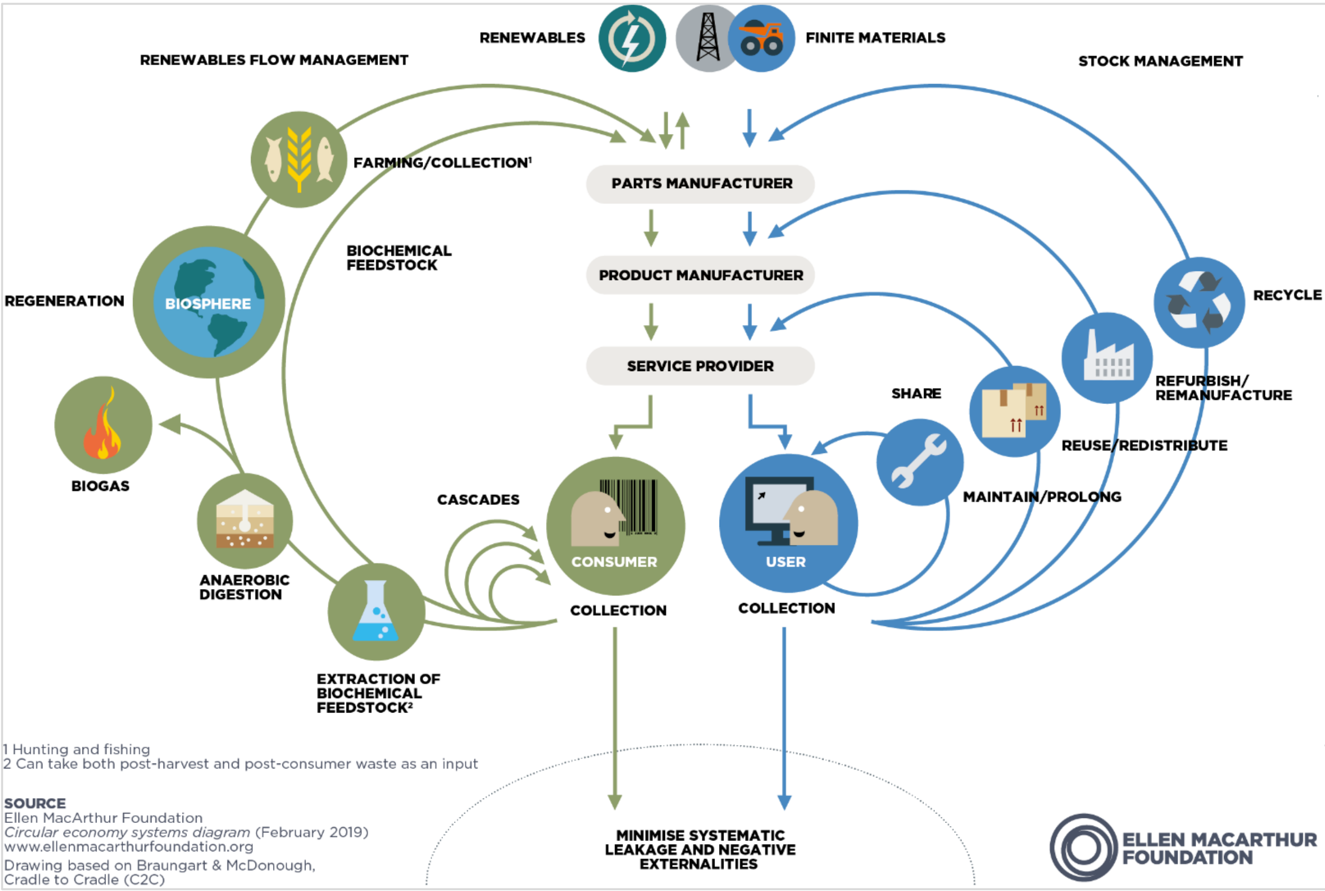

Figure 3. The "butterfly diagram" of the industrial ecosystem (The Ellen McArthur Foundation).

The CE can be applied to the mining industry as an operating model with the main goal to balance the resource flow within the natural ecosystem and the demands of the socio-economic system (Cisternas *et al*, 2021).

