Master Thesis

Assessment of the economic and environmental efficiency for the utilization of ferrous metallurgy slags

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Preface, Dedication, Acknowledgement

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Abstract

The linear economy has been the dominant type of economy over the past decades or even centuries. But this model of the economy has caused a large number of issues and problems related to scarce resources, the negative impact on environment components and the social well-being. In contrast to the linear model, the circular economy model has developed in recent years. In the circular economy waste and obsolete goods are sources of materials and energy that should be used. Mining and processing companies around the world are adopting new technologies to contribute to the achievement of Sustainable Development Goals and to the creation of the circular economy. Companies' experience shows that the treatment and reuse of solid waste has a positive impact on the achievement of the Sustainable Development Goals. But not all companies implement new technologies to use wastes and introduce circular economy methods to enterprises. The presented thesis introduces the assessment of negative impact on the environment from slag dumps at an operating enterprise. To reduce the impact a recycling method for the slag was proposed and the equipment was selected. The calculations were carried out on economic efficiency to prove the feasibility of the proposed project. The results showed that the implementation of the project in the enterprise pays off in less than a year, and allows to reduce the negative impact on the components of the environment.

Key words: circular economy, steel slag, environmental impact, economic viability.

Zusammenfassung

Die lineare Wirtschaft war in den letzten Jahrzehnten oder sogar Jahrhunderten die dominierende Art von Wirtschaft. Aber dieses Modell der Wirtschaft hat eine große Anzahl von Fragen und Problemen im Zusammenhang mit knappen Ressourcen, den negativen Auswirkungen auf Umweltkomponenten und dem sozialen Wohlergehen verursacht. Im Gegensatz zum linearen Modell hat sich in den letzten Jahren ein Kreislaufwirtschaftsmodell entwickelt. In einer Kreislaufwirtschaft sind Abfall und veraltete Güter Quellen von Materialien und Energie, die verwendet werden sollten. Bergbau- und Verarbeitungsunternehmen auf der ganzen Welt setzen neue Technologien ein, um zur Erreichung der Ziele für nachhaltige Entwicklung und zur Schaffung einer Kreislaufwirtschaft beizutragen. Die Erfahrung der Unternehmen zeigt, dass sich die Behandlung und Wiederverwendung fester Abfälle positiv auf die Erreichung der Ziele für nachhaltige Entwicklung auswirkt. Aber nicht alle Unternehmen implementieren neue Technologien, um Abfälle zu nutzen und Kreislaufwirtschaftsmethoden für Unternehmen einzuführen. Die vorgestellte Arbeit führt in die Bewertung der negativen Auswirkungen von Schlackendeponien in einem Betrieb auf die Umwelt ein. Um die Auswirkungen zu verringern, wurde eine Recyclingmethode für die Schlacke vorgeschlagen und die Ausrüstung ausgewählt. Die Berechnungen wurden zur Wirtschaftlichkeit durchgeführt, um die Machbarkeit des vorgeschlagenen Projekts nachzuweisen. Die Ergebnisse zeigten, dass sich die Umsetzung des Projekts im Unternehmen in weniger als einem Jahr auszahlt und es ermöglicht, die negativen Auswirkungen auf die Umweltkomponenten zu verringern.

Schlüsselwörter: Kreislaufwirtschaft, metallurgische Schlacke, Umweltauswirkungen, Wirtschaftlichkeit.

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1 Introduction

All resources of the Earth are interconnected and constitute the global system of nature. In the summer of 1970, an international team of researchers at the Massachusetts Institute of Technology began studying the implications of continued global growth. They found that it is likely that the planet's resources will not be able to support the current rate of economic and population growth after 2100, even with advanced technology. Five main factors that determine the Limits to Growth were investigated: population growth, agricultural production, depletion of non-renewable resources, industrial production and environmental pollution (“The Limits to Growth - Club of Rome” n.d.). The concept of planetary boundaries was introduced in continuation of the Limits to Growth. The authors of the concept identified nine key systemic processes taking place on the planet. These processes include: ozone depletion, biodiversity loss, chemical pollution and release of new compounds, climate change, ocean acidification, fresh water consumption, land use, aerosol pollution, biogeochemical changes (“The Nine Planetary Boundaries - Stockholm Resilience Centre” n.d.). For each of the nine identified keys earth system processes, the authors of the concept proposed a control variable that allows one to quantify the state of one or more relevant variables. Thresholds (planetary limits) for each variable that should not be exceeded have also been proposed to sustain a modern society, and avoid overloading these systems. As long as the state of the control variable is below the threshold for the corresponding planetary boundary, societies operate within an ecological carrying capacity called safe operating space (Rockström et al. 2009).

The concept of planetary boundaries, introduced in 2009, aimed to define the ecological limits within which humanity can safely operate. This approach has influenced the development of global sustainable development policies (Steffen et al. 2015). The transition to a sustainable society is a complex task that requires well-coordinated cooperation between the various sectors of production and consumption. Therefore, for a systematic approach and planning of coordinated actions, the general principles and goals of sustainable development were formed, which allow you to quickly combine the efforts of various sectors of the economy (Robèrt and Broman 2017).

Strong economic growth and more complex demands from the developed world have led to increased demand for minerals and metals. Although mining and processing of minerals is the main source of metals and other materials, the use of which ranges from urban construction to environmentally friendly technologies. But mining activities also have a negative impact.

The impact ranges from human migration to water, air and soil pollution with toxic substances from mining and processing that have not been properly contained or treated. Humanity is facing a decrease in the quality of environmental components and an increase in the risk of degradation of the biosphere, which is a significant problem. Also, the problem is accelerated with the continued growth of the population (Bastas and Liyanage 2019; Steffen et al. 2015).

Mining activity often have a positive effect at the local level, as it creates new jobs and provides development opportunities for the region. But in a number of other cases, it causes conflicts, especially in regions where mining and processing enterprises compete for land or water with other business sectors and stakeholders. Also, the local population is at risk and often faces social problems as a result of mining and processing of minerals. In addition, accidents and illnesses caused by the mining industry make it one of the most hazardous sectors, especially with regard to dust and noise associated with blasting, artificial air and light supplies, noxious gases and ergonomic hazards (Ranängen and Lindman 2017).

Mining and processing industries will play an increasingly important role as the world moves towards a low-carbon future (Sovacool et al. 2020). But the quality of mineral deposits declines over time, which leads to higher generation of waste (Mudd and Jowitt 2018). Also, mining and processing of minerals is taking place in increasingly remote and environmentally sensitive areas. The trend is likely to continue, because of development of remote monitoring and operations through automation, satellite imagery and other technologies (Mallett et al. 2021).

To implement the principles of sustainable development in enterprises, significant changes are needed, which present significant risks and opportunities for companies. Manufacturing companies need to develop their macro measurement capabilities to stay relevant and competitive in an ever-changing marketplace (Schulte, Villamil, and Hallstedt 2020). Therefore, companies that fail to contribute to or adapt to the principles of sustainable development will inevitably leave the market (Anderson 2009). But not only the fear of failure should motivate the actions of the enterprise. As markets become more sustainability-driven, companies are keen to be proactive about sustainability in order to capitalize on business opportunities that represent the positive side of risks (Robèrt and Broman 2017).

The Brundtland Commission reported that there is no single strategy for sustainable development and that the way countries and businesses achieve sustainable development will differ across different economic and political systems around the world. This fact has prompted a number of scientists, industrial entrepreneurs and government officials to present a personal view on the applicability of sustainable development to the mining industry (Hilson and Murck 2000).

According to some scientists, the management of mining enterprises should not be guided only by the environmental legislation of countries. Such an opinion exists, since sustainable development requires proactive environmental management, and requirements that go beyond regulatory requirements. In addition, because legal and regulatory frameworks vary widely around the world, in some cases, complying with legal requirements does not necessarily mean good environmental practice. In much of North America, Europe and Australia, comprehensive environmental legislation has been in place for several decades, but in a number of countries in South America, Africa and Asia, environmental legislation is still in the beginning and the enforcement programs are far from being implemented. Developing countries are usually the location of poorly managed mining enterprises, which, due to the "loose" regulatory framework, tend to use a number of rudimentary, low-tech methods of extracting and processing minerals. Thus, businesses that operate within or even outside the legal framework do not necessarily contribute to the improvement of the environment or sustainable development. Principle I of the Rio Declaration declares that “people are at the center of concern for sustainable development” and “have the right to a healthy and productive life in harmony with nature” (Epps 1997). Thus, one of the important elements of sustainable development is enhanced social and economic responsibility. Socio-economic responsibility involves the transfer of environmental and social consequences to the companies that cause these consequences. In this case, companies will assess and prevent negative impact in order to optimize benefits and reduce consequences. Socio-economic responsibility requires that industrial operations meet the needs of all stakeholder groups at various stages of work.

There is now an increasing possibility that corporations will act in accordance with societal groups potentially affected by industrial operations and take the needs of stakeholders into account when developing corporate policies. Once an important organizational foundation is in place, enterprise management can focus on implementing tools and technologies to improve operational efficiency. However, the first step is to improve environmental management practices, which not only help improve the efficiency of operations, but also allow faster adoption of environmental technologies. This is achieved through the adoption of a number of environmental management instruments, the most important of which includes (Garrod and Chadwick 1996): general environmental reviews; environmental accounting; environmental reporting; environmental audits; environmental policy; environmental management system; life cycle assessment. These tools are common for industrial use, but each must be redesigned to address specific industry problems. The use of these tools in the context of mining and processing of minerals is the key to minimizing the environmental impact at each major stage of the production process. Each environmental management tool serves a specific purpose, helping to improve the effectiveness of a given area of activity. However, it is the successful implementation of a set of environmental management tools that ultimately leads to improved environmental performance, allowing the mining industry to focus on the next stage of sustainable development (Hilson and Murck 2000).

1.1 Research framework

“From residential buildings and commercial establishments to manufacturing and logistics, every sector emits tons of waste every day” (Pavlas et al. 2020).

The history of ferrous metallurgy goes back many centuries. The first iron was obtained during the smelting of copper in furnaces. Pieces of iron found in Anatolia date back to 2000 BCE. And 1200 BCE is the beginning of the Iron Age (“Metallurgy | Definition & History | Britannica” n.d.). After that, the technology for producing and smelting cast iron and steel improved, but until the beginning of the 20th century, production was poorly developed. After the Second World War a number of countries had started the active development of the metallurgical complex. Since 1950 the global demand for steel has continued to increase with an acceleration since 2001 mainly due to economic growth in China. In addition, iron ore has the substantially highest production rate among key metals (A Rouch 2021).

The mining industry is the largest waste producer in the world. In addition, mining has a large impact on the environment (JP Casey 2020). In the mining industry, the possibilities of recycling large waste streams have not been extensively explored. Among the manufacturing industries, the largest amount of waste is generated in the metallurgical industry and the production of finished metal products. In ferrous metallurgy, steel scrap is one of the materials needed for production. There is a worldwide shortage of scrap steel, and the steel industry recycles as much scrap as is available. Therefore, recycling of scrap metal is not a problem. The main problems of mining and processing enterprises are the disposal of steelmaking and blast-furnace slag, as well as dispersed waste from aspiration systems (Pashkevich and Lytaeva 2014; “Steel in the Circular Economy: A Life Cycle Perspective - Worldsteel.Org” n.d.). In 2006 the total amount of slag from stainless steel production is estimated at 15-17 million tons per year, including slag from various technological stages, electric arc melting, argon oxygen decarburization and vacuum oxygen decarburization, ladle operations and casting (Cha, Kim, and Choi 2006). In 2020 more than a billion tonnes of waste were produced by the iron and steel sector. To make 1 tone of steel 1.15 tonne of raw material is needed (Cayumil et al. 2021). For a ton of steel, around 0.13–0.2 ton of slag is produced (Shi, Palomo S nchez, and Torgal n.d.). In 2020 China produced 1064.8 million tons of slag, so the generated amount of slag was around 181 million tones. The USA produced 72.2 million tons of steel and the production of slag was 12.4 million tons. In India, 100.3 million tons of steel were produced in 2020, hence about 17 million tons of steelmaking slag were generated. Also, 83.2 million tons of steel were produced in Japan, which resulted in the formation of approximately 14 million tons of slag. In Russia, 71.6 million tons of steel were produced in 2020, resulting in 12 million tons of slag. Figure 1 shows the drainage of liquid slag into trances for cooling and solidification. “Only 15-30% of metallurgical waste is processed to extract valuable components, approximately 20-30% is used in the construction industry, while the bulk of the waste materials are stored in dumps, tailings and sludge dumps” (Lytaeva 2013). In addition to recycling scrap for steel production, there is growing interest and incentives to use and recycle production residues as resources (“Annual and Sustainability Reports” n.d.).

Figure 1: Drainage of liquid slag into trenches

Source: Author

When iron ore is smelted in furnaces, cast iron, and blast-furnace slag are formed. Steel and steelmaking slag are formed with further melting of cast iron in converters. A valuable component can be selected from the slag and returned to production by simple magnetization. But the slag cannot be used in other processes and turns into waste according to the linear model of the economy. The slag is placed in dumps, which causes the problem of storage and negative impact on the environment. Without an isolation of the surface the dumps can cause emissions of dust into the air. Also, groundwater and surrounding soils can be polluted with leachate that forms in case of precipitations. In addition, large areas of land are occupied for dumping due to the formation of large volumes of the waste. Figure 2 shows dumps of slag.

Figure 2: Dumps of slag

Source: https://dprom.online

There are several possibilities for using waste: recovery of metals, storage for the future, recovery of metals from wastewater, etc. In a linear economy, waste from traditional mining can be recovered using recycling technologies. Slags in dumps contain a significant amount of valuable material and form man-made deposits. But the extraction of components from waste requires the development of new enrichment methods (Patokin 2021). In a circular economy, urban mining of industrial and municipal waste can recover material (Kinnunen and Kaksonen 2019; Xavier et al. 2021). Often, waste during their special treatment becomes by-products. For example, with the help of carbonization of large-tonnage waste - phosphogypsum, it is possible to obtain phosphochalk. In addition, the phosphogypsum processing process can use an off-gas containing CO2, which can reduce the carbon footprint (Suchkov 2021). Mining companies must improve waste management through recycling and reuse methods to achieve sustainable production and consumption patterns (Monteiro, da Silva, and Moita Neto 2019). Extended producer responsibility and pay-as-you-go policies, as well as community involvement, have enabled effective waste management practices. Taxation can change profitability and accelerate the transformation of the circular economy. Advances in technology can turn lower quality materials into a source of raw materials and make all raw materials valuable.

In addition, minor metals can be recovered in addition to base metals (Bringsken et al. 2018).
For consistent and productive sustainable development, all enterprises should build their production processes based on the seventeen Sustainable Development Goals (SDGs) presented by the UN in 2015. But in order to reduce the negative impact of production facilities on the components of the environment and the population, special attention is paid to SDG 6 (Clean water and sanitation), SDG 12 (Responsible consumption and production) and SDG 15 (Life on land).
The most important goal in the field of sustainable waste management is SDG 12. One of the main points of SDG 12 is to ensure the sound management of chemicals and all wastes throughout their life cycle and to significantly reduce their emissions to air, water and soil. It is also necessary to reduce the generation of waste through prevention, reduction, recycling and reuse. The other points are to: encourage companies, especially large and multinational ones, to adopt sustainable practices; ensure sustainable management and efficient use of natural resources; implement a framework for sustainable consumption and production programs; promote sustainable public procurement practices; ensure that information is accessible to people, as well as understanding for sustainable development and lifestyle ("Learn More About the SDGs – SDG Compass" n.d.).

