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Cost and environmental impact analysis of slag repurposing as alternative solution to bricks

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Abstract: The world's leading producer of Platinum Group Metal is South Africa and accounts for 94 percent of world's platinum. Platinum smelters produce around 10 525,90 tons of slag annual of which accumulates as stockpile, never utilised. More storage area is required for continuous operation of the smelters to store slag. The aim of the research is to investigate the cost and environmental impact of repurposing slag into bricks for low-cost housing. AnyLogic simulation model specifically the Discrete Event Modelling (DEM) was employed for the modelling and simulation because of its capabilities compared to other models such as Flexsim, Vensim, ANSYS. The results indicate that 92 human resources are required to have functioning business that is able to manufacture and deliver bricks enough to build 326 houses per month. The operation is labour intensive to ensure more job opportunities are created and a total 368 personnel are employed permanently on all sites. The smelter potentially saves over R1,5 billion per operation and R5,6 billion across 4 sites over a decade by giving the slag away for free. The environmental pollution is improved as five heavy plant equipment is removed from the operation. The operation has potential to generate R392,2 million profit over 10-years.

Keywords: *AnyLogic, Environmental impact, PGM, Slag, System modelling, Waste management.*

1. Introduction

SA have the highest reserves of PGM in the world with 80% in reserves and have operations located in the regions where PGM is found in high concentrations. The most precious metals are Rh, Pt and Pd and they are mostly used in industrial, jewellery, anticancer drugs, computer hard disks, mobile phones and glass, among others etc. The slag produced in two years between 2018/2019 and 2019/2020 is almost 20 000 T and it remain unutilised. The volume can fill approximately 10 Hectares and more storage area is required for future operational requirements. The research objectives of the study have been identified as to explore the possibilities of repurposing slag material into alternative brick solution and the researcher to utilise system model and environmental impact assessment to verify objectives.

Demirbas [1] Demirbas (2011) research highlight that waste is collected using different mode of transport to pre-treatment plants or sites where it gets processed and final abatement of residues. The research highlights that waste management promote waste generated reduction by recycling, re-introduction waste that end up into environment. By education, create awareness helps to ensure that waste is removed from the source, treated, disposed of or proper recycled. The research recommendation is that waste management should not be afterthought but rather incorporated as part of the project planning to manage waste on site and when properly done a lot of energy could be recovered from waste generated to minimise input costs.

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According to study by Hassan, et al. [2] Hassan et al. (2000), Malaysia manages to separate and recycle only 5% of the waste produced and it generate $60 per tonne. This means that Malaysia produces solid waste of about 3.5 million T per annum (pa) and this is critical since disposal sites nearly exhausted and 80% nearing capacity. The study results show that the amount of waste being recycled were:

- Paper, 1352 T per day,
- Plastic, 2097 T per day,
- Glass, 314 T per day,

In conclusion, a small percentage of waste was separated from the source thus improving collection, recycling and reducing collection costs. The waste collectors help to separate waste free of charge but recommendations are that they need to be registered and have proper personnel protective equipment/clothing (PPE).

According to the research by Taskin, et al. [3] Ash and Slag Waste (ASW) is waste generated from burning coal and could be the potential source to recover noble metals as they have actually recovered Au and Silver (Ag) from tested samples and could be a source of raw material for other industries. The research identifies lithogeochemical as methodology used where samples were analysed using atomic-absorption spectrophotometry (AAS) and neutron-activation analysis (NAA) to determine traces of elements content. The research results show high content of noble metals recovered from tested samples with Ag being higher than Au 0.1-0.45 g/t and other several metals were recovered.

Garole, et al. [4] discovered that various metals and non-metals that poses environment threat could be recovered by recycling of Li-ion batteries (LIBs) used on electronic devices such as laptops, cellular phones etc. These metals include Vanadium (V), Cobalt (Co), Nickel (Ni), Molybdenum (Mo), Lithium (Li), Aluminium (Al) and Iron (Fe), and non-metallic components such as sulphur (S), oil and carbon (C). The research methodology identifies hydrometallurgy and bio-metallurgy process that are widely used to recover Libs because they consume less energy, require less water usage for high metal recovery rate and high purity. The research states that by 2030 the world LIBs recycling business will generate $23.72 billion based on the market value analysis conducted in 2017 that was estimated to be $1.78 billion and the battery energy demand increase from 102-Gigawatt hour (GWh) in 2017 to 709-GWh by 2026. The results reveal that LIBs also contain poisonous electrolytes such as Lithium hexafluorophosphate ($LiPF_6$) and carbonaceous materials and present new opportunities for repurposing recovered materials to future applications.

Aznar-Sánchez, et al. [5] research highlight the importance of environmental awareness to be in line with the significance increase of mining activities. This results from increase demand of minerals resources of which yield to increase waste. The study indicates a significant research increase on mining waste management related topics from 14 articles in 1988 and to 279 articles in 2017. The result identifies United State of America (US) as the biggest contributor of with research work conducted on mining waste management articles while United Kingdom (UK) has 47.9 articles published in collaboration with other countries.

Bian et al. [6] as well as Haibin and Zhenling [7] reveal that in China is the biggest coal producer and consumer in the world with approximately 40% of total production. The coal mining wastes is traditionally dumped as a cone-shaped tip which causes a series of environmental issues. The research reveals that coal mining waste has been utilised to fills (subsidence land, underground cavity), fuels (power plant), cement materials, bricks material and waste dump. The research results have noted that there are different kinds of waste which largely depends on geographical mine location and different uses of mining wastes.

Kang and Schoenung [8] state that rapid change/upgrade of electronic equipment features and capabilities cause an increase of electronic waste (e-waste) and that the US generate 5% of e-waste per year. The research identifies the removal of hazardous and valuable components from e-waste before material could be recovered and sold, thereby making the processing of e-waste to be more complex.

The results noticed that recovering precious metals from electronic scrap is one of the greatest economic profits for the recycling industry.

According to study by Muhyuddin, et al. [9] plastics manufacturing worldwide increases at rate of 8.5 % pa and Europe produces 60 million T of plastic waste pa and globally over 300 million T pa. This is estimated to reach 500 million T pa by 2025 while 60% of it will end up as a waste. The research figured that plastics waste can be converted into valuable electrocatalysts. Generally, the three main products of pyrolysis are oil, carbonaceous char, non-condensable gas that can be refined and then used to run turbines, industrial furnaces, high-duty engines, and boilers. The study concludes that a large percentage of plastic waste is disposed in landfills without being recycled, reused, or recovered. Thus, its transformation in a value-added product is strongly encouraged. In conclusion, more than 95% of plastic waste is worth more than 100 billion euros and this sum is lost every year.

Chihiya, et al. [10] note that in order to promote waste management, waste sorting and separation must take place at the source where physical separating of solid waste occurs. This helps to reduce amount time required to separate waste later in the process. The study identifies poor solid waste management as one of the key factors contributing to declining environmental health conditions in Zimbabwe. The result shows that Unki Platinum Mine produces both hazardous and non-hazardous waste and failure to identify major waste producers often leads to poor waste management.