Some authors have defined CE through historical stages, labeling it CE 1.0, 2.0 and 3.0, similar to the way the industrial revolution has been defined. Between 1970 and 1990 the term circular economy became increasingly used in the realm of sustainability.

The CE 1.0 focused on how waste is generated and the disposal thereof in dump sites, while not taking the scarcity of resources into consideration or how waste can be prevented, but rather on ways to treat pollution at the end of the production line. This was clearly seen in publications from the mining and mineral processing industries, as the focus was mainly on detoxification methods of liquid, gas or solid waste emissions (Cisternas *et al*, 2021).

From 1990 to 2010 the next stage of the CE began, and the focus shifted to how profits could be increased by improving efficiency in processes through preventing pollution and waste. Various concepts came into play, particularly the concepts of industrial ecology, environmental design and cleaner production systems. Difficulty in implementing such concepts were most prevalent in the mining and minerals processing industries due to a lack of process innovation and environmental regulations not being strictly adhered to, especially in developing countries (Cisternas *et al*, 2021). The introduction of environmental management systems in industrial operations assisted in the implementation of regulations aimed at limiting environmental impact, as well as identifying benefits both technically and economically (Cisternas *et al*, 2021).

Since 2010, the CE 3.0 aims to increase value creation, growth and retention while separating it from resource extraction and encouraging smarter ways of mineral exploitation as well as the recirculation of natural resources (Cisternas *et al*, 2021). The mining and mineral processing industry has however fallen behind and still mostly deals with waste at the end of its value chain. The increased awareness of forecasted trends in population growth and consumption levels has sparked the awareness of the importance of sustainable mining.

The route of the CE model changed from being a reactive strategy to a proactive strategy, as various industrial processes, performance measures and technology have been evolving to incorporate sustainable principles and industrial ecology, with a key focus on waste and resources.

Cisternas *et al*, 2021 defines three types of loops associated with the CE model: short, medium-long and long loops. Each loop defines different alternatives to increase value of the product, by-products and waste, by using them in the same internal production processes or in industries outside of an organisation. This is known as the retention of value option or ReX. The concept of ReX derives from the prefix 'Re' which links to the recycling principles of circularity, where 'X' describes an option for value retention. The degree of proximity of the products to the consumers defines the difference between the three circular loops. The different loops of circularity are described in more detail below. A short loop is where the product remains in close proximity to the consumer and results in a more efficient system which uses refuse, reduce, resell/reuse and repair as value retention options and is therefore seen as being the most desirable form of circularity. The ReX options for the short loop CE are described as:

- R0 – Refuse or avoid the use of certain resources/materials.
- R1 – Reduce the amount of resources per product.
- R2 – Reuse or resell products.
- R3 – Repair of products to extend their life cycle.

A medium-long loop is where the products are updated and require the participation of producers to make the necessary changes for new applications. Refurbish, remanufacture and repurpose are seen as value retention options, and described as:

- R4 – Refurbish products through replacement or repair of certain components.
- R5 – Remanufacture products through the reconditioning of certain components.
- R6 – Repurpose discarded products and use in different functions than initially intended.

A large loop is seen as the traditional form of waste management, with products losing their original function. Recycling of materials, recovery of energy and remining of resources are seen as value retention options, and described as:

- R7 – Recycle materials to avoid the need for new resources to be extracted.
- R8 – Recovery of energy found in waste and integration into other production processes.
- R9 – Remine materials after a product has been disposed of.

The PGM mining industry has been traditionally focused on the extractive processes of resources through a linear model which depends on the availability of mineral and energy resources. Even though the industry has integrated various elements of the CE model over the past decade through the management of water usage and waste from PGM processing, an accelerated integration of CE principles will therefore be required if the growth factor of the PGM industry wishes to be independent from finite ore deposits and shortage of non-renewable resources. The following section explores how the application of the CE 3.0 value retention options and 4IR technology can be used as a future pathway to achieve sustainable growth in the PGM mining industry.