In this context, the circular economy (CE) has become a key approach to support the transition to sustainable development and increase the competitiveness of the industry on the path to sustainable growth. The CE is defined as "an economy that provides multiple mechanisms of value creation that do not involve the consumption of scarce resources", which is especially relevant in the context of manufacturing companies (Lieder and Rashid 2016; Pieroni, McAloone, and Pigosso 2021). A successful transition to the CE requires a systemic change in the way how companies understand and conduct business, with sustainability as the foundation (Kravchenko, Pigosso, and McAloone 2019; Millar, McLaughlin, and Börger 2019).

The CE is a concept that describes a paradigm shift regarding the use and recycling of materials and resources. The circular economy offers an innovative path to sustainable development by offering a different way of looking at natural resources when dealing with them. SDG 12 is most aligned with the principles of the circular economy. CE practices such as reuse, recycling, recovery, waste prevention and safe disposal are valuable assets for achieving SDG 12. In addition, the circular economy goes beyond sustainable production and also operates in the area of responsible consumption (Dantas et al. 2021).

Thus, the circular economy can become a key method for the industry to reduce the amount of waste, and reduce the negative impact on the environment.

1.2 Research gaps

The application of the CE model in the iron and steel industry can help to deal with this problem. Circular economy has significant environment and social benefits derived from it. In this case, the slag can be turned into a value-added by-product. In terms of applying the CE methods on the enterprises there are two approaches: open-loop system and closed-loop system. In closed-loop recycling the material can substitute the original new material and can be used in the same products. Opel-loop system the materials can be applied in other products and can substitute other materials (Huysman et al. 2017).

The slag contains impurities that are extracted from iron and steel during the production process. Reuse of the waste in a closed-loop system is not possible as it will lead to the ingress of impurities into the iron or steel. Therefore, it is necessary to use slags in open-loop systems which requires research on the properties of the waste.

Since the middle of the last century, the chemical and physical properties of steelmaking and blast-furnace slags from various enterprises have been studied. Various methods of implementation were identified in the study of the properties of the material. These properties are determined by the slag phase (crystalline or amorphous). For example, slag with an amorphous phase can be used for heat recovery (Oge et al. 2019). Many different studies confirm the possibility of using slag in the construction industry (Oge et al. 2019; Piatak, Parsons, and Seal 2015). Portland cement has advantages over other cement materials in terms of CO_2 emission, but has restrictions on its use for safety reasons (Oge et al. 2019). Ferrous metal slags can also be used in thermal power engineering, production of ceramics and surface coatings (Oge et al. 2019; Piatak, Parsons, and Seal 2015). Metallurgical slags effectively replace natural materials in the construction and repair of roads. The layers of asphalt roads made with the use of steelmaking slags are the absence of deformation under heavy traffic flow. Slag crushed stone is used for the upper and lower layers of bases on roads. An active slag-crushed stone mixture with a fraction of 40 mm is used as a wedging material (Panfilov et al. 1987). Crushed steelmaking slag with the fraction of 0.1-3.5 mm can be used as an abrasive material in sandblasting, since hard angular slag particles have an increased cutting ability. But slag abrasives are highly brittle, which leads to the formation of dusty particles and limits the possibility of reuse (Panfilov et al. 1987). Slags with a basicity modulus greater than one and a total content of calcium and magnesium oxides exceeding 43% are used as lime fertilizers to deoxidize the soil and enrich it with calcium, and reduce the content of aluminum ions (Vetoshkin 2019; Panfilov et al. 1987). Studies have also been carried out proving the possibility of using steelmaking slags in the treatment of wastewater from pollutants (Sladkova 2021).

As the composition of metallurgical slag is not constant and veries from one enterprise to another, there are no obligatory requirements for enterprises to utilize or recycle solid industrial wastes. But there are general tips on the possible implementation of metallurgical slags in varied ways. In addition, there is no single method for processing slags to obtain all kinds of products.

Industries face challenges to implement and adopt the concept of CE. The subsidies, financial aid and unconsidered externalities support the linear model of economy which makes the CE model unprofitable to implement. Also, in the short-term the cost of products produced in linear production processes is cheaper than in a circular model. Consumers' initiative in supporting sustainable products is also important to facilitate the transition of companies to a circular economy. In addition, all infrastructure processes such as waste management, treatment and recycling processes and others should support CE practices. One of the most important barriers is lack of knowledge and technical equipment for treatment processes (Melati, Nikam, and Nguyen 2021).

At present times, new businesses are considered as key drivers for the transition to a circular economy. New enterprises can include technologies, territories and devices for slag processing in their production chain at the first stages of planning the enterprise. They can focus on the type of slag products that are more necessary for their region and will be in demand. Also, based on the input data, new enterprises can build strategies for the most profitable ways of waste disposal based on the composition of the slag and adjust it.

But most of the ferrous metallurgy enterprises in Russia are old. For example, two of the largest steel producers in Russia - Severstal and Novilipetsk Steel began their work already in 1955 and 1934, respectively. For such an old business, the transition to a new economic model can be accompanied by significant financial losses, which makes the transition difficult or almost impossible.

Options for using the material are selected based on the study of its properties. Often, special processing equipment is necessary to treat the waste and turn it into a product.

Appropriate treatment technology and equipment are dependent on the methods of use. Some applications, such as in cements, abrasives or as a water treatment agent, require only grinding and separation into the required fractions. Other options, such as the production of rock wool or granulated slag, require the slag to be treated in the liquid phase using special methods.

The problem is that the principles of the circular economy were not laid down in the old enterprises when they were created. The slag has already been produced and accumulated over many years of operation of the enterprise. And not all methods can be used to treat old slag. This also limits the choice of equipment for slag treatment and does not allow the use of cheaper and more accessible technologies for disposal. Various companies offer their equipment for the processing of metallurgical slags. But such equipment does not allow complex processing of all formed slag, which can be used for different purposes. In addition, due to the limited choice of the utilization waste, the final products of slag may not be in demand on the local market. And transportation of the product to other regions may be unprofitable, which causes economic losses. Also, the safety of using the product should be proved by laboratory studies and field experiments that cause additional financial investments. That is why many iron and steel enterprises in Russia are not currently applying methods for the transition to a circular economy, or are just starting to apply them.

Currently, the main issue is the financial and environmental viability of the methods that will allow the transition of the old iron and steel enterprise to the CE. Therefore, it is necessary to find the optimal technology of slag treatment to minimize the financial risk of the enterprise.

1.3 Company Description

NLMK Group is a leading international manufacturer of high-quality steel products with a vertically integrated business model. Mining and steelmaking are concentrated in cost-efficient regions; finished products are manufactured close to our main customers in Russia, North America, and the EU (“About NLMK” n.d.).

The company produces 21% of all steel in Russia and is among the top 20 largest steel producers in the world. Steel production capacity exceeds 15 million tons per year. The main production site is located in Lipetsk city. The main products of the enterprise are coke, pig iron, slabs, hot-rolled steel, cold-rolled steel, galvanized steel, pre-painted steel, dynamo and transformer steel. At the moment the blast furnace “Rossiyanka” is the most productive furnace in Russia and located in Lipetsk. PJSC «Novolipetsk Steel» is an enterprise with a full metallurgical cycle, containing all the production facilities necessary to obtain the final metallurgical product from iron ore raw materials - uncoated and coated rolled products.

The general technological scheme of the plant's production includes: sinter production, coke production, blast furnace shops, steelmaking shops and rolling production. The normal functioning of the main industries is carried out with the help of auxiliary units: power production, repair shops, refractory shop, ferroalloy shop, pile driver shop, metallurgical slag processing shop, maintenance and repair center and others.

Ore for the production of iron and steel comes from the “Stoilensky” mining and processing plant, which belongs to the Kursk magnetic anomaly deposit. The ores of this deposit consist of magnetic iron ore with an iron content of 55-60%. The balance ore reserves of this deposit are estimated at 55 million tons.

The sintering and coking industries are the producers of the main components for blast-furnace production - sinter and coke. Since 2017, coke has been replaced by pulverized coal, which is a lower cost alternative. At the moment, 90% of the enterprise's capacity has been switched to pulverized coal.

Blast-furnace production is intended for the production of pig iron, which is a semi-finished product for steelmaking and a commercial product of the first processing stage. For the production of 1 ton of pig iron in the Rossiyanka blast furnace, 1245 kg of sinter, 336 kg of pellets, 287 kg of coke, 990 cubic meter of blast, 160 kg of pulverized coal are used.

Steel is produced in an oxygen converter by purging liquid iron with oxygen. Steel is also smelted in electric furnaces using graphite electrodes. Further, the steel is poured into continuously cast billets, which are used for the production of rolled products and are finished products of the second stage.

The rolling production is represented by the production of hot rolling, the production of cold rolling and coatings, the production of transformer steel and the production of dynamo steel. Hot-rolled steel is a commercial product of the third stage and serves as a blank in the production of cold-rolled steel. The plant implements technologies for the production of cold-rolled carbon steel without coatings, as well as with zinc and polymer coatings, and rolling of electrical steels.

Figure 5 shows five year highlights of the Novolipetsk Steel activity. As it can be seen from the table, the overall steel output is decreased, free cash flow is also decreased as well as net value. The total number of employees over five years has decreased by 2,100 people. Although labor productivity increased in 2020 compared to 2019, it also decreased over next the 5 years.

Indicators	2016	2017	2018	2019	2020
Financial performance,[1] $ m					
Revenue	7,636	10,065	12,046	10,554	9,245
Net profit[2]	935	1,450	2,238	1,339	1,236
EBITDA	1,943	2,655	3,589	2,564	2,645
EBITDA margin	25%	26%	30%	24%	29%
Operating cash flow	1,699	1,899	2,741	2,623	2,281
Investment	559	592	680	1,080	1,124
Net debt	761	923	891	1,786	2,495
Free cash flow	1,092	1,266	2,027	1,523	1,103
Dividends, $ per share	0.1535	0.2383	0.3525	0.2630	–
Operating performance,[2] '000 t					
Steel output	16,438	16,850	17,285	15,531	15,667
Steel output (with NBH)	16,641	17,076	17,493	15,696	15,833
Steel product sales	15,925	16,469	17,591	17,069	17,520
Finished steel sales	10,211	10,759	10,762	11,056	10,535
Sales to home markets	10,225	10,650	10,573	11,376	10,744
Sustainability performance					
NLMK Group headcount, '000 people	54.0	53.2	53.4	52.8	51.9
Labour productivity, t of steel/pers., NLMK Lipetsk	482	502	503	448	461
Specific air emissions, kg/t of steel	20.0	19.5	18.9	20.2 (18.9)[3]	19.8 (18.6)[3]
Specific CO_2 emissions, t/t of steel + merchant pig iron (Scope 1)	1.76	1.73	1.70	1.75	1.72

Figure 3: Five year highlights of Novolipetsk Steel

Source: (NLMK 2021)

1.3.1 Economic impact

According to NLMK Group's 2020 annual report, revenue decreased to $9.2 billion in 2020, due to lower prices for steel products and an increase in the share of semi-finished products in total sales. The share of semi-finished products in the turnover increased by 30% year on year due to the increase in pig iron exports. The share of finished products decreased to 65%. The share of the Russian market in turnover was 41%. The share of the EU and the US fell to 17% and 15% respectively.

EBITDA is earnings before interest, taxes, depreciation, and amortization. These values are used by NLMK Group to calculate an operating profit before equity share in net losses of associated and other companies accounted for using the equity method of accounting, impairment and write-off of assets, adjusted to depreciation and amortization. EBITDA reached $2.6 bn.

Commercial expenses totaled $845 m (did not change compared to 2019). General and administrative expenses decreased to $346 m (2%).

Net profit reduced to $1.2 bn due to the recognition of the NBH investment value impairment in the amount of $120 m in Q2 2020. Free cash flow decreased to $1.1 bn due to working capital financing as receivables grew.

Total debt in 2020 grew to $3.5 bn. Net debt increased to $2.5 bn due to cash outflow to dividend payments and increase of investment.

The NLMK Group's investment went up to $1.1 m. The increase of investment was due to the completion of large-scale upgrade projects at the NLMK Lipetsk blast furnace operations and active phase of investment program implementation in line with Strategy 2022.

NLMK invests resources in the training and development of its employees. Investment allocated to staff training and development measures in 2020 amounted to 1,383 million roubles, including 1,112 million allocated to construction of Corporate University campus in Lipetsk, 249 million roubles to training measures and 22 million roubles to in-house coaches payroll. Figure 6 shows social spendings during five years. The company has developed social support measures for its employees that aim to boost their motivation and satisfaction levels. Total social investments in 2020, including NLMK Group's international assets, stood at 8.4 billion roubles, of which 7.4 billion roubles was allocated to social support programs for NLMK Group employees. In 2019, the Company switched to disclosing social investments for the entire Group, including its international companies. Figure 4 illustrates social spendings of NLMK Group in five years.

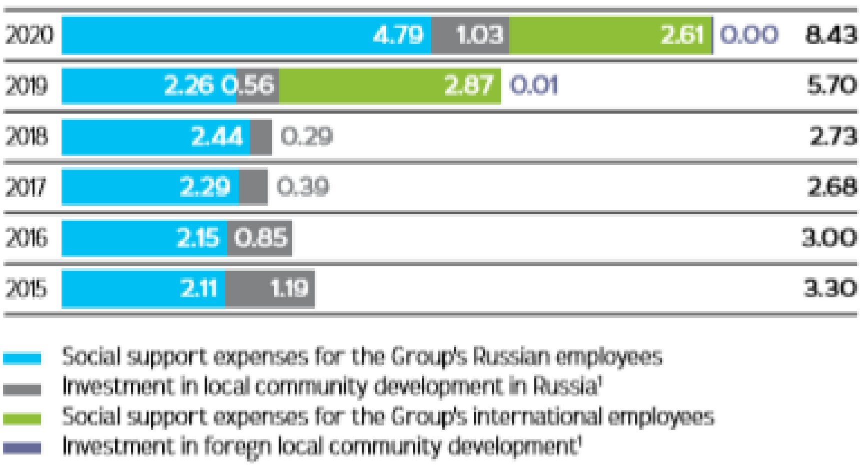

Figure 4: NLMK Group's social spending, rub bn

Source: (NLMK 2021)

1.3.2 Employees

According to the annual report 2020 of NLMK Group's average headcount was 51,900 people, of whom 48,500 (93.4%) were employed at the Company's Russian companies, 2,100 (4.0%) at European divisions, 0,200 (0.4%) at international auxiliary companies, and 1,100 (2.2%) in the United States in 2020.

Approximately 97% of NLMK Group employees work under permanent contracts, and around 3% under fixed-term contracts.

Currently, 25% of NLMK employees are women and 75% are men. As for administration and management staff, women account for 48% of all specialists, including 50% of specialists and office employees, 22% of office managers and 4% of shop-floor (revenue-generative) managers (the total share of female managers is 15%). Figure 5 presents the gender distribution of employees in various positions.

NLMK employees represent various age groups. In 2020, 23% of all employees were aged over 50, 61% were aged between 30 and 50, and 16% were under 30. Of those in management positions (shop-floor managers and office managers), 75% were aged between 30 and 50, and 21% were aged over 50.

NLMK is committed to supporting gender diversity within its governance bodies in a way that takes into account the specific nature of the Company's activities.