According to research by Sari, et al. [11] e-waste is the result of an increase availability and affordability of electronic products in the market worldwide. According to the authors, Indonesia produced about 1.274 million tons of e-waste by 2016. The results mention that government is central to make e-waste collection possible by implementing relevant regulation to curb the increase of e-waste. The research by Zhang, et al. [12], indicates that e-waste recycling has potential to partially fulfil the global demand for metals, especially in regions enduring resource shortages. The authors further stated that China process about 70% of e-waste generated every year. The research recommends that government employ rules and regulations to protect the environment and people from threats by e-waste recycling. In addition, manufacturers should also assume the responsibility of reducing environmental hazards from their products.

According to research by Yankelevsky U and Avnon [13], construction waste recycling offer three benefits namely:

1. to reduce raw material demand,
2. reduce transport and production costs and
3. reuse waste and saves landfills.

The study recommends the implementation of reuse, recycling and reduce (3Rs) approach to minimise the environmental impact caused by construction activities as it causes environmental pollution.

The research by Tam and Tam [14] identify six waste disposal methods from low to high environmental impact namely reduce, reuse, recycle, compost, incinerate and landfills. The study identifies the importance of 3Rs whereby recovered material can be a source of new raw material and minimise environmental pollution.

The research by Nishihara, et al. [15] state that the effect high-level radioactive waste (HLW) can be reduced by introducing Partitioning and/or transmutation (PT) technology which produced waste with different chemical and physical properties. The study indicates that PGM are separated for two reasons: to enhance the loading of the residual waste elements into vitrified waste form, and to recycle PGM for their economic value as rare metals.

The aim of the research is to investigate the cost and environmental impact of repurposing slag into bricks for low-cost housing. This is an attempt to solve housing challenges in a cost effective and environmentally sustainable way. This study is significant because of the growing population of South Africa and cost implications of building materials. The investigation of the cost and environmental implications of the process of converting slag into bricks for low cost housing has not been sufficiently highlighted by the existing literature.

2. Literature Review

2.1. Slag, Uses and Recovery

Andrew, et al. [16] confirm that matte consists of sulphides of Ni, copper (Cu), and Fe, which has higher relative density than gangue materials that make up the slag, the sulphides sink to the bottom of the furnace as a matte bath while oxides float above as slag. The research experiment was conducted in 2013 using furnace feed data where its temperature was at 1600 ºC and was found to be 671 kWh/t concentrate. The data whereby the furnace was running low load or off were removed and energy was calculated for various feed mixers. The results indicate that concentrate material from different sites is blended to get constant results. to increase slag flowrate lime, alumina and silica are used while slag temperature maintenance is critical to manage furnace energy balance.

According to research by Jones [17], the most economically heavy metals are Pt, iridium (Ir), and osmium (Os), with densities of 22 g/cm^3 and Pd, Rh, and ruthenium (Ru) are less prevalent and much lighter with relative density of 12 g/cm^3. The research states that PGMs belong to the transition metals of Group VIII in the Periodic Table, as do Fe, Ni, and Co. The research confirms that these metals are found in high concentration and have similar geochemical behaviour. The research identifies the properties of PGM to have high heat resistance, excellent catalytic properties and are widely used in the chemical industry and in automobile catalytic converters (ACC).

These metals are used as follows [18]:

- Rh is used for catalyst in making nitric acid, ACC, coating of optic fibres and electric contact material.
- Pd is used in jewellery application, fuel cells and ACC, to store and filter hydrogen.
- Pt is used for jewellery application, medical and biomedical application, ACC, electrical contact material, electronics industry applications.

Benson, et al. [19] mentioned that PGMs are present in very small quantities in this class of catalysts and, given their intrinsic value, it is worth recovering them from the spent exhaust system and about 90% of precious metal can be recovered. The research used Pyrometallurgical and Johnson-Matthey processes to recover high-rate metal with less impurities. This was achieved when the furnace operating temperature of 1500°C –1700°C is maintained and PGM material have dens viscosity causing impurities to float as they have lower density. The research recommended that recoveries of the PGM in used cars is very important to minimise disposing of such critical metal and the removal of exhaust must be done before vehicle is scrape to increase recovery process.

Akinmusuru [20] study confirms that iron slag from steel industry has been widely used for manufacturing of cement for construction industry. The research experiment was conducted by casting concrete cubes, cured by water immersion for every 7days until day 28 is reached and taking strength measurement until maximum has been reached. The results of samples where slag was used as substitute for sand has better results compared to where slag replaced cement. Based on the results recommendation for further studies to investigate the use of slag in pavement design has great potential.

According to research by Ding, et al. [21] the differences between Alkali-Activated Concrete (AAC) and Ordinary Portland Cement Concrete (OPCC) largely depend on the proportions of raw materials in the concrete. The slag to fly ash ratio may be a very influential factor, to produce 1 tonne of OPCC, 0.85 tonne carbon dioxide is released into atmosphere and 4 Giga Joules (GJ) of energy is used. The research confirms that AAC exhibits better bond performance with steel reinforcement and better strength performance. The casted sample reached 60 MPa within a day and could reach over 100 MPa in a year. The results prove that other types of bonding have been explored in order to move away from the use of cement. OPCC produces 50-80% more volume than that of AAC while AAC has better acid resistance, sulphate attack, and chloride penetration.

Ravindra, et al. [22] as well as Ravindra, et al. [23] notice the significant increasing usage of PGMs in ACC over the years. In addition, some applications whereby PGMs are utilised include industrial applications, jewellery, anticancer drugs, computer hard disks, mobile phones and glass, among others etc.

According to the research by Chompunoot, et al. [24], Pt recycling is forced by the scarcity and high price of Pt. The research methodology was to conducted experiment where Pt content was extracted from the solution and chemical analysis was discovered by means of titration and recovered content was analysed using Raman spectrometer machine. In conclusion, to minimise process loss during recovery of Pt was achieved and found to have linear relationship between platinate capacity and the calculated optical basicity.

According to research by Sun, et al. [25] within PGM, Pt is widely used in petroleum, automobile and pharmacy industries, Pt was successfully recovered from spent Aluminium (III) oxide (Al_2O_3) carrier catalyst. The research mentioned that leaching process using sulphuric acid was utilised and raw material where matte was crushed and melted at 1400 ^oC for 50 minutes. The results achieved a high Pt recovery of 89.54% while using ratio of 0.1:1 and could be further improved to 97.92% by increasing pyrite dosage to 0.6:1.

According to research by Avarmaa, et al. [26], the recoveries of lost precious metal from slag becomes crucial since the high increase of copper production. The research experiment was conducted to determine the quantity of precious metals lost. This was done at furnace temperature range of 1250 ^oC - 1350 ^oC and results shows that precious metals in slag were lower than expected and almost negligible.

