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INTEGRATED LIFE CYCLE ASSESSMENT AND SYSTEM DYNAMICS MODEL FOR PREDICTION OF CEMENT PRODUCTION AND ENVIRONMENTAL IMPACT OF CEMENT INDUSTRY.

BY

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Declaration

I, Oluwafemi Ezekiel Ige, declare that this thesis is the original of my work and any published work of another person has been duly acknowledged and referenced. It has not been submitted for any degree or examination at any other university. This work is being submitted for the degree of Doctor of Engineering (D.Eng) in the Department of Industrial Engineering.

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Dedication

This work is dedicated to God Almighty, my helper, who saw me through this program.

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I thank the Almighty God for His unending mercy and grace before and during this point of my doctoral degree program. I sincerely thank my main and co-supervisors, Dr. Oludolapo A. Olanrewaju, Prof. Kevin J. Duffy & Dr. Obiora C. Collins, for their supervision, encouragement and assistance during this research. I am very grateful.

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Abstract

Cement is one of the most produced materials globally. The cement industry faces significant environmental challenges due to high raw materials usage and energy consumption, resulting in emissions that are global and local environmental concerns. The industry faces challenges globally in reducing its carbon dioxide (CO_2) emissions while saving material and energy resources. The cement industry contributes to high global greenhouse gas (GHG) emissions due to the calcination of raw materials and fuel burning. Globally, cement plants are among the sectors with the highest energy consumption and the highest release of potentially harmful health-threatening carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and dust particles. This study focused on Portland cement production and environmental impact-related problems and found the best ways to discuss the potential policies and scenarios to reduce CO_2 emissions and ensure sustainable cement production while maintaining the strength of the equipment and the quality of the plant production requirement. Since the cement industry's environmental impacts are expected to increase, assessing the cement production and carbon emissions produced at each stage of the cement life cycle is compulsory to mitigate these environmental impacts.

Life cycle assessment (LCA) has been used in many studies to assess the environmental impact of cement production and investigate ways to improve environmental performance. In this thesis, the first step uses life cycle impact assessment (LCIA) based on the Recipe 2016 v 1.04 midpoint and endpoint methods to investigate the environmental impact of 1 kg of Portland cement produced in South Africa using Ecoinvent database v3.7.1, integrated with SimaPro 9.1.1. software to assess the impact categories. The study was conducted using data modelled from South African cement plants and uses a cradle-to-gate system boundary. The integration method includes data collected between 2000 and 2017 on cement production and real GDP. Data on cement production were obtained from the South African greenhouse gas inventory report of 2017. The data on South Africa's real GDP in US dollars were obtained from World Economics. The LCA-SD framework of cement production in South Africa involves three main stages, (i) gathering data for key LCA processes, (ii) assessing the impacts of production processes using LCA SimaPro 9.1.1 software and (iii) integrating the results of the LCIA as input variables with system dynamics (SD) to predict the possible future dynamic and long-term environmental impact of cement production in South Africa. An integrated LCA-SD methodology is used to assess and predict the environmental impacts of the cement industry.

This research uses the LCA method together with the system dynamics framework in the form of a mathematical model to study how to reduce GHGs in cement production. The possible dynamics of cement production and the long-term environmental impact of cement production in South Africa were investigated using these methods. According to the results, clinker production and electricity usage stages contribute the most to atmospheric impact (global warming, which causes climatic change due to high CO_2 emissions), followed by raw materials and fuel consumption, contributing to the toxicity and resource depletion impact category. These stages contribute more than 76% of CO_2 eq. and 93% of CFC-11 eq. In the midpoint method, CO_2 is the most significant pollutant released. Among the three main damage categories in the endpoint method, human health is the most affected by releasing substances into the air during Portland cement production. The clinkering stage is the most harmful production stage for human health and the ecosystem since it produces the highest amounts of CO_2 gas.

From our projections, the pollutant outputs of cement production in South Africa will approximately double by the year 2040, with the associated long-term impact of an increase in global warming. The proposed LCA-SD model methodology enables us to predict the future dynamics of cement production and its long-term environmental impact, which is the primary research objective. Using these results, several policy changes are suggested for reducing emissions, such as introducing more eco-blended cement production, carbon budgets and carbon tax.

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List of Acronyms

AFS	ALTERNATIVE FUELS
AoSL	AREA OF SIGNIFICANCE TO LIFE
AR	ALTERNATIVE RESOURCE
BAT	BEST AVAILABLE TECHNIQUE
CCS	CARBON CAPTURE AND STORAGE
CED	CUMULATIVE ENERGY DEMAND
CH_4	METHANE
CKD	CEMENT KILN DUST
CLD	CAUSAL LOOP DIAGARAM
CO	CARBON MONOXIDE
CO_2	CARBON DIOXIDE
CO_2eq	CARBON DIOXIDE EQUIVALENT
DALY	DISABILITY ADJUSTED LIFE YEARS
DCB	DICHLOROBENZENE
ECRA	EUROPEAN CEMENT RESEARCH ACADEMY
E_q	EQUIVALENT
FU	FUNCTIONAL UNIT
GDP	GROSS DOMESTICS PRODUCT
GGBFS	GROUND GRANULATED BLAST FURNACE SLAG
GHG	GREENHOUSE GAS
GT	GIGA TONNES
GWP	GLOBAL WARMING POTENTIAL
HH	HUMAN HEALTH

IEA	INTERNATIONAL ENERGY AGENCY
ILCD	INTERNATIONAL LIFE CYCLE DATABASE AND GUIDELINES
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ISO	INTERNATIONAL ORGANISATION FOR STANDARDISATION
KM	KILOMETRES
KW	KILOWATTS
KWH	KILOWATT-HOURS
KZN	KWAZULU-NATAL
LCA	LIFE CYCLE ASSESSMENT
LCIA	LIFE CYCLE IMPACT ASSESSMENT
LCI	LIFE CYCLE INVENTORY
MJ	MEGAJOULES
MT	MILLION/ MEGA TONNES
NPC	NATAL PORTLAND CEMENT
N_2O	NITROUS OXIDE
OPC	ORDINARY PORTLAND CEMENT
PPC	PRETORIA PORTLAND CEMENT
RDF	REFUSE DERIVED FUEL
SCMS	SUPPLEMENTARY CEMENTING MATERIALS
SETAC	SOCIETY OF ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY
SD	SYSTEM DYNAMICS
TE	TERRESTRIAL ECOSYSTEM
TDF	TYRE DERIVED FUEL
TONS	TONNES

UNEP	UNITED NATIONS ENVIRONMENT PROGRAMME
UNFCC	UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
VOCs	VOLATILE ORGANIC COMPOUNDS
1,4-DCB	1,4-DICHLOROBENZENE.

Research Outputs

This section presents publications that have been published/accepted/submitted.

ISI/SCOPUS/DoHET Accredited Journals

O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins (2021) A review of the effectiveness of Life Cycle Assessment for gauging environmental impacts from cement production Journal of Cleaner Production, p. 129213, 2021/10/02/ 2021. https://doi.org/10.1016/j.jclepro.2021.129213 (Published)

O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, "Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method," Energies 2022, 15(7), 2708; https://doi.org/10.3390/en15072708 (Published)

O. E. Ige, K. J. Duffy, O. A. Olanrewaju and O. C. Collins, "An Integrated System Dynamics Model and Life Cycle Assessment for Cement Production in South Africa," Atmosphere 2022, 13(11), 1788; https://doi.org/10.3390/atmos13111788 (Published)

O. E. Ige, K. J. Duffy, O. A. Olanrewaju, and O. C. Collins, "Environmental Impact Analysis of Portland Cement (CEM1) Using the Endpoint Method. (Preparation)

Book Chapter

O.E. Ige, F. L. Inambao, O.A. Olanrewaju, K.J. Duffy, and C.C Obiora, "Drivers and Barriers to Industrial Energy Efficiency: A Case Study of South Africa's Cement Finishing Mill Plant". Advances in Energy Research Vol 33 eBook ISBN: 978-1-53618-136-4, 2020. Nova Science Publishers.

https://novapublishers.com/shop/advances-in-energy-research-volume-33 (Published)

CHAPTER 1 : Introduction

1.1 Introduction

Global environmental issues, such as global warming (climate change) and resource depletion, have been among the human race's most difficult worries since the nineteenth century [1]. Numerous new technologies, including electricity, were developed during the second industrial revolution, increasing the demand for fossil fuel energy [2]. Today, energy is considered one of the most critical factors in the formation and development of industrial society. Energy is among the most debated topics in economics and the most important subject in the economics literature. The energy crisis is among the crucial problems facing the world recently, involving the scarcity of energy supplies and increases in daily energy consumption. The inputs used in producing most goods and services are energy, raw material capital and labour [3]. Governments and international organisations have begun to move toward sustainability goals due to the world population's rapid growth, rising energy demands, fossil fuel limitations and the threats of greenhouse gas (GHG) emissions that lead to global warming. The industrial sector plays a vital part in energy consumption globally. Global warming is one of the most significant threats to life, constant problems such as GHG emissions have been recognized as a crucial hazard to humanity and the environment. Since energy production uses fossil fuels, such as coal, petroleum, crude oil, and natural gas products that produce carbon dioxide (CO_2), the environmental effects are critical. Between 1750 and 2005, CO_2 emissions contributed the most to climate change [4, 5].

Energy is essential for economic development globally and the lack of adequate energy is a major concern in energy-intensive industries. The cement industry accounts for a substantial share of these energy-intensive industries. It emits dangerous health-threatening greenhouse gases (GHGs) such as carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxides (NO_x). These gases are released mainly from the burning of fossil fuels during the production of cement. The sector is essential because cement is the main constituent needed in the construction industry. In recent years, energy consumption in cement production and the associated environmental impact has increased. Concerns around industrial energy consumption and its harmful environmental effects have led manufacturers to set up energy management teams. The cement sector will continue to play a pivotal role in expanding global economies with increased housing and modern infrastructure requirements. Cement production is expected to increase by more than 5 billion tons by 2030 [6]. This forced the cement industry to produce enormous amounts of cement products to meet the demand, classifying cement production as an intense industry in terms of energy and environmental impact. However, the sector is facing many environmental impacts. Thus, knowledge of the long-term environmental impact of cement production is required because the energy and materials consumed in the process are increasing.

Environmental impact has become a priority for both the government and the private sector [7]. Also, Global warming is one of the most critical environmental issues of the 21st century, with significant effects on human health, the environment and the global economy. Due to the enormous raw materials and energy consumption in cement production, the industry is considered as one of the industries that cause natural resource depletion and negative environmental impacts [8, 9]. The cement industry is an energy-consuming subsector that causes an environmental impact at every production stage [10]. The total energy consumption of the cement production process is heavily reliant on electricity and coal usage [11]. CO_2 emissions have increased since the second industrial revolution due to energy demands via combustion. For example, fossil/coal-generated energy results in massive CO_2 emissions from industrial processes such as cement. CO_2 emissions have significantly contributed to global warming, which has led to different efforts, strategies, and policies worldwide to mitigate CO_2 emissions, including the Paris Agreement [12, 13]. Over 195 countries have signed the Paris Agreement, including South Africa, as of 2015 [12, 14]. These parties seek to reduce CO_2 emissions by at least 2°C or less to achieve a global temperature. As a result of the inherent carbon-intensive nature of the industry, cement producers are under pressure to make long-term process changes and adopt a more sustainable environment. Therefore, this work seeks to predict the future dynamics of cement production and the long-term environmental impact using an integrated LCA-SD framework for the cement industry in South Africa and to find potential mitigation strategies and policies to reduce the GHGs produced.

1.2 Research Background

The word "cement" involves a variety of substances used as binders or adhesives and it’s produced in large volumes. Portland cement is the most produced and widely used for buildings, bridges, roads, construction, dams, and other infrastructure. A sustainable environment cannot be built without cement, as it is essential in many areas of life. The cement production process is a multiplex processing that uses a large amount of raw materials (Limestone), fuels (energy thermal), and electricity, as well as auxiliaries such as water and air [15-18]. It takes about 110 kWh of electricity and 60 to 130 kg of fuel oil to produce one tonne of cement, depending on the cement type and the manufacturing process [19, 20]. As we all know, cement is among the widely used construction materials and Portland cement is commonly used as a binder constituent. Continuous increase in cement demand cause the use of aggregate (limestone) to increase since limestone is an essential component of Portland cement [21, 22].

The production of Portland cement needs a substantial amount of energy and significantly impacts global GHGs emissions. Portland cement production is currently under examination due to the environmental pollution from coal, anthropogenic pollutant emissions and raw materials mining activities. The cement industry ranks as the second largest anthropogenic source of GHGs after the steel industry [23-25]. The sector accounts for 5% of total GHGs emissions globally [23, 26, 27]. Recently, GHGs and their impact on the climate and threats to the environment have received much attention regarding policy, legislation and public call for technological solutions for their reduction and removal.

1.3 Global Cement Production

Demand for cement is increasing globally due to population growth and urbanization. According to Olivier et al. [28], the global demand for cement is over 4 billion tons per year, equivalent to 4 billion tons of CO_2 released into the atmosphere [29]. In 2012, global cement production in 2012 was about 3700.0 Mt. China produced 2150.0 Mt., followed by India with 250.0 Mt and the United States came in third with 74.0 Mt [30]. Global cement production continued to increase in 2016 at around 4650 Mt, with China accounting for 52% and the rest of the world accounting for 48% [31]. As of 2019, global cement production is estimated at nearly 4.1 billion tons due to higher growth rates in China and India's continuous growth as shown in Figure 1.1 [32] and it is expected to increase by 1.3-1.4%, reaching about 4.83 billion tons in 2030 [33].

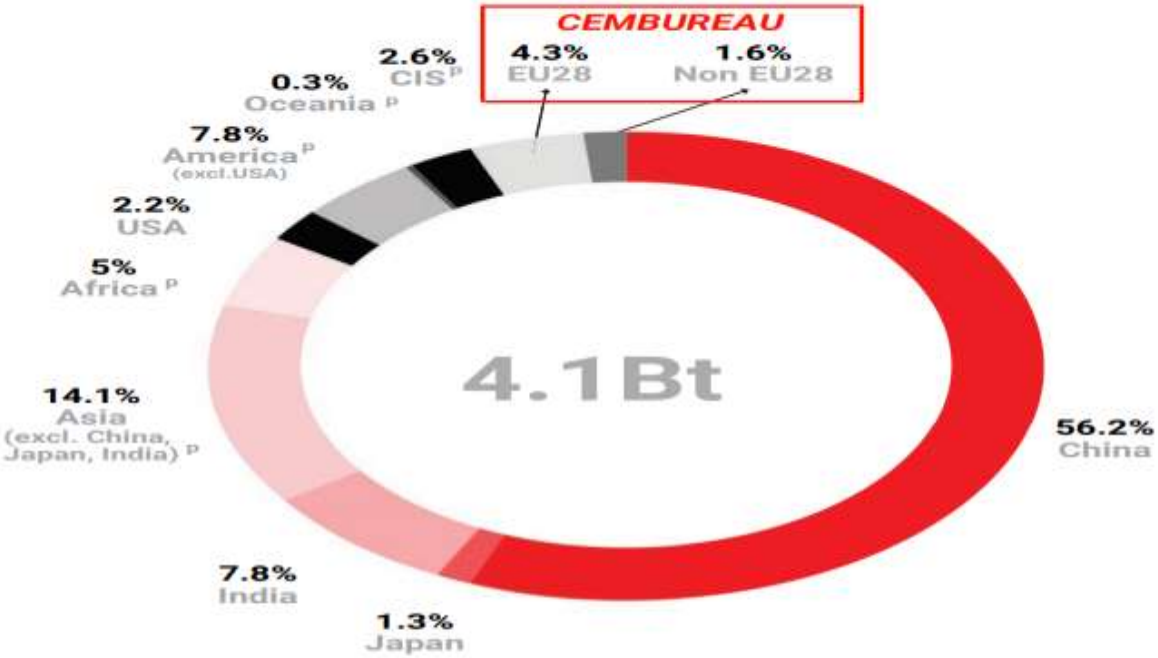

Figure 1-1 Global cement production [32].

However, volume for these two major players is highly uncertain. The world's cement production continues to be dominated by China, which produces roughly 56% of the world's cement. In comparison, the EU28 with 4.4% and The European Cement Association (Cembureau) members with 5.9% produce much less cement worldwide, as shown in Figure 1.1 [32]. As a result of the Covid-19, global cement production fell by 0.04% yearly to 4170.13 Mt, with many cement producers forced to close their plants temporarily [34].

During the 21st century, energy consumption has increased rapidly, resulting in the depletion of non-renewable resources [35]. CO_2 emissions, energy consumption and pollution, are the determining factors within the subsector. Since the cement is the product, most used in the construction and building industry, it is crucial to understand the environmental impact and cement production trends for future energy use developments, related GHGs emission and mitigation opportunities.

Most of the energy used in cement production comes from burning fossil fuels. A study by the Intergovernmental Panel on Climate Change (IPCC) [36, 37] indicated that from 1750 until 2011, fossil fuel combustion and cement production produced approximately 375 GtC annually. Cement production is expected to rise further in the coming years due to economic growth and increased urbanization in developing countries. Global anthropogenic greenhouse gases (GHG) emissions are shown in Figure 1.2. In 2010, the total GHG emissions released by electricity and heat production and other energy sectors was 35%, AFOLU 24%, industry 21%, transportation 14% and the building sector 6.4% [37], as shown in Figure 1.2.

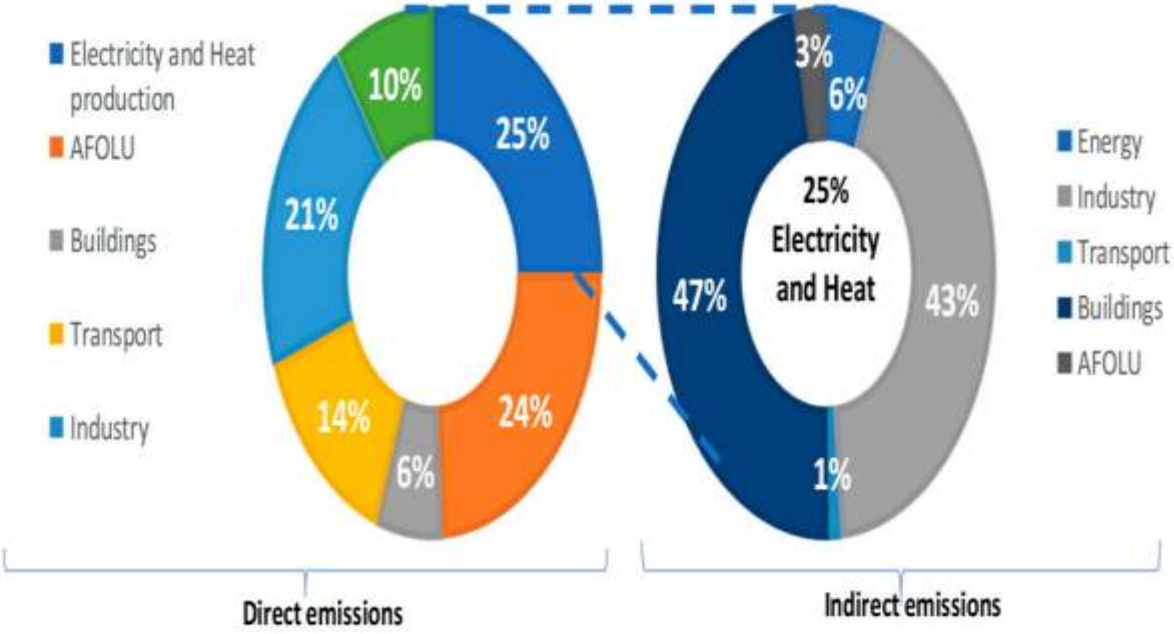

Figure 1-2 Greenhouse gas emissions by economic sectors [36, 37]

Electricity and heat production (25%), industry (21%) and transportation (14%) are the three economic sectors that contribute the most direct global GHG emissions. As shown in Figure 1.2, they represent 60% of direct global GHG emissions. Technological improvements could reduce the impact of these three economic sectors' anthropogenic

GHG emissions. Therefore, it would be reasonable to anticipate that these economic sectors will likely contribute less GHG emissions in the nearest future. The industrial sector faces a lot of challenges in terms of reducing GHG emissions. While indirect GHG emissions mainly come from buildings (12%) and industry (11%) [37]. When direct and indirect GHG emissions from both economic sectors are considered, the impact of buildings (18.4%) and industry (32%) becomes significant.

The average emissions of fossil fuels and cement production between 2002 and 2011 increased by 3.2% (from 7.6 to 9.0 GtC). This is significantly higher than the annual growth rate in the 1990s, which was only 1%. As of 2011, fossil fuel emissions reached 9.5 GtC per year [2]. Fossil fuel burning continues to be the primary source of global CO_2 emissions due to economic and population growth.

According to International Energy Agency (IEA), the direct CO_2 strength of cement production increased by 0.3% yearly between 2014 and 2017 and global cement production is expected to increase further by 2050 due to population growth, urbanization, and infrastructure construction [38]. The demand observed in countries such as China and India [39], force the production of cement, pollution and GHGs emission to increase globally. In Africa, the demographics of increasing population growth, urbanization and economic development will also lead to increases in cement production and the concomitant negative effects.

1.4 An overview of the South African energy sector

South Africa's geographical features are dynamic, with a coastline of about 2500 km. Namibia surrounds South Africa along the west coast and Mozambique along the north. South Africa is known for its fast-growing economy with advantages in natural resources, energy and financial strengths. According to the South African Department of Energy Statistics (DOE), the South African economy relies heavily on its rich coal resources. Despite its influence on human health, air quality, climate change, and wildlife, coal is the dominant energy source in South Africa. The data by DOE shows that coal accounts for about 90% of the country's electricity generation, followed by nuclear 5.2% and natural gas 3.2% [40].

South Africa is rated sixth in the world regarding recoverable coal reserves and the country's energy production depends mainly on coal [41]. South Africa is the 12th highest CO_2 emitter globally and Africa's top producer of GHGs [42]. The energy production and distribution system in South Africa is well-planned. This plan includes short, medium and long-term responses [43]. The short and medium-term plan includes increasing energy generation capacity and improving Eskom power plant maintenance [44]. The long-term plan includes finalising a master plan for long-term energy security [45]. Although South Africa is rich in coal energy production and import, its crude oil and natural gas reserves are limited. There are also several renewable energy sources available in the country. The DEM report (2016) indicates that the country's abundant sunshine is being used for potential electricity production for industrial and domestic use. The South African energy sector contributes 15% of the national output (i.e., Gross Domestic Product, GDP), which provides around 250,000 job opportunities for South African citizens [46].

1.5 South African cement production and consumption

As of 2016, the cement industry in South Africa has a total installed capacity of 21.7 million tonnes, but nearly 4 million tonnes of this capacity are idle [47]. In the South African cement industry, Portland cement is the most used binder for recycling works in construction and mortars due to its price, availability, and ability to stabilize pavement materials [48]. Portland cement production in South Africa represents 0.57% of the total global cement produced [49]. Portland cement and its many blends are examples of hydraulic cement. Cement product depends on whether it's hydraulic or non-hydraulic. Hydraulic cement can be found in wet states, whereas non-hydraulic cement must dry before it hardens.

Portland cement is made from different raw materials classified into ferriferous, siliceous, calcareous and argillaceous. The Portland cement consumption in South Africa in 2014 was 12.07 Mt, 8% less than the 12.17 Mt sold in 2013 [50]. This brings per capita consumption to 216 kg in 2014. The total included 1.3 Mt imported mainly from Pakistan. According to International Cement Review (ICR) [51] report, cement imports in South

Africa increased from 0.76Mt in 2012 to 1.1 Mt in 2013 due to the mixing capacity and differences between newly integrated plants. The average capacity of a single plant in the country in 2014 was 1.18 Mt. This is calculated based on reported consumption of 12.07 Mt and imports of 1.3 Mt of 10 integrated plants and 8 downstream plants in the country, as shown in Table 1.1.

Table 1-1 Largest South Africa Portland cement production as of 2014 [47, 52, 53]

Company	**Number of plants**	**Capacity (Mt/year)**
Pretoria Portland Cement (PPC)	7	4.75
Lafarge Africa	2	3.40
Natal Portland Cement (NPC-Cimpor)	3	3.15
Sephaku Cement (Dangote)	2	2.50
AfriSam	3	2.05
Mamba Cement	1	1.20

Due to transportation problems, the cement industry is sometimes divided by geographic location. Therefore, the quarry should not be more than 250 kilometers from the plant [54]. Although transport by sea is the most efficient way, the case is different in South Africa, where the product is transported by road. The following are the major players in the production and marketing of Portland cement in South Africa:

1.5.1 Pretoria Portland Cement (PPC)

Pretoria Portland cement was Incorporated in 1892 as the first cement producer of ordinary Portland cement (OPC) in South Africa. Over the years, PPC has expanded across Sub-Saharan Africa as a strong establishment that adapts and responds to changes in various operating environments. The company has 7 cement factories, 5 milling plants, 2 blending capacities and 27 ready-mix plants in the sub-Saharan Africa region, allowing it to meet the high demand in markets at a competitive price with a production capacity of 8 million tons of cement per year [55, 56]. According to Brown [47], PCC is the leading cement producer and supplier in South Africa, with about 35% production capacity installed in 2016. The company operates in five provinces in South

Africa, including Zimbabwe and Botswana. The company has now integrated a pan-African business across the continent, including Zimbabwe, Rwanda, Congo (DRC) and Ethiopia [56].