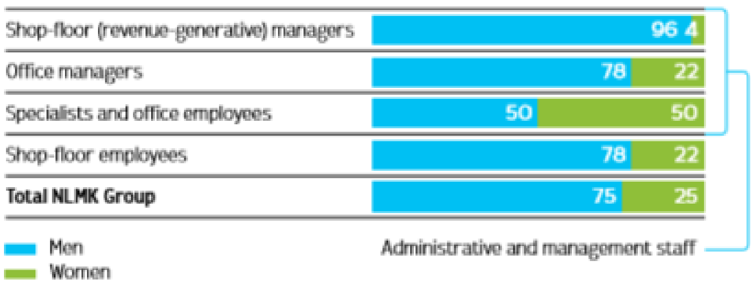

Figure 5:Staff breakdown by gender and category in 2020, %

Source:(NLMK 2021)

In 2020 labor productivity across NLMK Group stood at 305 tons of steel per person, growing year-on-year as major investment projects were implemented to upgrade the sites' main equipment. The changes vs previous years are due to preliminary hiring and personnel training in anticipation of higher output in 2021 (+2 million tons at the Lipetsk site vs. 2020).

The average salary of NLMK Group employees at Russian companies in 2020 was 70,900 roubles which is a 10% increase versus 2019. The increase was significantly ahead of the inflation rate due to additional measures to support employees during the COVID-19 pandemic.

To increase the share of highly qualified specialists in the labor market, NLMK cooperates with more than 30 specialized educational institutions in the regions where they operate. Employees undergo thorough training in competencies that are relevant to NLMK, undergo internships at NLMK Group facilities, perform real work tasks and participate in the company's projects. In addition to diplomas and specializations, recent graduates receive education in three specialties, which ensures rapid professional and career growth at NLMK.

In order to address the need for engineering talent and specialists with higher education, a new internship program the Steel Opportunities Academy launched in 2021 for university students and graduates. Candidates from over 600 leading specialized universities in Russia will be considered for internship positions, and the selected applicants will be gradually immersed in NLMK's corporate culture and production system. In 2020, the NLMK employees received a total of 3,173,228 man-hours of training. Divided by NLMK Group's average headcount, this implies 61.1 hours of training per person (65.1 hours divided by the average headcount of the Russian companies). NLMK Lipetsk employees also provide training on the Company's professional competencies to students of basic educational institutions. These trainings promote the development of the mentors themselves as well as potential employees for NLMK Group.

1.3.3 Environmental impact

Water consumption and discharge:

For industrial water supplies, the companies use water from surface water bodies, underground sources, and rainfall. NLMK Group does not use wastewater from other organizations. NLMK withdraws a small proportion of their water from external sources for production and drinking purposes (less than 4% of the Group's total water consumption). In 2020, the Lipetsk site started working on a project for feeding treated household wastewater back into the company production water supply, which will reduce the intake of fresh natural water by 2 to 8 million m^3. In 2020, there was a downward trend in water consumption volumes compared. Figure 6 shows the total volume of water consumed by NLMK Group (NLMK 2020).

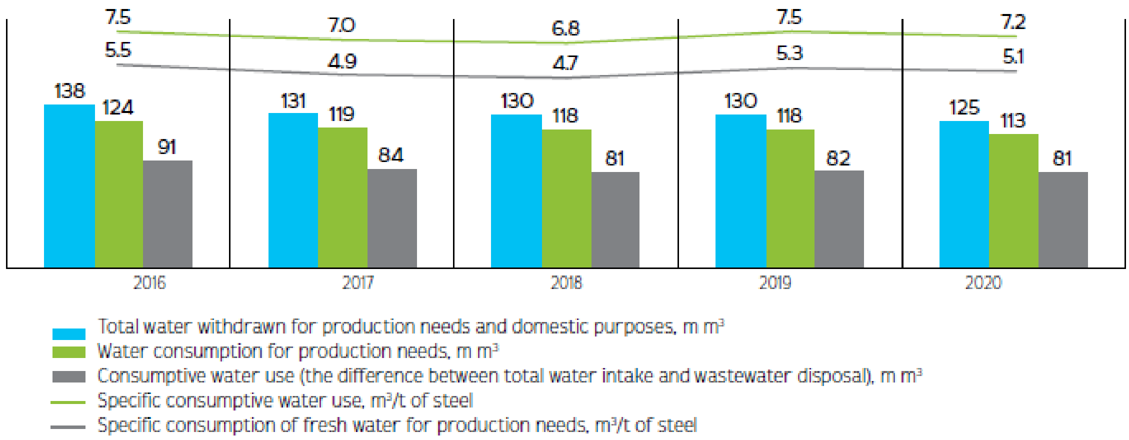

Figure 6:Total volume of water consumed by NLMK Group

Source: (NLMK 2020)

Fig. 7 shows the table of the total volume of discharge by receiving water body, M M^3. Volume of wastewater disposal reduced by 0.7 million m^3 (-8%) comparing 2020 year to 2019 year. Also, inflow of pollutants into the water body reduced by 1,900 tonnes (-19%). All discharged materials have a mineral content of less than 1,000 mg/L. No untreated discharges are made into water bodies. The Company's Environmental Strategy sets the goal of reducing the discharge of pollutants with wastewater into water bodies by 25% compared to 2018(NLMK 2020).

Indicator	2016	2017	2018	2019	2020
Total volume of water discharge for NLMK Group[1]	**46.5**	**47.3**	**49.0**	**47.7**	**43.3**
Water discharge as % from total water supply	**1**	**1**	**1**	**1**	**1**
Into surface water bodies, including rivers, lakes, reservoirs, and canals	44.4	45.2	46.8	45.7	41.6
including into seas and oceans	0.2	0.2	0.3	0.3	0.3
Transferred to third-party organizations for treatment	2.1	2.1	2.1	2.0	1.7
Specific water discharge[1], m³/t of steel	7.5	7.0	6.8	7.5	7.2

Figure 7:Total volume of discharge by receiving water body, M M^3

Source: (NLMK 2020)

Air pollution:

74% of NLMK Group's emissions consist of carbon monoxide, a low-hazard substance of hazard class IV, which is not regulated as a harmful substance in many countries, and cannot harm human health, since it comes from high pipes, is lighter than air, and is dispersed without forming high concentrations in the surface layers of the atmosphere. At the same time, substances of hazard classes I–II account for only 0.2% of the Group's gross emissions.

In 2020, gross emissions decreased by 4,000 tonnes (by 1.3%) compared to 2019. Specific emissions per tonne of steel were also reduced, driven by implemented investment projects. Specific emissions display a planned decline towards the target of 18.0 kg/t of steel in 2023 with production output kept flat. Volume of significant air emission by NLMK Group is presented in figure 8 (NLMK 2020).

Indicator	2016	2017	2018	2019	2020
Total, '000 t	**332.4**	**333.8**	**331.5**	**317.0**	**313.3**
NO_x emissions, '000 t	24.8	27.1	27.2	26.2	26.1
per unit of production, kg/t	1.5	1.6	1.6	1.7	1.7
SO_2 emissions, '000 t	28.9	31.8	31.7	29.5	31.0
per unit of production, kg/t	1.7	1.9	1.8	1.9	2.0
Particulate matter emissions, '000 t	25.2	25.7	24.4	22.5	23.0
per unit of production, kg/t	1.5	1.5	1.4	1.4	1.4
CO emissions, '000 t	249.6	245.9	244.8	235.3	230.1
per unit of production, kg/t	15.0	14.4	14.0	15.0	14.5
Volatile organic compounds, '000 t	2.6	2.6	2.7	2.8	2.6
Hazard class 1 substances[1], t	1.4	1.2	1.3	1.2	1.2
per unit of production[1], g/t	0.09	0.07	0.08	0.08	0.08
Hazard class 2 substances[1], t	560	552	547	514	480
per unit of production[1], kg/t	0.04	0.03	0.03	0.03	0.03

Figure 8:Volume of significant air emission by NLMK Group

Source: (NLMK 2020)

The number of emission sources produced by NLMK in the city of Lipetsk is 2582, of which 1880 are organized (emission of harmful substances through a specially constructed device) and 702 are unorganized (such as parking lots, roads, slag dumps and others). The main pollutants released into the atmosphere are:

-CO emissions are 292049.6 t/year;

-SO_2 emission are 25109.6 t/year;

-NO_2 emission are 14777.2 t/year;

-NO emissions are 6816 t/year;

-H_2S emissions are 77 t/year;

-Inorganic dust emissions are 4044.9 t/year;

-FeO emissions are 13553.6 t/year.

The second converter shop makes the largest contribution to carbon monoxide emissions. The leading production in terms of sulfur dioxide emissions is sintering production. In terms of emissions of nitrogen compounds, the converter shop and the shop for the production of refractory materials are in the lead. In terms of hydrogen sulfide and inorganic dust emissions, the leader is the slag processing shop, where slag dumps are located.

Land use:

The territory of the enterprise has workshops of the main and auxiliary productions, closed and open warehouses of various materials, open waste dumps, parking for motor vehicles, railways roads. Also, facilities for water purification and open facilities for cooling water (pools and cooling towers) are located at the enterprise's territory. Total area of NLMK Group in Lipetsk city is about 28 square kilometers. None of the disturbed area on the main site was not reclaimed in 2020. In 2019, NLMK reclaimed 15 hectares of disturbed land(NLMK 2020).

In 2019, VIZ-Steel (Ural site of the NLMK Group) completed a project to reclaim land at the "Lesnoy" industrial waste landfill. The landfill was excluded from the Sverdlovsk Regional Waste List with the status of "reclamated". The land plot for recreation purposes was transferred to the owner for forestry. The implementation of the project ensured the complete restoration of land with an area of 4.1 hectares and created an ecologically favorable environment on the territory of the former landfill. The results of constant monitoring of the accredited environmental laboratory "VIZ-Steel" confirm that the state of the soil, water and air environment in the "Lesnoy" area complies with sanitary standards

Also, VIZ-Steel launched a project to restore land on the territory of a decommissioned industrial waste warehouse. In 2019, at the technical stage of reclamation, asphalt and topsoil were removed from the site, the bottom layer was leveled, and fertile soil was applied. The biological phase of the work will take place in 2020 (NLMK 2020).

In October 2019, under the program of measures to replace the green fund of the plant, 680 poplars and 1250 shrubs (spirea, lilac) were planted along the route. In 2020, it was planned to plant more than 530 maple seedlings on this site and prepare sites for planting young seedlings by 2021. The main goal of this long-term program is the renewal of the green fund and the creation of a favorable microclimate and a natural green barrier to reduce the impact of production on the environment (NLMK 2020).

1.4 Research questions and goals scope

The goal of the thesis is to investigate the possibility of the creation of an open-loop system at Novolipetsk Steel to utilize steelmaking slag. Also, there is a need to assess the economic and ecological viability of the proposed solution. Thus, the main research question can be formulated as follows:

Would it be economically and environmentally profitable to create an open-loop system on an old metallurgical enterprise to utilize solid waste?

The main question can be divided into three sub-research questions as follow:

1. How does the circular economy affect the iron and steel industry?
2. How much damage does steelmaking slag cause to the environment?
3. What is the economic benefit of implementing waste disposal measures?

In order to answer these questions, it was needed to investigate the circular economy model and its differences from the linear economy model. Also, the problems associated with circular economy should be considered as well as the evaluation of the application of the CE, and how existing iron and steel companies apply the circular economy model in their production process. When answering the second question, it is necessary to assess the damage caused to natural resources when steelmaking slag is stored as waste. For this purpose, two methods were analysed to determine the greater damage and find differences. To answer the third question, it is necessary to study the methods for assessing the economic efficiency of investment measures, and use one or more methods to evaluate the economic efficiency of the proposed measure. The opportunity of creation of the open-loop system on the enterprise should be based on the obtained results. And it is also necessary to make a choice in favor of obtaining a by-product or dumping the material as waste.

The overall goal of this study is to prove the economic and environmental efficiency of using circular economy methods at Russian iron and steel enterprises.

1.5 Structure of thesis

This master thesis consists of five sections. The first chapter contains the main information and key points that have led to this research. Also, the main questions are highlighted in the first chapter and are answered in subsequent chapters. The second chapter contains general information about the circular economy, its methods, goals, types. In addition, the chapter describes the problems that arise with application of this model of the economy. Cases of various metallurgical companies are considered, in particular, waste management of world companies in the field of ferrous metallurgy. The third section describes the methods for calculating environmental damage that have been applied in different situations. Also, methods for evaluating the economic efficiency of projects are considered. Chapter four shows the calculations of environmental damage. Calculations of the economic efficiency of the proposed project are presented in another part of the chapter four. The last part of the master thesis contains obtained results, an explanation, a discussion of the results, and a conclusion that was made based on it.

2 Circular economy in the waste management of the iron and steel industry

A literature review was conducted among articles in magazines, books, annual reports of companies and various Internet portals. Among the systems used were Scopus, Google Scholar, Research Gate, ELibrary, web sites of large metallurgical companies in Russia and the rest of the world. The most cited and relevant articles were selected from the search lists, and articles describing the experience of implementing the circular economy model at ferrous metallurgy enterprises were studied in more detail. Key words included such phrases as: "circular economy", "ferrous metallurgy", "waste dumps", "steel slag", "sustainable development", "mining industry".

Based on the studied literature, a detailed description of the circular economy, its goals, methods and methods of evaluation was compiled. Also in the selected literature, issues that may be associated with the introduction of a circular economy to enterprises and the implications for the United Nations' Sustainable Development Goals were considered. The case studies found made it possible to evaluate the experience of companies in introducing a circular economy to their industrial sites.

Implementation of models of circular economy (CE) on plants is changing the production processes. To assess the impact of the introduction of CE models on production, it is necessary to understand the basics of this economic model. This chapter is aiming to give a short description of the circular economy concept and its differences from the linear economy. It is also necessary to give descriptions of key characteristics, levels, and perspectives of this model of economy. Like every concept, the circular economy has its own disadvantages, which are disclosed in section 3.2. Afterward, the methods of assessment of CE are presented in section 3.3. The section 3.4 provides examples of the experience of ferrous metallurgy plants in the implementation of CE models at production sites.

2.1 Linear economy

Linear thinking as well as the economic model has dominated since the beginning of the third industrial revolution (Jørgensen and Pedersen 2018). The linear economic model is about taking resources and turning them into products. Eventually, in linear economy all products become waste. The model has a step-by-step plan, where raw materials are collected, transformed into usable products and then discarded as useless material ("Opportunities for a Circular Economy - PBL Netherlands Environmental Assessment Agency" n.d.). The figure 9 (Wautelet 2018) shows 5 steps of the product life-cycle which begins with extractions of infinite resources followed by production, distribution and finally disposing of the waste.

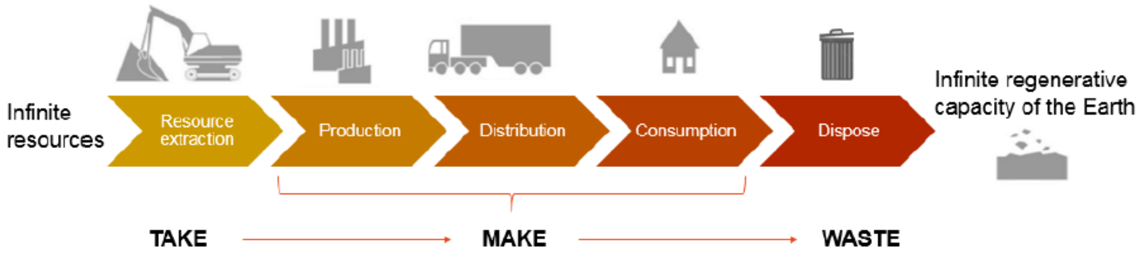

Figure 9: The linear economy

Source: (Wautelet 2018)

Industrialization and consumerism have occurred and developed mostly because of the linear model of the economy. The linear model made it possible to extract cheap and affordable materials, energy from fossil fuels and cheap labor. This economic model has allowed many regions to become prosperous (Jørgensen and Pedersen 2018). And until now the linear economy is prevalent in the world. This model still provides widespread accessibility to goods and services.