According to the research by Kekkonen, et al. [27], slag remove impurities, non-metallic inclusions (oxides and sulphides) and refining metals. The slag physical properties are mostly influenced by viscosity and temperature during matte separation process. The research identifies Lida and modified Urbain models to produce accurate results about slag viscosity. In conclusion more experiment is required to provide the data to test and optimise the models for these very complex conditions.

Riley [28], indicated that slag could be air-cooled and water-quenched and air-cooled slag could be used as lightweight aggregate whereas water-quenched slag could be used for binding material because they have high glass content. The experiment was conducted whereby slag partially substitute cement specimen (slag-cement) was cured in seawater for 28 days until maximum strength was reached. The results revealed that ordinary concrete strength decay much faster than that of slag-cement and the 50% ratio has life expectancy of 22.9 years; the 10%-30% ratio has higher corrosion resistance.
Table. Presents the chemical composition and physical properties of slag.

Table 1.
Chemical composition and physical properties of slag.

Composition	Silicon dioxide (SiO_2)	33.46
	Aluminium oxide (Al_2)	15.74
	Ferric oxide (Fe_2O_3)	0.56
	Calcium oxide (CaO)	38.81
	Magnesium oxide (MgO)	7.65
	Sulphur trioxide (SO_3)	1.96
	Loss on ignition	0.10
Physical properties	Specific density/ Blaine (cm^2/g)	3,988
	Specific density	2.88

[28]

2.2. Health and Environmental Impact

Reno [29] states that whether generated waste is toxic or not, it is the moral responsibility of waste producers to develop effective waste manage practises as most waste end up on streams, streets, open land etc. The study identifies industrial waste as major waste contributor and also has potential to inspire new products. This has greater risk to human health and environmental impact by dumping

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toxic and dangerous waste to environment. The results identify those scavengers could have serious illness, get injured due to their involvement and such activities are not controlled, sometimes unsafe.

Bian, et al. [30] state that the world's largest chronic waste producers are mining and mineral-processing wastes and they are difficult to recycle and most waste end up on streams, lakes to cause environmental pollution. The research identifies that there are practices that are allowed in one country but not allowed in another such as the use of mine waste for roadways and parking. Therefore, no universal laws could be imposed without understanding the specific laws of each country. In conclusion, environmental impact may be reduced by reuse of mining and mineral processing waste but may introduce new environmental risks.

Hughes, et al. [31] study mention that Papua New Guinea (PNG) deep sea bed was pristine environment until deliberate waste disposal in the form of Deep-Sea Tailings Placement (DSTP) happens by island mines. The research sample was conducted on three stations at different depths in PNG from year 2007 to measure the and assess the state of benthic infauna communities. The results show that significant community effects of DSTP are apparent even at a coarse level of taxonomic resolution and provide the basis for future monitoring of recovery rates in impacted deep-sea sediments.

Lottermoser [32] indicates that environmentally waste management is one of the major concerns in maintaining the quality of the Earth's environment as it causes land degradation and resource depletion. The research states that the reuse and recycling of mine wastes, like all other recycling efforts, create financial assets, reduce the rate of consumption of natural resources, limit waste production, encourage innovation and local industries, create jobs and teach responsibility for the environment shared by all. The result identifies slags as mineralogically, chemically diverse and heterogeneous where the extraction of metal and non-metals could be recovered by employing innovative, cost-effective reclamation technologies and sustainable rehabilitation methods.

Awuchi, et al. [33] state that industrial waste deals with all types of waste produced throughout the lifecycle of the product and can pose threats to human health and industrial waste management are to reduce the effects. The research identifies multiple industries of which produce and release all sort of toxins and hazardous material which get disposed of in landfills and in water. The results prove that conducting risk assessment (RA) on industrial waste is critical to identify hazard and characterization, exposure assessment, and risk characterization.

Ravindra, et al. [22] and Ravindra, et al. [23] state that the increase of mining of PGM over the years have a direct increase of environmental impact and also an increase traces of PGM found in waters, soil and food chain. This leads to PGM traces found in human bodies fluids, tissues in high concentration especially to precious metal workers. The study identifies that PGMs contribute or cause illness like asthma, nausea, increased hair loss, increased spontaneous abortion, dermatitis, and other serious health problems in humans. The study reveals that catalytic converter help to reduce the emission of gaseous pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC) by converting over 90% of emission into carbon dioxide (CO_2), water (H_2O) and Nitrogen (N) of which are harmless. The study used several dynamometer experiments were performed on various engines to evaluate the PGM emission from the three-way ACC of diverse ages.

Scoble, et al. [34], indicated the ongoing revision of mining and environmental legislation have forced compliance in waste management and disposal and will be difficult for new miners to get mining rights without having proper documents. The research reveals that waste disposal generated from underground mines has become increasingly difficult and selective mining is promoted to minimise waste. The research indicates that the Chamber of Mines of SA has developed innovative method in coordination with Witwatersrand to process Au ores from underground mines with 98% successful recovery rate. The research recommends consolidated waste management expenses to be transparent by making it part of mining and operating costs.

According to the research by Wilson [35], the protection of environmental was focused around 1970s by developing world's system waste management to eliminating uncontrolled disposal and increased enforcement of technical standards. The research recognises that the introduction of incinerator with electrostatic precipitators whereby waste toxins is treated before released to atmosphere to reduce environmental impact was one way to manage uncontrolled disposal. The research reflects the importance of climate change having to change focus away from landfills of biodegradable waste by introduction of reuse, recycle, reduction. The target was to increase energy generated by waste in 2020 by 35% of energy utilised in 1995.

Chiyangwa [36] highlights that disposal of mine waste generates mine dust, leading to increased rates of air pollution, triggering health risks due to exposure of communities living in close proximity to the mine dumps. The research experiment was conducted in two communities residing within a close proximity more than 2 kilometre (km) and those as far as 5 km away from dump sites. The results discovered that people residing closer to mine dumps have developed chronic rhinosinusitis (CRS) allergic disease symptoms and recommend barrier wall to be erected between residents.

According to the research by Sepadi [37] and Sepadi, et al. [38], South African mining industry is one of the largest producers of Pt in the world. The fine dust particles are produced during crushing of mine waste rock and they pose a respiratory health risk though inhalation during mining operation. The produced fine dust particles are associated with various causes of silicosis, pneumoconiosis, tuberculosis (TB) and chronic lung disease. The result proves that all workers are at risk of developing health effects due to dust exposure but the risk level could differ from person to person.

Fornalczyk and Saternus [39] reveal that ACC is made from PGM and millions of car are fitted with them to minimise environmental pollution. The results identify that ACC can minimise emission by 12 billion Mg of harmful gases that could have been released to atmosphere by converting them into CO_2, H_2O and N.

Popov, et al. [40], Ukraine accumulates 8 million tons of ASW annually, covering an area of more than 22 thousand hectares and is classified as one of the hazardous waste in terms of volume and geographical location. The research was conducted by reviewing literature addressing the impact of ASW on the environment, and only 15% of wastes in Ukraine gets recovered. The results proved that ASW has the potentially to create health risks for the Ukraine population as it is dangerous sources of environment pollution.