1.5.2 Afri-Sam

Anglovaal Portland cement Company Ltd started in 1934 in South Africa. In 1996, after operating for 60 years, the company changed its name to Alpha (Pty) Limited when the Anglo-Alpha Hippo Quarries and Pioneer Concrete merged. It restructured its management hierarchy to support the South African legislative policy on Black Economic Empowerment (BEE) that was passed into law in 1994. In 2008, after another 13 years of trading, following a historic BEE transaction, Holcim, South Africa's head company of Alpha (Pty), formed the AfriSam brand [57, 58]. As of 2013, Afri-Sam employs over 2,000 permanent employees and close to 1,000 contractors across Southern Africa, such as Lesotho, Swaziland, and Botswana, where it operates. There are six production facilities and nine cement depots at Afri-Sam, with a total annual capacity of 4.6 million tons.

Afri-Sam can produce 800 000 tonnes of slag cement annually and 200 000 tonnes of blended cementitious materials at its Vanderbijlpark operation, making Afri-sam a leading slag cement producer in South Africa [58]. Afri-Sam continues to differentiate itself from other South African cement producers by delivering pre-blended dry mix cement and plaster products on-site construction using a pneumatic volume cement tanker which is drawn into a sealed silo. This method prevents dust from the construction site and makes it more environmentally friendly than the conventional way of transporting dry mixtures in open trucks [58].

Afri-Sam is a major cement and concrete producer in Sub-Saharan Africa. In 1994, AfriSam was the first cement, aggregate and ready mix manufacturer to issue an environmental policy [59]. Afri-Sam has developed a comprehensive sustainability roadmap, which identifies and addresses many priority areas, including waste and energy management.

1.5.3 Lafarge

The operation of Lafarge began in England in 1913. Lafarge was founded by an English company named White's South African Cement Company. In 1914, Lafarge started producing cement in South Africa at Hennenman in the former Orange Free State and now present the Free State province. It is one of the major cement manufacturers in sub-Saharan Africa [60, 61]. Increased industrialization and cement demand prompted the Blue Circle South Africa to expand its cement operations and in 1948, the Lichtenburg plant (in Northwest province) opened. In 1998, after 50 years of the Lichtenburg plant inauguration, Lafarge acquired Blue Circle South Africa and rebranded it in compliance with the South African BEE requirements; Lafarge Industries South Africa (Pty) was created.

Lafarge South Africa is a member of the Lafarge-Holcim group. It is a leading producer and supplier of cement, aggregates, ready-mixed concrete, fly-ash gypsum plasterboard and a major supplier of construction materials in the country. As of 2008, the Lafarge cement facility at Lichtenburg in the North West Province produces 2,4million tons per year [61]. Lafarge Lichtenburg proved its commitment to the future of South Africa by commissioning a project worth R1.2 billion to boost its cement production by one million tons annually, making its production capacity over 3 million tons of cement yearly with over 2000 staff [53, 62].

1.5.4 Sephaku Cement (Dangote)

Sephaku Cement was the first new entrant to enter the cement market in South Africa in 1934. According to Sephaku Cement, limestone is one of the most scarce resources in South Africa, but the company secured supplies from the Anglo-American mining company in 2006 [63]. In 2009 the financial year, Sephaku Cement acquired a limestone mining license. Aganang cement plant in Lichtenburg North West province started initial production at a single kiln clinker line with a 2.5mt/year capacity in 2014 [64]. The company entered the cement market because it believes in long-term sustainable cement growth. More work still needs to be developed in South Africa, even with its relatively good infrastructure. Moreover, aged production facilities have caused production to remain static when it should be increased cost-effectively.

The Sephaku Cement plants are supported by state-of-the-art technology, contributing to competitiveness and cost-efficiency. The South African cement market was quite complex and developed when Dangote entered the market by acquiring controlled shares in an established company in the country. Dangote Industries Limited (DIL) purchased an additional 44.24% share to add up to a 64% stake in Sephaku Cement South Africa in 2010 [65]. Sephaku Cement changed its name to Dangote Cement in November 2015. Despite this, the company decided to keep the Sephaku brand in the country [64, 65]. Dangote Cement currently operates two production plants at Aganang and Delmas in Johannesburg. The Aganang plant has a 1.8 Mta capacity, while the Delmas plant has a 1.5 Mta. Capacity.

1.5.5 Natal Portland Cement (NPC Cimpor)

The history of the NPC-Cimpor can be tracked back to 1964, following the operation of Durban Cement Limited in Bellair, Durban, KwaZulu-Natal (KZN) province, South Africa. The company was renamed Natal Portland Cement (NPC) in 1984 primarily due to its operations and expansions confined to the Natal region of Newcastle, Port Shepstone, and Durban. Alpha PPC and Lafarge managed the NPC until 2002 when CIMPOR (Cimentos de Portugal) completely took over the company [66, 67]. NPC-Cimpor operated independently for five years before joining a 26% BEE shareholding partnership in compliance with the South African empowerment policy drive. NPC-Cimpor was eager to fill the cement shortage gap by installing the latest kiln at its Simuma plant in South Africa in 2008 (the old kiln installed in the country was more than 20 years). The modern cement kiln was installed to improve efficiency and cut costs. A leading cement manufacturer in KZN, NPC-Cimpor can produce 1.5 million tonnes of cement annually and employs more than 1000 permanent employees [66]. Natal Portland Cement South Africa is a proud member of the Inter-cement Group of Companies [66].

1.6 Material and energy flow of cement production process

Thermal and electrical energy is the energy consumed in the cement production process [68]. Due to the energy consumption at different stages of the production process and the interconnected effects of the various substantial energy users are obvious. In the cement production process, the large energy users include grinding, mainly electrical energy, and pyro processing primarily uses thermal energy obtained from burning fossil fuels, as shown in Figure. 1.3.

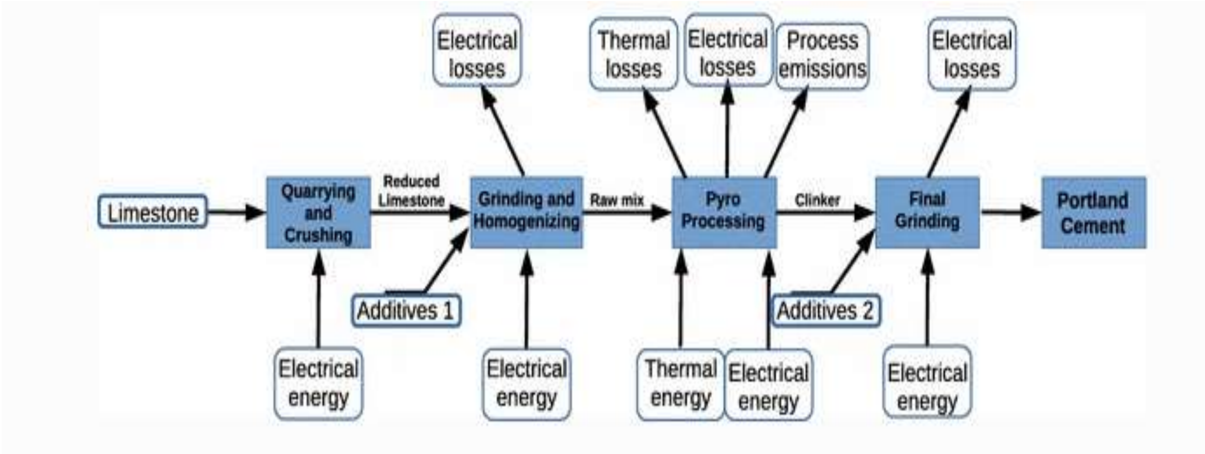

Figure 1-3 The material and energy flow into the main production sub-processes [69].

Cement plants are energy-consuming because of the large amount of thermal and electrical energy required, as shown in Figure 1.3 above [69, 70]. The main cement production process converts the main raw material and limestone into the final cement product [71]. The cement production process involves several steps using different energy sources (Figure 1.3). The cement milling process usually uses electrical energy and is the most consumed electricity in cement production [72]. Typically, a finishing mill uses nearly 40% of the total electricity used in cement [73]. Preparing raw materials is the first stage in cement production, i.e., moving the materials received to their required location (Cement plant). At this stage, the most used energy sources are electricity for conveying and crushing materials and fuels for transportation [19]. In a cement plant, the secondary milling processes happen using electricity to drive the motors, where the raw mill blends the raw materials to produce clinker [19].

Preparing fuel is likewise a milling process that mills coal into better particles for use in the kiln-burning process. The burning process (clinkering) in cement production involves using a kiln to convert raw materials into clinkers [19, 71]. The fuel (coal) is used to heat the kiln, the main contributor to the cement plant's overall energy consumption [19, 71]. The kiln is rotated by an electric motor while fans were used to cool the exterior. Both processes consumed electricity [74]. It is obvious from Figure 1.3 that a typical cement plant's process and energy flow are mostly integrated with different energy sources.

1.7 Think through Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an environmental methodology that has been widely utilized around the world to assess the environmental and economic impacts of a particular process system [75]. When using LCA the same methodology is applied across all products and during all stages, including production, energy consumption, transportation, maintenance and disposal or recycling at the end life of a product. The entire LCA considers the impacts of energy consumption and emissions related to the product's life, e.g., cement. Several studies have been conducted to measure the environmental impact of energy consumption in cement plants [76, 77]. However, the results of LCA may vary due to the use of different LCA methods and process inputs such as raw material composition, system boundaries, fuel combinations, etc. The word "life cycle" means the main activities during the lifespan of a product, i.e., from its production, through its use and maintenance to its final disposal, including acquisition of the raw materials required. Also, LCA is a tool that can be used to determine the environmental impacts of processes defined by the International Organisation for Standardisation ISO [78, 79] by considering all the inputs and outputs related to the entire system’s life cycle [80]. Using LCA depends on the raw data quality and how reflective the data is of the real-life cycle of the processes [16].

LCA is among the most essential and known tools for environmental assessments [81-83]. According to the ISO 14040, LCA comprised of four main stages:

i. Goal and Scope Definition – This defined the basis and scope of the process's stages assessment.

ii. Inventory Analysis – Here all process stages are mapped and linked, from raw material extraction to wastewater treatment.
iii. Life cycle impact Assessment – Here consumption and emissions are converted into environmental effects. These environmental effects are weighted and classified into different impact categories.
iv. Life cycle Interpretation – It is the final step where the areas of improvement are determined.

LCA can assist decision-makers in comparing all main environmental impacts caused by their activity when determining between two or more alternatives. Specifically, LCA is a method for assessing the environmental qualities and potential impacts related to products, processes, or services in the following ways,

- Making an inventory of energy and material-related inputs as well as environmental emissions.
- Assessing the potential environmental impacts related to identified inputs and output.
- Interpreting the results to assist decision-makers in making more informed decisions.

Many software programs for LCA calculations have been developed in recent years. Gabi, SimaPro, Open LCA, and Umberto [84] are examples of different types of software programs. Many consumers preferred Gabi and SimaPro, the two most used software applications, as a significant support utility [85]. Gabi, SimaPro and Umberto are tools used mainly in cement plants as they focus on materials and products.

1.8 System Dynamics

System Dynamics (SD) is a method for studying the behaviour of complex systems developed by Jay W Forrester to assist managers in better understanding industrial processes [86, 87]. SD is a modelling approach that describes a system as a feedback system. It was built on Forrester's novel work, which described it as "the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organisational form and guiding policy" [86, 87]. System dynamics is a method for analysing the long-term behaviour of complex systems through systems thinking and also models the change in a dynamic system over time [88]. Since process systems are complicated, highly dynamic, or involve many feedbacks, the SD technique can be used to model the processes as a feedback system and simulate the interactions between the various components.

System Dynamics (SD) is a simulation method used in various industrial areas, including carbon mitigation, CO_2 emissions and energy consumption for decision making, policy planning, and evaluations [89-91]. It is a universal and non-discrete model technique that is gaining traction in carbon policy assessment planning due to its ability to deal with complex socio-economic factors when evaluating and estimating trends such as cement demand [92].

In this study, we use an integrated methodology to assess and predict future dynamics of cement production and long-term environmental impacts of the cement industry in South Africa. In this way the factors that produce carbon emissions during the life cycle of the cement production process are determined. The proposed method uses the LCA-SD modelling framework for the cement industry in South Africa by integrating the LCA library into a system dynamic model. This study analyses the environmental impact of the cement production process in South Africa using LCA and then employs SD to predict the long-term environmental impact of cement production in South Africa.

1.9 Research Problem

Cement is crucial because it is needed for the structures and buildings that make up modern living environments. Globally, CO_2 reduction from cement plants is very important. However, activities in the cement industry have a wide range of environmental implications that harm humans and other species. Due to the high overall amount of raw materials used, the cement production process significantly impacts the environment [93]. Global warming is among these impacts, which results in changing climatic conditions due to increased atmospheric greenhouse gas (GHG) emissions. Cement is the major factor causing emissions of CO_2 in the concrete industry, accounting for 94.7% of the total emissions [94]. According to Potgieter [95], sustainability in the cement industry relies mainly on improvements in the production process to reduce waste, reduce pollutants, and use the by-products of other manufacturing processes.

Also, high energy consumption in cement production has another environmental impact because it can be a source of GHGs and other pollutants that harm our environment. The use of fossil fuels, the release of CO_2 from combustion and the decarbonization of limestone are the major environmental problems related to cement production. Despite the availability of different types of fossil and alternative fuels, historically, coal was the primary fuel used in the cement production process and is still commonly used today [96]. Therefore, reducing the demand for energy consumption from cement plants will minimize CO_2 emissions.

As a result, the cement industry may expect intense pressure to cut the environmental impact profile as countries seek ways to meet the climate mitigation targets set out in the Paris Agreement. According to the Paris Agreement, countries must reduce GHG emissions and avoid global temperatures increasing by more than 2°C above preindustrial temperatures [97]. In the Energy Technology Perspectives study [98], the International Energy Agency (IEA) examined the mitigation possibilities for the global cement industry and calculated those emissions required to be reduced to 1.7 Gt to fulfil the 2 °C targets.

1.10 Research Motivation

According to Gao et al. [99] and Schneider et al. [100], the cement production process encounters the following problems, i.e., the need to reduce GHG emissions, the increase in energy supply costs, the shortage of good quality raw materials and huge energy consumption during the process. These problems highlight the need for more reasonable solutions and optimal technologies for cement production. Furthermore, cement plants are also high in CO_2 emissions and other pollutants. Therefore, sustainability can be seen as a broad and complex concept in the cement industry because it encompasses many vital issues, including energy management and emissions reduction [101]. Therefore, cement industries need to give serious attention to reducing energy consumption and environmental emissions globally [102, 103]. The production of Portland cement is the focus of this research. Most carbon emissions occur in clinker production, including burning via limestone calcination [96].

To address this issue, environmental impact assessment, performance analysis, and process parameter monitoring are key assets to reduce GHG emissions. The environmental impact of cement can be investigated using various technologies, regulatory approaches, management strategies and policies [104, 105]. The use of LCA in this study is to determine the environmental impact of 1 kg of cement production in South Africa. It is an important approach to identifying and quantifying GHG emissions.

Next, a system dynamic model is developed to predict the impact of cement production in South Africa. Also, the model points to which components and methods might best save resources and reduce the environmental impact caused by cement production.

1.11 Research Aim

This research aims to find an effective way to minimise GHGs in cement production through the LCA method and a system dynamics modelling approach. Specifically: (1) this study explores the use of LCA to assess and analyse the environmental impacts of the cement production process, as stated in ISO 14040 [78], which has now been extended to organisational assessments ISO/TS 14072 [79], (2) then integrates these LCA results with a system dynamics model to predict the future dynamics of cement production and its long-term environmental impact of cement in South Africa.

1.12 Research Objectives

The objectives of the research are:

- To assess the various impacts related to cement production processes using LCA.

- To provide information on potential environmental impacts of various life cycle stages of cement production.
- To identify the hotspots of environmental impacts from the cement production process.
- To predict possible future dynamics of cement production and the long-term environmental impact from 2000 to 2040 using an integrated LCA-SD framework for the cement industry in South Africa.

1.13 Research Questions

The following questions need to be answered to address the research objectives.

i. What is the primary cause of environmental impact during the cement production process?
ii. What production process contributes to the impact of global warming (CO_2)?
iii. What are mitigation policy options available in the South African cement industry to reduce the long-term environmental impact and protect the environment?
iv. What are the best mitigation strategies and policies to mitigate CO_2 emissions from the cement industry in South Africa to meet the Paris Agreement?

1.14 Methodology

Due to methodological limitations, the system boundaries excluded packaging, waste treatment, cement consumption and final cement disposal as waste. Carbon dioxide (CO_2) is the most significant environmental pollutant released by cement industries, followed by particulate matter (PM), sulphur dioxide (SO_2), methane (CH_4) and nitrogen oxide (NO_X). The LCA assessed the 18 impact indicators using the ReCiPe Midpoint (H) method and 22 impact indicators using the ReCiPe Endpoint (H) method for the South African Portland cement. The environmental impact of 1 kg of cement was assessed using the midpoint and endpoint ReCiPe (H) methods and SimaPro 9.1.1 software with and ecoinvent database v3.7.1 was used to tailor recommendations.

As shown in Figure 1.4, the framework of cement production in South Africa involves three main stages, gathering data in the ecoinvent inventory, assessing the impacts of production processes and integrating the results into the SD to predict the possible future dynamic and long-term environmental impact of cement production in South Africa.

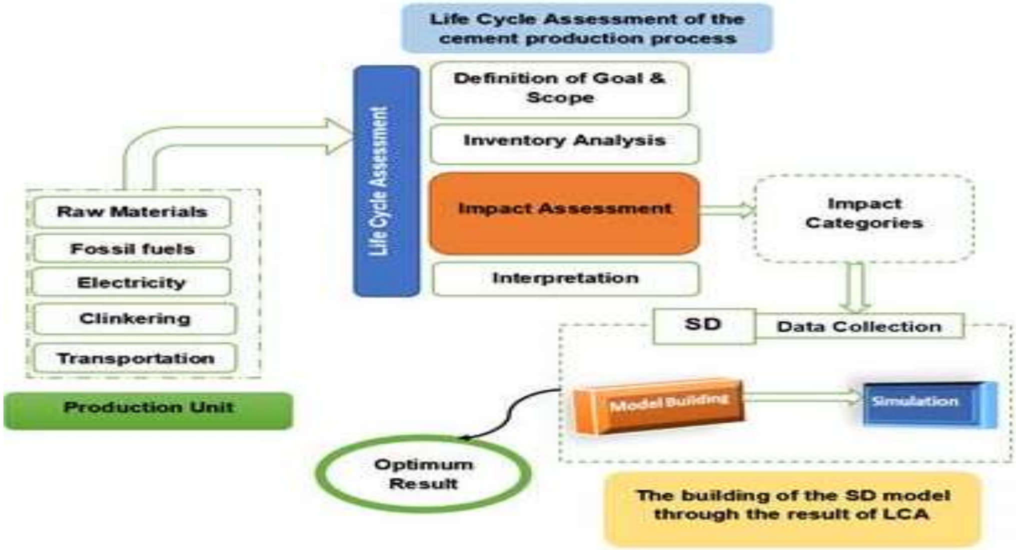

Figure 1-4 The integrated LCA and SD framework for Cement production.

Figure 1.4 describes the structure of the methodology used for integrating Life Cycle Assessment (LCA) into the System Dynamics Model. This integrated LCA-SD methodology can be used to assess and predict the environmental impacts of the cement industry. LCA is used to analyse cement production's environmental impact, as shown in Figure 1.4. The scope of the LCA is cradle-to-gate, starting from raw material acquisition, cement production stages and transportation (within the plant). The inventory data, which includes all input and output data necessary for cement production, has been collected and entered into the LCA simulation software. The functional unit used is 1 kg of cement produced in South Africa, with the system boundary represented in Figure 1.4.

This study assessed the environmental impacts and identified the hotspots related to cement production in South Africa, focusing on the LCA of the entire cement production process. The LCA characterisation results at the midpoint are then integrated into an SD model as input variables to establish their relationship to perform a more comprehensive analysis. Subsequently, SD model simulation is performed using the LCA results to predict the output variables' values in different scenarios. Finally, the results recommend a suitable environmental cement plant.

1.15 Research Contribution

Using system dynamics in the form of mathematical modelling with an LCA methodology, there is no research regarding long-term projections (i.e., 2040) of environmental impact and future dynamics of cement production. This work contributes by providing an integrated LCA-SD-based research framework to assess the various processes impacting cement production, leading to the prediction of the long-term environmental impact and future dynamics of cement production in South Africa. Exploring alternative strategies for reducing the environmental impact (GHGs emissions) in the cement production market using models aims to develop a better understanding of the long-term impacts of various mitigation strategies. Also, novel modelling methods are developed and could lead to further modelling innovations.

1.16 Thesis Structure

This thesis has seven chapters.

- Chapter 1 presents an introduction, research background, study motivation, research problem, aim, objectives and methodology.
- Chapter 2 highlights existing literature on cement production, energy consumption, emission, life cycle assessment tools and system dynamics model.
- Chapter 3 reviews the limitations/differences of the cement production life cycle impact assessment.
- In Chapter 4 presents the environmental impact analysis of Portland cement (CEM1) using the midpoint method.
- Chapter 5 presents the environmental impact analysis of Portland cement (CEM1) using the endpoint method.
- Chapter 6 discusses an integrated system dynamics model and life cycle assessment for cement production in South Africa.
- Chapter 7 presents the conclusions and recommendations of the study.

1.17 Conclusions

This chapter provided a background overview of the research topic. It has provided comprehensive details regarding global cement production's development and current state. Also, cement production, consumption and producers in South Africa are well-detailed. Among the critical areas identified in the study is the research problem, which addresses the CO_2 reduction from cement plants (cement environmental impact) and the aim of the study, which require reducing the cement GHGs emissions through integrating LCA and a system dynamics model. This chapter presented the objectives, the proposed methodology, the motivation and the contribution of this study. This chapter also highlighted the structure of the thesis and provided an overview of the study.

CHAPTER 2 : Literature Review

2.1 Introduction

This chapter reviews the literature needed to accomplish the objectives of this study. This consists of the cement production process, energy consumption, CO_2 emissions, and Life Cycle Assessment (LCA) applications in the cement industry to reduce greenhouse gas (GHG) emissions. This chapter also includes the system dynamics model and various LCA software tools. The cement sector plays a vital role in the GHG scenario. Globally, cement is the most widely used construction material and a ton of Portland cement emits about one ton of CO_2 into the environment.

2.2 CO_2 emission from the cement production process

Cement is among the basic requirements for economic growth and is an essential construction material [9, 106]. As aforementioned, cement production globally is projected to increase significantly, as cement production increased from 2310 MT to 4000 MT between 2005 and 2013 by 73% [107]. Hasanbeigi et al. [108] estimated that by 2050, production and demand for cement are projected to be between 3,680 MT and 4,380 MT. This intensity of cement production is frightening as cement plants currently emit nearly 0.9 tons of CO_2 per ton of cement produced [9]. Chen et al. [109] investigated the cement industry using the LCA approach. They concluded that it would be difficult to evaluate China's carbon emissions using the IPCC's suggested value.

Furthermore, according to Liu et *al.* [110], the emission factors for coals suggested by the IPCC on climate change are 40% higher than the actual position in China. Therefore, reducing the CO_2 emissions from cement production has become an environmental problem that must be resolved. A detailed review of the cement production process is crucial to know the source of CO_2 produced during the production process to address the CO_2 emission.

According to Habert et al. [111], the cement plant's CO_2 emission can be represented in Figure 2.1, while Benhelal et al.[112] stated that CO_2 is emitted from four different sources, for example;

- Energy generation for raw material transportation (electricity use and transport)
- Raw material transportation (Material-derived CO_2)
- Fossil fuel combustion (fuel-derived emissions)
- Limestone decomposition

Historically, coal has been the primary fuel used in the cement production process and is still commonly used today, despite the availability of various fossil and alternative fuels [96]. Material-derived CO_2 emitted 50% of the total emissions, fuel-derived emissions accounted for 40%, while electricity use and transport contributed 5% each [113].

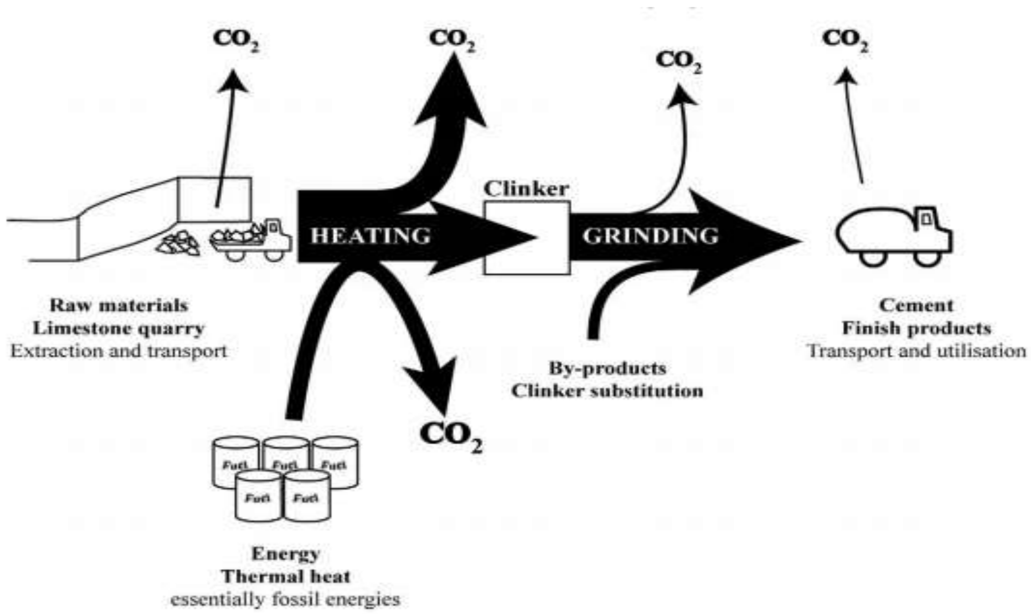

Figure 2-1 Basic cement production process with a focus on CO_2 emissions [111]

The cement production process related to CO_2 emissions is summarized in three stages [114]:

(i) Raw material preparation.
(ii) The pyro-processing (clinker production).
(iii) Clinker grinding and cement production.