Despite the advantages of the linear economy, this model has many more disadvantages. The rising demand of resources has become unsustainable (Way et al., n.d.). The linear economy has short, medium, and long-term problems. Firstly, this model leads to the overproduction of goods, which is the short-term problem. Many products are placed on the market in bulk, but not all of the products can be sold. This leads to excess stock on which the company will lose money. The next problem is reduction of a life-cycle of materials. The accelerated pace of production and consumption leads to proportional waste generation. In the same way, the introduction of new models of a particular device and the so-called planned obsolescence, especially in the case of technological products, means that the old version will soon be obsolete. While this can generate revenue for the business in the short term, it can negatively impact the users' economy. Also, the accelerated life cycles cause the excessive accumulation of waste. The generation and accumulation of large amounts of waste causes health issues and environmental problems if these actions are not handled properly. With high rates of waste generation proper and safe management cannot be ensured. For example, plastic is a material which does not necessarily come from parts of the product itself, but of its packaging. This waste contributes to climate change, pollution of the world's oceans, the death of marine life, and other serious problems. In addition, there are depletion and over-exploration of natural resources which lead to the cost increase of the resources such as minerals and fossil fuels ("C-Voucher - Circular Economy vs. Linear Economy" n.d.). Also, the linear economy treats resources and materials as disposable. That is why the model does not take into account environmental impact, public health and costs of natural resources (Ayres 2008; Hardin 1968).

All of the listed problems led to the creation and development of the concepts of another type of economy - the circular economy.

2.2 Circular Economy

In contrast, a circular economy focuses on the establishment of a recycle-production use industry, where waste is transformed into usable resources or products. Firstly, a cyclical production system was proposed in 1966 by Kenneth Boulding. And only in 1990 Pearce and Turner explained the concept of circular economy (Pearce and Turner 1991). Also, the circular economy is described as a "concept for optimum and recurring usage of resources, which has its foundation based on the principles of sustainability" (Mhatre et al. 2021). The concept has a framework of three principles: eliminate waste and pollution, keep materials and energy in use, are regenerate the natural system. Recycling, remanufacturing and sharing are used to create a loop system for "better" use of resources (Upadhyay et al. 2021). The model proposes to reintroduce materials from secondary resources in a regenerative system and attempts to integrate limited resources in the economy (Xavier et al. 2021). Circular economy aims to restore the original value of products at the end of their use to ensure economic efficiency. And it also has a goal to reduce the negative impact on the environment through operations to restore this initial value, which leads to the fulfillment of social, economic and environmental requirements of sustainable development (Vetrova 2018). Figure 10 ("The Butterfly Diagram: Visualising the Circular Economy" n.d.) shows the "butterfly" diagram with two sides: biological cycle (left hand side) and technical cycle (right hand side). In the technical cycle materials and products retain their integrity and highest utility at all the times. Biological cycle is a regenerative cycle (biological materials that can be return to the natural system) where feedback is vital. Flows of energy, information and material are not lost for the economy, but valorising and appreciating.

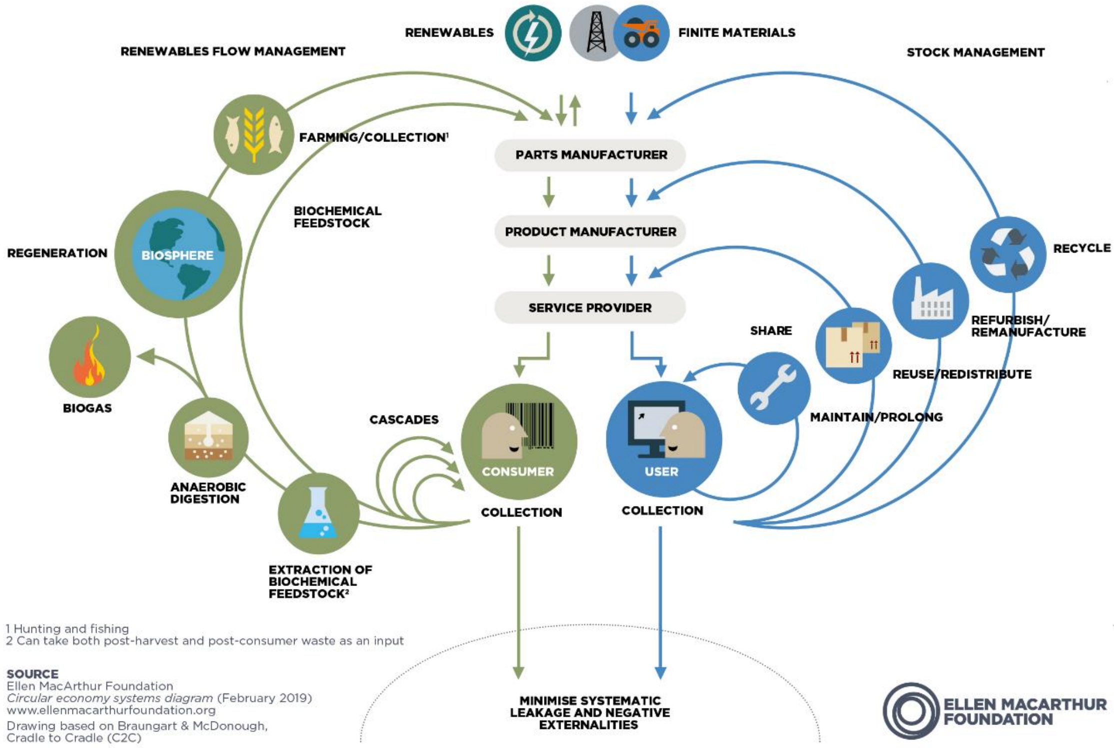

Figure 10: The circular economy

Circular economy contains two systems: closed-loop and open-loop. The closed-loop system aims to supply chain sustainability and materials and manufactured goods that can be recycled and usually used for the same products. The whole production process needs to be designed with recycling in mind. Open-loop system is a system where re recycled materials become new raw materials and waste products. The materials entering the recycling process are transformed into new raw materials that can be used as raw materials for another. In that process various types of products are involved with the same degradation of the recycling material and loss of attached materials that cannot be recycled ("Open-Loop vs Closed-Loop Recycling | General Kinematics" n.d.).

There are several R-imperatives of the circular economy and most used of them are: recycling, reduce and reuse (Panchal, Singh, and Diwan 2021). Recycling has been the most popular strategy for looping back materials into the system and creating a circular economy in enterprises (Tomić and Schneider 2018). The 3R can reduce the pressure on global resources considerably. But the complex application of these principles makes progress in statistical measuring a difficult procedure (Reh 2013).

For waste utilization a key strategy of the circular economy has been to divide waste into recyclable, bio-degradable, high calorific, value waste and trash. Using waste for energy generation helps to decrease the dependency from fossil fuels. (Tomić and Schneider 2018). But in order to efficiently maintain the flows of materials and energy, it was proposed to divide them into two cycles: technical and biological. This approach helps to categorize materials and resources for determining technology that is more suitable to maintain a circular flow model and move away from focusing on waste treatment. Technical cycle includes materials and substances that are dangerous or hazardous for the environment. In this cycle possible strategies are: recycle, remanufacture, reuse or redistribution, maintenance or prolongation. Biological cycle contains raw materials which were obtained from nature and are part of the biological loop. Proposed strategies for this cycle are: extraction of biological feedstock, anaerobic digestion, regeneration, farming or collection (Mhatre et al. 2021).

Three levels of circular economy implementation are existing. Micro-level consists of individual industries, organizations and firms. Circular economy initiatives at micro-level are often implemented by electric and electronic, construction, paper and printing industries. Meso-level includes a group of industries that perform initiatives together. There are IT, wood and paper, metals fabrication units, electrical and electronic industries. And macro-level initiatives are developed at a city, region or on a national level. Most initiatives of macro-level are modeled by the government. Some industries like waste management, electrical and electronic equipment, construction are pioneers in the circular economy implementations. But mining and quarrying, health equipment, entertainment and recreation industries have a slow approach towards circular economy (Mhatre et al. 2021).

Velenturf and Purnell captured perspectives of a circular economy in three categories of models: energy from waste which means the destruction of the materials; resource recovery from waste that needs changes in production patterns; waste prevention by reusing and repairing (Velenturf and Purnell 2021). In the world literature there are five types of circular business models that are used today by global manufacturers. Business models are a conceptual description of entrepreneurial activity (Osterwalder and Pigneur 2010). The first one is circular supplies. The supplier provides a supply of fully recyclable or biodegradable resources that underlie the circular system of production and consumption. The second one is resource recovery, which means elimination of resource losses due to waste generation and increases the profitability of the production of products from return flows. Product life extension is the third. This business model Provides the preservation or improvement of a used product through its repair, modernization, reconstruction or restoration. The fourth are sharing platforms for interaction between product users, individuals or organizations. And the last one is product as a service. The business model serves as an alternative to buying a product, providing it for use, for example, through a lease, leasing, which increases incentives for creating durable products, extending its life cycle (“Delivering the Circular Economy: A Toolkit for Policymakers” n.d.; Vetrova 2018).

Also, for industries and countries which move towards the circular economy the ReSOLVE framework has been invented. Figure 11 illustrates the ReSOLVE framework. It contains six action areas: regenerate, share, optimize, loop, virtualize and exchange. The “regenerate” action includes shift to renewable energy and materials, reclaim, retain and restore health of ecosystems, and return recovered biological resources to the biosphere. The “share” action consists of shared assets (like rooms, appliances, vehicle), reusing and prolonging life through maintenance, design for durability, upgradability. The “optimize” action means increasing performance or efficiency of a product, removing waste in production and supply chain, leveraging big data, and automation. The “loop” action includes remanufacturing products or components, recycling materials, extracting biochemicals from organics, digesting materials anaerobically. The “virtualize” action means dematerialize directly through boolks. DVDs, CDs or indirectly through online shopping. And the “exchange” action contains replacing old with advanced non-renewable materials, applying new technologies and choosing new products or services (Gower and Schroder 2016; McKinsey Sustainability 2015; Moreno et al. 2016). For example, the ReSOLVE framework can be used to evaluate projects and programs with the elements, and see where changes need to be done. Also, the ReSOLVE framework may help to initiate discussion with clients and highlight key elements of circularity to be prioritized in the life cycle of the project (Iyer-Raniga 2019).

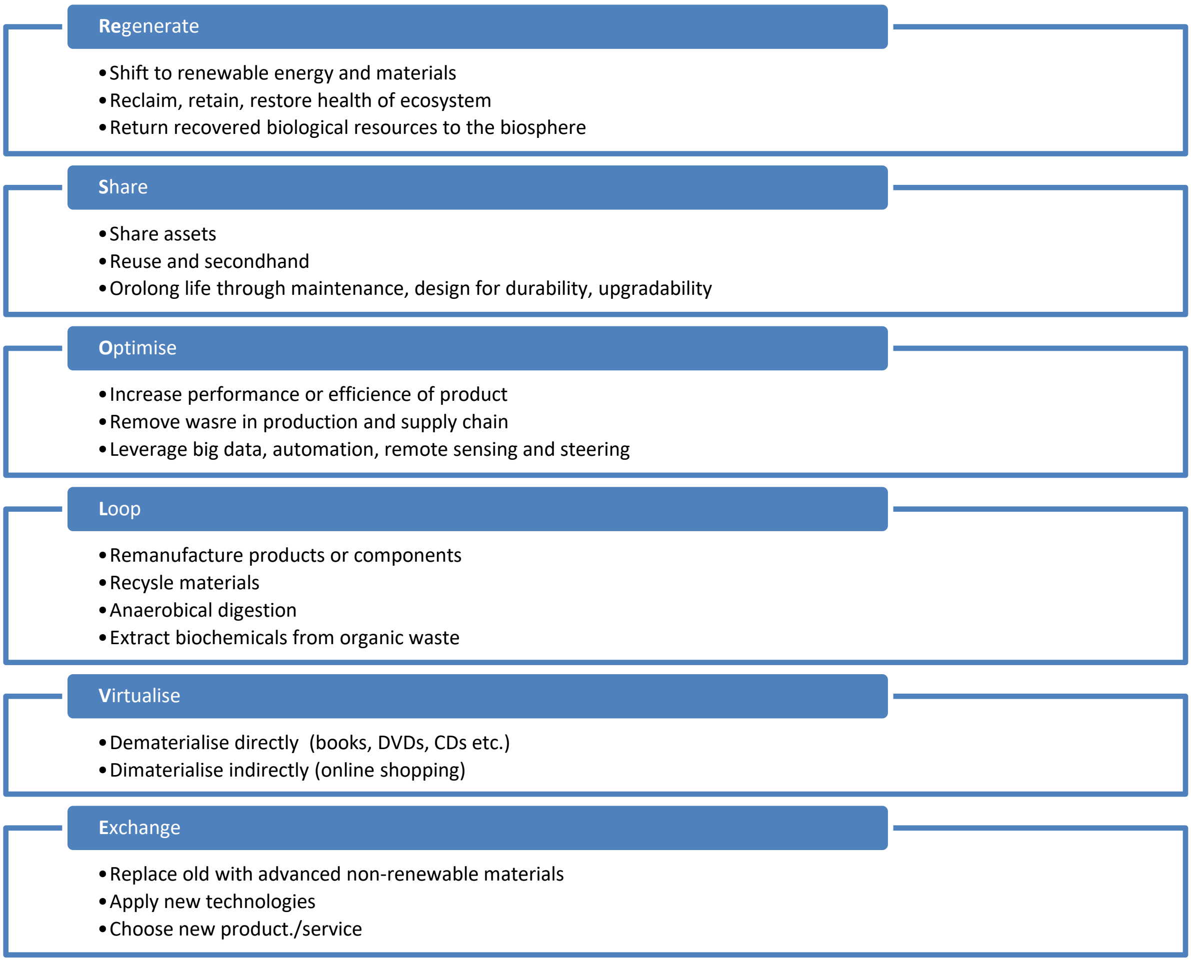

Figure 11: ReSOLVE framework

Source:(Gower and Schroder 2016)

Producers, suppliers, and consumers need to make a foundation towards the transition to the circular economy. Along with communities, these stakeholders can ensure a responsible production and consumption stewardship (Mhatre et al. 2021). Also, to stop the current use and throwing away production cycle and minimize generation of waste, companies need to invest in research and development to encourage environmental innovation at industrial sites (Xavier et al. 2021).

As part of the formation of a circular economy, it is proposed to integrate responsible consumption and production (SDG 12) in the following ways (“Mining and the SDGs: Huge Potential, Limited Action - Responsible Mining Foundation - RMF” n.d.):

- reducing the use of resources and waste (minimizing the use of water, energy, land resources, chemicals; reducing the production of waste, effluents, emissions; alternative use of waste rock);

- implementation of the life cycle concept (analysis of mineral and chemical products in the process of search, transportation, storage, use and production);
- ensuring that suppliers are able to supply responsibly.

And at the same time, there are risks, which should be avoided ("Mining and the SDGs: Huge Potential, Limited Action - Responsible Mining Foundation - RMF" n.d.):

- externalization of the socio-economic and environmental costs of mining;
- avoiding the transition to reuse and circular economy;
- inadequate solution to the problem of waste management, waste management and pollution prevention;
- mining of low-grade ores that generate excess waste.