Fox, et al. [41] the main environmental concern surrounding the continuous casting of steel is fluorine emissions because they emit toxic gases into atmosphere and fluorides additives is the source of problems. The results state that fluoride was successfully removed from a conventional billet flux and substituted with a combination of B_2O_3 and Na_2O to match the viscosity trend against temperature of the original flux. The low-fluoride slag and fluoride-free Electroslag remelting (ESR) slag not only reduce environmental pollution, but also needed for vacuum ESR which is considered a promising technology [42].

Mudd [43] PGMs must meet future technological needs without significantly impacting the environmental and social impacts such as water pollution, unfair village relocation, economic disparity and compensation issues. The detailed RA to be conducted and reviewed within PGM industry to ensure future sustainability. The financial requirements for environmental costs such as water, energy and greenhouse gas emissions must be built in the operational costs [44].

Popov, et al. [40] research identify thermal power plant and cogenerating plant as the major source of air pollution in Ukraine by emitting various harmful substances into the atmosphere and also increase the amount of solid waste in landfills. The research identifies ASW as toxic and can contaminate the atmosphere, soil, groundwater and surface water in areas located a few kilometres from the waste dump sites. The research concludes that Ukraine's fuel and energy complex are potentially dangerous sources of environment pollution, and they create health risks for the population living in the surrounding areas.

The research by Ordóñez [45] identifies mining activities as the basic provider of raw material for human development, however it has undesirable impact for population as soil, water and air get polluted in the process. The results identify the importance of treating or confinement of mining waste to minimise environmental impact and improve population leaving conditions.

2.3. Housing Demand in South Africa (RDP-Houses)

According to report by Settlement [46], the Department of Humans Settlement (DHS) have been mandated to establish and facilitate National housing process working with all stakeholders in provinces and local municipalities in accordance with the Constitution of the Republic of SA. The report mentioned that the DHS targets to deliver 30 000 social housing by 2024, 180 000 subsidised housing units and issue 388 104 title deeds to beneficiaries from low-income households. The report states that household must earn a minimum of R1 850 and maximum of R22 000 gross per month to qualify for social housing.

The unemployment rate in SA is at all time high of 32.7% and the total of 11.7% SA are informal settlement dwellers [47].

The democratic government aims to address historical racial influenced inequalities by providing both free housing to the poor and low-cost housing subsidised by government to individuals that cannot qualify for mortgage bonds [48].

According to report from Department of Co-operative Government [49] their core responsibility is to optimally deliver integrated and sustainable human settlement to SA citizen to restore their dignity. The report acknowledges that government makes provision to supply affordable houses encompass all the low-cost houses that are subsidized by government and provided to the poor people that cannot afford to get Bank home loans from private banks. The report notes that department has long term plan on how they are going to strategically deliver houses to the needy and secure land where these houses can be built.

Weimann, et al. [50] mentioned that Africa is experiencing urban growth and as a result the majority of masses from urban areas are forced to live in slums and informal settlement of which are characterised by poor housing conditions, unhealthy natural environments, and inadequate infrastructure and services, including insufficient healthcare. The research identifies Western Cape Province to have 440 informal settlement and City of Cape Town (CCT) having 235 informal settlements. The result in the Global South, highlight the importance to improve health through housing interventions that has potential to improve people's health.

Huchzermeyer [51] and Huchzermeyer [52] state that in SA the housing policy was negotiated between 1992-1994 and the agreement referred to as Housing White Paper (HWP) of 1994, was reviewed in 1999 until the Reconstruction and Development Programme (RDP) was developed. The study notes that housing is fundamentally a basic need in SA as it is enshrined in the 1996 Constitution of the Republic of SA. The study identifies the misalignment of housing policy to overcome race and class-based policy that seeks to treat everyone equally. The majority of the indigenous SA are leaving in poverty and without proper housing infrastructure. To protect their dignity, government to provide decent housing and other basic needs to the people.

According to study by Huchzermeyer [53], the South African democratic elected government has extensively provided housing since the dawn of democracy but the mushrooming of informal settlement continues and has received national attention since 2003. The research refers to the Millennium Development Goal (MDG) where it seeks to improve lives of 11 million slums dwellers by 2020 and the plan was piloted and developed by provincial governments. The research results states that social inclusion is supported through participatory decision making in (a) the layout planning, (b) the provision of social and economic amenities, and (c), where required, in the relocation process.

According to research by Tissington [54], SA is one of the few countries in the world who have a socio-economic rights as it is enshrine in their Constitution of the Republic of South Africa Act 108 of 1996. The research identified SA to have different housing typologies such as flats, private rentals, social housing, shacks, public and privately-owned land, RDP houses, rural housing etc of which makes housing issue complex. The research has identified three state organs has developed and formulated Housing Act 107 of 1997 with respect to housing development.

Ganiyu, et al. [55] suggest that SA government focuses to deliver low-income housing to cater for historically disadvantage citizen, the shortage of affordable housing in SA is due to an increase population and meeting the demand is a challenge. The study confirm that National Department of Human Settlement has built 2.3 million houses to accommodate 11 million people. The study results note the increase in waiting list for people waiting for houses and there's a gross abuse by beneficiaries of housing subsidy in SA.

Gilbert, et al. [56] study states that urban areas alone have about 1,075,000 households living in informal settlement in year 1994 and majority are blacks. The results conclude that poor quality shacks force the rental price to be low and mostly tenants are responsible for erecting their shacks.

According to Ballard and Rubin [57] study, SA government under leadership of African National Congress (ANC) has prioritised providing houses for poor citizen to redress ills of the past by apartheid government and has delivered 3.7 million over two decades. The study identifies megaprojects as a new approach where all housing would be delivered in large scale projects of more than 15,000 units.

According to study by Bradlow, et al. [58], the informal settlements were of poor quality, too small and in locations far from livelihoods and services; SA government has refused to upgrade existing housing and more than 200,000 houses were built yearly. The research states that since 1994 the backlog count has risen from 1.5 million to 2.1 million.

Crankshaw and Parnell [59] study identify that democratically elected government have inherited a large population who live in informal settlements (slums, remote settlement camps, displaced urban settlements and hostels) and new government have adopted RDP to redress the inequalities created by previous government. The study states that under apartheid, indigenous people were forcefully displaced into Bantustan, their land handed over to white farmers and moved far from metros and cities.

2.4. Research Gaps

There gaps identified in the literature accessed are detailed as following:

- No details about the health risks caused by handling slag in the long run.
- Not much attention has been given to the repurposing or reuse of platinum slag.
- The hidden value of slag remains unknown.
- Government plan to work with small, medium and micro enterprises (SMME) not clearly explained.
- The correct slag, cement, water mix ratios to make bricks not properly covered.
- The number of people affected or suffering from slag health related disease are not covered in details. No test conducted on people leaving a certain radius from where smelters operate.

The researcher makes assumptions where little or no information is available.