All these stages can be associated with four sources of CO_2 emissions. The production of clinker is the main contributor due to the burning of fossil fuels and the decomposition of limestone. According to Gartner [113], the CO_2 released from the cement production process comes from either raw materials or those generated by burning fossil fuels known as 'fuel-derived" which represent about 50 and 40% of the total CO_2 emission from cement plants, respectively [112, 115]. In addition, Benhelal, Zahedi and Hashim [112] stated that 90% of the emissions from the cement plant are generated by pyro-processing. Some researchers emphasize the need to examine the process using the following methods.

I. Replace ordinary Portland cement (OPC) with ground blast furnace slag (GGBS) or geopolymer cement [107, 116]
II. Using more energy that is efficient by burning waste tires [100] and municipal solid waste (MSW) in the cement production process [108].

Many studies have devised approaches for limiting cement plant heat loss and have improved cement raw mill energy efficiency to reduce energy consumption [100, 117, 118]. In addition, the cement industry's energy and exergy use of main components was investigated [119-122]. Due to critical environmental issues in this sector, many studies have investigated the cement industry's energy consumption and emissions of CO_2 [123-126]. Xu et al. [127] used the Long-Mean Divisia index (LMDI) method to analyse the Chinese cement industry's energy consumption and CO_2 emissions and the variables that drove them from 1990 to 2009. Their finding showed that an increase in cement production was the most critical factor driving energy consumption and CO_2 emissions. Also, the result showed that reducing clinker production and process structure reduces energy consumption. Oggioni et al. [128] used data envelopment analysis (DEA) and a directional distance function method to provide an eco-efficiency measure for 21 prototypes of operational cement industries in various nations. Their results showed that countries that use advanced kiln and alternative fuels and raw materials in the production process are environmentally efficient.

Mandal [129] used DEA to evaluate the energy efficiency of the Indian cement industry. The empirical results showed that estimates of energy efficiency are subjective when only acceptable output is measured. The results also show that environmental regulations can promote energy efficiency. Mikulčić et al. [130] investigated the Croatian cement industry's energy consumption and CO_2 emissions. They evaluated three scenarios to predict possible CO_2 emission reduction up to 2020. Their study explored how to reduce the clinker ratio to cement by introducing different additives, substituting fossil fuels with alternative and biomass fuels and increasing the energy efficiency of the stimulating kiln process. Ke et al. [131] investigated the current energy and CO_2 emission trends from the cement industry in China. The study models output and efficiency improvements in the cement industry in China from 2011–2030. The result showed that the policies to reduce total cement production provide the most direct means to reduce total energy consumption and CO_2 emissions. Moya et al. [132] conducted a cost-effectiveness study of some of the Best Available Technologies (BAT) to reduce energy consumption and CO_2 emissions in the EU cement industry. The results show that regardless of the capital budgeting decision criteria employed, the number of cost-effective retrofitting options accessible is significant compared to the yearly rate of improvement undertaken by the sector.

According to Sathaye et al. [133], the current best practice for electrical energy consumption is about 75-80 kWh/ton of clinker. Regular electrical energy use in the South African cement plant is estimated at 110 kWh / ton of cement produced, including the consumption of other devices, for instance, office equipment [9, 134, 135]. In summary, the sources of CO_2 emissions from the cement production process are summarised in Table 2.1.

Table 2-1. Summary of the source of CO_2 emission in the cement plant [136]..

Items	Kg of CO_2 emission per tonne of cement produced	Share (%)
Decarbonisation of limestone	530	51.96
Combustion of fossil fuel	390	38.24
Electricity consumption	100	9.80
Total	1020	100

Using fossil fuels in cement contributes significantly to the production of anthropogenic greenhouse gas emissions [137]. The production of cement requires a large amount of energy in the kiln, ranging from 3000-6500 MJ / ton of clinker, depending on the type of process used, which demands a huge amount of fossil fuels [138]. More focus should be on the pyro-processing stage as it is the most energy-consumed stage in cement production. The stage used approximately 90% of the total energy used in the cement production process. For an accurate assessment, the fuel burning and emission control technologies must be considered when calculating emissions during the pyro-processing stage in an LCI.

2.3 Greenhouse gases (GHGs) environmental impacts

Recent increases in GHG concentration in the atmosphere have made climate change a global threat. The gases that contribute to global warming include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), perfluorocarbons (PFC_s), sulphur hexafluoride (SF_6), tropospheric ozone (O_3) and chlorofluorocarbons (CFC_s) [139-141]. Radiation from the sun heats the Earth's surface and GHGs trap some of that radiation in the atmosphere. As a result of the heat generated by warming the lower atmosphere (troposphere) trapped radiation, the Earth's surface has become hotter in this period than in the 19th century [139]. According to the Department of National Treasury of South Africa DNT [141], the country emitted a total of 547 Mt of GHGs into the atmosphere in 2009, with the main GHGs as CO_2, CH_4, N_2O, and PFC_s and the cement industry in South Africa contributes 1% to the emissions. According to Mwakasonda [142], CO_2 emissions in South Africa in 2009 made up 40% to 60% of the total emissions from Sub-Saharan Africa. In 2009, Ohanyere and Alexander [135] ranked South Africa ninth among the countries with the highest CO_2 emission and the first in Africa with locally run-on coal.

As stated in Gao et al. [143], the world encounters terrible results due to the unchecked and unmitigated emission of CO_2 by the cement industry, making it a significant contributor to global warming [9]. A variety of authors describes these terrible outcomes as follows [139, 144-146]:

- A projected rise in global temperatures between 1.4 ^oC and 5.8 ^oC would threaten several systems and biodiversity, causing the death of about 20% - 30% of animals and plants.

- Climate change will increase the risk of extreme weather events, including tropical cyclone intensity, extreme precipitation events and heatwave intensity.

Global efforts were made by the United Nations Framework Convention on Climate Change (UNFCCC) to address the negative impacts of GHG emissions at the Copenhagen conference and with the Kyoto Protocol, in which some countries agreed to significantly reduce their emissions of GHG [141, 147]. The South African government has committed to employing appropriate action at the national level to mitigate the GHG emissions under the Copenhagen accord based on reducing GHG emissions from the average business-as-usual growth path [141].

2.4 Potential for GHG emission reductions

As early discussed, the sources of CO_2 emissions from the cement industry are the fuel used in raw materials preparation (calcination and sinterisation) that depends on the fuel's nature and thermal energy efficiency during the burning process [111]. The emission from the raw material decarbonization process in the kiln is about 0.53 kg of CO_2 per kg of clinker [139]. This represents about two-thirds of the CO_2 emitted from cement plants [148]. Four methods have been identified to reduce GHG emissions [149-152]. These are thermal and electrical energy efficiency improvement, alternative fuels used, clinker substitution, and CO_2 capture and storage (CCS) technology.

2.4.1 Cement thermal and electrical energy efficiency improvement

Cement plants can improve energy efficiency by deploying the BAT in new plant construction, upgrading existing plants with more energy-efficient equipment, and optimising production processes [153]. There are various ways to improve the thermal and electrical efficiency of the cement production process. The production processes, including the wet, semi-wet, and dry, differ significantly in energy efficiency (thermal and electrical energy) [19, 154]. Among these processes, the wet process, which involves feeding a wet slurry into long kilns up to 200 meters in length, is heated and dried in the kiln, which is the least efficient, followed by the semi-wet process that is used in small cement plants [19]. The dry process uses smaller kilns (up to 50 meters) and only uses dry input materials, reducing energy consumption for removing water. According to Ali et al. [155], the dry process uses 13% less electricity and about 28% less fuel per ton of cement than the wet process.

Furthermore, due to multi-stage preheaters and pre-calciners, the dry process has improved dramatically in terms of energy efficiency [156]. Until the mid-1970s, the wet process was a leading technology in the cement industry. It was widely used until the dry process supplanted it. The energy crisis of the 1970s prompted companies to move to the more energy-efficient dry process, which is a more efficient way to make clinker than the wet process, which reduces GHGs related to the clinker production process and fuel usage.

However, the dry process needs input materials with a low moisture content, which isn't always available [156]. Dry production processes that include a pre-calciner and preheater are now the cutting-edge technology used in most new plants [149]. Therefore, reducing the cement industry's energy intensity and carbon emissions has always been a concern. Most of the literature focuses on the technologies used and how they compare to BAT. Several studies on cement environmental impact have been conducted, including the LCA method. Huntzinger and Eatmon [157] measured the impact of global warming as the primary interest, while Josa et al. [158] claimed that the greenhouse effect was the only cement production's global impact.

Chen et al. [159] identified the GWP impact among the major impact of cement production with other impacts such as acidification, abiotic depletion and marine ecotoxicity. According to Gartner [113], energy efficiency in the cement industry has improved because of the OPEC oil embargo in the mid-1970s, which prompted Western countries to increase research and development of new technology to upgrade the Portland Cement production process. The new technology relies on coal, coke, and various waste fuels to replace oil as the primary fuel.

2.4.2 Clinker substitution

The high share of CO_2 emissions in cement production comes from the chemical processes used to produce cement clinker, combined with the large amount of fuel required for clinker production, so using alternative materials for clinker in the final cement mix reduced GHG emissions. Alternative materials such as blast furnace slag (a by-product of the iron and steel industry), fly ashes (from coal-fired power plants) and pozzolanas (for example, natural volcanic ashes and limestone) can be used as a partial substitute material for clinker. Most of these alternative materials modify the cement's properties, resulting in a reduction in material strength at an early stage, thus limiting the importance of the cement. IEA&WBCSD [149] stated that the availability of alternative materials, standard practices, regulations and the acceptance of composite types of cement by construction companies and other customers is a barrier to increased use of clinker replacements.

There is wide variation in the use of clinker substitutes across countries today. Salas et al. [160] investigated the environmental impacts of cement production, identified alternative materials that could improve the impact of cement production processes and clarified methods and approaches when employing LCA. According to their review, using the dry production process and the best available technique was one of the efficient ways to improve energy efficiency in the cement production process; this application was possible and cost-effective.

2.4.3 Alternative fuels used (AFs)

Alternative fuels (AFs) offer many benefits to the cement industry by changing the heating fuel mix for the kiln to less carbon-intensive fuels, waste fuels, or biomass. These include GHG reduction and minor uses of non-renewable fossil fuels. The AFs are made by substituting fossil fuels with materials that reduce emissions after combustion, leaving residue. The process also reduces energy consumption. The AF fuel can be in the form of waste gases or heat. Due to waste management concerns, municipal solid waste, animal meal, waste oil, sewage sludge, used tyres and lumpy materials are the most widely used materials as alternative fuels. The use of tyres is one of the most potent alternative fuels because of their high energy content [100, 139, 161]. García-Gusano et al. [162] conducted a complete cement production LCA at a Spanish plant. The objective was to analyse the impact of using monoethanolamine as an absorbent for post-combustion CO_2 capture technology. According to their result, a fully optimised cement plant used BAT with a ratio of 7:10 clinker/cement and around 50% alternative fuel source. The impact of the post-combustion CO_2 capture reduced abiotic depletion potentials, ozone depletion, and global warming by 11%, 27%, and 15%, respectively. The other impact categories increase several times simultaneously.

Holt and Berge [163] used an LCA to investigate the cement production process using liquid hazardous waste as an alternative fuel to improve the system's environmental impact compared to a coal-fired facility. They discovered that when coal was replaced with hazardous waste, the environmental impact associated with global warming, freshwater ecotoxicity and acidification decreased, while the impacts associated with eutrophication and human toxicity that cause cancer increased. Schneider et al. [100] believed that replacing fossil fuels with alternative fuels could change the characteristics of clinker. However, they recognised the possible production of high-performance Portland cement by implementing full and proper production and quality control for effective alternative fuel substitution rates.

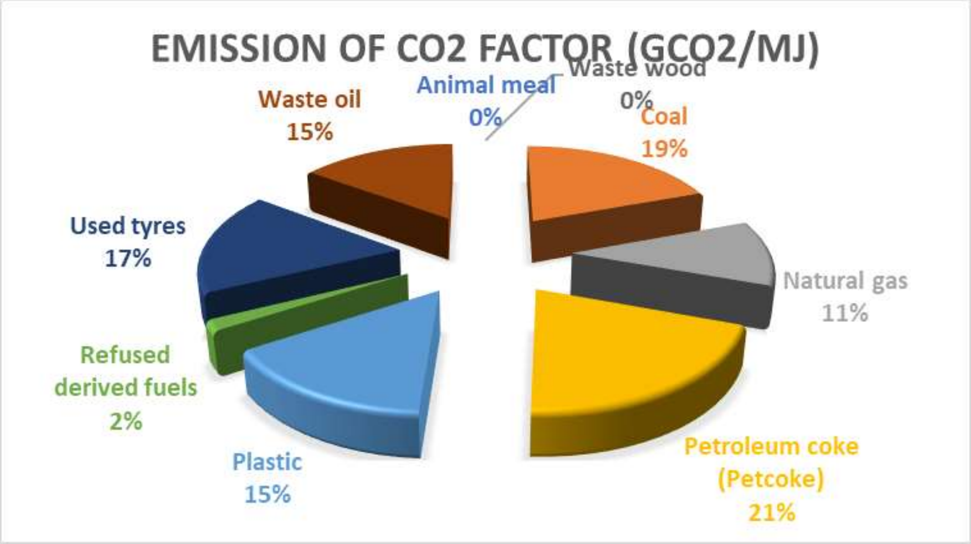

Figure 2-2 Alternative cement fuels [111].

According to Cembureau [31], by 2050, 40% of the thermal energy consumed in the kiln could be derived from the traditional fuel's combustion (i.e., 30% of coal and 10% of Petcoke) and 60% from alternative fuels (i.e., 40% of biomass), can reduce Fuel-Derived CO_2 emissions by 27%.

As reported by Habert et al. [111], the energy efficiency of the new process technology was 10% between 1973 and 1983 and the improvement rate decreased between 1983 and 2003, the improvement rate reduction combined with the need to reduce production costs and reduce CO_2 emissions paved for carbon-neutral fuels a new research area. As shown in figure 2.2, only waste wood and animal meal can be considered carbon-free fuels because of their zero net CO_2 emissions. Apart from the CO_2 net emissions observed when the materials listed in Figure 2.2 are burning in the incineration plant, the materials burned in the cement kiln can significantly reduce CO_2 emissions and improve environmental management as no waste is produced and the ashes are mixed in clinker [111, 139].

Furthermore, Damtoft et al. [139] claimed that burning waste wood and animal meal could be a reservoir for GHG and decay, resulting in methane, which is more potent than CO_2. Both Josa et al. [158] and Chen et al. [159] pointed out that the global warming impact of cement is mainly determined by its clinker concentration as the clinker production is the source of most emissions of CO_2 from the limestone decarbonised and the emissions from fuel.

2.4.4 Carbon capture and storage (CCS)

Carbon capture and storage (CCS) is the only technology that can significantly reduce GHG emissions from traditional cement production [164, 165]. In cement production, it is possible to use carbon capture to reduce CO_2 emissions from the cement kiln exhaust gases by capturing both process and combustion CO_2 emissions; this would reduce CO_2 emissions by about 80% per ton of cement produced. The cement industry has already initiated research and development activities and completed pilot tests on CCS [166]. The disadvantage of CCS is the extra energy needed to run the capture processing unit since steam is considered necessary to regenerate the amine compounds used to capture CO_2. There are several reasons why CCS does not currently make economic sense in cement plants: it will increase their capital and operating costs. These extra costs cannot be recovered without strict climate change mitigation policies. The cement production industry cannot integrate CCS within 5 - 10 years.

2.5 Life Cycle Assessment Software Tools

Selecting a software tool for use in LCA is critical, as several commercial software applications are available. According to Ormazabal et al. [167], environmental impact assessment is complicated. Therefore, performing this assessment through either variant or a clear relationship effectively used many available software tools, despite differences in the database, methodology, etc. While assessing environmental impact, they noted that some essential factors required by software tools are: user interface, volume, data quality, accuracy, and relevancy of data presented [167]. Few studies in the literature compare results when multiple LCA software tools are employed. LCA software can affect outcomes and decisions [85, 168, 169]. More than 45 LCA software tools are available in the market, some of which are more applicable for cement production than others. From the literature, SimaPro, OpenLCA, Umberto and GaBi are the most common software tools suitable for the cement sector [170], and they are computational tools linked to the LCA methodology. These software packages are based on common databases according to the ISO 14040 methodology. The ECOINVENT database is indeed integrated into these software tools to provide access to the different unit processes and other inventories covering various industrial fields.

2.5.1 OpenLCA Software

OpenLCA is a free and open-source software tool that makes it simple to analyse all stages of the LCA process. Ciroth [171] developed OpenLCA in 2006 with the assistance of PE International (the founders of GaBi), PRé Consultants (SimapPro developer) and the United Nations Environment Programme (UNEP) [172]. It was built initially to assess the environmental impact of products and processes, but it can now assess life cycle cost (LCC) [172]. The LCIA methods are not available in the OpenLCA Nexus database. LCIA method must be imported/created manually in each OpenLCA database to perform life cycle impact assessment. The whole environmental impact assessment method is configured to work with all available OpenLCA Nexus databases. Several studies have been conducted on the cement industry LCA using openLCA software [173-176]. It is possible to construct LCA studies that comply with ISO 14040 and 14044 using OpenLCA [177]. It also enables a graphical representation of the processes that caused the most impact and lists all impacts. It provides more graphic results, especially when comparing different products [172].

2.5.2 Umberto software

Ifu Hamburg developed the Umberto software in the mid-1990s. The Umberto is a user-friendly material flow analysis tool with many capabilities. Umberto software (2006) is an environmental management information system (EMIS) designed to analyze material and energy distribution networks and stocks within production systems. Individual datasets cannot be imported or exported in Umberto, and just a few dataset types are supported. Most software systems can manage and model costs and social elements to undertake sustainability life cycle assessments. Umberto is not as user-friendly as SimaPro and GaBi and does not provide substantial innovation compared to other software [167]. It includes the LCA and LCIA, which are the minimum requirements and suitable for flow accounting and solid materials processes. The Umberto software follows ISO 14040 directives for LCA in its operations. In the cement industry, many works have been investigated on cement LCA using Umberto software [178-180]

2.5.3 GaBi software

GaBi software is produced in Germany and marketed globally by PE INTERNATIONAL company. It is a product system modelling and evaluation software product that initially debuted on the market in 1992 [181]. This tool has a 25-year track record with over 10,000 users in 19 different countries and over 2,000 clients. It was created to allow users to perform a thorough LCA analysis and Life Cycle Costing (LCC). This software enables users to configure the database, impact assessment method and inputs with total clarity. It's accessible in three languages: English, Japanese, and German, and it's utilized worldwide [181]. It provides the most intuitive graphical interface for viewing and makes it possible to compare the results of several parameters. GaBi is a dynamic software application that provides users with a visual representation of an outcome when the parameters are altered and it operates according to ISO 14040 principles for LCA.

GaBi has a text editor that allows editing table and graphs and the automated modification of results when inventory changes. It enables the user the ability to model non-linear processes and supports recycling loops and allocation computations. The software databases comply with ISO TR 14049 standards and use HTML files to create hyperlinks to the individual dataset. Therefore, allowing data to be tracked back to raw materials [181]. Many works have been investigated within the cement industry using GaBi software [182-184]

2.5.4 SimaPro

Over two decades, SimaPro has been the leading software package for LCA worldwide. In over 80 countries, it is trusted by industry and academics. SimaPro is a professional tool built to help collect, analyze and monitor the environmental performance of products and services. Also, it helps to make powerful decisions to drive progress and change the life cycles of a product for the better, as well as provide the information required to make sustainable value. SimaPro software is the most widely used program for LCA, with many published research based on it [84, 85, 185-189]. SimaPro is now available in the following languages: English (US), English (UK), Danish, Dutch, French, Italian, German, Portuguese, Japanese, Spanish and Swedish. SimaPro as demonstrated consistent and flexible method that has been used by many companies, consulting firm and universities. It contains large average database and some voluntary databases. Ecoinvent database is alternative data resource of the SimaPro program. This database offered data on raw materials extraction, electricity production, water, transport, and fuels.

SimaPro is LCA software that includes an inventory database and impact assessment methods for conducting LCA studies (PRé, 2019). SimaPro databases contain energy and material requirements and waste emissions for more than 10,000 industrial and commercial processes (PRé, 2016). Through waste scenarios and waste treatment processes, SimaPro models the end-of-life cycle. Waste treatments track the emissions and impacts of landfilling, burning, recycling, or waste composting. (PRé, 2016). SimaPro has features that allow its wide use as product development and LCA management tool in many situations. This data is intended to be used as context information for the life cycle we are modelling, such as power or transportation. SimaPro has features that allow it to be used as a product creation and LCA management tool. SimaPro is very simple to use and adaptable. Various impact assessment options for system and block impact (e.g., easily accessible indicator values, characterization/normalization/valuation calculations, and ‘thermometer’ scales) are always available in the program. The SimaPro software has been used to analysis the cement LCA [15, 76, 157, 159, 162, 190-192]. Results presented in a graphical format are supported, but tables are not. Unique features of SimaPro include the following:

- Ability to link database entries.
- Access to numeric and visual indications of impact for each stage, assembly, process, and material in a life cycle system; and
- A multiple-user version of SimaPro is available (at a reduced cost for educational purposes), offering unique features such as data protection and networking.

2.6 Climate change dynamics in the cement industry

The industrial sector consumes a considerable amount of energy, about 30–70% of the total energy consumption globally, while the cement industry uses a large portion [17, 18, 193, 194]. It is estimated that by 2050, population growth, urbanization and infrastructure construction will increase and global cement production by 12-23% compared to 2014 [195]. The cement industry is among the sectors with high energy consumption and CO_2 emission [18]. With the increase in cement production, direct CO_2 strength rise by 0.3% per year [38]; however, it is difficult to limit the average temperature because there is a need to reduce emissions by 50% to 80% between 2000 and 2050 [196]. Therefore, cement production has raised concerns about its negative environmental impact due to its high energy consumption and GHG emissions [197].

The production of GHGs affected mainly by the types of fuels and raw materials employed during cement production. Meanwhile, from the start of cement production, conventional fossil fuels, for example, coal and oil, have been used as traditional fuels. In the cement production process, GHGs emissions can be divided into direct sources and indirect sources of emission [99]. The burning of fossil fuels and calcium carbonate decomposition breaking into calcium oxide and CO_2 in the production of clinker results in direct CO_2 emission, while the acquisition of raw materials, raw materials transportation, and electricity used for raw material processing and grinding cement results in indirect emission. Approximately 90% of the total CO_2 emissions in the cement production process are direct emissions, whereas indirect sources represent the remaining 10% of the total CO_2 emissions [143]. The most critical environmental problem in the cement production process is CO_2 emissions.

The considerable increase in cement production is related to the substantial increase in total energy consumption and CO_2 emissions in the cement industry [198]. We had a better understanding that CO_2 emission is among the GHG and leads to global climate change, the most significant environmental problem the world is confronting in this 21st century [199]. The major contributor to anthropogenic climate change emissions is the cement industry. However, it is sometimes difficult to determine the amount of GHG emitted by specific sources and how that corresponds to an equally unclear total. The values in the literature agree that man-made GHG emitted by the cement industry accounts for about 5% [96, 149, 200]. This will make the cement industry among the top five individual producers of GHGs after the steel industry [155, 200, 201]. With increasing attention to construction-related environmental issues, environmental considerations have become one of the essential factors in determining social and economic policy.

In 2002, the South African government agreed to the Protocol by adopting the National Policy on Climate Change Response. These plans have focused on reducing GHG emissions, mainly CO_2, which absorbs heat from the atmosphere. In 2011, due to the cement production process, approximately 2.6 Gt of CO_2 was emitted [202]. According to Gao et al. [99], the primary sources of CO_2 emissions in cement production are calcination and fossil fuel combustion. Furthermore, cement production also demands significant electrical energy for raw material crushing and milling, pyro processing, clinker cooling and cement mixing, which accounts for roughly 75 kWh/ton of cement [19]. Since cement production is one of the most energy-consuming and GHG-intensive processes, it’s crucial to measure its environmental impact and look for solutions that cement plants can use to reduce its negative environmental impact.

The clinker production process has a significant environmental impact compared to the preparation of raw materials and cement finishing mill. The focus of CO_2 emission reductions during cement manufacturing is on energy use, and the cement industry is working to reduce CO_2 emissions as much as possible. These environmental impacts are due to the direct emissions from the kiln. In addition, direct emissions from kilns contribute to the five main impact categories: global warming, ecotoxicity, terrestrial, photochemical oxidation, eutrophication and acidification [159, 187].

2.7 Conclusions

This chapter detailed the production process for Portland cement along with the sources of CO_2 emissions during the production process. Furthermore, the chapter also discussed best practices for reducing CO_2 emissions from the cement production process. Also, this chapter reviewed GHG environmental impacts and the possible ways to reduce GHG emissions in cement production. This chapter concluded by reviewing the LCA software packages considered most suitable for the cement industry based on a review of the basic requirements of such a software tool and comparing the available LCA software tools to determine which one is best for the sector.

CHAPTER 3 : A Review of The Effectiveness of Life Cycle Assessment for Gauging Environmental Impact from Cement Production

Environmental LCA helps analyse direct and indirect impacts of cement production by enhancing our perception of the environmental hazards generated during the product life cycle. Furthermore, cement manufacturers can improve production by reducing negative environmental impacts [15, 157]. The methodological outline for LCA applications presented by the International Standards ISO 14040 and 14044 [78, 203] defines its main stages as the definition of goal and scope; life cycle inventory (LCI); life cycle impact assessment (LCIA); and Interpretation [204]. In the literature, most cement production LCAs were the cradle-to-gate method with changing system boundaries, including technological and geographical differences. The literature summary showed that, despite the limitations within the literature, each study has its clear scope and goal definition. The content in this chapter of the literature review, co-authored with Oludolapo A. Olanrewaju, Kevin J. Duffy, and Obiora C. Collins, has been published in the Journal of Cleaner Production [205].