Thus, the circular economy is a relatively new concept, which was invented in the 1990s. Despite the fact, the economic model is highly developed and has strategies, levels and systems. Over the years, strategies have been developed to transfer businesses of different levels to a circular economy. A framework has also been developed to help transform the economy at different levels (from an individual enterprise to an entire country) to a circular type. It has also been observed that the circular economy has links to sustainable development goals. It has a particularly strong influence on the achievement of SDG 12 ("Opportunities for a Circular Economy - PBL Netherlands Environmental Assessment Agency" n.d.)

2.3 Dilemmas and problems with circular economy

Despite the aim of the circular economy to contribute to sustainable development and transform waste into resources, the model of economy has dilemmas and problems. There are not many studies that criticize approaches or policies that may be mistakenly considered circular or sustainable. The long-term impact of such programs could have undesired or unpredictable consequences (Zink and Geyer 2017).

Greer at al. describe the waste-resource paradox: "a certain material at any time could be considered a waste or a resource: depending on the perspective of the handlers, the practicality of its use at the end of life, the cultural and geographical context surrounding it, and the legal backdrop on which is it evaluated". Also, materials have limitations on circulation and looping production and consumption by keeping materials in the economy can cause rebound effects. If a business model has shortened the usage of virgin materials extraction from nature, it is a true circular innovation. But keeping the same level of resource extraction while simultaneously looping back waste leads to holding more materials in the system. The authors describe dilemmas which can appear with materials, energy, social and economic. The material dilemma is constant demand for unnecessary waste. It can be solved by cascading that slow the loops. The dilemma with energy describes an unnecessary increase of energy and fuel consumption that leads to shifting from material life cycle to energy life cycle. When waste becomes a commodity with a price, large businesses start charging for the materials that is contain the economic dilemma. The social dilemma analyzes the problem of toxic waste that can be perceived as a source of resources. Other countries may allow such waste to be disposed of on their territory, which negatively affects local communities (Greer, von Wirth, and Loorbach 2021).

Another problem is determining the sustainability of circular economy schemes. Velenturf at al. considering connections between circular economy and sustainable development. According to the authors, the circular economy has a big potential for contribution to sustainable development. But these concepts have a weak connection because practices of the circular economy often do not outweigh the benefits of sustainable development. “Sometimes, decarbonization potential is fake, because of shifting emissions from one part to another”. Five relationships CE and sustainable development (SD) were determined. CE & SD are interdependent when they are highly integrated, but the impact is neutral. CE is a condition for SD when they are integrated and impact is positive. CE has positive or negative impact on SD, it appears when they disintegrated and the impact is neutral. CE is a tool for SD when they are neutrally integrated and the impact is positive. CE is better than SD when they are disintegrated and the impact is positive. Distinguishing different types of circular economy and their ability to contribute to sustainability helps to answer the question: does the circular economy, in all of its diverse ways, indeed contribute to sustainable development (Velenturf and Purnell 2021).

Also, the circular economy has several barriers which prevent the implementation of the models in industries. These barriers can be divided into the following groups: financial, market, government policies and regulatory, organizational, and operational. The financial barrier may appear if there is a lack of capital, lack of funds for CE operations or for training, or lack of funds for research and development. The market barrier consists of high marketing costs for CE operations, low virgin material prices, lack of product standardization, and a low level of awareness of sustainable products. If there is a lack of infrastructure, a lack of stringent regulation for CE operations, a lack of promotion, a lack of compliance mechanism these will cause governmental and regulatory barriers. The organizational barrier could be possible in a lack of support for sustainability initiatives, a lack of expertise and decision making, a lack of culture for CE, and a lack of use of CE measures. The operational barrier appears when there is a lack of green procurement, a lack of green logistics, a lack of sustainable product design, a lack of use of advanced technology, a lack of integration of functions. Singh et al. have found that the governmental and regulatory barrier is the main problem for the implementation of the circular economy. But the results of the graph-theoretic approach show that the operational barrier has the highest intensity (Singh et al. 2020).

Gedam et al. described challenges for circular economy which can be divided into categories (Gedam et al. 2021):

- financial and infrastructure: a lack of knowledge and facility, a lack of economic benefits and high cost of investment;
- team management: a lack of AMD management plan, a lack of investment and availability of market, a lack of encouragement and cooperation;
- economic: a lack of governance measures and implementation, a lack of consumer interest and demand;
- supply chain/value chain: a lack of quality and management of value chain, a lack of long-term resource consideration, a lack of purity and homogeneity of mining tailings;
- social: a lack of managing social issue, a lack of top-down and or bottom-up approach;
- technology and policy: a lack of legislation/policy and permits, a lack of technology and innovation;
- environment: a lack of mine decommission plan and waste classification, a lack of diversified and responsible supply chains, a lack of environmental protection.

2.4 Assessment methods of circular economy implementation

Methods for assessing the damage caused to natural resources during the operation of solid waste dumps were selected on the basis of several assessments that were done by the authors of various articles. The experience of assessing environmental damage from solid waste dumps, as well as the damage from arranging various communications and laying roads was analyzed. The experience of states in conducting mandatory settlements for companies in the mineral resource sector was also studied.

The author analyzed articles where calculations were used for various situations when assessing the investment attractiveness of projects. Information from internet portals was

also studied to obtain a general view of economic feasibility calculations and assessment methods.
There are different approaches to analyze materials fate in the production and consumption processes, the ones considered most relevant for this analysis are described below.

The MaTrace model views the industrial material from a single resource in different products. The model is tracing the fate of materials over time and across products in open-loop recycling. “MaTrace can trace the process in which the materials embedded in a particular product made in a particular year are transferred over time into a variety of products and losses via successive cycles of disposal, recovery, and recycling: it can trace the fate of material embodied in a given product-cohort” (Nakamura et al. 2014). The MaTrace model uses a series of equations at each stage of the end product life cycle. These equations calculate the metal transition between products and over time (Jarrín me et al. 2021). Using the MaTrace model Nakamura et al. figured out the transition and losses of the stock of car steel during 100 years among different products. Results show that after 15 years, with cars reaching the end of the lifetime, the fraction of car steel used in cars dropped to 20% of the stock. And after 20 years the proportion dropped to 8% of the stock. The model can help to identify the issues within the recycling system (Nakamura et al. 2014). Another example is tracking the fate of aluminum in the EU. By using the MaTrace model the authors found that in baseline scenarios after 25 years 61% of initial aluminum will be lost. And the main contribution of the losses in the non-selective collection of end-of-life products (Jarrín me et al. 2021).

Material flow analysis (MFA) is a quantification and assessment of substances and matter, mass flows in a system during a different period. MFA looks at a single material in the whole economy system. The task of MFA is quantitative tracing of the fate of materials over time across products and different types of losses. The analysis contains four steps: identification of material flows; system analysis; quantification of mass flows of matter and indicator substances; identification of weak points; development and evaluation of scenarios and schematic representation; interpretation of the results. MFA can be used for environmental impact assessments, development of environmental policy for hazardous substances; waste management, sanitation planning, and etc. The MFA is an ideal technical basis for planning and decision-making methodology. The method allows to compare two or more development options. Also, the MFA helps to evaluate the environmental soundness of the options. In addition, the method allows a critical view of natural resource management. But in contrast, the MFA needs a lot of data to be implemented, while there is limited reliable data available in developing countries. And there is a need to deal with uncertainties (Forester, Schertenleib, and Belevi 2003). For example, the MFA method was used to trace the CaO, Mgo, Al_2O_3 and SiO_2 flows in the CSC Hsiao Kang Factories. The analysis showed that the major parts of the listed chemical substances go to the steelmaking and blast-furnace slag. So, the steel slag and blast-furnace slag are becoming a major problem and it is very difficult to find suitable utilization (Liu 2014).

Life-cycle analysis (LCA) trace the fate of different materials which go in one final product. The LCA allows decision makers to compare two products and select the one which has the lowest impact on the environment (Curran 2014). The LCA helps to quantify the potential environmental impacts associated with a product's life cycle (Biganzoli, Rigamonti, and Grosso 2019). The method provides a holistic view on environmental impact to avoid optimizing one environmental indicator without considering the effects on the other indicators. In addition, the LCA helps to find hot spots in the environmental impact to improve processes and reduce negative effects. But the method has limitations. "LCA studies depend on assumptions and scenarios, as LCA assesses the real world in a simplified model". Moreover, one study may exclude an impact or a process that will be included in another study, so the assumptions and scenarios may vary. As well as MFA, the LCA needs a large amount of relevant data. The study will not be comprehensive if the data is poor or not enough (Curran 2014). For example, the LCA was applied in the case study of packaging re-use. This analysis allowed to evaluate the total impacts of the life cycle and to understand if a system where steel drums are re-used performs better than a system where the same steel drums are used only once and then sent to recycling (Biganzoli, Rigamonti, and Grosso 2019).

In the case study of Wu'an city to assess the circular economy performance of China's iron and steel industry, four indicators were used. The first indicator: level of equipment used. The second: comprehensive utilization level of materials. The third: pollutant emission level. The fourth: resource consumption level of fresh water. Indicators 1 and 2 are positively correlated with CE performance. Indicators 3 and 4 are negatively correlated with the CE performance level. Circular economy efficiency composite index. Steel slag inner circle: steel slag has returned to a furnace to reuse calcium oxide, magnesium oxide and other trace components (it is an effective mode of utilization). Small fraction of the slag can be used in this manner (Ma et al. 2014).

2.5 Case studies

“From residences and commercial establishments to manufacturing and logistics, every sector gives out tons of waste each day” (Pavlas et al. 2020). The generation of solid wastes from the primary production of mineral and metal commodities is over 100 billion tons per year (Tayebi-Khorami et al. 2019). In the mining sector possibilities to loop back the large waste streams have not been widely studied. And the mining companies have not always considered and evaluated new possibilities around tailings. There are several opportunities to use waste: recovery of metals, storing for the future, recovering metals from wastewater, and etc. In the linear economy, waste from traditional mining can recover material through upcycling technologies. In the circular economy, urban mining of industrial and post-consumer waste categories may recover material (Kinnunen and Kaksonen 2019; Xavier et al. 2021). Mining companies must improve waste management through recycling and reuse techniques to achieve sustainable production and consumption patterns (Monteiro, da Silva, and Moita Neto 2019). The extended producers’ responsibility and pay-as-you-throw policies, along with community involvement, have all enabled efficient waste management practices (Bringsken et al. 2018). Taxation might change the profitability and boost the circular economy transformation. Technology development has the potential to turn lower-grade materials into a raw material source and make the whole raw material valuable. Also, minor metals could be recovered in addition to the main metals (Bringsken et al. 2018).

The properties of slags from various industries are studied in laboratory conditions to determine new applications. For example, copper slag shows great potential as a material whose processing can lead to a circular economy and more sustainable society. The analysis shows that the material can be applied in production of cement. Also, the slag was examined for metal recovery from it. Recovery of valuable metals from copper slag, recycling and disposal are more promising options for sustainable waste management than landfill. Copper slag shows great potential as a material whose processing can lead to a circular economy and more sustainable society (Phiri, Singh, and Nikoloski 2021). A practical example with steel slag with a fraction of 5-10 mm showed that earlier the material could be used as an adsorbent. And in order to support the circular economy initiative, it was necessary to look for the next implementation of the material. It has been found that after ion removal from wastewater, the material can be used in concrete to replace conventional coarse aggregate (Roychand et al. 2020). In another research of the properties of steelmaking slag, it was proposed to use the slag as a soil fertilizer that helps to create a closed-loop production system. The closed loop production system eventually will transform economy to circular economy (O'Connor et al. 2021).

Among the manufacturing industries, the largest amount of waste is generated in metallurgical production and the production of finished metal products. In the iron and steel industry, scrap steel is one of the materials required for production. There is a shortage of scrap steel throughout the world, but the steel industry recycles as much scrap that is available. Consequently, the disposal of scrap steel is not a problem. But the main issue remains the disposal of steelmaking and blast furnace slag ("Steel in the Circular Economy: A Life Cycle Perspective - Worldsteel.Org" n.d.). The total amount of slags from stainless steel production was estimated as 15–17 Mt/year including slags from different process stages, electric arc furnace melting, argon oxygen decarbonization and vacuum oxygen decarbonization converting, ladle operations, and casting (Horckmans et al. 2019). In addition to recycling scrap for steel production, there is growing interest in and incentives for utilising and processing residual products from production as resources ("Annual and Sustainability Reports" n.d.).

To determine the overall CE strategy for the disposal of blast furnace and steelmaking slags, a review of strategies of large European and Russian steel producers.

One of the largest steel companies in Russia is Severstal. The company uses slag processing. During the processing, scrap is removed for return to production, and also granulated slag, blast-furnace crushed stone of various fractions and steel-smelting crushed stone are produced. Severstal has its own patent for a unique technology for using granulated blast furnace slag. It allows replacing up to 45% of cement in concrete for the construction of concrete roads and soil strengthening with granulated slag. This reduces the cost of construction, increases the durability of roads, and also allows the use of related products obtained from blast-furnace waste (Severstal 2021).

Swedish mining company LKAB is developing processes for extracting rare earth elements and phosphorous from the waste generated in iron ore production. Utilizing slag from steel production to produce the concrete substitute GGBS (ground granulated blast furnace slag) that is in turn used in rock reinforcement in the iron ore mines. The cement substitute GGBS, which is made of blast furnace slag from steelmaking, is an example of an important product based on secondary material flows ("Annual and Sustainability Reports" n.d.).

ThyssenKrupp is the world's largest producer of high-alloy steel. The company created a synthetic material called LiDonit from the calcium silicate-rich converter slag in accordance with the Linz-Donawitz steel manufacturing process. The product can be used in asphalt production, because the grain size is preferred for the top layer of the road coating. Also, the cubic shape of the grains ensures stability and water permeability in bedding layers for footpaths. BaseLith is a material which is mainly used for constructing forestry roads and paths, for parking areas in landscape and outdoor applications. Eolit is another product made from electric furnace slag and it is applied as chippings and gravel or in mixtures. The target industries for all three slug products are: road and path construction, landscaping and hydraulic engineering, agricultural industry, cement industry, manufacturing plants that require metal-rich recyclable material for reuse (“Slag Management” n.d.).

Arcelor Mittal has a leading market share of around 17% of the global market share in the automotive steel business in 2020. According to the annual report of 2020, the company implements new methods to re-use of slag. The material can replace the natural ballast in foundations of offshore wind turbines, may be used as a source of fertilizers in agriculture; and can be applied as building material to protect building walls from noise and dust. In addition, there is a potential to use slag for water filtration and capturing greenhouse gasses (ArcelorMittal 2021).

Tata Steel processes about 12 million tons of by-products per year, which includes more than 25 product categories. Industrial by-products are used as raw materials in various industries, such as cement, chemical, construction, and others. According to the annual report, during the period of 2020-2021, the company has achieved process solid waste utilization of more than 99%. The use of recycled slag has been increased due to the use of an accelerated slag weathering unit. The efficiency of material flows and insurance of operation safety was increased because of the implementation of a flexible supply chain (TATA STEEL 2021).

International steel company Voestalpine is developing closed-loop cycles of materials for improving resource and material efficiency in production processes. The company expanded recycling chains for products and secondary raw materials in various supply chains. Also, Voestalpine creates symbioses for using steel production by-products as secondary raw material for manufacturing products in other industries. Slags obtained from the blast furnace and steelmaking processes are turned into high-quality construction materials. Metallurgical slag and lump slag are used as secondary raw materials in sectors such as the cement, insulation and road construction industries. These recycling processes contribute significantly to the reduction in use of natural resources and environmental protection. In addition, the company is promoting the development aimed at the efficient use of alternative and secondary sources of raw materials (VOESTALPINE 2021; “Slag Products” n.d.).