Future pathways to circularity

The CE 3.0 value retention options create a focused framework of circularity wherein the PGM mining and processing industry can function sustainably while retaining value in its operating model. Improving methods of extraction, reuse and reclamation of PGMs from ore bodies and waste created can be done through various circular approaches which incorporate ecological design elements with a focus on retaining value. The application of different ReX value retention options in the PGM mining and processing industry are described in the following sub-sections.

Refuse (R0)

The refuse option focuses on avoiding production processes which use significant amounts of critical resources such as water, generates vast amounts of waste or requires hazardous chemicals for PGM mining and processing. The expected increase in water and energy consumption for mining operations due to the forecasted increase in demand for metals and decreasing ore grades shines a light on the need to consider alternative approaches to traditional mining methods. Various global mining companies in water scarce areas have moved towards the rejection of fresh water for the beneficiation processes of minerals; instead incorporating dry processing technologies such as shallow air bed fluidisation techniques, and dense media separation, or even substituting fresh water with desalinated seawater (Cisternas *et al*, 2021). The refusal of coal powered electricity generation and substituting it with solar or wind will also drive sustainable use of energy, while drastically reducing CO_2 emissions.

Reduce (R2)

This value retention option relates to reducing consumption of critical resources in PGM mining and processing, such as water and energy, together with a reduction in waste rock, tailings and hazardous gasses and liquid waste. Conventional hydrometallurgy and pyrometallurgy consume vast amounts of energy while producing hazardous waste (Cisternas *et al*, 2021). Novel technologies have emerged over the past decade to allow for less environmental impact and resource consumption. Such technologies include selective electrochemical dissolution, biometallurgical processes such as bioleaching that use bacteria and other micro-organisms to extract PGMs from solid samples, as well as magnetic separation methods and microwaves to assist in platinum extraction (Mudd, 2010). The consumption of resources and the creation of waste is closely linked to the process efficiency within a mine's operating model, and therefore requires innovative development of technology to assist in the reduction of resources and waste. Waste rock and tailings can be reduced through the advance of technology to better identify ore grades and the methods used to extract the ore from the earth (Mudd, 2010). Significant social benefits can also be achieved through the implementation of sustainable water management strategies and technology, as many mining operations must compete with neighbouring communities for water resources. The 'reduce' option can be approached in two ways, namely the improvement of water usage efficiency and the substitution of fresh water with recovered wastewater, or even other alternatives such as seawater. This option for water and waste management is closely linked to the reuse option, which is described in more detail below.

Reuse (R2)

The reuse value retention option also has a place in the PGM mining and minerals processing industry, as this option can be applied by treating and reusing wastes within the mining industry or using it as a resource in another industry. Tailings from mining operations have recently been studied as a possible resource in the cement manufacturing industry due to its small particle size, which will drastically reduce the need for virgin limestone, clay, sand, bauxite and gypsum to be extracted. The recovery of wastewater also links to the reuse option, as this can be applied to limit the need for fresh water in hydrometallurgical processes by substituting it with recovered wastewater (Cisternas *et al*, 2021). The application of this value retention option however requires extensive innovation into wastewater management while making it a cost-effective alternative to traditional PGM mining methods.

Repair (R3), refurbish (R4) and remanufacture (R5)

The purpose of these value retention options is to extend the life cycle of products. In the context of PGM mining and processing, this can be applied to the equipment and tools used to execute operations and can therefore form part of the maintenance strategy (Cisternas *et al*, 2021). The extension of equipment and tool lifecycles traditionally forms part of any mining operation's predictive and preventative maintenance strategy, but for maintenance strategies to fall in line with CE principles, new and innovative design and development of equipment and tools are required. Focus will therefore have to be on the durability and modularity of equipment and tools, including standardisation of parts, and designing for ease of assembly, reassembly, disassembly, upgradability, maintenance and repair.

Repurpose (R6)
The concept of repurposing is well known in the industrial design sphere, and links closely to the reuse value retention option where unwanted materials are used in another function. An example of how this option can be applied in PGM mining and processing is the sequestration of CO_2 by applying carbon capture and storage, or commonly known as mineral carbonation, through mining waste. Silicas of calcium, iron, magnesium, oxides and hydroxides react with CO_2 to create geologically stable silica and carbonate species. The CO_2 emissions footprint from mining operations can be significantly reduced using this form of mineral carbonisation (Cisternas *et al*, 2021).