This research work/ report is going to provide proof that indeed there's value in the slag as it has been discovered with other waste such as paper, plastic, cans etc. This research work will enable smelter companies to decide how to manage their waste and create revenue in the process instead of spending fortune to handle slag.

There is sufficient literature to support repurposing of slag as it has been used in the construction industry to make concrete, hollow bricks etc. and some tests were carried out where slag was used as substitute for cement. The sample were tested in sea water and prove to have higher strength than normal cement and have high corrosive resistance.

The recycling of waste proved to be a lucrative business and it has proven across the different waste produced as most waste generated have potential to be repurposed to be raw material for future products. Human health to be considered always to ensure scavengers lives are not at risks due to toxics and other harmful substances found in waste, therefore, proper personal protective equipment to be utilised and regulations passed to govern the industry.

There environmental impact due to slag handling is well understood and sufficient literature to support. Traces of Pt has been found in areas where it was less present before due to transportation and

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products used. There has been work done to understand the impact each waste product has on environment and developed way on how to safely handle/ manage it.

There is high demand of RDP housing in SA of which have the potential to be the biggest consumer of the finished product. The demand for low-costs housing forces the government to deliver more houses as it is the basic human's right of every South African. Housing access give citizen dignity, comfortable and self-esteem and it is the basic humans right that must be enjoyed by all who leave in the country as it is enshrined in the constitution. There are basic human rights of which all citizen should enjoy and one of them being shelter, running water, sanitation etc.

3. Methodology

3.1. Modelling and Simulation Technique

There are multiple simulation models that may be employed to conduct the study and only AnyLogic, Vensim, FlexSim and ANSYS Simulation model to focus on for this research. The pros and cons as well as the capability of each model are explored to ensure suitable model is selected.

Maria [60] study confirms that a model is a graphical representation of the system and could be utilised to construct a model that represent a system itself. The study explains that a model enables analyst to predicts how the system behaves under changing conditions to determine if it is worth introducing changes on the system it represents. In addition, the study states that the model could be experimented with versus the system it represents.

AnyLogic model could be used to create complex systems model such as banking, manufacturing plant, process operation etc. [61]. Carson [62] states that simulation could be used to proposed changes to existing system or process by modelling different scenarios to determine system efficiency and compare results. The study states that model incorporate mathematical equations, algorithm and logic to solve complex systems. In addition, the study mentioned that simulation has capacity to merge different models to give better understanding of the system performance.

AnyLogic builds model using different methodologies namely system dynamics (SD), discrete-event modelling (DEM), and agent-based modelling (ABM) [63]. AnyLogic is employed to construct the operating system and simulate to determine how much tonnage of slag is fed into the model from smelters, consider other input variables such as cement and water required to produce bricks.

Karpov [64] research has tabled the benefits of using system modelling (simulation) versus analytical traditional method as presented in Table 2.

Table 2.
Analytical vs simulation.

Analytical	Simulation
Helps to find some solutions + Easy to implement - Hard to capture time, dynamics - Hard to capture complex causal dependencies - Hard to model time-related constraints - Cannot play the model in time May miss a good solution or even give incorrect one	Naturally captures causal dependencies and timed constraints of any complexity + Easily captures stochastic nature of the problem + Can play the model behaviour in detail + Enables to measure virtually anything - Takes more time and skills to develop Gives better, more informed solutions

[64]

Borshchev [65] study describe AnyLogic as that model that support three methods on a single platform and the three methods are namely: system dynamic (SD), discrete event simulation (DEM) and the agent-based simulation (ABM)

Table 3 Reflects the analysis on different simulation models to select the most preferred method.

Table 3.
Analysis of different modelling and simulation techniques.

	AnyLogic	Vensim	FlexSim	ANSYS
ABM	Yes	Yes	-	-
SD	Yes	Yes	Yes	-
DEM	Yes	Yes	Yes	-
Free download	Yes	Yes	Yes	Yes
User friendly	Yes	Yes	Yes	Yes
Integrate with other models	Yes	-	-	-

Based on the ingenuity, capabilities, user friendly of the model, AnyLogic is the preferred simulation model to conduct research because it has capability to work with another model Vensim.

There are multiple simulation models in the market and for this study AnyLogic, Vensim, Flexsim and ANSYS Simulation model were explored in greater details. Table 3 enable decision making to choose the most suitable model was drafted and AnyLogic is selected as most preferred simulation model by the researcher because of its capabilities.

3.2. Modelling and Simulation Methodology

Error! Reference source not found.1 presents the model constructed using AnyLogic to represent the slag repurposing process.

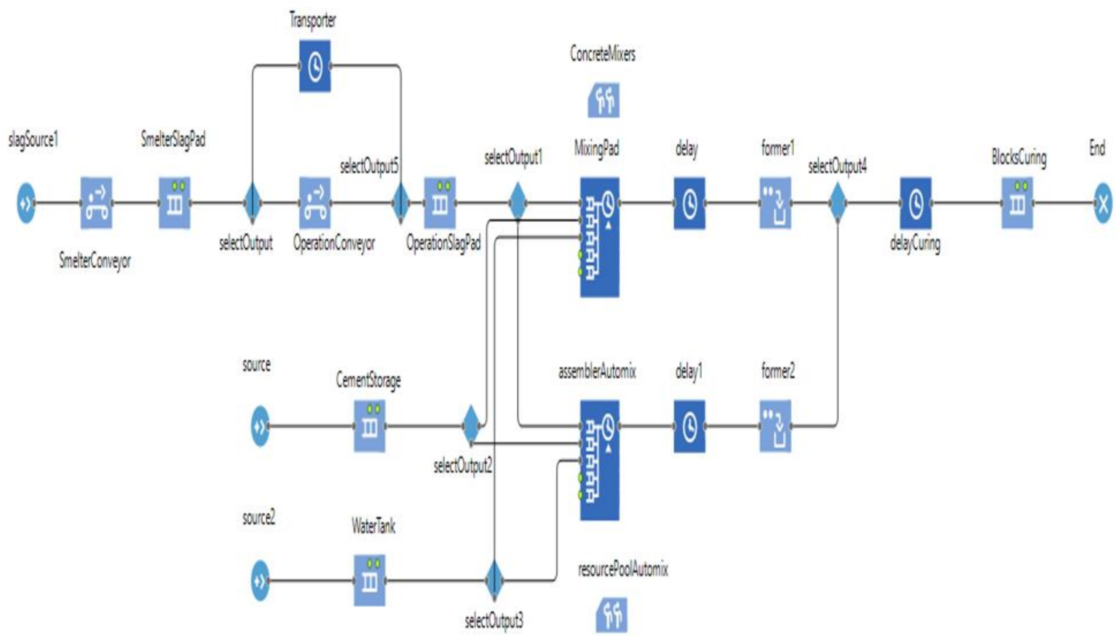

Figure 1.
The model of the slag repurposing process.