One of the main problems of the steel industry is the disposal of slag from the production of stainless steel. Most of this waste is landfilled. Slag utilization ranges from zero to one hundred percent, what depends of three factors (Wang 2016):

1. Chemical and mineral composition of the slag and potentially adverse properties;
2. The relationship between the adverse properties and the properties and performance requirements of the end product;
3. The rational use of the end product with different properties to ensure its optimum application.

Small plants such as stainless-steel plants prefer to landfill the slag as it is more economically effective. Therefore, landfilling was an easy solution in the short term. But since this type of slag contains elements such as chromium, nickel, molybdenum, titanium and other metals, it is environmentally unsafe for disposal. Another problem is the complex chemical composition of the slag, which makes utilization difficult. But at the same time, any approach to solutions for a circular economy for stainless steel slags will have serious economic and environmental potential (Holappa et al. 2021). One of the solutions is rapid cooling of the slag. This process allows the production of an amorphous material that can be used in road construction.

As a conclusion of the chapter, it needs to be mentioned that the circular economy concept is based on the principle of recycling waste in the production chain. This concept can contribute to changing production and consumption patterns and make mining environmentally sustainable. Also, an economy close to the circular concept can contribute to sustainable development, as it stimulates the reduction of losses and an increase in income by improving the management of production processes (Kinnunen and Kaksonen 2019).

For recovery of the most valuable components the methods for selecting need to be established. Designing industrial complexes for optimal use of resources and supporting research in the field of economics and technology are necessary to make the recycling of used products into a successfully expanding industry (Reh 2013). By-products can be used to reduce the use of primary natural resources, as well as to provide additional benefits such as CO_2 sequestration. Reuse of steelmaking slag provides an alternative to the use of raw materials, the production of which is environmentally unsafe, and also provides control of existing environmental damage (Fisher and Barron 2019).

3 Calculating methods

This chapter includes descriptions of some of the existing methods for assessing the negative impact on the environment from various industries, waste, and etc. Five different assessment methods are presented, including the Russian State Methodology. This methodology is the main one for calculating the negative impact on the environment in Russia. The calculation of the negative impact on the environment is mandatory for enterprises located in Russia, and this methodology is mandatory for use. Also, this section contains methods for calculating the economic feasibility of the project. The undiscounted and discounted valuation methods are described here.

Methods for assessing the damage caused to natural resources during the operation of solid waste dumps were selected on the basis of several assessments that were done by the authors of various articles. The experience of assessing environmental damage from solid waste dumps, as well as the damage from arranging various communications and laying roads was analyzed. The experience of states in conducting mandatory settlements for companies in the mineral resource sector was also studied.

The author analyzed articles where calculations were used for various situations when assessing the investment attractiveness of projects. Information from internet portals was also studied to obtain a general view of economic feasibility calculations and assessment methods.

3.1 Calculation of environmental impact

There are several methods of assessment of land use and related environmental impacts. One of the methods is to estimate the cost of ecosystem services (ES). Ecosystems have a range of services that are valuable for humans. And because of human activities ecosystems can lose some of their functions or even can be destroyed completely. So, expressing ES in monetary units allows differentiating the importance of various ecosystems and their functions (de Groot et al. 2012). With the method of ES assessment, Tost et al. estimated the costs of the reduction of ES due to mining extraction activities of four metals all over the world. This work was based on the assumption, that the original ecosystems are fully destroyed once mining takes place.

According to the results, the overall ecosystem services cost, which were depleted by mining of four metals, of about USD 5.4 billion/year. In addition, the analysis led to the conclusion that "Coastal wet-lands" should be prohibited for gold and bauxite mining, because the revenues will be lower than losses (Tost et al. 2020). De Groot et al. highlighted services and assessed each one with monetary value. There are 22 services in total which are combined in four groups: provision (food, water, raw materials, medicinal resources, ornamental resources), regulating (air quality regulation, climate regulation, disturbance moderation, regulation of water flows, waste treatment, erosion prevention, nutrient cycling, pollination, biological control), habitat (nursery service, genetic diversity), cultural (esthetic information, recreation, inspiration, spiritual experience, cognitive development). Table 1 shows the total monetary value of ecosystem services per biome (Values in Int.$/ha/year, 2007 price levels).

	No. of estimates	**Total of service mean values**	**Total of St. Dev. of means**	**Total of median values**	**Totals of minimum values**	**Total of maximum values**
Open oceans	14	491	762	135	85	1,664
Coral reefs	94	352,915	668,639	197,900	36,794	2,129,122
Coastal systems	8	28,917	5,045	26,760	26,167	42,063
Coastal wetlands	139	193,845	384,192	12,163	300	887,828
Inland wetlands	168	25,682	36,585	16,534	3,018	104,924
Rivers and lakes	15	4,267	2,771	3,938	1,446	7,757
Tropical forest	96	5,264	6,526	2,355	1,581	20,851
Temperate forest	58	3,013	5,437	1,127	287	16,406
Woodlands	21	1,588	317	1,522	1,373	2,188
Grasslands	32	2,871	3,860	2,698	124	5,930

Table 1: Ecosystem services values

Source:(de Groot et al. 2012)

Environmental impact can be estimated by life-cycle assessment, which was observed in chapter 2.3. LCA tracks the extractions from and emissions to nature (Simonen 2014). This methodology is used to determine the real cost and environmental impact of a product over its life (Hermon and Grant 2015). In the study of Environmental and economic assessment of 'open waste dump' mining in Sri Lanka, LCA and life-cycle costing methods were used to estimate the environmental impact. Two scenarios were compared in the study. Scenario 1 consists of direct selling of refuse derived fuel as an alternative fuel, while the second scenario comprises thermal treatment of refuse derived fuel for energy generation. The LCA endpoint interpretation addresses several impact categories such as ozone depletion, human toxicity, and etc. Obtained results showed that both scenarios are beneficial environmentally and economically. More than 1.6 million tons of CO_2 could be released into the atmosphere if the proposed scenarios are not applied. Figure 12 demonstrates environmental impacts of two scenarios and comparison to the "Do-nothing scenario". The bar graphs evidence that proposed scenarios have more positive environmental impacts than the "Do-nothing" scenario. (Maheshi, Steven, and Karel 2015b).

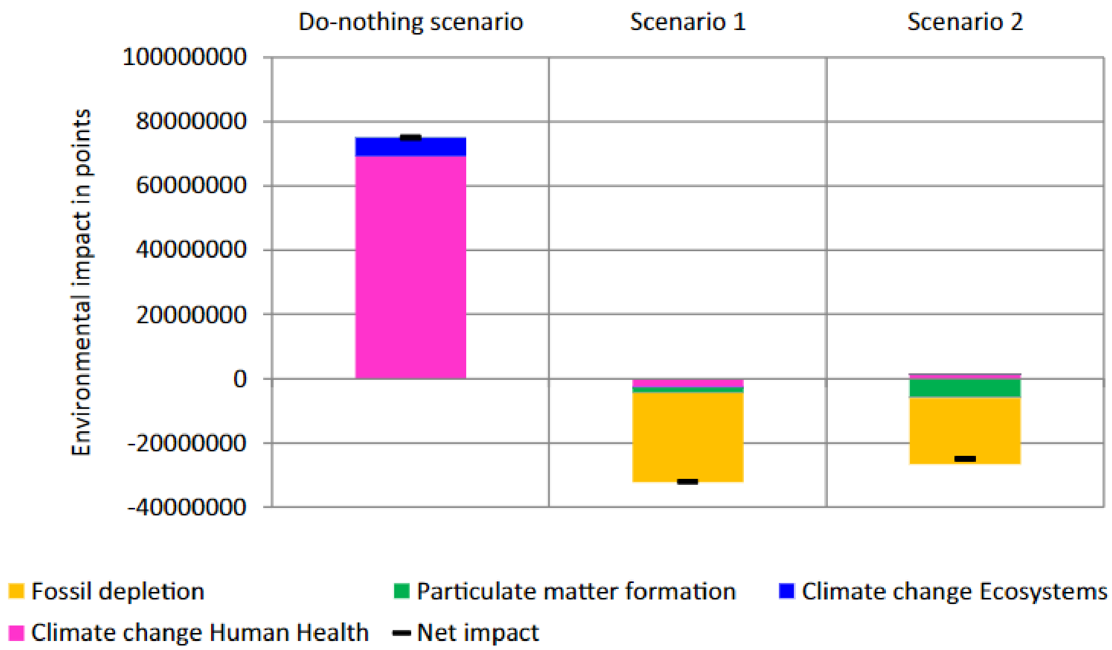

Figure 12: Environmental impact of Do-nothing scenario and waste valorisation scenarios
Source: (Maheshi, Steven, and Karel 2015b)

Another method to estimate an environmental impact was described in the work of Rashid and Shahzad. The study is devoted to the utilization potential of food waste into organic fertilizers. The methodology included calculations of environmental saving and costs benefits of recycling value-added products. Environmental savings include carbon credits and dumping fees. Carbon credit value depends on the methane emission potential and can be calculated by the IPCC method. Dumping fees are the amount of money that should be paid to the waste disposal site for waste transportation and dumping. Figure 12 demonstrates the economic and environmental benefits of organic food waste recycling to produce compost. The obtained results evidence the recycling and reusability of food waste will help reduce the operational and environmental issues that are now present in waste management of Makkah city (Rashid and Shahzad 2021a).

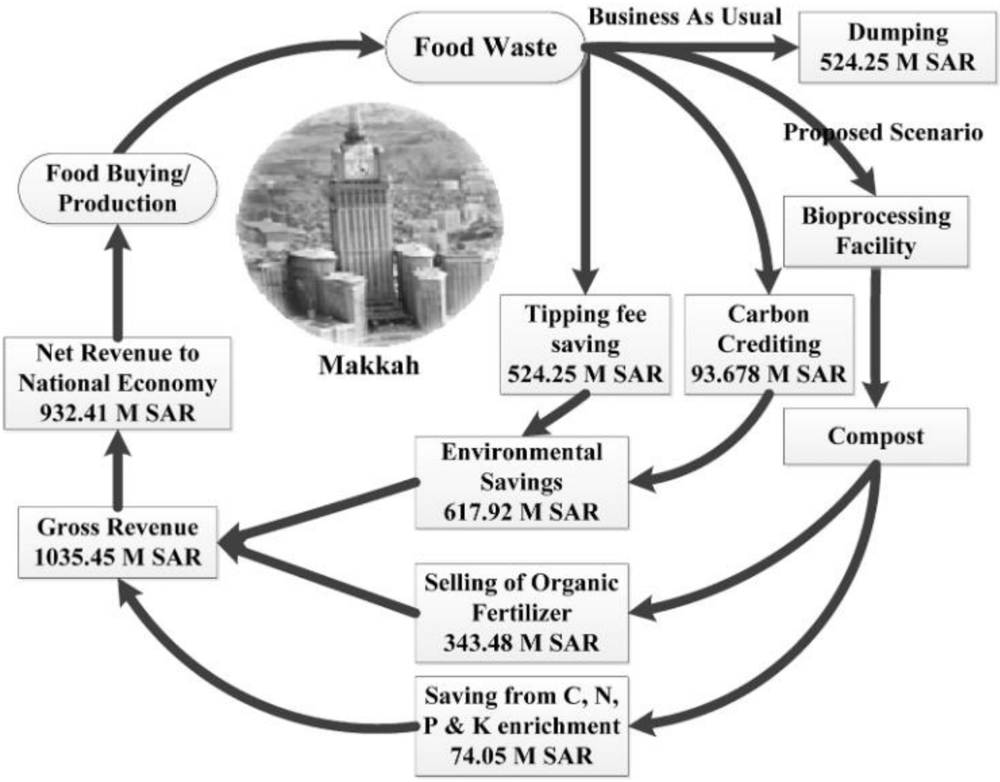

Figure 13:Environmental and economic benefits of food waste recycling in Makkah city
Source:(Rashid and Shahzad 2021a)

In Russia, there is a special state methodology for calculating the assessment of the negative impact on the environment. The methodology allows to calculate negative environmental impact in monetary units and identify the scale of the impact. The methodology includes the calculation of payments for emissions of pollutants into the atmosphere, for the discharge of substances into water bodies, for the placement of production and consumption waste. This methodology is obligatory for every company that produces waste. Using this methodology, enterprises calculate the negative impact on the environment from the generation of waste and the amount of payment that must be paid to authorized organizations to compensate for the negative impact. Enterprises can estimate the amount of waste generated and find possible methods for reducing waste. The described method also motivates companies to turn waste into secondary products to reduce negative impact fees. (Government of Russian Federation 2017). The advantage of this methodology is that it takes into account the danger of waste for the natural environment. If the waste contains components such as mercury, then its negative impact is much stronger than the inert waste. The disadvantage of the Russian state methodology is that it does not take into account the value and fragility of the biomes where the waste of the enterprise is located.

In the presented Master Thesis the author decided to use two methods to evaluate the environmental impact of steel slag dumps on the territory of Novolietsk Steel and compare the results. Two methods are needed to compare the results and draw a conclusion about the need for waste disposal. Ecosystem services method and Russian state methodology are used in the work. The ES methodology assesses the importance of a biome in monetary terms what allows to understand the severity of the damage done qualitatively and quantitatively. The Russian state methodology makes it possible to assess the damage from a particular type of waste. If the waste is not hazardous, then the value of the harm caused is much less than from waste containing hazardous components. Thus, the Russian state methodology allows assessing the damage to natural resources disturbed during the operation of the enterprise. It is possible to obtain the value of the damage caused to the natural environment in monetary terms by these two methods. As a consequence, the results can be compared with each other. The obtained and compared costs of negative impact will make it possible to assess the need and urgency of introducing circular economy methods to the enterprise.

3.2 Calculation of the economic viability of the project

There are several approaches to assess the investment attractiveness of a project. All approaches can be divided into two groups: discounted and non-discounting. Non-discounting techniques include Payback Period and Accounting Rate of Return method. And the discounted cash flow method includes Net Present Value method, Profitability Index method, Internal Rate of Return and Modified IRR methods. Non-discounting methods do not consider the time value of money.

Payback period (PBP) is a method that allows to calculate the period of time in which the supply will generate cash to recover the initial investment. It takes into account only the cash inflow, the economic life of the project and the investments made in the project. The decision on the profitability of the investment is made on the basis of the number of years required to cover the investment. If the payback period is more than a certain time, then the project is rejected. Formula 1 shows the calculation of the PBP (“Capital Budgeting Techniques, Importance and Example” n.d.).

$$\text{Payback period} = \text{Investment}/\text{Cash flow} \quad (1)$$

Accounting Rate of Return (ARR) is also a non-discounting method, but it can help to overcome the limitations of the Payback Period method. Generally, ARR uses the percentage rate of return that is expected from an investment or asset compared to the initial cost of investment. This method uses a special minimum rate, which is determined by the management of the company. If the project has a rate below the minimum, then it is rejected. This method takes into account the entire economic life of the project, but also does not include the time value of money and the life of the project. Formula 2 demonstrates the calculation method of ARR ("Accounting Rate of Return (ARR) | Definition & Formula | GoCardless" n.d.).

$$\text{Annual Rate of Return = Average Annual Profit/Average Investment} \quad (2)$$

In discounted methods discounted cash inflows and outflows are compared. The methods consider the interest factor and the return after payback period.