Recycle (R7)
Recycle is the process of creating new materials through the transformation of waste materials from products which have reached their end-of-life cycle, with the aim of preventing the overconsumption of new materials and resources (Cisternas *et al*, 2021). This option can be applied in the broader PGM industry through the recycling of consumer waste where PGMs are present. A unique characteristic of metals, such as PGMs, is their ability to be indefinitely recycled, meaning that every gram of a PGM used in a product can theoretically be recovered and recycled (less a small percentage lost in recovery) (Unterfrauner *et al*, 2017). This can include a vast variety of products, such as catalytic converters in vehicle exhausts and oil refineries, fuel cells, electronic components such as smartphones, and medical equipment. As the demand for PGMs is expected to grow over the coming decades due to the increasing usage of electronic equipment, such as smartphones and fuel cells in solar energy systems, it is expected that an increase in 'urban mining' will occur as PGM deposits and ore grades decrease (Ryan *et al*, 2010).

Recovery of energy (R8)
Energy recovery in an industrial sphere refers to the capturing of energy found in waste generated. In the context of the PGM mining and processing industry, energy recovery can be applied through the integration of energy utilisation within operating processes where excess energy, such as heat generated from operations, is recovered and used in another application (Cisternas *et al*, 2021). For example, the latent heat generated during the smelting process in PGM processing, as well as the heat generated from waste gases, can be utilised to generate electricity in other areas of the mining and processing operation.

Remine (R9)
The most widely used value retention option currently used by the mining and minerals processing industry is the remining of dumped waste to further extract mineral species (Cisternas *et al*, 2021). This is especially applicable to strategic metals whose natural resource availability is finite, such as PGMs. The dumping of large amounts of waste in the form of tailings, waste rock and overburden still contains traces of these metals due to the extraction of PGMs not being optimal. Remining also includes the concept of 'urban mining' as mentioned in the recycle option, where metals are extracted from products after reaching the end of their lifecycle. Remining therefore aims to fill the gap between the primary supply of PGMs from traditional mining operations and the growing demand for these valuable minerals in the future (Woodall *et al*, 2019).

CONCLUSION

The PGM mining and processing industry forms part of cornerstone industries within South Africa, whose contribution is crucial to the economic and social development of the country. Unfortunately, the development of mining in South Africa has resulted in a negative impact on the natural environment and surrounding communities, and therefore creates a need to do things differently and more sustainably if this valuable contributor to our economy is to be viable in the future. The framework towards circularity provides a roadmap for the PGM mining and processing industry to move towards a sustainable future, where energy and resources are managed smartly by technology, waste is turned into resources for internal operations or other industries, water is consumed and recycled efficiently, and operating models function within an industrial ecosystem where value is retained, the relationships between value drivers are understood clearly and measured accurately. The concept of value retention methods throughout the whole supply chain (or rather a supply loop) is described through different options, or ReX's, such as refuse, reuse, recycle etc. These value retention options are dependent on designing extraction, production and consumption of resources specifically for the CE, and will require overcoming various barriers to implementation. These barriers include the dependence on technological advances and changes in socio-economic and political structures, as well as the willingness of stakeholders to engage. Increasing research and a knowledge base on this topic will therefore be required to implement changes. Another barrier to circularity is the way we measure the impact on the environment and how we drive value within an organisation. Until we generate a standardised method to accurately measure environmental impact, value retention and which value levers drive ESG performance (and how we benchmark it across industries), the focus will remain on financial returns and not the cost to our economy due to resource wastes and environmental destruction. The mining industry therefore needs to find a way to accurately quantify the impact on the environment to include value driver mechanisms and ESG metrics in our decision making. A holistic perspective on how environmental and socio-economic elements are impacted by value drivers, production processes, consumption rates, economic measures and resource utilisation will be the cornerstone of sustainable decision making and how investments in companies are done. The competitive advantage of the PGM mining and processing industry in the coming decades is dependent on the way the industry retains value, drives value and how it positions itself in terms of environmental and investment sustainability - a factor which can make or break the PGM industry in the future.

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