3.3. Human Resource Requirement

The material is mixed at appropriate ratios before mixing to ensure optimum results. Wheelbarrow is used to move material closer to mixing pad and easy to carry. Water is measured using bucket containers to ensure correct quantity is used. Extra care to be considered during rainy season to prevent mixture being too wet.

Table 4 presents the resource utilisation where different resources are tracked to ensure maximum utilization.

Table 4.
Operation resource requirement.

Resource Requirement			
Description	**Equipment**	**Personnel/shift**	**No of teams**
Tipper truck	1	1	1
Flat-bed Truck	1	1	1
Front-end Loader	1	1	1
Automatic mixer	1	1	1
Forklift operator	1	1	1
Manual mixing	6 shovels, 6 wheelbarrows	14	2
Automatic mixing	2 shovels, 2wheelbarrows	2	1
Brick forming	4 egg-lying formers see **Error! Reference source not found.**	12	4
Bricks sorting		8	4
General labourer	1 broom	1	2
Site Supervisor	1	1	2
Safety Representative		2	1
		45	
Site manager	1 laptop, office space	1	1
Administrator/ Buyer	1 laptop, office space	1	1
		2	
Night Shift coverage		45	
Total		92	
sub-Total		368	

The total number of human resources required for the functional operation is 92 as per Table 4 above. The operation requires additional resources as and when required on temporal basis. The four sites need a total number of 368 permanent stuff and a number of temporal staff for short term. This is crucial to ensure that complementary resources are available for activities that are lagging. Further assessment to be conducted to verify if the temporal individuals could not be employed on permanent basis.

According to research by Zankoul, et al. [66] state that simulation is used to study construction labour productivity on site, to estimate the productivity output.

AnyLogic, DEM simulation tool is selected for this study to determine how many bricks/blocks are manufactured using different resources. The output results are utilised to determine how many housings can be completed within a year and how many job opportunities can be created. This is achieved by breaking down the planned number of houses and slip them over a year. The basic calculations are carried to determine bricks output per year. The simulation is used to select the combination that yields maximum results while ensuring maximum resource utilization.

Running multiple experiments helps to understand the system performance under different conditions and resource availability. This ensures that most scenarios are tested to ensure that selected option yield better results compared to others. The created model results proved to be reliable as certain facts around the results can be verified using different methods. The model is set to run for 30 consecutive days so that results can be analysed. The researcher applied the strategy whereby the system was first drawn to represent the process flow and later translated into the model where each block representing the process was drawn. The complete model was run couple of times to create unique experiment to identify process bottleneck and identify the experiment that yield maximum results. The researcher did not explore the capabilities of the model in full whereby the 3D modelling can be created to help visualise the action

4. Results and Discussion

4.1. Resource Utilisation

Figure 2 presents the resource utilization as extrapolated from the model during simulation.

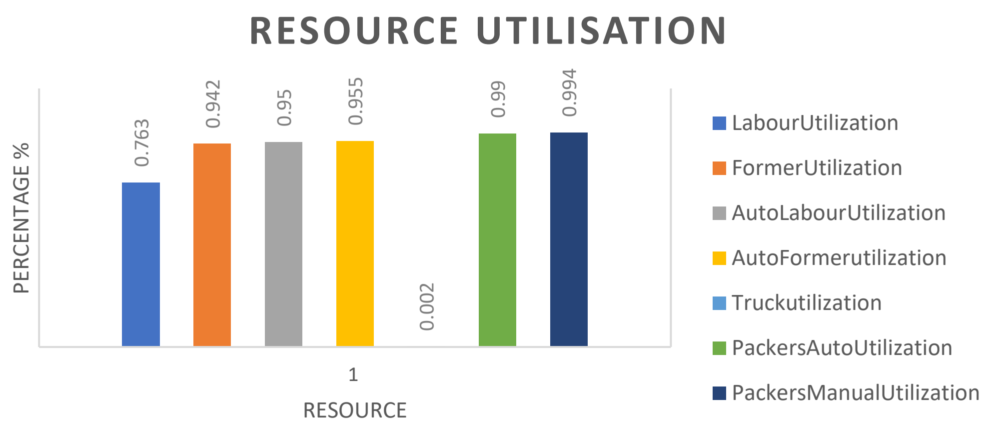

Figure 2.
Resource utilisation.

Based on the Figure 2, most resource utilisation is above 90% of which is represent maximum utilisation except for the Truck which is underutilised. This resource utilisation results in maximum number of bricks manufactured per day. Additional resources to be acquired to ensure that personnel have break in between tasks to prevent burn outs. Overworking people result in absenteeism and less production over time due to fatigue. To prevent plant stoppage due to operators unavailable, a recommendation to train all personnel to operate the automatic mixing batch plant is recommended and have additional drivers forming part of the team readily available to operate mobile equipment in case of absentees of some of the operators. Labourers to be trained in all aspect of the business to ensure that people can be moved around as and when required.

According to research by Chen and Yucesan [67], the model can provide graphical representation. The simulation can be accessed using different we browsers and accessed in any computer.

The most experienced team members to supervise bricks sorting to ensure that rejects are removed from the storage and destroyed to ensure quality work is guaranteed. The reject has been ignored as the team gets better with time to produce quality bricks and increase production output. The product is placed on pallets for easy of loading and offloading. The forklift is utilised to load ready for dispatch products onto the trucks. This prevent handling issues whereby finished product can be damaged during loading. The lowbed is fitted with jib to offload bricks at destination.

4.2. Housing Requirements

Figure presents the number of houses that can be completed within the year to meet DHS target.

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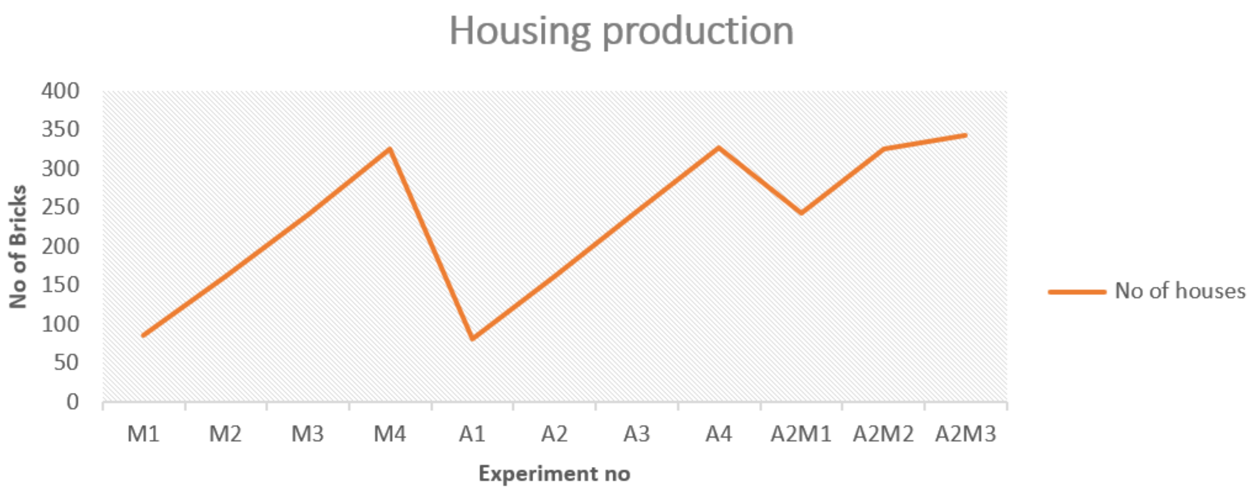

Figure 3.
Housing production.