3.1 Introduction

The industrial sector consumes a considerable amount of energy, which is about 30–70% of the total energy consumption globally, while the cement industry uses a significant portion of this total energy [17, 18, 193, 194]. The cement industry is among the sectors with ample raw materials, high energy consumption and CO_2 emissions [18]. The global cement production returned to 4.1 gigatons (Gt) in 2018, a 1% increase after annual declines of 1% between 2014-2017 [206]. Between 2014 and 2017, cement production's direct CO_2 strength increased by 0.3% per year [38]. It is estimated that by 2050, population growth, urbanization, and infrastructure construction will lead to an increase/upsurge in global cement production. This is calculated to be around 12-23% compared to what it was in 2014 [195]. Researchers are currently looking for innovative solutions to cement industry issues due to increasing population growth, rapid use of energy resources, and waste disposal issues. When thinking of waste as a source of raw materials, recycling the used raw materials has gained tremendous support and has pushed many countries to use and improve energy more effectively [207, 208].

Cement production contributes significantly to environmental pollution resulting from anthropogenic pollutant emissions, raw materials mining activities, and coal, the primary energy source used in cement plants. An estimate of 5% -10% of total anthropogenic CO_2 emissions globally is from cement production [209-211]. Thus, it will be challenging to limit the average temperature and reduce cement production emissions by between 50% and 80% as required by 2050 [196]. Consequently, there are serious concerns about the significant adverse environmental impacts of cement production, such as high energy consumption and greenhouse gas (GHG) emissions [197]. The production of GHGs primarily results from the types of fuels and raw materials employed during cement production. From the beginning, cement production has conventionally used fossil fuels such as coal and oil. The CO_2 emission source is direct or indirect [99]. Most GHG emissions from cement production are direct and are produced during the calcination of limestone when heated, the primary source material during the production of clinker [212]. Therefore, GHG emissions from cement production are distributed between direct emissions from calcination (50%) and fuel consumption (40%), and indirect emissions from electricity production (10%).

Other indirect emission sources include the acquisition of raw materials, raw materials' transportation, electricity used for raw material processing, and cement grinding. Approximately 90% of the total CO_2 emissions in the cement production process are direct emissions, whereas indirect sources represent the remaining 10% of the total CO_2 emissions [143]. The most critical environmental problem in the cement production process is CO_2 emissions. Production of one ton of Ordinary Portland Cement (OPC) results in nearly 700-900 kg of CO_2 equivalent emissions released into the environment [160]. However, the environmental impact of cement production is not limited to CO_2 emissions that occur during specific stages of the life cycle. A comprehensive assessment method is required to analyze and quantify the overall environmental impact of cement production. Life Cycle Analysis (LCA) is the most suitable method. LCA is an important tool for assessing the environmental impact of cement production. For example, it is used to evaluate resource use, and its release into the water, air, and soil, of a service or product throughout its life cycle.

LCA applications may vary depending on the research objectives and mainly involve extraction of raw materials through production, logistics, use, end-of-life treatment, recycling, and final disposal (from the cradle to the grave) [213]. It is crucial to understand the full range of impacts of cement production and its components using the LCA method in a cradle-to-gate life cycle setting. However, the usefulness of LCA is largely determined by the correctness and completeness of a life cycle inventory (LCI), which collects input and output data of mass and energy over the various life cycle processes. Without a reliable and comprehensive LCA, the usefulness of LCA may be compromised due to uncertainties presented at a later life cycle impact assessment (LCIA) or by the possible incompleteness of environmental impact categories. In other words, reliable LCA for cement production depends on comprehensive and dependable LCIA.

This study aims to review general limitations/differences in the information provided through LCA applications when initiating a cement production project. This aim focuses on the system boundary, functional units, data sources, and data quality assessments used and aimed to determine the level of compliance with International Organisation for Standardisation (ISO) standards. This study also aims to provide some possible improvements, thereby meeting the needs of major LCA users. Past studies on the environmental impacts of cement production are reviewed with a focus on those studies that employed the application of a LCA analysis.

3.2 Cement manufacturing process

The cement production process involves three major stages: i.e., preparation of raw material, pyro-processing and preparation of cement [160].

3.2.1 Preparation of raw material Stage

The raw materials' preparation consists of quarrying, raw materials crushing, pre-homogenization and raw meal grinding.

3.2.1.1 Raw materials extraction

Limestone, the primary raw material in cement production, is extracted using drilling compressed air and explosives in the quarry. The use of explosives is required in the mining process, while fuel (diesel) is typically used for transporting the extracted materials to the processing plant. Portland cement is made from limestone mixed with smaller quantities of iron and aluminum, which are extracted and transported to the processing plant. Cement plants are generally close to the limestone quarry. The closeness of the quarry to the plant saves additional transportation costs and consequently makes cement production more economical.

3.2.1.2 Crushing

The extracted raw materials are dried and then subjected to a series of screening, crushing and grinding to achieve the optimal size to produce cement. The optimal size of the raw material after crushing is about 20mm - 80mm. After the grinding process, the size of the crushed raw material can be reduced further to between 0.2 mm to 25 mm, using a crusher for ease of transport via the stacker conveyors. It is then stored in a stockpile before transport to the cement plant. The crushed limestone material is conveyed for additional grinding via conveyor belts. The crushed limestone, ferrite and bauxite are kept in feed hoppers and are fed in the required ratio to the raw mill through weigh feeders.

3.2.1.3 Pre-homogenization and raw meal grinding

Homogenizing and grinding procedures of cement production are completed in the raw milling process. Raw meal preparation is for pyro-processing, where all raw materials such as limestone, shale, iron ore, and clay are mixed. Both chemical composition and variations in the raw material composition have negative impacts on clinker quality. Therefore, it is crucial to reduce the variations in chemical composition by efficiently homogenizing and mixing the raw materials in the silos [99]. At this stage, the two main devices that consume energy are the roller mills and separators or classifiers. Roller mills are used to grind the raw materials, while the separators or classifiers are used to separate the crushed particles. Gradually, the dried material is moved into the grinding chamber and ground using grinding media balls. The composition of the ground material is stored as a raw meal in silos with a capacity of about 14400 tons. The stored content in the silo is ready for the preheating chamber following the final grinding.

3.2.2 The pyro-processing Stage

The pyro-processing stage includes preheating, pre-calcination, clinker production in rotary kilns, cooling and storage in a silo. This stage is the most energy-intensive in the cement production process.

3.2.2.1 Preheating

Preheating is among the methods commonly used in the modern cement industry to improve cement plant energy efficiency. In this method, raw meals are preheated before entering the main combustion chamber, allowing smaller amounts of thermal energy demand. The preheater tower has several cyclones where the raw meal from the top of the cylinder is passed and hot flue gas is supplied from the bottom of the cylinder [99].

3.2.2.2 Pre-calcining

Modern-day cement production processes contain a pre-calcining stage after preheating. Mostly 60-65% of total calcination occurs during the pre-calcination process [99]. The pre-calciner is positioned at the bottom of the preheater, where a portion of the C_aCO_3 decomposes into C_aO and CO_2. The pre-calcining process has a high impact rate on greenhouse gas production because this process allows carbon combined with minerals to be converted into CO_2 [187]. The pyro-process uses a wet or dry process to produce Portland cement. The dry process includes grinding and heating the raw materials first before feeding them into the kiln, while the raw material is crushed, grounded, and mixed to make a slurry in the wet process.

3.2.2.3 Clinker production

The prepared constituents are then fed into a rotary kiln through a preheater after being heated to 1450°C Salas et al. [160] to produce clinker, the primary cement component [148]. The kiln is known as the heart of the cement production process. This process makes chemical and physical changes that turn the raw meal into a clinker. Natural gas, petroleum coke and coal are the fuels used for heating the kiln. The chemical reaction (decarbonization) starts in the pre-calcined materials as the temperature increases and then they melt and mix to form lumps. The kiln process is divided into the decomposition, transition, sintering and cooling zones. The clinker is an intermediate product in cement production before adding additives to cement [214]. Because of the high-water content, a massive amount of thermal energy evaporates the moisture from the raw meal.

3.2.2.4 Cooling and Storing

The hot clinker is cooled by the assistance of atmospheric air with the help of cooler fans from temperature about 1350-1450^{o}C to lower temperature approximately 120^{o}C, after passing through the kiln to recover its thermal energy, which can then be used in raw meal preheating and the pre-calcination system [99]. The primary cooling technologies used are reciprocating grate coolers and planetary coolers. The designs of these clinker coolers have significantly changed in recent years. Being at the heart of efficient clinker production, the impact of these cooler designs has always been significant in fuel consumption.

3.2.3 Clinker grinding and cement production stage

The preparation of cement consists of grinding cement, blending and cement storage in silos [148]. In this stage, the clinker is ground and mixed with additives and other raw materials such as gypsum, fly ash, and slag, forming the final product cement [149]. By varying the moisture content, the cement production process can be divided into four types: dry, semi-dry, semi-wet, and wet methods. Dry and semi-dry processes are the most cost-effective and widely used processes today [9, 16, 215]. The energy required to reduce the size of a material to a specifically required fineness will depend on the material's hardness, the particle shape, compressive strength, fragility (elasticity or placidity), material's moisture, size and material's temperature.

3.2.3.1 Cement Grinding

In cement production, the final grinding of the clinker is the final phase to produce a fine grey powder. The clinker is extracted and kept in the hopper close to the cement mill, while the gypsum is taken out of the stockyards and kept in the hoppers. The constituents needed to produce Ordinary Portland Cement (OPC), the most used type of cement, are clinker and gypsum. The OPC contained approximately 93-97% of the share of clinker [76]. During the grinding process, a small amount of the gypsum is added to the mix to control the hydration rate of the cement setting process. The required proportion and related materials are sent to the mill via the hoppers using belt conveyors and electronic weigh feeders. The cooled clinker is then mixed with gypsum ($CaSO_4$) and other additives in inter-grinding to produce finished cement.

3.2.3.2 Blending

About 4-5% of gypsum and other additives is mixed with the cooled cement to manage the final cement settling time [216]. The types and quantities of additives included in the mixtures depend on the cement requirements and 19 additives that are available [99]. A waste product such as fly ash from a coal-fired plant and granulated blast furnace slag can be used as a partial substitute for Ordinary Portland Cement by inter-grinding with the clinker to form blended cement [76]. In required ratios, the discharged cooled clinker and other additives are mixed in the stockpile and then conveyed to the cement ball mill using a Deep Bucket Conveyor for final grinding.

3.2.3.3 Cement Silo

After that, the output or fine cement is transported to the cement silo via the bucket elevator for final storage. The final cement product is stored in cement silos and then transferred to the packing unit or transported by a silo truck [149].

3.3 Environmental impact of cement production

In Europe, there are five main types of cement, within the accepted range of chemical composition, according to the content of clinker as shown in Table 3.1. On average, OPC CEM I mostly contain 95% of the clinker. Blended cement can be produced using slag (65%) or fly ash (35%) and can replace ordinary Portland cement (CEM I) in most applications [217]

Table 3-1. Ratios of clinker in different types of cement [217].

Type of Cement	**Clinker Ratio**
Ordinary Portland Cement (CEM I)	95 %
Portland Composite Cement (CEM II)	65 – 94 %
Blast Furnace Cement (CEM III)	5- 64 %
Pozzolanic Cement (CEM IV)	45 – 89 %
Composite Cement (CEM V)	20- 64 %

The two major processes in cement production are wet and dry. The wet process ingests additional energy due to a 30% evaporation of slurry water before heating the raw materials to the temperature required for calcination. Currently, the cement industry is the third-largest industrial energy user and the second-largest emitter of industrial CO_2 worldwide [218]. Therefore, the production of cement is among the largest emissions sectors in the world, accounting for about 25-27% of overall industry emissions, with roughly 5-7% of CO_2 emissions globally Rodrigues and Joekes [219], and accountable for 12-15% of industrial energy use worldwide [155]. In 2013, global CO_2 emissions were 36 Gt (9.9 Gt of C) due to fuel usage and cement production. This is a 61% increase from 1990 compared to a 2.3% increase in 2012 [220]. The average energy intensity of cement production is between 4-6 GJ/ton, depending on the different production processes. The environmental impact of cement production per unit varies on plant production capacity [109]. The high-energy requirement for cement production is mainly because of the endothermic calcination nature of the calcium carbonate, which is about 2.80 GJ/ton, and the burning stage that requires temperatures of up to 1600 °C. In addition to thermal energy, the cement production process also requires electrical energy to extract the raw materials and crushing the mixture.

A large amount of CO_2 is released from the decarbonation process, along with GHG emissions from energy use which account for about 60% of total emissions from cement production. In addition to carbon dioxide, the cement industry is also responsible for carbon monoxide emissions and heavy metals [221]. The primary sources of heavy metal pollution in the environment are human activities, for example, mining and industrial processing [222]. The photochemical formation of ozone, heavy metals and carcinogen substances caused by cement production largely depend on the raw materials and fuels used (electricity and fuel) in the energy production processes [158]. The major cement production impacts on land quality result from mining, material storage, waste disposal and atmospheric deposition [222]. Emissions of SO2 and NOx primarily produce acidification and its overall value depends on the cement clinker content. The primary cause of eutrophication is the emission of NOx, while CO_2 emissions contribute mainly to the global warming effects of cement, varying between 98.8% and 100% of the total emissions [158]. Other gases such as CH_4 or N_2O have little effect despite higher characterization factors [158].

Presently, different techniques are being developed to obtain environmentally friendly types of cement. The outlooks include industrial energy consumption optimisation and reduction of the environmental impact (CO_2 emissions). Furthermore, specific challenges are identified upstream of the process. Five factors that cause changes in GHG emissions from cement production are the energy structure, energy emissions, the energy intensity, clinker production activity, and cement production activity [215]. The main factors that increase greenhouse gas emissions are cement production and clinker production activities [158]. Production process optimisation is linked with the geological and geographic constraints at the local scale, particularly the operations of limestone mining in heavily populated areas, protected natural areas, or those overloaded with an excessive thickness [223].

Therefore, the main options discussed to reduce the cement plant environmental impact are to improve energy efficiency, reduce the clinker/cement ratios, develop CO_2 capture and sequestration (CCS), recover waste heat, increase cement recycling rates, and use alternative greener fuels [11, 155, 160, 161, 198, 214, 223-227]. The possible reduction of CO_2 emissions varies by region. Globally, the IEA pathway of cement technology Roadmap is to reduce average annual CO_2 emissions by 24% below the current levels by 2050 through a combination of technologies and policy solutions under the 2 °C situation or 32% reduction in cement's global direct CO_2 intensity [218]. The need to reduce CO_2 emissions is recognized as required throughout the life cycle of cement and concrete production and all aspects of the built environment in general. The life cycle includes the extraction, production process, materials handling, usage and end-of-life. Life cycle assessment (LCA) of cement is an essential tool for determining the environmental impacts, developing, and selecting possible technologies of the cement production process. Many researchers have applied the LCA in clinker and cement production [228-231].

3.4 Discussion

3.4.1 Cement Life Cycle Assessment

The Life Cycle Assessment (LCA) is mainly used to evaluate the environmental impact from a complete cement production process, as stated in ISO 14040. It measures the possible environmental impacts of such approaches within specified categories and boundaries. According to ISO 14040, the LCA comprises four main stages. These stages are the definition of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [78].

3.4.2 Goal and scope definition

At this stage of the LCA, the definition of the goal and scope of the study is established, the functional unit is selected, and system boundaries are determined. The functional unit refers to the reference unit of the system where all environmental impacts are measured. The purpose of the study determines the definition of the system boundaries and the functional unit. There are many methods of determining the system boundaries in cement LCA studies. The following are examples of system boundaries identified in the literature:

i. Cradle-to-grave refers to the entire life cycle from the raw material extraction through the stage of the products use to its end-of-life stage and product disposal [232, 233].
ii. Cradle-to-consumer involves raw material extraction to product consumption [234].
iii. Cradle-to-gate entails raw material extraction and the materials production to the factory gate [235].
iv. Gate-to-gate refers to the environmental impact of a particular overall operation (environmental impacts on-site) [236].

The functional unit chosen must be cautiously defined as this can affect the results significantly [16]. The study system boundaries include those on energy, fuels, raw material transportation, and emissions. In some studies, raw material extraction (Quarrying) is omitted [68, 229, 237]. The results of these studies show that some researchers define functional units differently. Several studies identified the functional unit as 1 kg of Portland cement per ton of cement [68, 76, 157, 159, 229]. One study used 1 ton of Portland cement with a strength of 42.5 MPa as the functional unit Li et al. [238], while an equivalent weight of 20 bags of cement (OPC) which is about 45.4 kg used as one functional unit [157]. Two other studies selected 1 ton of clinker and 1 ton of cement as the functional units depending on the cement life cycle, for example, each of CEM I, CEM II, CEM III, CEM IV and CEM V were evaluated [228, 237]

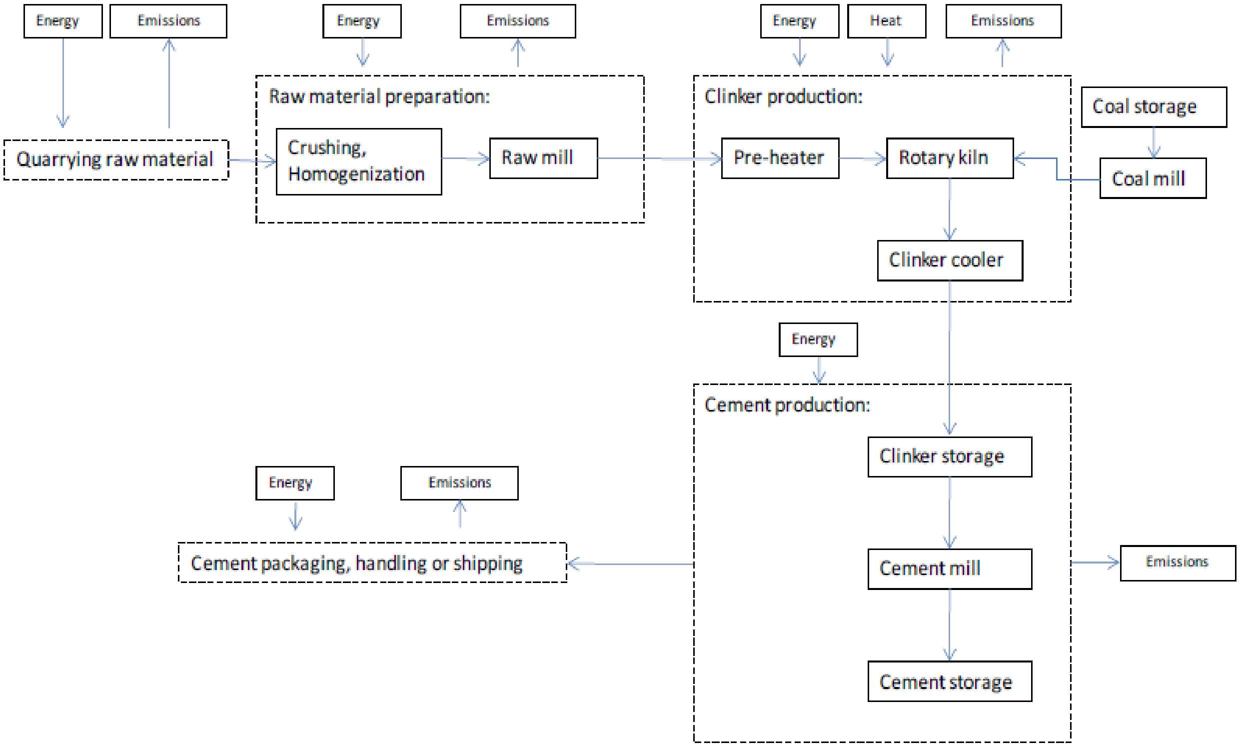

Figure 3-1 System boundaries and material flow of cement LCA cradle-to-gate [157, 239].

Figure 3.1 shows an example of the traditional cement production cradle-to-gate approach LCA with the system boundaries including all the inputs and outputs, such as raw materials extraction (quarrying), transportation (handling and shipping), raw materials preparation (crushing, homogenization, and mixing), energy use in each process step, and production of clinker in rotary kilns [240]. In some cases, a complete analysis of the entire life cycle (cradle-to-grave) is impossible in a cement production process because the cement end-use goes beyond the plant's gate. For this practical and factual reason, the cement production assessment must use a "cradle-to-gate" or "gate-to-gate" approach [68]. From the literature, as shown in Table 3.2, most cement LCA studies are established based on a cradle-to-gate method. The scope of cradle-to-gate studies is diverse. Some studies on the cement LCA omit the extraction of raw materials because they consider it insignificant in terms of energy use (2% total energy use) or there is a lack of data availability or data quality [68, 157, 229, 241]

At the raw materials extraction stages, the energy consumption is relatively low, representing 2% to 5% of the total production. However, in terms of the environmental impact, raw material extraction may add up to a considerable amount from a global point of view. Apart from those found in Josa et al. [68] and [158], the main cement production processes (for example, preparation of raw material and clinker production processes) are investigated individually in all LCA, as shown in Table 3.2. All the studies in Table 3.2 emphasize the highest energy-consuming stage of the cement production process. The pyro-processing stage consumes approximately 90% of the total energy used [242].

A cradle-to-gate LCA method, based on primary data obtained from a plant, has been used to assess the environmental impacts of cement production in Southern Europe using scrap tires and refuse-derived fuel wastes as a partial substitute for fossil fuels Stafford et al. [202]. One ton of OPC was used as a functional unit and the impact assessment was based on ISO 14040 indicators. The impact categories investigated were acidification, global warming, eutrophication, photochemical oxidants, and abiotic depletion.

Table 3-2. Scope of a cradle-to-gate method of cement production from different LCAs studies.

Functional Unit **Processes Stages**	**1-ton cement** **1-ton clinker**	**1-ton clinker** **1-ton cement**	**1-ton P.O. cement** **1-ton clinker**	**1-ton cement**	**1 kg clinker**	**1 kg clinker**	**1 kg CEM I**	**1-ton cement**	**20 bags of P.O. cement**	**1kg cement**	**1 ton of P.O. cement**
Raw Material Extraction (Quarrying)	✓	✓		✓	✓	✓	✓	✓	✓		✓
Raw Material Preparation (Grinding and mixing)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Fuel Preparation		✓			✓		✓	✓			✓
Clinker Production	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Cement Production	✓	✓	✓	✓			✓		✓	✓	✓
Transportation of final product	✓			✓					✓	✓	✓
Reference	[243]	[228].	[237]	[76]	[15]	[244]	[159]	[229]	[157]	[68, 158]	[202]

The results showed that the atmospheric emissions in the kiln, fossil fuel consumption and electricity consumption in the mills were the processes that contributed most of the impact categories. In cement LCA studies, data on transportation are essential. It is necessary to obtain more specific data about raw materials' transport (distance) and final products for better results [245, 246]. Many studies include raw material transportation in their LCA analysis, whereas others included the final product transportation [76, 157].

3.4.3 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) stage considers the energy, materials inputs, air emissions, soil, and water requirements for manufacturing a product throughout its life cycle. Inventory analysis is the most vital stage of the LCA method due to the availability and quality of data involved. According to ISO standards, professionals can do three data quality assessments:

i. Completeness check (i.e., to confirm that the information is sufficient to draw conclusions).
ii. Consistency check (i.e., verify whether the assumptions, methods and data meet established goals and scope).
iii. Sensitivity check (i.e., to evaluate the impact of the chosen method and data of the LCA study results).

Subsequently, an inventory requires appropriate inputs and outputs for the environment and resources that must be established based on the data collected. The suitable inputs and outputs data are collected from the cement production plant, Environmental Production Declarations (EPDs), or LCA databases, for example, ecoinvent [233]. The inputs include the amounts of raw materials, energy consumption, and transportation data. Approximately 1.50 -1.70 tons of raw materials are used to produce 1 ton of clinker [15, 228, 244]. The LCI studies on cement production involve various inputs and outputs, depending on the scope of the study. Some studies include data from quarrying operations (i.e., drilling and blasting), while others have only data on raw material transportation. Table 3.3 presents the input and output data of cement production from the literature. In the existing studies, the LCI data and the composition of clinker or cement, raw materials, transport, energy use, fuel, and emissions were presented by the manufacturer using standard functional units [15, 68, 109, 159, 228, 237, 244, 247, 248].

Recently, raw material substitutes have been considered for cement production and studies show that fly ash, slag, mining waste, aluminium oxides, pyrite ash, ceramic waste are used [109, 237, 249]. Iron ore waste is also used in cement production as an alternative raw material [228, 247]. Industrial sludge and fly ash can be replaced by calcium, iron, aluminium and silicon [250]. Different types of fossil fuels such as natural gas, petroleum coke, lignite and fuel oil are used in the cement plant. Fossil fuels are used mainly in pyro-processing, which represent most fuels used in the cement production process. In the United States, most cement kilns are fired mainly by coal, a combination of petroleum coke and coal and alternative fuels [251]. In addition, the cement industry also uses large amounts of tires, waste-derived fuels, dewatered sludge, biomass fuels, solid and liquid waste as alternative fuels [159, 248, 252-254]. However, the exact ratio of a fuel mixture in cement production mainly depends on the plant and may consist of unique fuel combinations, including natural gas and alternative fuels [251, 253, 255]. The energy used in a cement plant is divided into thermal energy and electrical energy [68]. In the cement production process, electricity usage includes pre-homogenization, crushing, kiln rotation, grinding, start-up machines (e.g., fans, kiln drives), transporting the materials to preheaters, and cooling systems [252, 256].