The Net Present Value (NPV) method is based on the cash inflow that is discounted at a particular rate at different periods of time. This is a method of calculating the return of investment for a project or expenditure. The initial investment compares with the present values of the cash flow. Usually, NPV is used to compare projects and for making decisions about the viability of a project. And the initial investment compares with the present values of the cash flow. The decision is made taking into account this comparison. If the difference is negative, then the project is rejected. If several projects are compared, then the decision is made in favor of the project with the largest positive difference ("A Refresher on Net Present Value" n.d.). The value of the discount rate is used in calculation of NPV. In general, a discount rate is the rate of return used to discount future cash flow back to the present value. There are several types of discount rates that are used to discount cash flow back to the present: weighted average cost of capital, cost of equity, cost of dept, a pre-defined hurdle rate, and risk-free rate. Usually, the discount rate for businesses is 6 – 8%, depending on uncertainty risk and time value of money (higher discount rate implies greater uncertainty). NPV can be calculated with formula 3 and with simplified formula 4 ("Discount Rate - Definition, Types and Examples, Issues" n.d.).

$$NPV = \left[\frac{A_1}{(1+k)^1} + \frac{A_2}{(1+k)^2} + \frac{A_3}{(1+k)^3} + \cdots + \frac{A_n}{(1+k)^n}\right] - C = \sum \frac{A_1}{(1+k)^t} - C \quad (3)$$

Where A_1, A_2, A_3, A_n represent cash inflows; k is the company's cost of capital; C is the cost of the investment proposal; n is the expected life of the proposal.

$$\text{NPV = Present value of benefits – Present value of Costs} \quad (4)$$

Internal Rate of Return is a rate of return on an investment. It depends only on the costs and revenues associated with a project. IRR is defined as the rate at which the NPV of an investment is zero. Here discounted cash outflows are equal to discounted inflows. The method calculates the interest rate at which the funds invested in the project could be repaid from the inflow of cash. If IRR is more than weighted average cost of capital the project is profitable (Yescombe 2007; “Capital Budgeting Techniques, Importance and Example” n.d.). The IRR is calculated by trial and error(Gessinger 2009).

Profitability Index (PI) is the ratio of the present value of the future cash flow benefits to the initial cash outflow of the investment. It can be calculated as ratio of NPV benefits to NPV costs. Profitability index can be calculated with three given formulas (5, 6, 7):

$$PI = \frac{\sum_{t=1} \frac{A_1}{(1+k)^t}}{C} \tag{5}$$

PI = Present value of future cash inflows/Initial cash outlay (6)

PI = NPV(benefits)/NPV (Costs) (7)

where A_1 is cash inflows; k is a cost of capital; C is a cost of investment proposal; t is a period of time in years. The project will be accepted if the PI is more than 1 (“Capital Budgeting Techniques, Importance and Example” n.d.).

4 Calculations

This section contains calculations of the negative impact of Novolipetsk Steel steelmaking slag dumps. Calculations are carried out by two methods: the Russian state methodology and Ecosystem Services costs method. An economic evaluation of the extended slag treatment method is also carried out. The assessment includes the calculation of Net revenues, Payback period and Net present values. Calculations allow to get the number of years for which this project will pay off, and on their basis. In addition, these calculations help to conclude on the feasibility of investing in this project.

4.1 Environmental impact

In the given work the environmental impact is calculated by two methods. One of the methods is Russian State methodology, and the inflation rate is taken from Bank of Russia. And the other one is Ecosystem Services which was proposed by De Groot et al. The Ecosystem Services method can be used for any country or territory because the method is based on the concept of biomes. Average global inflation rate is used in this method. These two methods were chosen to calculate the environmental impact assessment for the placement of the slag dumps. In the future, the results obtained by calculations using the two methods can be evaluated and compared in order to select the most suitable method. Evaluation and comparison are in the Results and Discussion section.

4.1.1 Russian state methodology calculation

Every month Novolipetsk steel produces about 226 000 tons of steel slag, which is 2,712,000 tons per year. The slag is stored in 5 dumps on the territory of the enterprise. The total area of the dumps is 58.8912 ha.

According to Russian state methodology, the environmental impact should be calculated for each component of the ecosystem. Calculation of payment for the disposal of production and consumption waste can be done with formula 8:

$$П_{\text{лр}}^{m} = \sum(M_{лj} \cdot \text{Н}_{\text{пл}j} \cdot \text{К}_{\text{от}} \cdot \text{К}_{л} \cdot \text{К}_{\text{ст}}) \quad (8)$$

where is $M_{лj}$ – payment base for the placement of waste; $\text{Н}_{\text{пл}j}$ – is a rate of payment for the placement of 1 ton of waste (Government of the Russian Federation 2016); $\text{К}_{\text{от}}$ - additional coefficient to the rates of payment in relation to territories and objects under special protection in accordance with federal laws; $\text{К}_{л}$ - coefficient to the rate of payment for waste disposal for the volume or mass of waste disposed within the limits for their disposal; $\text{К}_{\text{ст}}$ - incentive coefficient to the rate of payment for waste disposal.

$M_{лj}$ is a volume or mass of disposed waste (excluding solid municipal waste) in an amount not exceeding those specified in the declaration on environmental impact. Since about 2,712,000 tons of steel slag are produced annually, this amount was not exceeded in the accounting year. The rate of payment for the disposal of low-hazard waste was 663.2 roubles in 2018. Taking into account inflation for 2018 – 2021, which is 8,4% (“About Inflation | Bank of Russia” n.d.), the fee rate is 718.9 roubles/ton. In this case, the coefficient $\text{К}_{\text{ст}}$ is 0.3, since this waste is produced and disposed of on the company's own territory. The coefficients $\text{К}_{\text{от}}$ and $\text{К}_{л}$ are 1 because the territory of the enterprise is not under special protection and the amount of waste is within the limits.

According the formula 1, the payment for the disposal of steelmaking slag is 584,904,200 roubles/year. As of January 11, 2022, the dollar exchange rate is 73.88 rubles (“Official Exchange Rates on Selected Date | Bank of Russia” n.d.), so the amount of payment is 7,916,949 $/year.

The dumps are located in an open area and are not equipped with a dust suppression system, which leads to the release of a large amount of dust into the atmosphere. According to the documents from Novolipetsk steel the dumps emit dust, suspended solids, CaO, Fe_2O_3. The Russian state methodology includes the calculation of the negative impact for air. Calculation of payment for the emission of pollutants into the atmosphere can be carried out according to formula 9:

$$П_{нд} = \sum_{i=1}^{n}(М_{нд i} \cdot Н_{пл i} \cdot К_{от} \cdot К_{нд}) \quad (9)$$

where $М_{нд i}$ is a payment base for the emission of a pollutant (amount of the emission, ton per year); $Н_{пл i}$ is a the rate of payment for the emission of a pollutant (Government of the Russian Federation 2016) ; $К_{от}$ - additional coefficient to the rates of payment in relation to territories and objects under special protection in accordance with federal laws (equals 1 in the given case, since the territory is not under special protection); $К_{нд}$ - coefficient to the rates of payment for the emission of a pollutant for the volume or mass of emissions of pollutants within the limits of allowable emissions (equals 1 in the given case, because emission of all substances are within the limits).

Table 2 contains information about the amount of emission and the rate of payment for each substance considering the inflation. The amount of emissions was taken from the official documents from the enterprise.

Substance	**Amount of emission, ton per year**	**The rate of payment, rubles per ton**
Inorganic dust with 20-70% of SiO_2	225.948	60.588
Inorganic dust with less than 20% of SiO_2	128.006	39.528
Suspended solids	0.035	39.528
CaO	640.755	40.5
Fe_2O_3	277.200	39.528

Table 2: The rates of payments

Source: (of the Russian Federation 2016)

According the formula 2, the payment for the disposal of steelmaking slag is 55,658.68 roubles/year. As of January 11, 2022, the dollar exchange rate is 73.88 rubles (“Official Exchange Rates on Selected Date | Bank of Russia” n.d.), so the amount of payment is 753 $/year.

Also, the state methodology allows to calculate the payment for the discharge of contaminated water into water bodies. Since the dumps are in contact with atmospheric precipitation, water can infiltrate through the body of the dump and rocks, which leads to groundwater pollution. But under these conditions it is impossible to reliably determine the amount and type of pollutants entering the groundwater.

Thus, the total amount of payment for the negative impact to the environment from dumps of steelmaking slag is 7,917,702 $/year (the 1st case).

Calculations are presented in the annex.

4.1.2 Ecosystem services calculation

The territory of Novolipetsk steel belongs to the Temperate Broadleaf and Mixed Forests biome. The biome in De Groot classification is Temperate Forests and the total economic value for the biome is 3013 $/ha/year (2007 price levels). Global inflation rate from 2008 to 2021 is 3,14% ("Inflation, Consumer Prices (Annual %) | Data" n.d.). The actual price of the biome in 2021 is 4,504 $/ha/year. To calculate the area of disturbed lands, a satellite image of the territory of the enterprise was used. The area was measured using AutoCAD. The total disturbed area is 58.8912 ha.

Figure 14: The dumps of steelmaking slag

Source: Yandex Maps

The ES cost can be calculated by multiplying the value for the biome by the total area of disturbed land. As a result, ES is 265,246 $/year (the 2nd case).

Calculations are presented in the annex.

Two results of the negative impact on the environment differ by 30 times. Results vary due to the density of the slag and the way it is stored. The main parameter for the calculation by the Russian State methodology is a mass of waste. Whereas the ES methodology uses the area of the disturbed lands. The volume of the slag is 2.5 times less than its mass, since the density of the material is about 2500 kg/m^3. Therefore, such a big mass of the slag does not require a large area to store. In addition, the slag is stored in pyramid-shaped dumps of significant height, which reduces the storage area.

4.2 Proposed method of utilization

Blast furnace and steel slag can be utilized with several methods. These methods are presented in paragraph 1.1. Mineral wool, granulated crushed stone, and slag pumice can be obtained from liquid slag. Each of these materials requires separate equipment. Also, in order to obtain products with a given quality and properties, it is most often necessary to adjust the composition of the slag in liquid form. Slags that have been cooled and solidified cannot be processed by the methods described above. However, solid form slags can be crushed and fractionated for use in building materials, as an abrasive, or in wastewater treatment.

At the moment, there are companies that manufacture equipment for grinding and fractionating slag. To determine the economic efficiency of using such a facility, the complex of the AMCOM company was chosen.

The AMCOM LLC is an international company, which offers custom made solutions for processing metallurgical slag and scrap, enrichment of iron ore and other equipment. Since 2000 the company has launched eighteen processing plants. The AMCOM designed and built processing complexes with capacities from 150 t/h to 375 t/h. Picture 14 demonstrated a production line which was built in Georgia for OJSC "Rustavi metallurgical plant" (AMCOM n.d.).

Figure 15: The production line for Rustavi metallurgical plant

Source: https://www.amcom-usa.com/ru/projects/rustavi-2008

The production line with capacity 350 t/h is proposed to be use for the processing of slag from Novolipetsk Steel. The finished products are fractionated gravel and road metal. The fractions of road metal are 0-10 mm, 10-100 mm, 100-300 mm and 300+ mm. This production line makes it possible to obtain fractions of 0-10, 10-20, 20-40, 40-70 mm from slag. Fractions are obtained by crushing and separating with a sieve method. This processing method was chosen because it allows to obtain products with the largest number of applications. These fractions can be used as additives in concrete, as an abrasive material, in the treatment of wastewater from pollutants, as well as in the construction of asphalt roads. The fractions of road metal are returned to production processes of metal. The figure 15 shows the general view of the production line (AMCOM LLC n.d.).

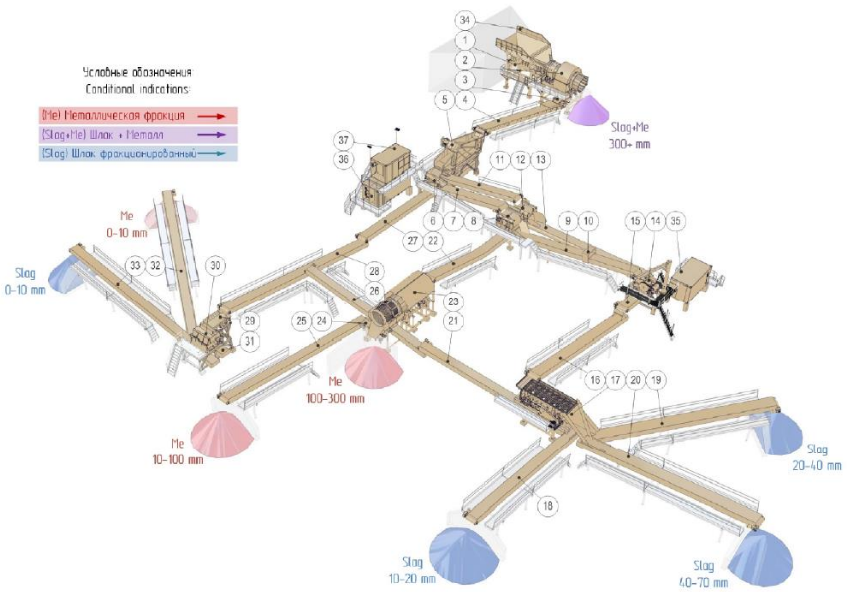

Figure 16: The general view of the slag processing equipment

Source: https://www.amcom-usa.com/ru

4.3 The economic viability of the project

The equipment and technology of AMCOM company is suggested to use on the enterprise to lower the environmental impact. But the implementation of the technology may not be economically feasible, considering only the environmental impact calculated with ES cost.

As was presented in the 3.2 the payback period method can be used to make a decision about economic feasibility of a project. The PBP will show how many years it takes for the profit to equal the amount of capital investment. The PBP is calculated using formula 10:

$$PBP = \text{Capital Investments}/\text{Net Revenues} \quad (10)$$

To calculate the investment attractiveness of turning steel slag into a by-product, it is necessary to calculate the income and expenses from the implementation of this project.

The capital investments consist of the cost of the equipment and land reclamation. The annual costs consist of the operational and maintenance of the equipment, energy, labor. The net revenue can be calculated with formula 11:

Net revenues = Gross Revenue – (Operational and Maintenance +Labor+ Energy) (11)

The annual costs consist of the operational and maintenance of the equipment, energy and labor. In the given case, the gross revenue is the income from selling the whole amount of the steelmaking slag of the year.

The first step of the calculation of the economic feasibility of the project was to calculate the gross revenue. The average price of steelmaking slag on the Russian market is 4.68$ (for fraction 0-10 mm), 3.08$ (for fraction 10-20 mm), 3.08$ (for fraction 20-40 mm), 3.21$ (for fraction 40-70 mm). The table 2 shows a list of products, taken from the data provided by the AMCOM company. The total cost highlighted in red is the gross revenue.

Name of product	Annual volume, tons per year	Annual volume, %	Total cost, $
Ferrous scrap:	452,904	16.70	Material is returned to the production process
fraction 0-10 mm	151,872	5.60	
fraction 10-100 mm	119,328	4.40	
fraction 100-300 mm	103,056	3.80	
fraction >300 mm	78,648	2.90	
Fractioned steelmaking slag:	2,259,096	83.30	8,740,817
fraction 0-10 mm	1,086,156	40.05	5,083,210
fraction 10-20 mm	439,344	16.20	1,353,180
fraction 20-40 mm	387,816	14.30	1,194,473
fraction 40-70 mm	345,780	12.75	1,109,954
Total amount, tons per year	2,712,000	100%	-

Table 3: The list of products

Source: Author

According to the data which have been obtained from AMCOM company, the cost of the processing equipment is around 5 million euros, which equals to 5,272,283 $ (using an exchange rate 0.95$=1€) ("1 USD to EUR – US Dollars to Euros Exchange Rate" n. d.). And the annual service cost is 7% of the total cost of the equipment, which is 369,060 $/year.