Table 1 represents the number of houses that can be completed within the year to meet DHS target.

Table 1.
A2M2 houses performance vs demand.

A2M2	Bricks	Houses
Per day	16333,33	10,87
Per week	122500	81,50
Per month	490000	326
Per year/ operation	5880000	3912
No of operations		4
Total	23520000	15648

The plant is capable of producing 16 333,33 bricks per day. The simulation is based on the 24-hours operation. That means 122 500 bricks are manufactured in a week and 490 000 bricks in a month. That means the operation is capable of producing enough bricks to complete 326 RDP houses per month. Each operation is capable to produce enough bricks to complete 3 912 houses in a year.

According to report by Settlement [46], DHS targets to deliver 30 000 social housing by year 2024, for this exercise that will be used as annual target. Therefore, if the operation is capable to produce 15648 of 30 000 is equivalent 48 % of the required target as shown in Figure 46. A greater study to be conducted to ensure that night shift operation can be done safely without putting the lives of the involved personnel at risk and achieved desired quality product. When the conditions are in favour, night work can continue to maximise product output.

Figure 4 presents the housing demand chart as to what degree the housing by DHS will be achieved.

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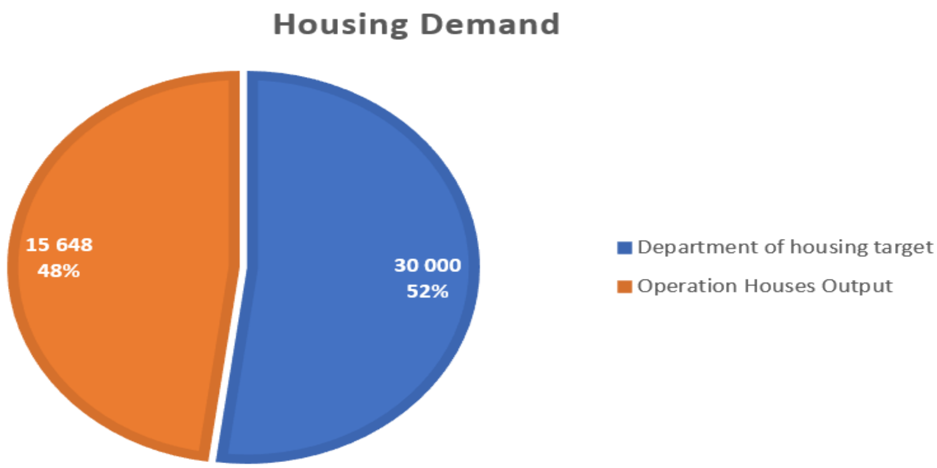

Figure 4.
Housing demand.

4.3. Smelter Savings

The smelter stands to save money by giving slag away free of charge to the operation to manufacture bricks.

Table 2 represents the savings to be realised by smelter in ten-year's time.

Table 2.
Smelter savings.

	Smelter potential savings		
			Fuel costs/Liter
1	Equipment diesel consumption	Quantity	R25,00
	per day	25	R625,00
	per year	365	R9 125,00
	No of equipment	5	R45 625,00
	Total diesel saving in 10 years	10	R456 250,00
2	Personnel	Quantity	Yearly Package
	Operators	5	R500 000,00
	Total salary per year		R2 500 000,00
	Total Salary saving in 10 years	10	R25 000 000,00
3	Maintenance Costs	Quantity	Budget per Year
	Plant Equipment	5	R50 000,00
			R250 000,00
	Total maintenance saving in 10 years	10	R2 500 000,00
4	Equipment Replacement Costs	Quantity	Price per Plant
	Plant Equipment	5	R3 500 000,00
	Saving Equipment once in 10 years		R17 500 000,00
5	Slag pad preparation reinforced concrete 300mm deep (m^2)	1	R136 300
		10000	R1 363 000 000
6	Pollution control dam 15 000 m2 x 6 m deep	1	R3 133
		15 000	R46 995 000
7	Land acquisition (Hectare)	1	R10 000 000
Total save over 10-year period per site		1	R1 465 451 250
Total saving across 4 sites		4	R5 861 805 000

The removal of 5 identified equipment results in R13 687 500,00 on diesel in ten years. The removal plant equipment will result in the removal of 5 operators at the saving of R25 million in ten years. The removal of 5 equipment results in total maintenance saving of R2,5 million in ten years. The smelter is going to save R 1,4 billion per operation by giving the slag away free of charge to manufacture bricks and potentially save over R5,8 billion across all sites in ten years. The savings can be utilised to finance other critical projects required to keep smelter running.

According to the research by Chen and Yucesan [67] simulation run allocation scheme for maximizing efficiency in simulation experiments for decision making under uncertainty. The purpose of simulation is to minimize the total computation costs and maximise simulation quality. Simulation technology such as DES is commonly used to evaluate large-scale real systems with complex stochastic behaviour. The large number of simulation experiments runs are required to determine budget estimate for each design alternative.

The savings will be as the results of using minimum space to store slag, not requiring additional pollution control dam to store water drained from slag pad. Only two plant equipment required to move material across to new site. That means plant operators, diesel and equipment maintenance budget is potential saving.

Table 3 represents the cashflow over 10-years period to determine Net present value (NPV), Internal Rate of Return (IRR) and payback period.

Table 3.
10-year plan.

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
year	1	2	3	4	5	6	7	8	9	10
Initial costs	-111 667 600	-27 916 900	-27 916 900	-27 916 900	-27 916 900					
Running costs	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133	-126 604 133
Inflation 9%		-11 394 372	-11 394 372	-11 394 372	-11 394 372	-11 394 372	-11 394 372	-11 394 372	-11 394 372	-11 394 372
Tax 27%		-34 183 116	-34 183 116	-34 183 116	-34 183 116	-34 183 116	-34 183 116	-34 183 116	-34 183 116	-34 183 116
	-126 604 133	-172 181 620	-172 181 620	-172 181 620	-172 181 620	-172 181 620	-172 181 620	-172 181 620	-172 181 620	-172 181 620
Sales	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000	188 160 000
Inflation 9%		16 934 400	16 934 400	16 934 400	16 934 400	16 934 400	16 934 400	16 934 400	16 934 400	16 934 400
Tax 27%		50 803 200	50 803 200	50 803 200	50 803 200	50 803 200	50 803 200	50 803 200	50 803 200	50 803 200
	188 160 000	255 897 600	255 897 600	255 897 600	255 897 600	255 897 600	255 897 600	255 897 600	255 897 600	255 897 600
Cashflow	-50 111 733	55 799 080	55 799 080	55 799 080	55 799 080	83 715 980	83 715 980	83 715 980	83 715 980	83 715 980
Cum cashflow	-50 111 733	5 687 347	61 486 427	117 285 506	173 084 586	256 800 566	340 516 545	424 232 525	507 948 505	591 664 484

Table 4 represent the NPV, IRR and payback period.