The primary electricity consumers in a cement plant are mills and exhaust fans, and they consume over 80% of the electrical energy used in a plant [254]. Both trucks and conveyors are used in many cement plants with on-site quarries to transport raw materials to processing sites. Also, energy use for other transport, auxiliary, and non-productive activities (for instance, lighting, office equipment, etc.) in LCI must be used as input [252], while thermal energy is primarily used in a clinker kiln [257]. The energy consumption per ton of clinker is 3000-6000 MJ, while the electricity consumed per ton of cement is 90-150 kWh, depending on the raw materials used and the technology used in the kiln and properties of the fuel. In Europe, the average heat expected from the operating kiln system is 3600 MJ / ton of clinker, of which the dry and semi-dry kilns have 3500 MJ / ton of clinker [229, 254].

Li et al. [237] calculated the electricity use in a cement production process as 71 kWh/ton of P.O. cement and they indicated that electricity use in the grinding process varies with the grinding capacity of clinker, gypsum, and various mixtures. The use of fossil fuels and energy consumption in the cement production process contributed significantly to the potential of acidification and eutrophication impacts because fossil fuels are used to produce electricity.

Some researchers have also studied and compared LCAs of different types of cement with each other [76, 77, 228]. In addition to the composition of the clinker, depending on the type of cement, the cement grinding process also contains different components such as pozzolan, gypsum, fly ash, blast furnace slag, limestone etc. [228].

Feiz et al. [76] measured the clinker GWP for three different types of cement (CEM I, CEM III / A and CEM III / B) in 2009 using 1 ton of cement produced as a functional unit. The cement products evaluated were: 92% of CEMI I (Clinker cement), 50% of clinker B.C. along with CEM III/A (Granulated Blast Furnace Slag) and 27% of clinker together with CEM III/B (Granulated Blast Furnace Slag). The result of GWPs for CEM I, CEM III/A and CEM III/B were 779 kg CO2-eq/t, 452 kg CO2-eq/t, and 265 kg CO2-eq/t, respectively. Josa et al. [68] also established that the CO_2 emission of CEM was around 800 kg/ton of cement, in agreement with the result of Feiz et al. [76].

Garcia-Gusano et al. [228] studied the environmental impact of five cement types: CEM I, CEM II, CEM III, CEM IV, CEM V, and other cement types using LCA. They noticed that up to 30% of OPC (CEM I) contributes to each environmental impact evaluated. In addition, CEM II (fly ash), CEM II (composite), and CEM II (limestone) similarly have major effects on all impact categories. The air emissions from the kiln system are the major output from cement production. These can be classified as combustion gases from physical and chemical reactions relating to raw materials and fuel combustion. Based on cement plant properties, the amount of CO_2 emission is between 650 to 920 kg /ton of cement. The global average is around 830 kg of CO_2 /ton of cement [258].

Table 3-3. Summary of the LCI of clinker and cement production from literature.

References	[68]	[159]	[248]	[15]	[244]	[109]	[237],	[247]	[228]
Input/output									
Limestone (t)		1.22	1160	1.181	1.18	1050	1150		1.12
Clay (t)	0.057	0.31		0.346	0.35				0.0797
Sand (t)			6.10	0.069	0.07	54.81	40	4.7	0.0273
Iron ore /Iron oxides (t)	0.019		1.70	0.013	0.01		7.5		
Gypsum (t)	0.050	0.01	50			50.51	50		
Blast furnace slag (t)	0.109								0.00316
Fly ashes (t)	0.09					241.39	155-200		0.00298
Water m^3		0.2E-03	180[a]	5.56E-04		360[a]	0.165		0.00162
Hard coal/Bituminous coal (GJ)		9.8E-03	94.69	5.61E-09	5.61E-09	101.94			0.0437 [b]
Pet coke (GJ)		4.5E-02		1.06E-01	0.106			96.45	2.89[b]
Heavy fuel oil (GJ)		1.6E-02		1.61E-09	1.61E-09			1.73	0.0341 [b]
Electricity (kWh)		13.5E-02	103.39	7.57E-02	0.0757[a]	81.93	71	29.08	92
Emissions:					1.48E-04			1.14E+00	
CO_2 (Kg)			760					1.51E-02	
CO_2, biogenic (Kg)	0.01	4.9E-04		3.00E-05		6.5E-02	0.095	6.18E-02	
CO (Kg)	0.355	6.9E-01	0.15	8.56E-01	3.71E-01	620	605	7.35E+02	5.28E-01
PM / Dust (Kg)	0.00096	1.2E-03	3.6E-02	1.55E-03	1.60E-03	1.9E-01	0.68-1.65	1.04E+00	

SO_2 (Kg)		4.5E-05	9.0E-02		5.54E-06		0.3047[c]	1.37E-02	
NO_x (Kg)	0.00043	8.2E-04	9.3E-01	5.06E-04	1.60E-03	2.3E-02	0.036-0.113	9.84E-02	
VOC (Kg)		3.3E-06						4.53E-05	
NMVOC (Kg)								9.41E-03	
Ammonia (Kg)			1.2E-02 [c]				0.00332 [c]	9.60E-13	
Benzene (Kg)		7.2E-04						4.83E-03	
Dioksin (PCDD/Fs) (Kg)					5.54E-06			8.88E-06	
CH4 (Kg)		3.2E-08			5.17E-05		7.62-27.4[d]	1.20E-08	
Ni (Kg)		9.8E-07	1.00E-02 [c]		1.12E-11		1.60-13.95 [d]	7.61E-05	
Mn (Kg)		1.6E-07			5.62E-10			2.18E-06	
Cr (Kg)		2.8E-07	5.28E-03 [c]		1.35E-12		1.14-1.52 [d]	1.72E-05	
As (Kg)			5.09E-05 [c]					3.00E-09	
Zn (Kg)		2.2E-07	1.00E-02 [c]					9.68E-06	
Cu (Kg)		3.4E-08	3.02E-03 [c]		4.18E-12		0.572-0.91 [d]	3.30E-08	
Hg (Kg)		2.8E-07	2.40E-01 [c]					1.09E-05	
Cd (Kg)		1.4E-08	7.92E-04 [c]					4,00E-09	

[a]: kg; [b]: GJ; [c]: g; [d]: m

The main components of the kiln system output are defined as CO_2, PM, SOx and NOx. Noise emissions are generated during the cement production process along with outputs such as NOx, CO_2, PM, and SOx emissions; C.O., HCl, TOC/VOC, H.F., PCDD/F as well as some metals (such as Cd, Hg, Ni Tl, Sb, As, Pb, Cr, Co, Cu, Mn, V) discharged from cement kilns system [254]. Particulate matter (PM) emissions come from quarrying, crushing, and grinding of raw materials and transportation of raw materials with lorries or conveyors, raw material storing and cement loading. PM emissions can be substantial despite the low energy consumption at this stage. Hence, for a better evaluation, an investigator, consultants etc. should also consider the trends and regulations of each stage when conducting an LCA.

3.4.4 Life Cycle Impact Assessment (LCIA)

In LCIA, the inventory analysis results are used to assess the product's environmental impact using characterization models. The LCIA can be divided into four major phases: classification, normalization, characterization and weighing. The impact categories from product or process are selected and calculated using various impact assessment methods based on the study purpose and criteria. The LCIA methods applied in the ecoinvent data v2.0: CML 2001 are Cumulative energy demand, Ecological footprint, Eco-indicator 99, Ecosystem damage potential (EDP, EDIP’97 and 2003), Ecological scarcity 1997, IPCC 2001 (climate change) and IMPACT 2002+, TRACI [259]. The two primary methods employed in the literature for impact assessment are problem-oriented methods (EDIP, CML 2002, etc.) and damage-oriented methods (IMPACT 2002+, EPS, Eco-indicator 99…. etc.) [158, 159, 233].

Hischier et al. [259] quantified problem-oriented impact categories using the CML 2001 method, while Goedkoop et al. [260] used the eco-indicator method to calculate the damage-oriented impact categories using the LCIA approach. Besides the CML 2001 method, the IPCC GWP method is also a problem-oriented impact category. The LCIA only measures GHG emissions (in kgs of CO_2 equivalents) and does not affect climate change (disability-adjusted life-years-DALY). Only the IPCC GWP method should be used if the study's primary aim is to determine the GHGs [233].

In Europe, Boesch and Hellweg [229] measured the LCIA of different types of cement (CExD, climate change, human toxicity, acidification, and eutrophication). Climate change impact categories reported as 903 kg CO_2-eq for (CEM I), 742 kg CO_2-eq (CEM II), 354 kg CO_2-eq (CEM III), 628 kg CO_2-eq (CEM IV) and 412 kg CO_2-eq (CEM V). Among all the impact categories, the production of CEM I cement has the highest impact measured. Emissions of CO_2 from cement production are affected by energy efficiency [229]. The LCIA method is considered in various studies from the literature [15, 109, 202, 228, 229, 244, 247, 248].

A few studies conducted on impact assessments based on cement production stages (such as calcination, transport, mining, clinker production, packaging, etc.), are summarized in Table 3.4 [228, 247].

Table 3-4. Summary of LCIA accomplished from the literature.

LCIA method used	ILCD 2011	CML-IA	IMPACT 2002+	IPCC (100y) CML 2000	RECIPE	IMPACT 2002+	IPCC (100y) CML 2001	CML 2001
Impact Category								
Global warming potential	✓	✓	✓	✓	✓	✓	✓	✓
Eutrophication	✓	✓	✓	✓	✓	✓	✓	✓
Abiotic Depletion		✓						✓
Acidification	✓	✓	✓	✓	✓	✓	✓	✓
Ozone layer depletion	✓	✓	✓	✓	✓	✓		
Aquatic eco-toxicity	✓	✓	✓	✓	✓	✓		
Photochemical oxidation	✓	✓		✓	✓			✓
Terrestrial eco-toxicity	✓	✓	✓		✓	✓		
Cumulative Exergy Demand	✓	✓		✓			✓	
Cumulative Energy Demand								

Ionizing radiation	✓		✓		✓	✓		
Particulate matter formation					✓			
Respiratory effects	✓		✓			✓		
Human toxicity	✓	✓			✓	✓	✓	
Land use	✓		✓		✓	✓		
Mineral extraction			✓			✓		
Resource depletion					✓			
Non-renewable energy			✓			✓		
References	[228]	[247]	[109]	[15]	[244]	[248]	[229]	[202]

In a cement production process LCA study, clinker can have a significant impact (about 80%), influencing all mid-point impacts except for terrestrial eco-toxicity [247]. For instance, the endpoint impact categories, human health, resource depletion, climate change and ecosystem quality have been assessed in some LCIA studies in the literature. Another study by Usón et al. [244] used four scenarios to investigate sewage sludge environmental analysis used as secondary fuel in cement production. The LCIA was analysed using midpoint and endpoint methods. All the mid-point impact categories were improved when sewage sludge was used as a substitute for pet coke, apart from human toxicity, marine eco-toxicity and terrestrial eco-toxicity. The high heavy metals content was described as the primary cause in the selected sewage sludge [244]. Simultaneously, some methods found different scenarios, such as using sewage sludge as a raw material substitute or fuel substitute in cement production [244, 248], and compared the differences. Generally, energy use and emissions during clinker production play a vital role in environmental impacts [248]. A summary of the general methodologies adopted in the literature reviewed are illustrated in Table 3.5. Chen et al. [109] conducted a hybrid LCA to examine the environmental impacts and possible improvement for pollutants produced from the Chinese cement industry. They measured four cement production scenarios using dry rotary kilns and shaft kilns.

Table 3-5. Summarizes LCA methodologies used in various studies extracted from the literature.

Country	Study description	Scope	Functional unit	Data collection	Software/Database	Reference
France	Cement production and the difference between plants	Extraction and production of cement	1 kg of P.C.	Register of the European pollutant emission	SimaPro 7/ Eco-invent v2.0	[159]
China	Portland cement	production of cement and power station	1 ton of P.C. and 1 ton of P.C. with 42.5 MPa strength	On-site, estimation with coefficients, mass, and heat equations		[238]
Spain	Applying of CO_2 post-combustion capture to cement production	Production of cement	1 ton of grey cement	Past studies	SimaPro 7.3.3/Ecoinvent v2.2	[162]
United State	Comparative of the OPC traditional process with alternative technologies	Production of cement	200, 100 (lb-bags of OPC)		SimaPro 6.0	[157]
Germany	Attributional comparative LCA for four cement products.	Production of cement	1 ton of cement	Records on the plant, on-sit	SimaPro 7.3/Eco-invent	[76]
China	Portland cement, clinker	Production of cement	1 ton of P.C. and 1 ton of clinker	On-site	Eco-invent v2.2	[237]
Italy	Plastic as an alternative fuel, resource productivity improvement, co-incineration, LCA	Production of cement	1 ton of cement	On-site		[261]
China	The impacts and improvement potential of pollutants generated from production cement.	Production of cement	1 ton of P.C	On-site, past studies, statistics records, monitoring data		[109]
Spain	BAT implementation to the production of cement	Production of clinker in cement kiln	1 kg of clinker	Records on the plant	SimaPro 7.2/Eco-invent v2.2	[15]
Switzerland	Comparative LCA.	From extraction of material to aggregates and building.	1 m^3 of concrete	On site-specific	Eco-invent v2.2	[262]
Persian Gulf	Cement (Zeolite in marine environments)	Using the phase of extraction and production of cement	1 m^3 of concrete (15 years of service life)	On-site, plant reports, field experiments,		[263]

P.C = Portland cement, BAT = Best Available Technologies.

Average production using shaft kiln scenarios showed comparatively more environmental problems than large and medium production scenarios in most categories. The results showed that large and small scenarios had a GWP value of 734 and 693 kg CO_2 eq., while the shaft kiln scenarios had 802 and 1000 kg CO_2 eq. They concluded that the cement production process contributed the most categories of non-cancerous respiratory organic and non-renewable energy. The transport process contributed the most to the carcinogen categories, ozone layer depletion and ionizing radiation.

Garcia-Gusano et al. [228], in a similar study, identified five scenarios: material substitution, electrical efficiency, fossil fuel substitution, thermal efficiency and ideal categories to implement the Best Available Technologies (BAT) and assess its impacts on the life cycle of each scenario using the mid-point method. They established that change from primary materials to secondary materials, for instance, fly ash and blast furnace slag resulted in 10-13% reductions for each impact category. Using alternative fuels as a substitute for fossil fuels reduces the cement impact categories of photochemical ozone formation and acidification by 37% and 33% respectively. The results also showed a substantial reduction in CO_2 emissions by increasing thermal and electrical efficiency by substituting 50 % of total fuel with alternative fuels which reduced the clinker-to-cement ratio from 0.8 to 0.7. [228]

Strazza et al. [261] investigated an operational cement plant's environmental performance in Italy that uses recovered plastics as a fuel substitute. The caloric fuel substitution was 22%. The results showed that the GWP reduced 2%, POCP 1%, A.P. 27%, ODP 18% and E.P. 0%. They concluded that the use of alternative fuels is an ideal way to reduce environmental impacts. The impacts on several mid-point categories, for example, global warming, terrestrial eco-toxicity, respiratory inorganic and non-renewable energy, have a vital influence on cement production [109, 248]. The related greenhouse gas emissions investigated in LCI are CO_2, CH_4 and N_2O [15, 158]. In particular, CO_2 produced during the calcination phase and fuel-burning are significant GHG sources in cement production [229]. NOx, SO2 and particles are substances found in the respiratory inorganic waste [248]. The primary materials of non-renewable energy are coal and crude, which produce energy and impact that category [109]. Heavy metals, toxic organic compounds and NOx emissions influence the category of human toxicity. Simultaneously, cumulative energy demand depends mainly on fossil fuel consumption in a rotary kiln [229].

Valderrama et al. [15] used a cradle-to-gate LCA to assess and measure the environmental impact of the possible improvements in an upgraded cement production line. The new line (L6) has been designed and built based on the best available technologies method for the Spanish cement plant to replace the previous lines (L3, L4 and L5). The system boundaries used include the extraction of raw materials to clinker products. It does not include clinker grinding, final blending and the other mineral processes used in Portland cement production. The LCIA related step was achieved using CML, the midpoint method of the SimaPro7.2 software.

The recorded environmental impacts of global warming, eutrophication and acidification are reduced by 5%, 17%, and 15% respectively for the new production line (L6) as compared with the previous lines. The most significant changes are related to kiln system energy efficiency, which uses less fossil fuel to produce 1 kg of clinker (with less atmospheric emissions). The European Commission introduced the BAT for the cement industry and it covers the IPPC technologies in cement production [254].

As shown in Table 3.6, from the literature, the system boundaries vary by country, including extraction (quarrying) and preparation of raw materials, transportation (including the raw materials, and the handling and shipping of the cement), crushing grinding and mixings, and energy consumption in each production process. However, the cradle-to-gate method is predominantly used in cement LCA studies, as shown in Table 3.6.

Table 3-6. Summarizes LCAs system boundaries (Cradle-to-gate) from the literature.

Country	System boundary	Method	Reference
		Gradle to gate	
France	This includes extraction and preparation of raw materials at the quarry, raw materials mixing and the cement kiln process, the clinker grinding and its mixing with gypsum and considered both alternative and primary fuels transportation with the exclusion of raw materials transportation as the quarry close to the cement plant.	✓	[159]
China	This includes cement production accompanying its raw materials preparation, transportation of coal and raw meal process and energy use, grinding and mixing of clinker with gypsum, and cement plant and power station.	✓	[238]
Spain	This includes raw materials extraction process to the cement production process and considered all related to	✓	[162]

	CO_2 capture process excluded transportation and CO_2 storage.		
United State	This includes the extraction and acquisition of raw material, processing production stages to the cement packaging and transportation of the finished cement product.	✓	[157]
Germany	This includes extraction of raw materials, production/upgrading of materials, cement production and transportation within this scope. Transportation of cement outside cement plant such as road, railroads were not included	✓	[76]
China	This includes raw materials, process preparation, coal and raw materials transportation from yard to mill, grinding, mixings and energy use crossing the boundary of the cement plant.	✓	[237]
Italy	This includes raw materials preparation, energy use (fuels and fuels for transport), mixings and cement grinding, excluding alternative fuels and raw materials, explosives and grinding media.	✓	[261]
China	This includes raw material extraction, crushing, clinker production, mixing with water, ball-making, incineration in the kiln, grinding of cement energy consumption, road transport, direct emissions and infrastructure were considered in each process.	✓	[109]
Spain	It includes from mining to the production of clinker in cement kiln, excluded the blending and grinding of clinker and other raw material for cement production.	✓	[15]
Spain	It includes raw materials extraction to cement production, including waste from refuse as secondary materials and alternative fuels. Electricity mixture is excluded from the system.	✓	[228]

The present study considered the Life Cycle Inventory (LCI) data and the Life Cycle Impact Assessment (LCIA) results of the cement production processes as described in the literature and rigorously evaluated and analysed the findings. Previous studies on the use of LCA to analyse the environmental impact of the cement production processes are reviewed. Identified are critical problems within the system boundaries corresponding to the "cradle-to-gate" system of cement production processes as stated by ISO (14040:2006).

3.5 Limitations, possible improvement of cement LCA and novelty of the study

Even though LCA is the most reliable method for investigating the environmental impact of cement production process, it is important to know that is has some limitations. Some of its major limitations observed in the literature and possible improvements are discussed in this section.

The most critical stage in any LCA is to gather a reliable LCI for a successive LCIA that can be investigated. The data used in inventory analysis affects the results of the cement LCA. The LCI data can be primary data, which is obtained from on-site surveys/investigations or secondary data sources. In most studies, primary data was collected directly from product manufacturers, processes operators, or service providers. In contrast, secondary data are generally collected from consultants (software databases), national databases, generic data, or research groups. Primary data is preferably used to establish the ideal LCA if it is available. The primary data availability is often a major challenge as the primary sources, manufacturers and industries often have confidentiality problems surrounding the publishing of such data. Based on this explanation, access to primary data is one of the limitations of LCA.

An area that needs improvement in cement LCA is the data quality. To the best of authors' understanding, there are no detailed discussions on data quality assessment in the cement LCA literature. The data quality assessments include completeness checks, consistency checks, and sensitivity checks. The possible reasons could be slight interest given to data quality verification or difficulty encountered during data collection. The quality of the data directly influences LCI results obtained from cement LCA analyses. Hence, to obtain a good result from cement LCA, crucial for improving the environmental impact of cement production, data quality assessment on cement must be taken into consideration.

Another possible area for improvement is in the descriptions regarding the standards used in establishing system boundaries because selection of boundaries determines the processes to be included or omitted from the product system. Importantly, system boundaries are related to research costs and/or data quality. Consequently, system boundaries affect the results obtained from cement LCA analyses. Improvement in descriptions of system boundaries is a necessity for better results. Some studies have ignored outputs such as hazardous air pollutants (PAH, PCDD/Fs, HCl etc.) and heavy metals (As, Hg, Cd, Cr, etc.). Heavy metals can badly affect cell structure and plant functions. However, to measure all environmental impacts from cement production processes using alternative raw materials or alternative fuels (such as fly ash and sewage sludge etc.), it is important to consider all outputs (including the hazardous air pollutants, heavy metals, solid wastes, and wastewater).

Lastly, another area of possible improvement is the impact of emissions from cement production processes on economic development. Authors established from literature that dust from a cement kiln has among the worst environmental and human health problems. Exposure of workers and communities to dust emissions can lead to many health problems. To achieve sustainable development, it is suggested that focus be placed on technologies that produce effective emission controls, are energy efficient and are environmentally friendly themselves.

3.6 Conclusions

The study highlights the main problems related to LCA of cement production processes, also presented are suitable recommendations. Issues were found with system boundaries, functional units, sources of data, and data quality assessments. Results show general gaps in the methodology and documentation of all stages of LCA. In general, the scope of an LCA for a particular application consider gate-to-gate, cradle-to-gate, or cradle-to-grave situations. In this study, the cradle-to-gate method was found to be the method predominantly used in cement production. The most relevant issues found in this review revolve around the definition of functional units, system boundaries and lack of comprehensive environmental impact assessments. The quality of the data directly influences LCI results obtained from cement LCA analyses. Improvements in descriptions of system boundaries are a necessity for better results. The lack of comprehensive environmental impact assessments is a problem that needs serious attention. The cement industry needs to engage in an in-depth assessment and work closely with LCA researchers. Future LCA studies must provide more details on system boundary criteria and provide detailed data quality assessments. The cement production LCA literature mainly focuses on energy consumption and GHG emissions. Critical issues include volatile organic compounds, heavy metals, and other toxic emissions. Without a comprehensive assessment, it is impossible to understand the overall environmental impact of cement production. The most crucial potential impacts are highlighted during the weighing phase. More research is needed to evaluate the impact of these alternative raw materials and fuels on cement production and identify the best technologies available in the production process for sustainability of the industry within acceptable environmental concerns.

3.7 Recommendation and future work

Researchers are acquiring experience in LCA studies at a quick pace globally. Compared to last two decades, when most LCA studies focused mainly on methodology descriptions and LCA concepts. The LCA studies we reviewed highlighted the main features needed to improve the LCA, such as the definition of the goal, functional units, system boundary, and impact assessment. However, compared to international research in a similar field, the LCA studies need more detailed boundary criteria, present detailed data quality assessments, expand to other data sources, and assess their limitations critically. To increase LCA awareness and improve the LCA studies quality, industries, associations and organisations should take a more active role in the assessments and work closely with LCA researchers. The government may perhaps fund pilot projects to support LCA research. Furthermore, international collaboration can help LCA researchers to embrace global best practices more effectively.

CHAPTER 4 : Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method

This chapter present results of the environmental impact analysis at midpoint. Based on International Organisation for Standardisation, ISO 14040 [78] (Principles and Framework), ISO 14044 (2006) [203], and ISO/TS 14072 [79] (requirements and guidelines) for LCA, this chapter analyses the environmental impact of 1 kg of Portland cement (CEM I) in the South African cement industry using the LCIA based on the Recipe 2016 v 1.04 midpoint method. The study merged the entire cement production process into five processes, i.e., raw material usage, fuels usage, electricity usage, transportation and clinker production. The impact categories of the five production stages were assessed using the LCA methodology based on the Ecoinvent database v3.7.1, integrated with SimaPro 9.1.1. software. This study used data modeled after the South African cement plant. The impact categories investigated were classified into three categories: atmospheric, resource depletion, and toxicity. The content in this chapter, co-authored with Oludolapo A. Olanrewaju, Kevin J. Duffy, and Obiora C. Collins, has been published in the Energies [191].

4.1 Introduction

Cement demand in many developing countries has increased rapidly due to the continued expansion of the construction industry, driven by fast urbanization. Cement is among the most used and produced materials in construction globally [96, 264]. Despite a significant increase in cement production, from 3280 Mt to 4290 Mt, between 2010 and 2014, it has remained relatively stable at approximately 4100 Mt since 2019 [265]. Recently, attention to environmental protection and interest in environmental issues related to construction grew rapidly, and environmental considerations have become one of the main criteria for formulating social and economic policies [266]. The majority of these efforts have centered on lowering greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which is responsible for absorbing heat from the atmosphere. Global warming and resource depletion are among the critical concerns of the cement industry. Cement production has many environmental impacts, varying from high levels of GHG to high resource usage and high energy consumption, i.e., fossil fuels and electricity. Measuring this impact is a critical step towards mitigating them. It is estimated that the cement industry causes about 5% of total anthropogenic CO_2 emissions and accounts for 12–15% of global industrial energy use [23, 244]. Many countries (especially developing countries) use coal as a calcination fuel and emit large GHGs. Globally, the calcination process accounts for 50% of the total CO_2 emissions from cement production, and others come from burning fuel in the kiln [76, 267, 268]. The amount of clinker (the primary ingredient) used in cement production is directly proportional to the CO_2 emissions. For example, between 2014 and 2018, the clinker to cement ratio increased at an annual rate of 1.6 percent on average, resulting in a proportional increase in direct CO_2 emissions [269].