Also, for the operation of the equipment, it is necessary to involve 15 people per shift. Since the equipment operates 24 hours a day, a total of 60 people are needed per day. The shift requires: a foreman for the movement of raw materials and products (1 person), a dump truck driver (6 people), a loader driver (2 people), an excavator driver (2 people), a bulldozer driver (1 person), a mechanic (1 person), electrician (1 person), shift foreman (1 person). Other employees are present at the enterprise. Average salaries at

Novolipetsk Steel by position/profession: foreman – 604 $/month; dump truck driver – 604 $/month; loader driver - 510 $/month; excavator driver – 483 $/month; bulldozer driver 506 $/month; locksmith – 380 $/month; electrician - 402 $/month; shift master – 671 $/month. The total cost of labor is 392,304 $/year.

The number of hours of equipment operation per year - 6800 hours/year. The wattage for the equipment is 815 kW per hour. The total amount of the wattage is 5,542 MW, and the total cost of the energy is 427,011 $/year.

The equipment occupies an area equal to 0.64 hectares, then Ecosystem Services cost is 2,883 $/year.

The table 4 demonstrates the total cost of every annual investment.

Annual Investments	**Total cost, $**
Operational and Maintenance	369,060
Labor	392,304
Energy	427,011
Ecosystem Service	2,883

Table 4: Annual Investments

Source: Author

In the next step, the author calculates the net revenues for 1st and 2nd cases. These calculations are based on the formula 11 which were mentioned above. The net revenues for the 1st case are 7,552,442 $/. The costs of energy, labor, operations and maintenance are the same for the 2nd case, but it was also needed to consider the ES cost of the land which will be occupied by the operating equipment. So, the net revenues including ES cost is 7,549,559 (the 2nd situation).

The next step of the calculations was to calculate the capital investments, which are needed to get the value of PBP for both cases.

The capital investments include the cost of the processing equipment and the cost of reclamation of territories that were occupied by slag dumps. The cost of the processing equipment is 5,272,283 $.

The cost of the technical and biological stage of reclamation consists of flattening the territory, applying a fertile layer and sowing seeds. Flattening of the territory can be done by one bulldozer driver per month of work (506 $/month). The enterprise has a warehouse of fertile soil, and it can be used for the reclamation purpose. Application of a fertile layer of soil can be carried out with one bulldozer and a dump truck (506 $/month and 604 $/month respectively). The average cost of hydroseeding is 1,14 $/m^2. The total cost of the reclamation of the territory is 672,976 $.

The total value of the capital investments is 5,945,259 $.

Payback period was calculated for both cases using formula 10. For the 1st case and 2nd cases the PBP is 0.8 year (≈ 10 months). Projects that have a PBP is 3-4 years or less are economically viable. In this case, the proposed project is economically viable and should be implemented at the enterprise.

Also, to assess the viability of a project the net present value (NPV) technique can be used. The NPV considers time value of money in evaluating capital investments. Formula 12 can be used to calculate NPV:

$$NPV=NR_t*(1/(1+Rate)^n) \quad (12)$$

where is NR_t – net revenues values of the given period of time; n is the number of years; Rate is discount rate (8% for the given case, because the enterprise is interested in the income).

According to the calculation of PBP, it takes less than a year to equalize the capital investments and revenues. Therefore, a period of time equal to 1 year was chosen to calculate NPV in this case. Using formula 12 NPV is 6,993,002 $ (for the 1st situation), and NPV is 6,990,332 $ (for the 2nd situation).

The economic viability of the project can be assessed by comparing the obtained NPV values and capital investments. For the 1st situation the difference is 1,047,743 $, and for the 2nd situation the difference is 1,045,073 $. Since the differences in both cases are positive, the project will pay off in a year.

5 Results and discussions

As it was discussed in Chapter 1, the purpose of the thesis is to investigate economic and environmental profitability of the creation of an open-loop system on an old metallurgical enterprise to utilize solid waste.

To answer this question, three main sub-questions were identified that helped in the study of this topic:

1. How does the circular economy affect the iron and steel industry?
2. How much damage does steelmaking slag cause to the environment?
3. What is the economic benefit of implementing waste disposal measures?

While studying the circular economy and its impact on the iron and steel industry, several important points emerged. The circular economy began its development not so long ago, if one compares it with the linear economy. Despite the short history, CE already has strategies, levels, methods of application and evaluation. Also, the concept of a circular economy has its drawbacks, limiting the possibilities of its application. To answer the main question, it was necessary to investigate the experience of different metallurgical companies in case of utilization of solid waste. Several global metallurgical companies were selected to study their solid waste management strategy. The experience of the companies has shown that processing and turning waste into a by-product allows to replace primary raw materials, lower the consumption of non-renewable natural resources and reduce the negative impact on the environment.

Five ways of waste utilization were proposed in the Directive 2008/98/EC of the European Parliament and of the Council. The ways were listed by priorities (from the most preferable to the least)("DIRECTIVE 2008/98/EC on Waste and Repealing Certain Directives" 2008):

a. prevention;
b. preparing for reuse;
c. recycling;
d. other recovery, e.g. energy recovery;
e. disposal

In the given case the most prioritized variants – prevention and preparation for re-use are unsuitable. So, the next variant is recycling, and it was proposed for the research.

Previous studies (Maheshi, Steven, and Karel 2015a; Rashid and Shahzad 2021b) to determine the level of negative impact of waste on the environment have shown a significant positive impact on the environmental situation. Waste was proposed to be used to generate fuels, as well as fertilizers. The positive economic effect of the proposed project was also shown. The research presented in the thesis confirms the economic and environmental efficiency of implementing the principles of a circular economy into the industry.

To determine the scale of the negative impact on the environment, two methods were chosen: Ecosystem Services and the Russian State Methodology. The results of calculations by these two methods showed a significant difference. The fee for negative impact according to the Russian state methodology exceeds Ecosystem Services costs by 30 times. This difference can be explained by the fact that Ecosystem services takes into account the area occupied by this waste, while the Russian state methodology uses the mass of generated waste. With continued storage of this waste on the territory, the occupied area will steadily increase and eventually reach a million or more dollars.

In the proposed project the economic efficiency is achieved by selling products from slag. About 60 million tons of crushed stone were consumed in the first six months in 2019 in Russia. Novolipetsk Steel is located in the Central Federal District, which is the largest consumer of crushed stone (about 16 million tons of crushed stone were consumed in the first six months in 2019) (“Crushed Stone Consumption in Russia in June of 2019” n.d.). Part of this crushed stone can be replaced by crushed slag obtained by the proposed method. Also, the cost of natural crushed stone varies from 7 to 17 dollars per ton, which is significantly more expensive than crushed stone from steelmaking slag. Therefore, this crushed stone from slag can become a substitute for primary raw material.

The assessment methods of environmental impact, used in the study, do not consider the impact of waste on the pollution of water and the contribution to the generation of CO_2 emissions. The air quality is not considered in the ES methodology. The Russian State methodology takes into account only the mass of waste generated during a year, but not all waste generated over the entire time. So, the accumulated negative environmental impact can be more significant. In further studies, it is necessary to take into account the impact on these natural components, as well as the accumulated harm from waste storage over a long period of time.

During the economic evaluation of the proposed project, it was found that it would pay off in less than a year. Since the PBP is less than 4 years old, this project can be considered profitable.

Environmental savings have not been taken into account in this economic assessment. Taking into account environmental savings, net revenue for this project in the first case will be $15,470,144 and in the second case $7,814,805. In this case, when calculating the negative impact on the environment according to the Russian state methodology, PBP will be only 6 months.

Thus, the presented master thesis shows that the creation of an open-loop system at an old metallurgical enterprise has a positive effect on the economic situation of the enterprise and the ecological situation of the location area. The use of solid waste from ferrous metallurgy in other areas of industry reduces the use of primary raw materials and lowers the negative impact on the environment. The study demonstrates the importance of applying circular economy methods to metallurgical enterprises in Russia. Also, in order to continue the application of circular economy schemes in different industries, it is necessary to continue studying the properties of industrial waste to include them in the production-consumption circle.

I started to study for a Bachelor's degree in environmental protection in 2016. Even before the course I was aware of ecological problems such as air pollution, ozone layer depletion, plastic waste problems. I saw some problems in the generation of household waste and its utilization. After I starting my studies in university, I got acquainted with issues of industrial enterprises and industrial waste utilization. Before I started my master program, I was familiar with the circular economy, but did not understand the significance and practical application of the principles.

The course "Sustainable developments" helped me to see the impact of the circular economy on achieving the Sustainable Development Goals. In a detailed study of the concept of the circular economy and its implementation I realized that some methods of CE are already being applied in enterprises. For example, Novolipetsk Steel collects scrap metal at all its sites to return valuable resources to the production cycle. So, this method formed a closed-loop system.

The circular economy has a positive impact not only on the economy of companies. During the study, I realized that the CE has a positive impact on the environmental situation from local to global levels. I am aware that some managers of Russian companies are distrustful of new concepts and implementations in the companies. But some methods that are part of the circular economy have already been put into practice in many enterprises. Experience in the successful implementation of these methods should motivate enterprises to improve production processes.

In the future, I plan to continue my development in the field of ecology and sustainable development. I also plan to put my knowledge into practice and help the companies build waste management strategies to create a circular economy in enterprises.

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7 List of Figures

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9 List of Abbreviations

CE	Circular economy
SD	Sustainable development
SDG	Sustainable Development Goal
MFA	Material flow analysis
LCA	Life cycle analysis
LCC	Life cycle costing
EOL	End-of-life-cycle
RC	Recycled content
PBP	Payback Period
ARR	Accounting Rate of Return
NPV	Net Present Value
IRR	Internal Rate of Return
PI	Profitability Index
EBIDA	Earnings before interest, taxes, depreciation, and amortization

Annex

1. Calculation of environmental impact by Russian State Methodology:

Calculation of payment for the disposal of solid waste:

$$П^{m}_{лр} = \sum (M_{лj} \cdot Н_{плj} \cdot К_{от} \cdot К_{л} \cdot К_{ст}) = 2{,}712{,}000 \cdot 663.2 \cdot 1.084 \cdot 0.3 \cdot 1 \cdot 1 =$$

$$= 584{,}904{,}200 \; roubles$$

$$П^{m}_{лр} = \frac{584{,}904{,}200}{73.88} = 7{,}916{,}949 \; \$$$

Calculation of payment for the emissions of chemical substances into the atmosphere:

$$П_{нд} = \sum_{i=1}^{n} (М_{нд i} \cdot Н_{пл i} \cdot К_{от} \cdot К_{нд}) =$$

$$= (225.948 \cdot 60.588 \cdot 1 \cdot 1) + (128.006 \cdot 39.528 \cdot 1 \cdot 1) + (0.035 \cdot 39.528 \cdot 1 \cdot 1) + (640.755 \cdot 40.5 \cdot 1 \cdot 1) + (277.200 \cdot 39.528 \cdot 1 \cdot 1) = 55{,}659 \; roubles$$

$$П_{нд} = \frac{55{,}659}{73.88} = 753\$$$

Total negative environmental impact in value terms:

$$П^{m}_{лр} + П_{нд} = 7{,}916{,}949 \; \$ + 753\$ = 7{,}917{,}702\$$$

2. Calculation of environmental impact by Ecosystem Services costs:

The price of a hectare of Temperate Broadleaf and Mixed Forests in 2021:

$$Price = 3{,}013\$ \cdot \left(\frac{100\% + 3{,}14\%}{100\%}\right)^{2021-2008} = 4{,}504 \; \$ \; per \; ha \; per \; year$$

The Ecosystem Service cost of the disturbed area:

$$ES = 4{,}504 \; \$ \; per \; ha \; per \; year \cdot 58.8912 \; ha = 265{,}246 \; \$/year$$

3. Calculation of the economic viability of the project:

Net Revenues for the 1st situation (considering Russian State methodology):

$$Net \; Revenues = Gross \; Revenue - (Operational \; and \; Maintenance + Labor + Energy)$$
$$= 8{,}740{,}817 \; \$/year - (369{,}060 \; \$/year + 392{,}304 \; \$/year + 427{,}011 \; \$/year)$$
$$= 7{,}552{,}442 \; \$/year$$

Net Revenues for the 2nd situation (considering the Ecosystem Services cost)

$$Net \; Revenues = Gross \; Revenue - (Operational \; and \; Maintenance + Labor + Energy + ES)$$
$$= 8{,}740{,}817 \; \$/year$$
$$- (369{,}060 \; \$/year + 392{,}304 \; \$/year + 427{,}011 \; \$/year + 2{,}883 \; \$/year)$$
$$= 7{,}549{,}559 \; \$/year$$

Capital investments calculation^

$$Capital \; Investments = Equipment + Reclamation = 5{,}272{,}283\$ + 672{,}976\$ = 5{,}945{,}259\$$$

Payback Period calculation for the 1st case:

$$PBP = \frac{Capital \; Investments}{Net \; Revenues} = \frac{5{,}945{,}259\$}{7{,}552{,}442 \; \$/year} = 0{,}8 \; year \approx 10 \; moths$$

Payback Period calculation for the 2nd case:

$$PBP = \frac{Capital\ Investments}{Net\ Revenues} = \frac{5{,}945{,}259\$}{7{,}549{,}559\ \$/year} = 0{,}8\ year \approx 10\ moths$$

Net Present Values calculation for the 1st case:

$$NPV = Net\ Revenues \cdot \frac{1}{(1 + Rate)^n} = 7{,}552{,}442\ \$/year \cdot \frac{1}{(1 + 0{,}08)^1} = 6{,}993{,}002\ \$/year$$

Net Present Values calculation for the 2nd case:

$$NPV = Net\ Revenues \cdot \frac{1}{(1 + Rate)^n} = 7{,}549{,}559\ \$/year \cdot \frac{1}{(1 + 0{,}08)^1} = 6{,}990{,}332\ \$/year$$

Economic viability of the project for the 1st case in the first year:

$$NPV - Capital\ Investments = 6{,}993{,}002\ \$/year - \ 5{,}945{,}259\ \$ = 1{,}047{,}743\ \$/year$$

Economicl viability of the project for the 2nd case in the first year:

$$NPV - Capital\ Investments = 6{,}990{,}332\ \$/year - \ 5{,}945{,}259\ \$ = 1{,}045{,}073\ \$/year$$

4. Calculation of economic feasibility considering environmental saving:

Net Revenues for the 1st case:

$$\begin{aligned} Net\ Revenues &= Gross\ Revenue - (Operational\ and\ Maintenance + Labor + Energy) \\ &\quad + Environmental\ Savings = \\ &= 8{,}740{,}817\$/year - (369{,}060\$/year + 392{,}304\$/year + 427{,}011\$/year) \\ &\quad + 7{,}917{,}702\ \$/year = 15{,}470{,}144\ \$/year \end{aligned}$$

Net Revenues for the 2nd case:

$$\begin{aligned} Net\ Revenues &= Gross\ Revenue - (Operational\ and\ Maintenance + Labor + Energy + ES) \\ &\quad + Environmental\ Savings \\ &= 8{,}740{,}817\$/year \\ &\quad - (369{,}060\$/year + 392{,}304\$/year + 427{,}011\$/year + 2{,}883\$/year) \\ &\quad + 265{,}246\ \$/year = 7{,}814{,}805\ \$/year \end{aligned}$$

Payback period for the 1st case:

$$PBP = \frac{Capital\ Investments}{Net\ Revenues} = \frac{5{,}945{,}259\$}{15{,}470{,}144\ \$/year} = 0{,}5\ year = 6\ moths$$

Payback period for the 2nd case:

$$PBP = \frac{Capital\ Investments}{Net\ Revenues} = \frac{5{,}945{,}259\$}{7{,}814{,}805\ \$/year} = 0{,}8\ year \approx 10\ moths$$