Table 4.
NPV, IRR, PBP.

NPV	**247 927 031,99**	**10yr NPV =**	**R247 million**
PB period (C4)	3 years		
IRR	114%		

Therefore, the NPV is R 247 million, payback period is 3 years and IRR is 114%.
Figure 5 presents the 10-year cashflow plan.

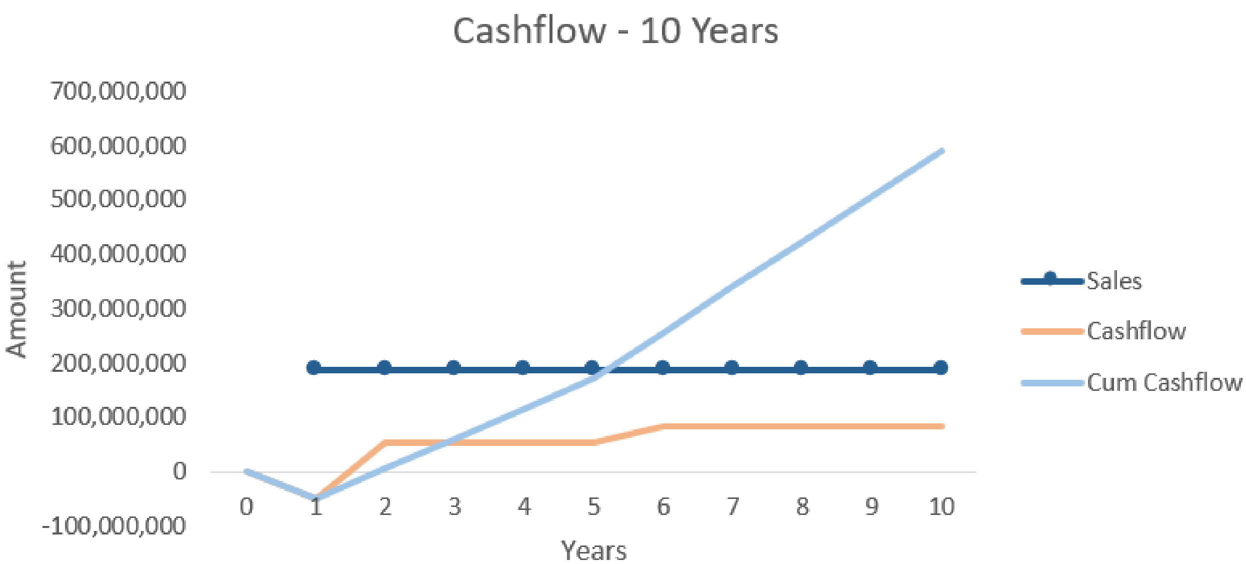

Figure 5.
10-year cashflow plan.

4.4. Environmental Improvements

Slag pad is prepared by make use of concrete slab to prevent water seepage into water table. Preparing the grounds affects the environment as there's no vegetation that can grow in the prepared area. To prepare the area, selected land is stripped and all trees and grass within the area is uprooted. The more the area is kept in its original state the better for environment. Three trucks or more are required to move the slag from silos to extended areas for proper placement. Excavator is utilised to level the material once transferred onto the slag pad. The environmental impact caused by exhaust fumes can be quantified and impact measured. The bricks manufacturing process can operate with one truck to move material across and one FL to load material onto the truck. That means the operation uses two trucks less than the current set-up. The excavator is not required to level the material the need to level is eliminated. In total five plant equipment is removed from the equation of which is good for environment. This improves air quality and save monies for operators, diesel and equipment replacement.

5. Conclusion and Recommendations

The purpose of this study was to repurpose the slag into bricks for low-cost housing. This was achieved by implementing the Discrete Event Modelling (DEM) in the AnyLogic software. The results achieved from running multiple experiments are captured and analysed. The simulation experiment A2M2 is selected based on the number of bricks produced per calendar month when compared to other experiments. The operation will consume 1.5 of what the smelter produces per year. That means the operation will consume 667 m3 per annum of slag from material accumulated over the years. The experiment A2M2 will give optimal performance with less resources compared to A2M3 which produces 17 more houses with higher input costs. This experiment has potentially to create +90 job opportunities per site and +360 overall direct employments. The operation has capacity to create indirect job opportunities such as material delivery, security, equipment maintenance etc. This experiment has manufacturing output capacity of 326 houses in thirty (30) days and 3 912 houses per year. This means all operation has total capacity of 15 648 houses per annum. That is 47% of building material (hollow-bricks) required by the DHS to deliver by 2024. The smelter will save money by giving the slag for free and will enjoy this benefit for as long as they are in business. The operation has positive environmental impact as it changes the life cycle from "cradle to grave" to "cradle to cradle". The identified five earth moving plant equipment currently used for slag maintenance will no longer be required and that will significantly reduce air pollution over time. The operation needs the initial investment of R111 million in the first year and R27 Million for the next four years. This will allow the gradual business growth at manageable rate over the years. The operation has potential to have positive cashflow from year two and projected profit of R591 millions over ten years.

The study contributed positive to the body of knowledge by demonstrating that waste has potential to create new product or used as raw material for future products. There are multiple beneficiaries that are linked to the successful implementation of the findings.

This study is limited to simulation modelling and did not conduct any laboratory experiment to obtain quantitative and qualitative data. Future work is recommended whereby laboratory experiment be conducted to verify mortar mixing ratios for optimum results. The prepared samples to be tested and approved by the South African Bureau of Standards (SABS) to ensure that it meets all requirement for building. The start-up funds required to get the operation running are high and therefore a proper business case is required to access funding. The operation efficiency can be upgraded with time to that the operation produces maximum results.

- The unavailability of experimental data limited the evaluation of the developed model to the use of simulated data. Future work can consider the use of primary data set for the evaluation of the developed predictive model.
- The use of student version limited the experiment running time as it stopped when maximum units have been reached. Future simulation to be modelled on the full version for extended running period.
- The bricks curing time is estimated. The recommended future work is to conduct experiment as different weather patterns are experienced in SA. Understand the effects of quick curing as some areas in Limpopo experience too much heat.
- The environmental impact assessment could not be finalised. Future work to include measuring the exact quantity of emissions released by each plant. This to consider the physical condition and engine capacity for each plant.
- This study was completed using DEM only. Future work to use multiple modelling such as ABM, SDM and combination of system to compare results.
- The health impact due to handling the slag is unknown. For future to conduct study to determine minimum health & safety requirement that needs to be in place to protect employees from suffering in long term due to exposure or handling slag.

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