Cement production involves the extraction of raw materials such as limestone, sand, and clay, which contain the four primary constituents needed: lime, alumina, silica, and iron. The chemical reactions that mix these constituents expose them to high temperatures convert the partially molten raw materials into clinker. These materials are crushed and mixed before firing at 1450 ° C. Many industries also use selected residues as additives or partial substitutes for raw materials [270]. The resulting clinker is mixed and grounded with gypsum and other minerals to form cement, a fine grey powder. Cement kilns use multiple energy sources to achieve the high temperatures required to produce clinker [151]. The cement production process comprises three main stages: raw material preparation, clinker combustion (pyro-processing) and cement preparation [148]. Cement production can be further categorized into four processes based on the moisture content of the material: dry, semi-dry, semi-wet, and wet process. The dry process is usually preferred because it uses less energy than the wet process[148]. Numerous fuels can be used, including fossil fuels such as coal, petroleum coke, fuel oil, diesel, natural gas, and alternative fuels such as waste or biomass [19]. The cement industry is energy-intensive and has become a source of environmental worries because of the large amounts of raw materials, the energy required, and total cement produced. This is primarily because of high carbon dioxide (CO_2) emissions from the use of fossil fuels, as well as the limestone decarbonization to calcium oxide in the clinker production process [96, 155].

Cement production is well known for its massive total industrial energy consumption, approximating 30–40% in many countries [49, 271]. Cement production employs a variety of energy sources, including thermal and electrical energy [205]. The thermal energy used in cement production accounts for roughly 90% of total specific energy consumption, with the primary fuel sources alternated between coal, fuel oil, and other notable fuels, such as biomass and animal wastes, while electricity used the remaining 10% of the total specific energy consumption [272, 273]**.** The energy required to produce Portland cement ranged from 3–6 MJ/kg clinker, depending on the raw materials and the type of process used [49]. Cement plants in South Africa use fossil fuel (Coal) for their process and the kiln is the main energy-consuming stage in the entire cement production process. In South Africa, the energy consumption of cement plants varies considerably, in terms of electricity, as it is affected by the function and size of the plant. This occurs because most plants operate mainly in cement finishing mills, while others perform the whole process, from raw materials to cement production. Cement plants in South Africa use several megawatt-hours per year, with annual limits ranging from 55 to 194 megawatt hours (MWh) [274].

The greenhouse gas (GHG) emissions from energy consumption are the primary cause of global warming and climate change [275-277]. The energy consumed in the industrial sector represents about 28.3% of total global energy consumption and, consequently, releases about 38.5% of CO_2 [278]. Nearly 33% of global emissions are directly related to energy consumption [279]. Cement plants are responsible for up to 7% of CO_2 emissions worldwide [155, 280]*.* South Africa ranked seventh in the world on CO_2 emissions in 2019 and first in Africa, which is largely due to the country's dependence on coal [281]. According to the Department of Environmental Affairs' 2014 [282] reports, annual greenhouse gas emissions from cement production increased by 27% between 2000 and 2010, from 3.3 MT CO_2e to 4.2 MT CO_2e. The South African cement industry accounted for 1% of the country's GHG emissions [283]. South Africa's leading electricity service provider, Eskom, generates 95% of the country's electricity used. The country generated 93% of this electricity from coal-fired plants, while nuclear, hydro and gas turbine plants account for the remaining 7% [284-287]. As a result, lowering the electricity demand in South African cement plants will help to reduce CO_2 emissions.

Environmental saving, in terms of reducing carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions and energy costs, is a major global concern [102]. Energy use is directly responsible for 33% of global emissions, with the cement industry liable for up to 7% of global CO_2 emissions [90, 155]. Apart from GHG emissions, cement production also emits other atmospheric pollutants, such as nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM) and sulphur dioxide (SO_2), among others, mainly due to the use of coal [155, 288-290]. Raw materials' extraction can also lead to natural resources depletion [291], air pollution [158] and land degradation [222]. Several studies have assessed cement production's environmental impact with different methodologies, system boundaries, variables, and environmental impacts (e.g., raw material composition, technology types, and fuels) [16].

Life cycle assessment (LCA) is a method that has been successfully used in many studies to assess the environmental impact of cement production and investigate ways to improve environmental performance. The LCA method has now been extended to Organisational assessments ISO/TS 14072 [79], increasing the applications for the approach and increasing its ability to reach high-level decision- and policy-makers. The LCA methodology, recommended by ISO/TS 14072, covers the scope of ISO 14040 (2006) [78] and ISO 14044 (2006) [203], to all Organisational activities standards and includes four stages: definition of goal and scope, inventory analysis, impact assessment and interpretation of results [79]. Definition of goal and scope: The first stage defined how to conduct the LCA research goal and scope and its extension. Inventory analysis: All the relevant data are researched, collected, and analysed during the life cycle inventory (LCI) stage. Impact Assessment: This stage provides more information to help assess the LCI results of a product's system and understand their environmental impact better. Interpretation: This is the final stage of LCA, where the results of an LCI, LCIA, or both, are summarized, discussed and interpreted, according to the study's goals for possible recommendations. In addition to ISO 14040 (2006) [78] and ISO 14044 (2006) [203], ISO/TS 14072 [79] provides additional requirements and guidelines for effective application to Organisations.

According to Petek Gursel et al. [257], the critical stage in any LCA is the collection of reliable LCI, which can be used to conduct LCIA. The data constituting the LCI can be either primary or secondary data. The primary data are the on-site data collected from manufacturers, processes, services and associations, while secondary data are those from the published datasets, journals, consultants and considered generic data [292]. LCA is among the methods used to assess the environmental impact of cement production [157, 229, 293]. LCA has drawn much interest to various available tools, regarding environmental assessment and human health impact. Its scope is the main advantage of LCA. It means LCA can present a comprehensive picture of the impact caused by the product's entire life cycle, from the extraction of raw materials to final disposal [294]. Therefore, LCA is an effective tool for Organisations to provide a scientific basis to support Organisations' decision-making, to reduce environmental impact during life cycle management [295-297]. The environmental impact of cement production has been compared in LCA studies for different types of cement [76, 77] and stages of production [109, 162, 298, 299]. Many LCA studies developed various scenarios for replacing raw materials and fuels to reduce cement production's harmful environmental impact [162, 244, 248, 261] or identify the best available technology [15].

Further, the reduction in cement proportion in concrete and the addition of different cementitious materials, such as pumice, zeolite, fly ash, metakaolin, and nanomaterials, has shown strong improvements in fresh properties, mechanical strength, and durability of concrete productions [300-306]. Steel slag can be used as supplementary cementitious material (SCM) to produce blended cement. Steel slag could be used as a partial substitute for cement (10%), without affecting the compressive strength [307], and also as a partial substitute for limestone in kiln feed [308, 309]. Replacing the same amount of clinker with various SCMs, such as steel slag in cement production, has already proven to be one of the most effective methods of reducing GHG emissions from cement production [310]. Steel slag showed good hydraulic properties and offered a standard-setting time, contributing to resource, energy, and environmental saving [311]. However, different functional units and impact assessment methods make it difficult to compare LCA studies [15, 68, 157, 159, 244]. This study aims to analyse the environmental impact of a cement plant in South Africa that produces Portland cement (CEM1), using life cycle assessment (LCA). The impact categories were classified into three categories: atmospheric, resource depletion, and toxicity categories to achieve this aim.

On average, the cement industry discharges about 500–950 kg of CO_2/ton of cement produced [154]. This depends on many factors, including the amount of clinker in the cement, the type of fuel used, and the system's energy efficiency [9, 312]. Approximately 60% of these emissions are caused by process (limestone calcination), 35% by fuel combustion, and 5% by electricity application [312]. Wang et al. [215] discovered five significant factors affecting GHG emissions from cement production, namely: energy emission factor, energy structure, energy intensity, cement production and clinker production. Cement and clinker production activities account for most of the increased GHG emissions. The cement industry contributes the most to global warming, with CO_2 emissions ranging from 98% to 100%. Despite higher characterization factors, Other GHGs, for example, CH_4 and N_2O, have less impact [158, 313]. Tun et al. [314] used the LCA method to evaluate the environmental impact of Myanmar's cement industry using the Recipe 2016 method to identify the major contributors' environmental impacts. They discovered that major environmental impact is climate change, ecosystem damage, photochemical oxidant formation, fine particulate matter formation, terrestrial acidification, and fossil resource scarcity. These impacts are caused primarily by CO_2, SO_2, NOx and PM2.5 emissions during the clinker production stage and the use of fossil resources.

Marceau et al. [242] performed an LCI for Portland cement produced in the United States. They found that limestone calcination and fuel burning in the clinker production stage contributed about 60% of the total CO_2 emission (553 kg per ton of cement) and 39% (365 kg per ton of cement) of total CO_2 emissions, respectively. Feiz et al. [76] compared the Global Warming Potential (GWP) of three cement products with different clinker contents and found that the product with the least clinker had the lowest value. Thwe et al. [315] used the LCA approach to assess the environmental impact of OPC production in Naypyitaw, Myanmar. They developed various alternative fuel scenarios for thermal energy consumption. Their study found that current cement production practices cause different environmental impact, including GHG emissions, eutrophication and acidification, particulate matter formation, photochemical oxidant formation, fossil depletion, etc. These are due to the calcination (clinker production stage). Rosyid et al. [316] found that the kiln process activities were primarily responsible for global warming and acidification impact at an Indonesian cement plant. According to Chen et al. [109], the cement industry has three significant environmental impacts: (1) global warming, (2) respiratory inorganics, which are related to direct emissions from coal and limestone consumption, and (3) non-renewable energy, which is related to energy consumption (i.e., electricity and coal).

4.2 A Recipe

A Recipe is a method for LCIA. It was developed due to collaboration between PRé Sustainability, RIVM, Radboud University Nijmegen, and Leiden University in 2008 [185]. In the Recipe, 18 midpoint indicators and three endpoint indicators are determined. Each method midpoint and endpoint include factors based on three cultural perspectives: individualistic, hierarchist and egalitarian perspectives. These perspectives signify a series of choices about issues, such as time or the expectation that proper management or future technology development can prevent future damage. The individualistic perspective relates to the short-term concern, impact types that are certain, and technological optimism about human adaptation. The hierarchist perspective relates to the scientific consensus model about the time frame and impact mechanisms credibility. The egalitarian perspective relates to the long-term precautionary perspective, as it considers the long-term time frame and all impact pathways for which data are available. The main objective of the Recipe method is to reduce life cycle inventory results into a limited number of indicator scores. The scores for these indicators indicate the relative severity of the environmental impact category. The Recipe 2016 improves on Recipe 2008, CML 2000 and Eco-indicator 99. The method is regularly updated to integrate new data and research. Radboud University is now in charge of the most recent update.

The Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, PRé and Norwegian University of Science and Technology collaborated to develop Recipe 2016 [317]. Goedkoop et al. [318] developed ReCiPe2008, an LCIA method that includes harmonized category indicators and characterization factors at the midpoint and endpoint levels. Therefore, this study aims to analyse the environmental impact of the production of Portland cement (CEM I) in the South African cement industry, using the LCIA with the Recipe 2016 v 1.04 midpoint method, according to atmospheric, resource depletion and toxicity categories. The LCA methodology was used to estimate the 18 midpoint impact categories, except for water consumption and land use, due to minor impact. This method allows for the identification of environmental hotspots in the production process and compares them with similar production scenarios, assessed using LCA. All cement plants in South Africa are produced via a dry process.

4.3 Methodology

Life cycle assessment is a method that has been successfully used for assessing promising environmental impact and resource usage throughout the lifetime of a product, from the acquisition of raw material to the production stage and use phases to waste management [78]. LCA method considers the environmental impact of products, services, and processes. The analysis is conducted according to ISO/TS 14072 guidelines for Organisational life cycle assessment. An LCA study must include four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation, with all guidelines followed. Therefore, this section discusses the LCA method of cement production stages and explains how the impact assessment was conducted based on the above stages.

4.3.1 Goal and Scope Definition

The intended goal of this study is to investigate environmental impact based on data availability from a cement production unit. Regarding the system boundary, standard LCA is a cradle-to-grave method. In recent times, cradle-to-gate, gate-to-gate, gate-to-cradle are possible in some cases, even cradle-to-cradle methods. Most studies on the environmental impact of cement use the cradle-to-gate method. As shown in Figure 4.1, a cradle-to-gate analysis was considered in this study. Cradle-to-gate includes the acquisition of raw material, transportation (within the plant) and production stages. In this study, the system boundary was limited to raw material consumption, fuels, electricity use, transportation, production of Portland cement, the final product and emissions from the process. The boundary excluded the packaging unit, waste treatment, cement consumption, final cement disposal as waste due to the methodological issues. Furthermore, 1 kg of cement produced in South Africa was used as the functional unit to compare the results. To simplify the production process, the entire production process merged into five processes, i.e., raw material usage, fuels usage, electricity usage, transportation and clinker production.

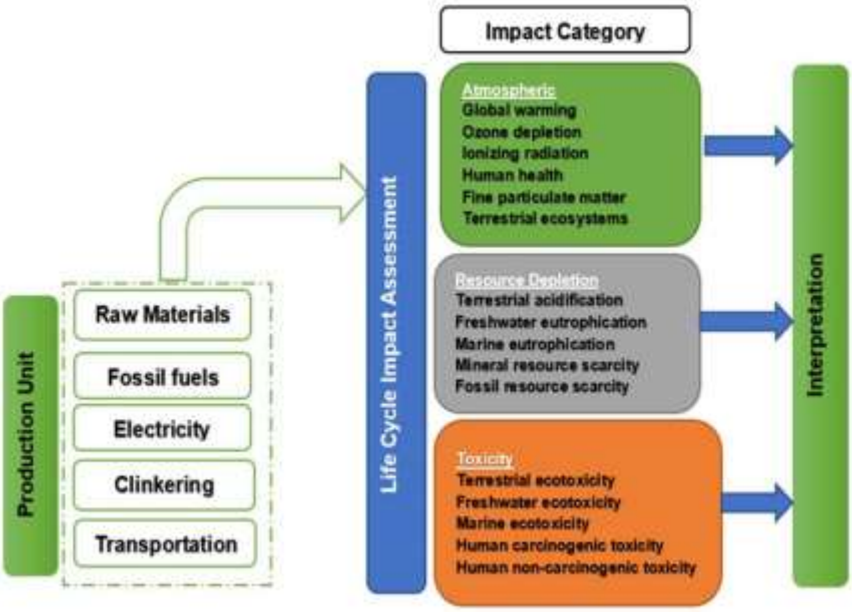

Figure 4-1 System boundaries of the LCA of Portland cement in South Africa.

4.3.2 Life Cycle Inventory

The inventory was developed using average South African cement production data between the 2017–2019 operations. The inventory data for the system background were obtained from the Ecoinvent database v3.7.1 [319]. Ecoinvent's inventory data for South African cement production were primary data collected from five cement plants that characterized 90% of the country's cement industry's market share. The inventory input/output data for 1 kg of the South African Portland cement are included in Table 4.1.

Table 4-1. List of input/output data of Portland production [319].

	Amount
Cement Factory	5.36×10^{-11} unit
Input	
Clinker	0.902 kg
Gypsum, mineral	0.0475 kg
Limestone	0.05 kg
Ethylene glycol	0.00019 kg
Steel, low-alloyed	5.25×10^{-5} kg
Electricity	0.0376 kWh
Output	
Emissions to air (Heat, waste)	0.135 MJ

Products (Cement, Portland)	1 kg

According to Petek Gursel et al. [257], developing a life cycle inventory includes quantifying and gathering all inputs, outputs, energy consumption and waste generation related data to make a functional unit of the product within the system boundary investigated. The data include all raw materials and energy used in the production process. The figures are computed based on original data on South African cement production.

4.3.3 Life Cycle Impact Assessment

The LCIA process combines the inputs and outputs quantified in an Inventory Analysis to estimate their potential environmental impact. There are a variety of LCIA methodologies available, with some of them being included in commercial software [320]. Most methods are based on impact categories and characterization factors and include the following steps: classification, normalization, characterization and valuation. In classification, the environmental impact measured in the inventory is grouped into a limited set of recognized environmental impact categories considering the scientific information available about the processes. The study's goal guides selecting correct impact categories and practical considerations should limit their number. In the LCIA methodology, the characterization step assessed the relative contribution of each environmental impact [321]. The characterization is done by multiplying each substance's amount by its characterization factor and adding all of the figures together. Characterization factors are substance-specific, measurable interpretations of a substance's potential impact per unit emission. They determined each impact category that a substance/process could possibly contribute to [322]. Equation (1) represents generic factors while Equation (2) represents non-generic factors; the former factor is usually the outputs of characterization models and is accessible in the literature as a database.

$$S_j = \sum_i Q_{j,i}\, m_i \qquad (4.1)$$

Where S_j= impact category *j* indicator

m_i= size of the intervention of type *i*

$Q_{j,i}$= characterization factor that links intervention *i* to impact category *j* [323].

Equation (2) represents some non-generic characterization factors and potential variables in human health and the natural environment impacts setting [323].

$$Q_{j,s,t} = \sum_{l} \frac{Effect(i,l,t)}{Emission(i,s)} = \sum_{l} \left(\frac{Fate(i,l,t)}{Emission(i,s)}\right) \cdot \left(\sum_{l} \frac{Exposure(i,l,t)}{Fate(i,l,t)}\right) \cdot \left(\sum_{l} \frac{Effect(i,l,t)}{Exposure(i,l,t)}\right) \tag{4.2}$$

Where Subscript *i* = substance,
s = location of the emission,
l = related exposure area of the receptor
t = period during which the potential contribution to the impact is considered [323].

The normalization stage of the LCIA method refers to a process used to compare impacts across impact categories and protected areas to prioritize product alternatives or resolve trade-offs between them [323]. This stage also discovers an impact category that has little or no impact on the overall environmental impact, reducing the number of factors that must be evaluated. According to Finnveden et al. [324], normalization has two goals: placing LCIA indicator results in a broader context and adjusting the results to have common dimensions. A reference value is used to divide the sum of each category indicator result.

$$N_k = {}^{S_k}\!/_{R_k} \tag{4.3}$$

where k = impact category
N = normalized indicator
S = category indicator from the characterization phase
R = reference value

The reference system is generally selected by considering the result of the overall indicator for a specific country or region for a particular year. In an LCA study, the results of the normalization can allow input grouping or weighting impact categories or directly judge the relative importance of different impact categories. This study carried out the impact assessment using the Recipe 2016 v 1.04 midpoint method consisting of 18 midpoint impact categories as shown in Table 4.2. The method is known as Recipe because it offers a “recipe” for calculating impact category indicators. Furthermore, this method combines two well-known techniques, resulting in a unified and consistent impact assessment structure. For simplicity, the impact categories investigated were grouped into atmospheric, resource depletion, and toxicity categories. These impact categories are affected by the substances listed in the inventory. Table 4.2 includes the midpoint impact categories and they can be classified as local, regional, and global impact of cement production.

Table 4-2. The environmental impact indicators investigated (Mid-point impacts categories).

	Atmospheric	
Environmental Indicator	**Abbreviation**	**Unit**
Global warming	GWP	kg CO2 eq
Ozone depletion	ODP	kg CFC11 eq
Ozone formation, Terrestrial ecosystem	EOFP	kg NOx eq
Ozone formation, Human health	HOFP	kg NOx eq
Particulate matter formation	PMFP	kg PM2.5 eq
Ionization radiation	IRP	kBq Co-60 eq
	Resource Depletion	
Terrestrial acidification	TAP	kg SO2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
	Toxicity	
Human carcinogenic toxicity	HTPc	kg 1,4-DCB eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB eq
Freshwater ecotoxicity	FETP	kg 1,4-DCB eq
Marine ecotoxicity	METP	kg 1,4-DCB eq
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB eq

The inputs and outputs in the cement production system shown in Figure 4.1 are divided into five production stages: raw materials consumption, production fuels consumption, clinker production, transportation and electricity. Each stage is linked to the impact categories studied using the LCA methodology. All calculations were done using SimaPro 9.1.1 software application [317, 325]. Table 4.3 shows all processes studied in each production stage.

Table 4-3. Processes studied in each production stage of Portland cement in South Africa.

Production unit	**Processes considered**
Raw materials	Limestone and steel. Clinker and ethylene glycol, including the inputs and outputs
Fossil fuels	Diesel, coal, light fuel oil and lubrication oil, including inputs and outputs.
Electricity	Electricity used in mills and other equipment, in agreement with South Africa production and distribution regulation
Transportation	The transportation of raw materials, fuels and energy resources from the extraction site up to the gate of the plant
Clinker production	Particulate matter, NOx, CO2, emitted by the kiln during clinker production

4.4 Results and Discussion

Figure 4.2 presents the contribution of each of the five production stages to atmospheric impact categories. Global warming is the most studied impact related to cement production and is measured in kg CO_2 eq [9, 76, 106, 109, 326-329]. Global warming potential (GWP): Clinker production showed a high contribution, with 7.63 × 10^1 kg CO_2 eq, to those impact in this study due to the high CO_2 emissions associated with clinker production. This means 1 kg of cement produced emitted 1 kg CO2 eq, whereas other compounds, such as 1 kg of methane is equal to 25 kg of CO_2 eq.

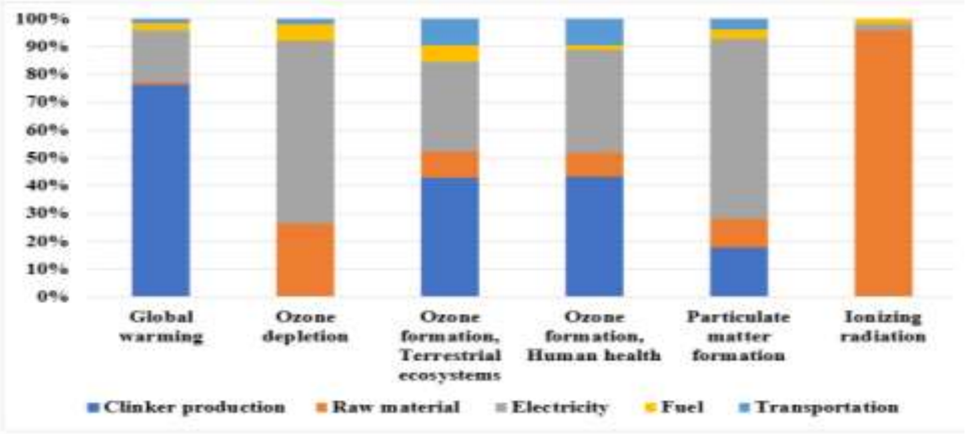

Figure 4-2 Contribution of each production stage to atmospheric impacts.

According to earlier studies, CO_2 emissions from cement production (calcination reaction and coal burning) are major GWP contributors [76, 157-159, 330]. Cement production emitted an average of around 0.8–1.0-ton CO_2/1 ton of Portland cement globally [76, 270, 331]. Furthermore, global warming has been one of the most widely studied impact categories in the broader LCA literature. This study discovered that the clinker production stage is the primary source of GHG emissions and this is consistent with most studies [9, 76, 106, 109, 328, 329, 332]. According to Wang et al. [215], the clinker production stage is the primary source of GHG emissions in the cement industry. In this study, the South African cement industry contributed 9.93×10^{-1} kg of CO_2 eq to GWP. This result is consistent with the values reported in the literature, ranging from 0.628 kg to 0.92 kg CO_2 eq per 1 kg of cement [109, 158, 228, 238].

Ozone depletion (OD) happens when the rate of ozone destruction is accelerated by recalcitrant chemicals from anthropogenic emissions containing chlorine or bromine atoms [318, 333]. The OD impact is measured in kg CFC11 eq (trichlorofluoromethane or Freon11) and contributed to all the stages, except clinker production. The raw materials consumption and electricity usage were due to limestone extraction and raw material transportation to the plant. The 1.90 kg CO2 eq value can be explained by the different fuel mix and the effect of transportation considered. The ozone depletion value from this study is 1.94×10^{-7} kg CFC11 eq. The result is in line with previous studies, i.e., 3.97×10^{-6} to $2.54 \times 10-4$ kg CFC11 eq [109, 298]. The electricity usage contributes to all atmospheric impact categories, except Ionizing radiation, as shown in Figure 4.2. The highest harmful atmospheric impact category of the raw material consumption stage was ionizing radiation impact, due to the limestone extraction. Furthermore, emissions from other production stages contributed to atmospheric impacts.

The ozone formation (terrestrial ecosystems and human health) contributed to all the production stages. It is affected by the atmospheric impact, mainly on clinker production and electricity usage. The contribution of the obtained clinker, which is considered a raw material in cement production, cannot be overlooked when it comes to transportation. Fine particulate matter (FPM) is measured in kg PM2.5 eq and it contributes to atmospheric impact production stages. The FPM contribution is due to the coal used in electricity production during the raw material consumption stage. The atmospheric impact from the clinker production and fuel consumption stage also contributed to the calculation. The size of CO_2 released from cement production clarifies why CH_4 and N_2O have more significant characterization factors among GHGs pollutants and leading causes of climate change.

Figure 4.3 presents the contribution of each of the five production stages to resource depletion impact categories.

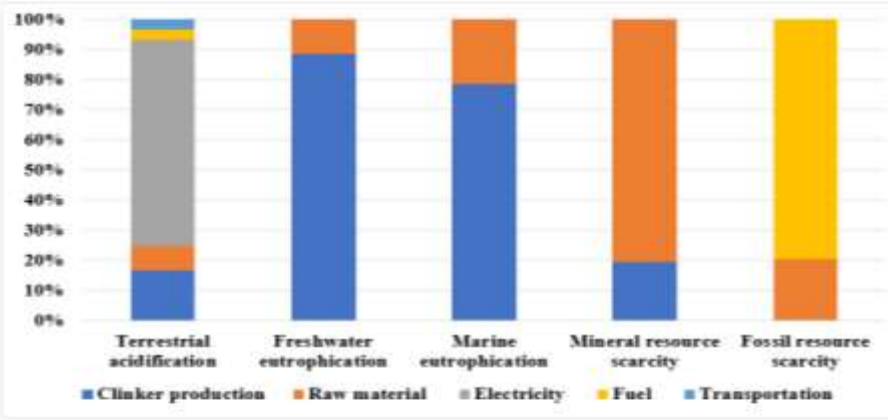

Figure 4-3 Contribution of each production stage to resource depletion.

Terrestrial acidification (TA) contributed to all production stages. Electricity usage is the main contributor due to the mix, dominated by fossil fuel, followed by clinker production and other resource depletion impacts. TA is a regional environmental impact, primarily related to the SO_2 and NO_x emissions during fuel burning for calcination and transport, as identified in other cement LCAs [270, 314]. The result of the Terrestrial acidification 2.44 × 10−3 kg SO_2 eq in this study is in line with Li et al. [238], in the range of 1.144–1.467 kg SO_2 eq and Josa et al. [158] in the range of 0.71–3.33 kg SO_2 eq. Clinker production due to coal burning contributed to the value of 3.60×10^1 in the resource depletion category.

Freshwater is measured in phosphorous (kg P eq) and Marine Eutrophication (ME) is measured in nitrogen (kg N eq) equivalent. They are primary contributors to clinker production and raw material consumption due to SO_2 and fewer NOx emissions. The ME contribution to the raw material consumption stage is due to ammonia emissions from explosives, with 2.67 kg N eq. Marine eutrophication is influenced by nitrogen compounds, produced primarily by the oxidation of molecular nitrogen in combustion air (thermal NOx) and the nitrogen compounds oxidation in fuel (fuel NOx) [334].

Fossil resource scarcity is measured in oil equivalent (kg oil eq) and contributes mostly to fuel consumption. However, if fossil fuels control the fuel mix used to generate electricity, this can affect terrestrial acidification. In addition, mineral and fossil resources scarcity contribute to raw material consumption and clinker production due to fuel burning and the explosives used, as identified by Stafford et al. [298]. The contribution of the transportation stage to the terrestrial acidification (3.40 kg SO_2 eq) value was due to the transportation of raw materials and fossil fuels in clinker production. Fuels used as primary energy sources in cement production, such as crude oil, natural gas, and coal, contributed to the value of fossil resource scarcity (1.39×10^{-1} kg oil eq) in cement plants.

The freshwater ecotoxicity and marine ecotoxicity impact categories showed similar profiles. The main contributors to the toxicity impact are raw material and fuel consumption due to fossil fuel extraction and raw material extraction, obtained with the values of 4.19×10^{1}. Fossil consumption contribution is attributed to coal burning. The low toxicity in transportation was due to energy usage during raw material transportation. The human carcinogenic toxicity contribution to the fuel consumption stage was due to the coal burning in the kiln and electricity generation for the process. Human non-carcinogenic toxicity is also crucial in fuel consumption and raw material. Due to the efficient use of electricity in South African cement plants, electricity usage makes no significant contribution to any impact category. The average consumption in the United States is 142 kWh/ton of cement, while 110 kWh is consumed in South Africa [134, 135].

Figure 4.4 presents the contribution of each of the five production stages to toxicity impact categories.

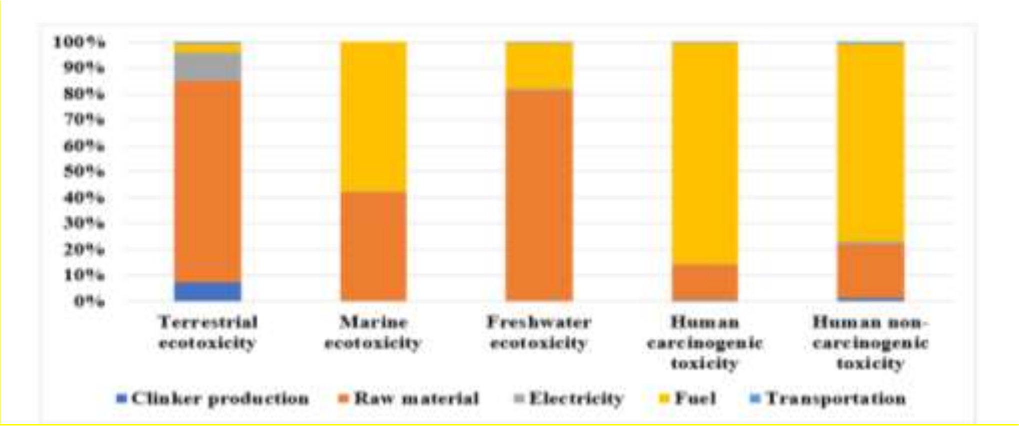

Figure 4-4 Contribution of each production stage to toxicity

Although there are some differences in the methods, it is widely agreed that the atmospheric category from the kiln is the primary cause of impact in the cement industry. As shown in Figure 4.4, these impacts depend on the fuels used, raw materials and installed technology. The Cement Sustainability Initiative states that replacing fossil fuels in cement production could reduce atmospheric emissions, if well controlled, and can be an excellent means of reducing fossil fuel usage [335]. According to Ecoinvent, extracting 100 kg of diesel oil can release 62.7 kg CO_2 eq and contribute 127 kg oil eq to fossil depletion [319]. The heavy use of traditional fuels (coal) in the South African cement kiln can be replaced with alternative fuels, for example, waste-derived fuels. Using waste-derived fuels instead of traditional fuel reduces emissions and fossil resources used in the cement industry, making it a sustainable method for recycling various waste materials [336, 337]. Hence, it could be agreed that the choice of materials and fuels directly influence the relationship between the cement plant and the environment.

4.5 Conclusions

In this study, the cement production stages, i.e., raw materials consumption, production fuels consumption, clinker production, transportation and electricity, were analysed using the life cycle assessment method. The findings show that each process impacted the environmental categories according to atmospheric, resource depletion and toxicity categories. The environmental impact of each cement production process was proportional to the related inputs and outputs. In terms of the atmospheric impact of cement production, the kiln affected all impact categories, except ozone depletion and ionizing radiation. The kiln caused most of the global warming impact. This was expected, as limestone calcination, the primary source of

CO_2 emissions is known to contribute to global warming. The clinker production stage produces the most significant environmental emissions due to calcium carbonate decomposition and coal consumption, particularly GHG emissions. Global warming is affected by GHGs emissions.

The study's findings show that massive raw materials consumption and fossil fuels are the factors that have the most impact on the resource depletion and toxicity categories. The production of fossil fuels significantly contributed to the atmospheric impact category. In addition, electricity consumption was also a significant factor, contributing to the atmospheric impact of fossil fuels in generating electricity. Thus, alternative raw materials and fuels could be a sustainable way to reduce environmental emissions. According to the characterization results of the midpoint analysis, the highest environmental impact of cement production was on global warming, terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity. For each 1 kg of Portland cement produced, the highest environmental impact values were 9.93×10^{-1} kg CO_2 eq (global warming), 1.04 kg 1.4-DCB (terrestrial ecotoxicity), 4.97×10^{-1} kg 1.4-DCB (human non-carcinogenic toxicity), and 1.39×10^{-1} kg oil eq (fossil resource scarcity).

Apart from the fossil resources' scarcity, which is linked to the consumption of fossil resources, other impacts are related to direct emissions from the clinker production stage. In this situation, measures to improve the South African cement industry's sustainability should focus primarily on reducing emissions from the clinker production stage by upgrading the production process, increasing the ratio of clinker substitutes, such as slag and fly ash, the use of alternative fuels to reduce coal and fossil fuel use, and improving energy efficiency. Finally, further research is recommended concerning efficiency measures to reduce the environmental impact, using energy-efficient technologies in the kilns and implementing on-site energy recovery technologies.

This study indicated that the South African cement industry is responsible for significant environmental impacts, including global warming, terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity, all identified as hotspots in the midpoint method. The main factors contributing to these impacts are CO_2, NO_x,

SO_2, and $PM_{2.5}$ emissions. These are direct emissions from the clinker production and fuel consumption stage for energy (electricity and transportation). As the main impact hotspots have been identified, the options of implementing energy-efficient technologies and on-site energy recovery technologies can be considered, including fuel and energy-saving approaches and alternative fuels and materials. With the energy-efficient technologies option, fossil resource scarcity can effectively reduce and encourage the utilization of scarce resources sustainably. There are many ways to implement energy-efficient technology options, including process integration and modification, proper maintenance, plant optimisation, and energy recovery. For example, process modifications, switching from a wet to dry process and using a pre-calciner, could reduce thermal energy consumption in cement kilns by about 50%, resulting in a 20% reduction in CO_2 emissions [9].

Another promising way to reduce CO_2 emissions is energy recovery from exhaust streams. During the clinker production stage, there are thermal heat losses in pyro-processing due to the flue gas and hot air streams. The heat losses can be recaptured to produce electricity using steam turbines [9]. On-site energy recovery technology options include using alternative materials, fuels and the clinker used during the cement production process [9]. The chemical decomposition of $CaCO_3$ in the clinker production stage contributes the most to CO_2 emissions. It is possible to reduce CO_2 emissions during this stage by reducing the amount of clinker and replacing it with other supplementary cement materials, such as natural pozzolana (fly ash, slag, etc.). The high process temperature in cement kilns can help burn waste efficiently. Using waste co-burning or biomass material as a fuel substitute can, thus, reduce the amount of coal or fossil fuels needed in the clinker production stage (the kiln), thereby reducing CO_2 and other emissions. Furthermore, it provides a sustainable waste management solution, as it contributes to GHGs reduction and other air pollutants released by the open burning of waste [155].

CHAPTER 5 : Environmental Impact Analysis of Portland Cement (CEM1) Using the Endpoint Method

This chapter present the damage-oriented results at endpoint. According to International Organisation for Standardisation, ISO 14040 [78] (Principles and Framework), ISO 14044 (2006) [203], and ISO/TS 14072 [79] (requirements and guidelines),this chapter examines the damage done when producing 1 kg of Portland Cement in the South African cement industry. The chapter assessed the environmental impact of Portland cement (CEM I) at the endpoint using the Recipe 2016 v 1.04 method in the software SimaPro to analyse the effects of cement on human health, ecosystems and resources. The damage results of the five production process were assessed using the LCA methodology at the endpoint. The results reveal that the clinkering stage causes the most substantial damage to human health and the ecosystem due to large carbon dioxide (CO_2) emissions. Crude oil, coal, natural gas and aluminium are the most critical resources utilised in the production process and are subject to scarcity. This evaluation allows a country wide calculation of the value lost yearly due to the cement industry in terms of lost resources and the life expectancy of individuals, species, and economic value.

5.1 Introduction

The global state of energy is categorised by reducing fuel sources and environmental worries related to fossil fuel usage [338]. Although the global COVID-19 pandemic reduced carbon dioxide (CO_2) emissions by 5.8% in 2020, carbon emissions are estimated to attain roughly similar atmospheric levels by 2023 [339]. In line with a three-year delay created by the economic recovery situation, energy demand will lag behind compared to pre-pandemic projections [340, 341]. Environmental protection has grown in popularity recently and has become an essential measure for social and political settings [266, 342]. The most sought-after goal is reduction of greenhouse gas (GHG) emissions for example carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) that contribute to the greenhouse effect in an energy-intensive industry such as cement [343]. Cement production is a multiplex process that uses large raw materials such as limestone, marl, clay, and iron ore and various fuels such as coal, natural gas, fuel oil, petroleum coke and waste, heat and electricity. Cement production contributes to global warming through the CO_2 emission during the clinker production stage [344]. Cement is an essential material in the construction industry with high environmental impacts [76]. The global cement demand has risen due to rising population and urbanisation. Cement production in 2016 was about 809 × 10^6 t, making it the most-used produced substance globally [345]. Also, global cement demand was expected to climb 4.5% per year to reach 5.2 Bmt in 2019 [346]. The cement production growth rate is projected to rise in the following years.

The main impact of cement production is GHGs emissions, excess resource use and energy (fossil fuel and electricity) [298]. The main components in Portland cement are calcium (limestone), silicate, iron and alumina. Gypsum is used to improve the setting time of cement [347]. CO_2, CH_4 and NOx are the most common GHGs emissions from cement production [191]. Several Studies have indicated that the clinkering stage has the most significant impact, with CO_2 being one of the most released gases [192, 202, 348]. Coal is the primary fuel (thermal) used in the combustion process, contributing to these GHGs. The impact of cement production is affected by the raw material specifications and type of fuel, along with the technology used. Globally, cement production contributes to about 5% of CO_2 emissions, producing 0.81 kg CO_2-eq for one ton of cement produced [157]. Due to this, cement production faces tremendous challenges in meeting global demand while reducing CO_2 emissions.

In modern cement industries, both wet and dry rotary kilns are used [349]. Growing concern over the capacity of the Earth to sustain economic development arose due to the increasing threat of harmful global environmental change and mismanagement problems. Many international groups and developed nations have recommended different strategies and measures to mitigate these effects, including green economy, green growth, green transformation, green industrial blueprint and sustainable transformation [350]. Since cement is one of the most vital products in the world, it is crucial that the damage caused by this industry be critically analysed. To properly recommend and provide mitigation strategies, it is necessary to measure cement production and its impact on human health, ecosystems and resources in the production stages. Various mitigation strategies were recommended, including partial clinker replacement, alternative fuel use, etc. Also included in the suggestions was adopting the BATin the cement production [162, 163, 348]. Therefore, this study uses the endpoint Recipe 2016 v 1.04 life cycle assessment method to investigate the environmental impact of Portland cement production (CEM1) in South Africa.

5.2 Life cycle assessment

Life cycle assessment (LCA) is a critical assessment tool for analysing the effects of all stages of product production, from raw extraction to the waste disposal finish [78]. This tool is of great significance when it is necessary to know the environmental impact of various production stages. It also serves as a decision-supporting tool for cement producers, allowing them to improve the production process. The cement industry environmental impact can be assessed using an LCA. Several studies have been investigated using LCA to evaluate the environmental impact of cement production in various countries, including Spain [15, 162, 228], Egypt and Switzerland [351], China [109, 238], the European Union, the USA [158, 202, 348, 352] and others [192, 243, 314, 315]. The LCA tool can provide a comprehensive overview of the whole product lifecycle. Following the international standard organisation (ISO) 14040 [78], 14044 [203] and new extension ISO/TS 14072 [79], LCA methodology contains four stages: Definition of Goal and Scope, Life cycle inventory (LCI), Life cycle impact assessment (LCIA) and interpretation.

5.2.1 The definition of goal and scope

The definition of goal and scope gives a detailed assessment objective along with system boundaries, assumptions, and functional units of a product or process [353]. This study will use 1 kg of Portland cement as a functional unit. This will include all dataset, analysis and interpretations.

5.2.2 Inventory Analysis

The LCI stage covers all the input and output inventory data required to evaluate a product's production process [353]. The environmental impact database includes all emissions produced during the production process. This study uses inventory data from the Ecoinvent v3.7.1 [319] database, one of the most highly regarded databases for construction materials [354]. The data was modelled after the South African cement plant.

5.2.3 Impact Analysis

LCIA is a multiple-faced evaluation method used to reveal all the potential environmental impact categories based on the environmental resources data provided in the LCI. Several environmental issues are addressed in this assessment, including energy use, global warming, water pollution, etc., offering a comprehensive evaluation of the product's environmental impacts [78]. In the LCIA stage, all inventories are grouped into various impact categories, then the results of the LCIA and LCI are interpreted.

5.2.4 Interpretation

This stage explains the results of the LCIA based on the LCI [355]. This stage comprehensively present processes and substances with significant impacts with a clear presentation, after which we will formulate recommendations. This study will analysis the environmental impact of 1 kg of Portland cement (CM1) using the endpoint LCIA method to measure the impact and correctly provide appropriate recommendations. The investigation was carried out from raw material extraction to cement production, i.e., from cradle to gate system boundary.

5.3 Materials and Methods

The LCA method has been used to evaluate the environmental impacts and resource use across a product's lifetime, i.e. from raw materials extraction to the production line and use stages to waste [78]. The LCA method evaluates the environmental impact of products, services, and processes from "cradle to grave." Based on this data, the LCA analysis assesses the potential impact on the environment, natural resources and human health [356]. The methodology is one of the most crucial components of LCA tools. The analysis and the data validation follows the ISO/TS 14072 guidelines for organisational LCA [79] using the endpoint method of the SimaPro 9.1.1 software [317, 325]. The LCA consist of four stages: definition of goal and scope, inventory analysis, impact assessment and interpretation, following the guidelines of the International Organisation for Standards ISO 14040 [78], 14044 [203] and ISO/TS 14072 [79]. Therefore, this study describes the LCA methods for the various stages of cement production, i.e., clinkering, raw material usage, fuel usage, transportation and electricity usage explained by Ige et al. [191]. Since SimaPro uses different analysis methods, the method selected for this study is ReCiPe 2016 Endpoint (H) V1.04, which has three main impact categories; human health (HH), ecosystem (ES) and resources (RE).

5.3.1 Inventory Data

This study uses inventory data from the Ecoinvent v3.7.1 [319] database of the SimaPro for 1 kg Portland cement production. The basic materials model describes the production of various materials used in the life cycle of the South African cement plant. The input data for 1 kg of Portland cement include cement factory production capacity (5.36e-11 unit), clinker (0.902 kg), limestone (0.05 kg), gypsum (0.0475 kg), ethylene glycol (0.00019 kg), steel (5.25e-05 kg), electricity, (0.0376 kWh) and emissions to air (Heat, waste 0.135 MJ). The output of the system is Portland cement (1 kg). The data includes all raw materials and energy used in the production process. The figures are computed based on original data collected in South African cement plants. The data comes from 5 typical cement plants in South Africa, representing 90% of the cement market share.

5.3.2 Portland Cement Production Impact Assessment

As previously stated, the endpoint method employs three major impact categories, each of which includes specific impacts, as described below:

5.3.2.1 Human health

i. Global warming is measured in Disability-adjusted Life Years (DALY), caused by increased death and diseases due to climate change.
ii. Stratospheric ozone depletion is measured in DALY, resulting from increased UV radiation caused by ozone-depleting substances into the atmosphere.
iii. Ionizing radiation; expressed in DALY, causing by radioactive radiation.
iv. Ozone formation, Human health; the damage is measured in DALY. This effect is emissions of organic substances into the air caused by summer smog.
v. Fine particulate matter formation: the damage is measured in DALY. This effect is produced by sulfur, dust and nitrogen oxide emissions into the atmosphere caused by winter smog.

vi. Human carcinogenic and non-carcinogenic toxicity; the damage is measured in DALY. This result from carcinogenic effects due to carcinogenic emissions of substances to air, soil and water.

5.3.2.2 Ecosystem

i. Global warming; Terrestrial ecosystems and Freshwater ecosystems, Ozone formation; Terrestrial ecosystems, the damage to the ecosystem is measured in species/ year resulting from the emission of ecotoxic substances to air, soil and water.
ii. Terrestrial acidification, Freshwater and Marine eutrophication, Terrestrial ecotoxicity. Freshwater and Marine ecotoxicity; the damage to the ecotoxicity is measured in species/ year causing from the emission of acidifying substances into the air.
iii. Land use: the damage is expressed in species/ year. Either land conversion or land occupation causes this damage.

5.3.2.3 Resources

Mineral resource: the damage is measured in USD2013 due to decreasing mineral grades.

Fossil resource: the damage is expressed in USD2013, resulting from lower quality of the fossil fuel extraction.

5.4 Results and Discussion

5.4.1 The Characterisation Result (Endpoint)

The endpoint method measures the damage-oriented impacts of the processes and shows several impact categories that are further grouped into damage categories. According to the endpoint method, the flows are divided into 22 impact categories, as shown in Table 5.1. Endpoint methodologies assess Human health, ecosystems, and resource damage categories. In addition, the endpoint method shows impacts within various categories but removes other aspects not considering the emissions factors [318].

Table 5-1. The damage category investigated (Endpoint method).

Human health (DALY)

Global warming, Human health
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Water consumption, Human health
Ecosystems (species.yr)
Ozone formation, Terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Global warming, Terrestrial ecosystems
Land use
Global warming, Freshwater ecosystems
Water consumption, Terrestrial ecosystem
Water consumption, Aquatic ecosystems
Resources (USD2013)
Mineral resource scarcity
Fossil resource scarcity

Based on the endpoint method, Table 5.1 shows the endpoint impact category, which explains each impact in the damage category. This method presents 22 different impact indicators with three damage units, i.e., DALY, species/yr and USD2013, according to their impacts. The various impacts listed in Table 5.1 are grouped according to the area of significance to life (AoSL) damage categories, as shown in Table 5.2.

Table 5-2 Damage assessment results of 1 kg Portland cement using endpoint method

Damage category	Unit	Portland Cement, Production
Human health	DALY	1.6176×10^{-6}
Ecosystems	species.yr	3.9×10^{-9}
Resources	USD2013	1.686×10^{-2}

Figure 5.1 shows a graphical illustration of the impact categories of the five production processes. The characterisation result of the endpoint method shows a similar pattern as the midpoint method with additional four impact categories [191].

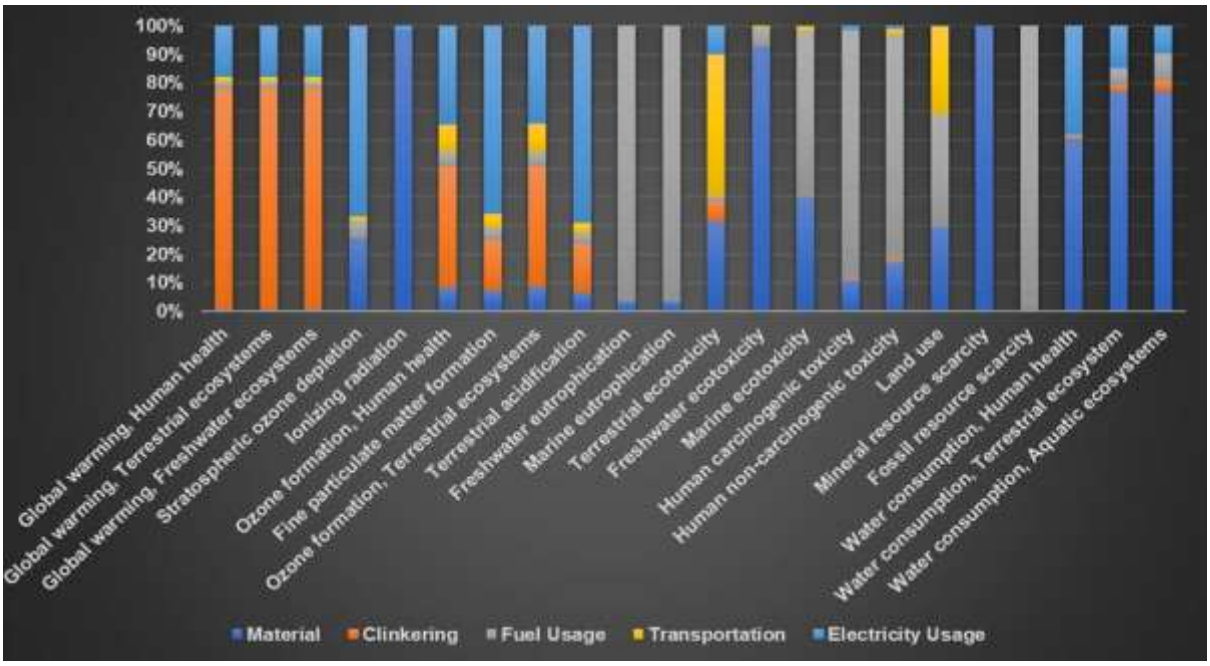

Figure 5-1 Endpoint environmental impact of cement production in South Africa.

The contribution of the five production processes, i.e., clinkering, raw material usage, fuel usage, transportation and electricity usage, to the damage categories is shown in Figure 5.2. These production processes were assessed and interpreted according to damage categories: Human health (HH), ecosystems (EC) and resources (RE). The evaluation and interpretation of the production processes are outlined as follows.

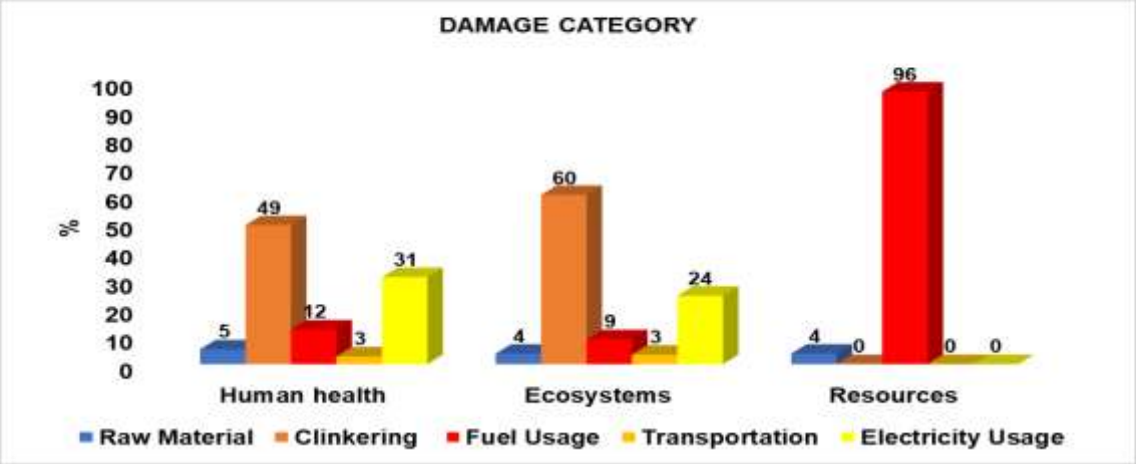

Figure 5-2. Damage assessment results for five production processes.

5.4.2 Raw material usage Stage

Raw material consumption contributed to all three impact categories, as shown in Figure 5.2. Human health (5%), Ecosystem (4%), and Resources (4%). Overall, raw material consumption had a minor impact on the damage categories. Therefore, raw material usage did not contribute significantly to damage categories.

5.4.3 Clinkering Stage

In Figure 5.2, the clinkering stage is responsible for 49% of the damage to human health and contributes to the ecosystem (60%) due to primary gas emissions such as CO_2, SO_2, NO_x and particulate matter, but clinkering stage had no impact on Resources.

5.4.4 Fuel Usage Stage

Figure 5.2 showed that Fuel usage contributed to all damage categories with human health damage (12%), ecosystem (9%) and significantly impacted resource damage with (96%). Most of these impacts were related to fossil resource consumption, direct emissions from cement production and transport materials during clinker production.

5.4.5 Transportation Stage

As shown in figure 5.2, transportation usage had a negligible impact on the damage categories. There was a 3% contribution to Human health and the ecosystem had no impact on resource damage.

5.4.6 Electricity usage Stage

Electricity usage did not impact damage to Resources, as shown in figure 5.2, but caused damage to human health (31%) and the ecosystem (24%). The following section further examined the damage category and the findings are detailed below.

5.5 Damage Assessment Result

The endpoint analysis classifies the various impact categories into the relevant damage categories based on their effects. Table 5.2 summarises the damage assessment under which each impact category falls: Human Health with a value of 1.6176×10^{-6} DALY, Ecosystems has 3.9×10^{-9} species/yr, and Resources with 1.686×10^{-2} USD2013. More in-depth analysis was done to determine the exact substance that contributed to these damage categories and their contribution level in the production process stage. Figure 5.2 compares the three damages in five production process stages, i.e., raw material, clinkering, fuel usage, electricity usage and transportation.

5.5.1 Human health

Damage to Human Health is measured in DALY and determined by many categories, including carcinogens, radiation, respiratory organics, climate change, respiratory inorganics and the ozone layer. The World Health Organisation (WHO) defines the unit of human health damage disability-adjusted life years as the total annual number of potential life lost or that a person is disabled due to a pandemic, disease, or accident. According to table 5.2, the damage to human health was 1.6176×10^{-6} DALY. Figure 5.3 shows the substances emitted during the clinkering stage that cause this HH damage.

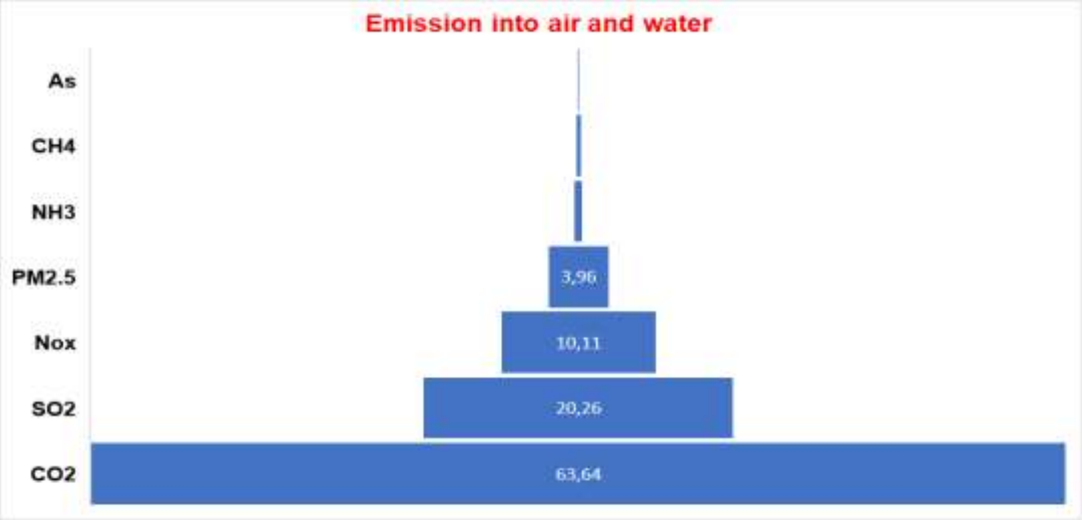

Figure 5-3. Contribution of substances to Human Health.

Figure 5.2 shows that 49% of the damage caused to HH is due to the clinkering stage. At this stage, the production of clinker causes massive damage to the HH. Others are raw material usage (5%), fuel usage (12%), electricity usage (31%) and from energy generation and transportation (3%). The substances resulting during the production stages are CO_2, CH_4, SO_2, NOx, Particulates, < 2.5 um, etc. Therefore, a detailed damage assessment was conducted on HH. CO_2 emissions have a high contribution, as shown in the midpoint method result from Ige et al. [191]. In Figure 5.3, the result showed that 64% of the damage is caused by CO_2 emissions, with other substances like SO_2 (20%), NO_X (10%), PM2.5 (4%), NH_3 (1%), CH_4 (0.4%), As (0.6%). All of which have different effects on human health. The reaction between the raw material and coal in the clinker causes the sulphur content to produce SO_2, one of the major gases released into the air and water.

5.5.2 Ecosystem

Damage to the Ecosystem is calculated in species/yr.; it refers to the number of species lost in a year due to emissions to the environment, water bodies, etc. Table 5.2 shows the ecosystem's damage is 3.9×10^{-9} species.yr per 1 kg of Portland cement produced. This damage was the average of species threatened calculated each year. In other words, for every 1 kg of cement produced, 3.9×10^{-9} species likely die yearly. The South African cement industry requires approximately 34.2 MT of cement annually, which endangers 133 species.

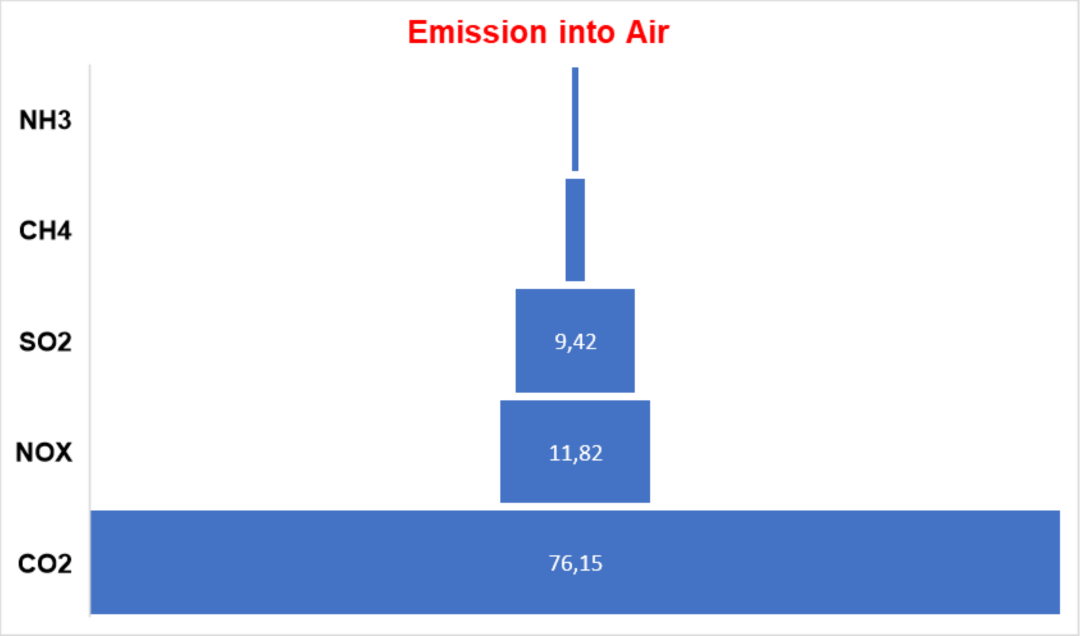

Figure 5-4. Contribution of substances to ecosystem

Figure 5.2 shows that the clinkering stage is responsible for 60% of the damage to the ES, as seen in the case of HH. However, the remaining percentage comes from electricity usage (24%), fuel usage (9%), raw material usage (4%) and transportation (3%). An in-depth analysis was done on the ecosystem damage according to the substances that cause this damage. Figure 5.4 shows the analysis results of the substances that cause ecosystem damage. The result showed that CO_2 has the highest emission (76%) due to energy generation, followed by NO_X (12%), SO_2 (9%), CH_4 (2%) and NH_3 (1%). Again, this proved that whatever affects the ecosystem affects human health and the other way around.

5.5.3 Resources

Damage to resources is expressed in USD2013. Table 5.2 shows the damage to resources is 1.686×10^{-2} USD2013. The potential marginal increase in the price of resources per kg of Portland cement produced was due to the scarcity of such resources. Therefore, for each resource used to produce 1 kg of Portland cement, the price of that resource will increase by 0.01685 USD in 2013.

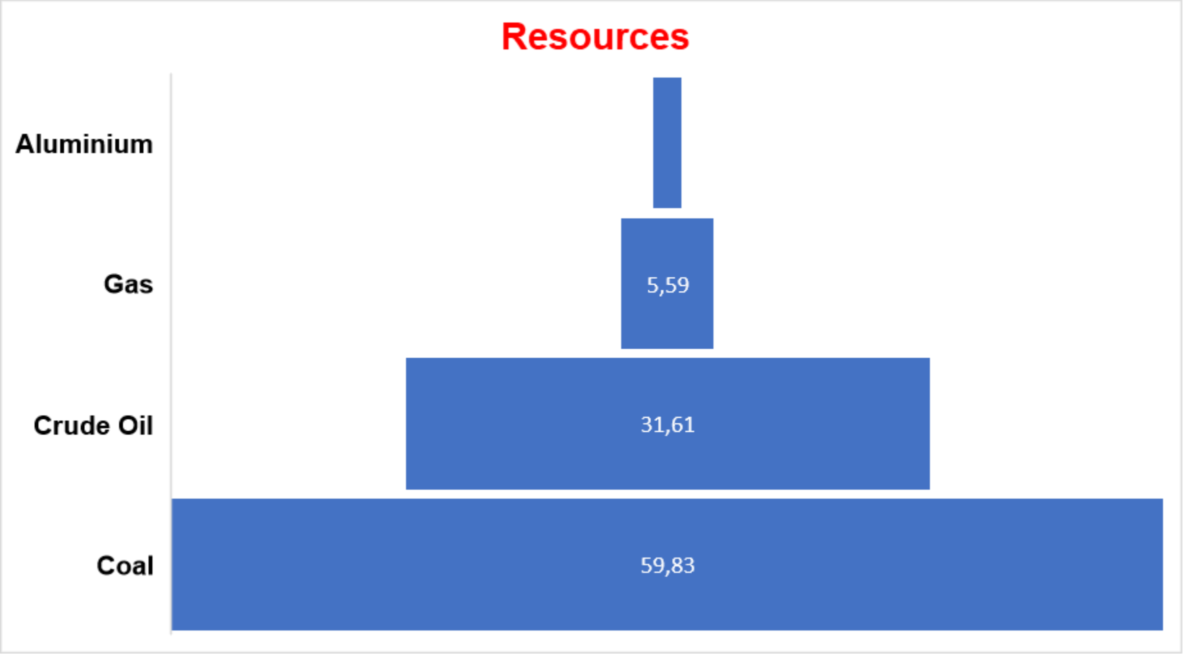

Figure 5-5. Contribution of substances to resources

Figure 5.2 shows the details of the total damage to resources. The main resource damage is fuel usage (96%) and raw materials (4%). An in-depth damage analysis was performed on the resources according to the substances that caused this damage. According to Figure 5.5, the result showed that Coal (60%), Crude Oil (32%), Gas (6%) and Aluminium (2%) contributed to resources.

The endpoint analysis's results are consistent with those found in the literature, with CO_2 emissions and the clinkering stage being the most significant contributors [109, 314]. The resources used by Chen et al. [109] and Tun et al. [314] differ because coal was the primary fossil fuel used to produce cement. According to Figure 2, the SO_2 emitted from clinkering stage, as shown in Figures 5.3 and 5.4, was due to the coal combustion in the South African cement plant, which established the production of SO_2 by Mittal et al. [357] and Ali et al. [351]. The sulphur content of the coal heavily influences the SO_2 emissions. Meanwhile, SO_2 emissions threaten human health and the ecosystem while harming people's chances of receiving clean air, as previously stated by Huntzinger and Eatmon [157], Chen et al. [109] and Song et al. [358]. In the clinkering stage (calcination process), NO_X is emitted during fuel burning. These emissions were emitted into the air and water.

5.6 Conclusions

In this study, we assessed the environmental impact of 1 kg of Portland cement at the endpoint in the cement production stages (raw materials usage, clinkering, fuel usage, transportation and electricity usage) caused by the South African cement plant. This study used the endpoint (damage approach) method of LCIA. The assessment was done using a dataset modelled after the South African cement plant using the data obtained from Ecoinvent database v3.7.1, incorporated with SimaPro 9.1.1. software due to a shortage of data. The characterisation results presented 22 impact categories in the endpoint method.

Based on AoSL, these impact categories were divided further into damage to HH, ES and RE. Human Health has a value of 1.6176×10^{-6} DALY, which means that for every 1kg of Portland cement produced, 1.6176×10^{-6} human lives are damaged. Ecosystems with the value of 3.9×10^{-9} species/yr show that 3.9×10^{-9} species are lost annually for every 1kg of Portland cement produced. Resources value of 1.686×10^{-2} USD2013 indicates that 1.686×10^{-2} USD worth of resources are wasted for every 1kg of Portland cement produced. According to this study, among the three main damage categories, human health is the most affected by releasing substances into the air during Portland cement production. Also, these emissions also have significant adverse impacts on global warming. The most released substances to air and water from all emissions are $CO_{2,}$ As, CH_4, NH_3, $PM_{2.5}$, SO_2 and $NO_{X.}$

The clinkering stage contributes 49% of the damage to HH and 60% to the ES, affecting the health of humans and other species due to the amount of CO_2 released at this production stage. The contribution of damage to human health and the ecosystem to substances is 64% and 76% from CO_2 emissions, respectively. These results are in line with the literature [15, 93, 162, 238, 243, 298, 348]. CO_2 emissions contribute to global warming, which causes climate change that impacts humans and ecosystems alike. In human health and the ecosystem damage categories, the emission of other gases such as A_s, CH_4, NH_3, $PM_{2.5}$, SO_2 and NO_X were released into the air and water; however, they were minor compared to CO_2 gas. In Portland cement production, resources like coal, natural gas, clay and petroleum may become scarce, particularly petroleum (crude oil).

In conclusion, this study concludes that the clinkering stage is the most harmful production stage for human health and the ecosystem since it produces the highest amounts of CO_2 gas. For every 1kg of Portland cement produced, approximately 0.74kg of CO_2 gas was emitted. The result also indicates that continuous cement production may cause a scarcity of resources such as coal, natural, gas and petroleum. Moreover, most of the emissions impacting human health also endanger the ecosystem. Species/yr refers to the number of species lost to water and the environment yearly; this can also be calculated for an entire country. Also, damage to resources is determined by the economic loss worth caused by the increased costs associated with extraction.

CHAPTER 6 : An Integrated System Dynamics Model and Life Cycle Assessment for Cement Production in South Africa

This chapter provide the results of an integrated LCA-SD-based framework using LCA characterisation result at the midpoint [191], then integrated with a system dynamics model to predict the future long-term environmental impacts of cement production. This study used SimaPro LCA software and system dynamics in the form of a mathematical model. Cement is one of the most produced materials globally. Population growth and urbanization cause an increased demand for the cement needed for more infrastructure. As a result of this circumstance, the cement industry must find the optimum compromise between growing cement production and reducing the negative environmental impact of that production. Since cement production uses a lot of energy, resources, and raw materials, it's essential to assess its environmental impact and determine methods for the sector to go forward in sustainable ways. The first step used the LCA midpoint method to investigate the environmental impact of 1 kg of Portland cement produced in South Africa. In the cement production process carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), methane (CH_4) and particulate matter (PM) are the major gases emitted. Therefore, the LCA concentrated on the impact of these pollutants on the global warming potential (GWP), Ozone formation, Human health, Fine particulate matter formation and Terrestrial acidification. The system dynamics model is used to predict the dynamics of cement production in South Africa. LCA impact results were used as input variables into a system dynamics model to predict the long-term environmental impact of cement production in South Africa. The proposed LCA-SD model methodology used here enables us to predict the future dynamics of cement production and its long-term environmental impact. The content in this chapter, co-authored with Kevin J. Duffy, Oludolapo A. Olanrewaju, and Obiora C. Collins, has been published in the Atmosphere [359].

6.1 Introduction

In recent decades, as industries have grown, energy consumption and emissions of various pollutants have increased, negatively affecting human health and the environment. This situation has caused substantial global environmental dangers to human health, including climate change, toxic wastes, toxic gas emissions, and environmental degradation. Cement production, for example, emits a significant amount of carbon dioxide (CO_2) that is environmentally harmful. The cement production process is a multiplex processing that uses a considerable amount of raw materials (Limestone), fuels (energy thermal), and electricity, as well as auxiliaries such as water and air [15-18]. A tonne of cement requires 110 kWh of electricity and 60 to 130 kg of fuel oil, depending on the cement type and the manufacturing process. It is important to note that CO_2 is the primary greenhouse gas (GHG) contributing to global climate change and is one of the largest environmental challenges in South Africa [283]. Globally, cement production accounts for 7% of the total industrial energy use, making it the world's third-largest energy user [360]. The World Business Council for Sustainable Development (WBCSD) predicts that by 2050 cement production will increase by 12–23%.

However, since the cement production process depends on many factors, reducing its emissions is not that simple. Nearly half of the GHG emissions from cement production are from material consumption, 40% from fuel combustion, 5% from electricity and 5% from transportation [23, 361]. The cement GHGs produced depend on factors which include the fuel used, the emission control system, the technology used, a plant's geographic location, and the source of electricity [23]. Raw material emission is through the limestone chemical composition that releases CO_2 during the thermal process to convert the compound to lime (CaO), the main component of cement. Our need for cement products, their environmental impact, and energy requirements make it essential for our search to reduce its emissions. The cement industry contributes roughly 5% of GHG emissions globally due to its reliance on fossil fuels and raw material calcination. In this context, many efforts are being made to protect the environment and improve its energy efficiency through alternative fuels or renewable resources. Therefore, understanding cement production and consumption trends are critical to understanding future developments in energy use, GHG emissions, and potential mitigation strategies. This paper discusses the options for sustainable cement production and the environmental impact based on policies and scenarios.

South Africa's cement industry has seen tremendous growth in recent years due to its rapid economic growth and urbanization. Cement production in South Africa has increased from 9.794 Mt in 2000 to 14.622 Mt in 2017, with 49.3% [362]. South Africa exported cement worth $95.7 million in 2020, making it the world's 35th largest cement exporter and the 111th most exported product in South Africa [363]. South Africa imported $57.9 million's worth in the same year, making it the world's 49th largest cement importer and the 222nd most imported product in South Africa [363]. South Africa is a growing nation and the third largest economy in Africa after Nigeria and Egypt. Historically, low energy prices have attracted and supported energy-intensive industries in South Africa, which played an essential role in its economic success. As a result, the cement industry emits significant levels of GHGs yearly. In South Africa, all cement plants use a dry process [364] and produce only Ordinary Portland Cement (OPC) and blended cement products. The different types of cement used are CEM I, CEM II, and CEM III, depending on the content of clinker within the accepted range of chemical composition, as shown in Table 6.1 [362].

Table 6-1. The percentage of different types of cement used in production, as well as their components.

Product	**Additives**	**Clinker Ratio**	
CEM I	Gypsum	>95%	
CEM II	Gypsum + pozzolanic components such as blast-furnace slag, micro silica, fly ash, and ground limestone	Group A	Group B
		80-94%	65-79%
CEM III	Gypsum + Slag	Group A	Group B
		35-64%	20-34%

Since 1994, six major competitors have dominated the South African cement industry: PPC Cement, Natal Portland Cement (NPC), AfriSam, Sephaku, Lafarge-Holcim, and Mamba Cement (Association of Cement Materials Producers). Until 2006, when Sephaku entered the market, these four companies were the major cement suppliers in South Africa, followed by Mamba Cement, a Chinese cement producer that arrived in 2016. Pretoria Portland cement limited has a leading market share (22%), followed by NPC (15%), Sephaku (12%), Afri-sam and Lafarge (9% each), and Mamba (5%), while imports have a share of approximately (5%). The remaining 23% of the market is held by third-party blenders [52, 55].

The cement production process emits about 0.97 tons of CO_2 for every ton of clinker produced. This distribution is mainly due to calcination (0.54 ton), coal and fossil fuels (0.34 ton) and electricity generation (0.09 ton) [365]. Approximately 0.9 tons of clinker is used to produce one ton of cement. As a result, each ton of cement emits 0.873 tons of CO_2 emissions [31, 32, 38, 366, 367]. In 2019, global cement production exceeded 4 billion tons due to higher continuous production growth rates in China and India [32], equivalent to 4 billion tons of CO_2 released into the atmosphere [29]. A large amount of the energy used in cement production comes from burning fossil fuels. In addition, the cement sector is responsible for 0.9 tons of CO_2 equivalent emissions released into the atmosphere by producing one ton of Portland cement which represents 5-10% of the total anthropogenic CO_2 emissions emitted globally [9, 115, 160, 197, 198, 209, 210, 288, 368-371]. Likewise, the need for cement in the construction industry, the demand observed in countries such as China and India [39], also by the demographic profile of Africa, such as population growth, demand for urbanization, and economic development, force the production of cement, pollution and GHGs emissions to increase globally.

However, the cement industry faces different environmental impacts that harm humans and other species. Global warming is one of the impacts caused by climate change due to increased GHG emissions into the atmosphere. Another environmental impact related to the cement industry is high energy consumption at some stage in the production process, producing GHGs and other pollutants and increasing the cost of production. Also, cement production is the second-largest anthropogenic contributor to GHGs [23-25], accounting for about 5% of total GHG on Earth after steel production, which contributes between 4% and 7% [23, 26, 27]. There are many challenges in the cement industry due to environmental and sustainability problems. Cement production remains popular among investors and profitable, but its energy-intensive and unfavourable environmental nature are not considered. Additionally, cement production contributes significantly to air pollution [95, 219]. The cement industry's greenhouse gas (GHG) emissions have been investigated and assessed [9, 164, 372]. The irregular disposal of cement industry wastes is dangerous and causes environmental pollution. According to reports, CO_2, sulphur dioxide (SO_2), nitrogen oxides (NO_x), and dust/particulate matter (PM) are the primary sources of air emissions from cement production [373, 374].

The pollutants emitted by it have caused dangerous atmospheric environmental impacts. Thus, this industrial sector must improve its energy consumption to save energy and reduce the environmental impact. Replacing coal in cement kilns with various waste or waste-derived fuels [93, 375, 376] by 5% and 10% would result in a gross GHG emissions reduction of between 2.33 $MtCO_2e$ and 4.67 $MtCO_2e$ across the sector [377]. The carbon footprint of the industry, as well as its carbon tax liability, would be further reduced depending on the alternative fuel used. Also, cement is a highly resource-demanding industry concerning raw materials. Cement production is expected to rise further in the coming years due to economic growth and increased urbanization in developing countries. Therefore, reducing cement's environmental impact is necessary without compromising cement production. Substituting fossil fuels with alternative fuel sources like municipal waste or tyres can reduce the emissions related to fuel use [161]. Switching from coal to another fuel source in cement kilns will reduce cement's direct carbon footprint and prevent landfill emissions. The cement industry needs a comprehensive mitigation policy to reduce the long-term environmental impact in the sector. Carbon Capture and Storage (CCS) is still far from commercial, there are already possible alternatives to the conventional materials and processes used to produce cement, including clinker replacements, fuel switching and energy efficiency.

Life Cycle Assessment (LCA) is an environmental methodology that has been widely utilized around the world to assess the environmental and economic impacts of a process system [75]. LCA uses the same method across all products and during all stages, including production, energy consumption, transportation, maintenance, and disposal or recycling at the end life of a product. The entire LCA considers the impacts of energy consumption and emissions related to the product's life, e.g., cement. Environmental impact has become a priority for both the government and the private sector [7]. Also, Global warming is one of the most critical environmental issues of the 21st century, with significant effects on human health, the environment, and the global economy. Several studies have been conducted to measure the environmental impact of energy consumption in cement plants [76, 77]. However, the results of LCA may vary due to different methodologies and processes of input, such as raw material composition, system boundaries, fuel combination, etc. Several studies have been conducted on mitigating the cement industry's GHG emissions using the LCA method [351, 378]. While exploring various policy options for future cement production, it is crucial to consider their environmental implications.

The system dynamics (SD) method can be used to examine policy option effects and related cement dynamics in the cement industry. This dynamic simulation method feeds information governing system connections through interactive feedback loops. The SD method is typically used for large and complex systems when the emphasis is on relationships between modelling and the study of the different variables in the system rather than on a single transaction [379]. Forrester developed the SD model in the mid-20th century based on feedback control theory to explain the time-variant behaviour of systems [87, 380-382]. It was also designed to determine how policies, structure, decision-making, and time delays are linked with others and how they influence the growth and stability of a particular system [383]. SD assists qualitative and quantitative problem-solving methods, allowing the use of written and numerical data in conjunction with mental models to understand better the underlying structure and the feedback links responsible for system behaviour. Combining the data available at various levels of detail helps uncover different aspects of the system that may be appropriate to various stakeholders. A system dynamics model is used to help policymakers with CO_2 reduction. SD can also provide time-step simulations to show significant changes in GHG emissions trends. The LCA and SD models can be integrated either by LCA into SD or SD into LCA method. Combining LCA and SD methods to analyse the cement production process may provide researchers with a better understanding of the long-term trends of environmental impacts, thereby identifying potential solutions for the development of cement sustainability.

Various policy options should be examined when determining the future need for cement production, considering their environmental impacts. Therefore, this study combines the LCA method with a system dynamics framework in the form of a mathematical model to predict future cement production and long-term environmental impact in the South African cement industry. This provided a suitable platform for predicting South Africa's cement production and environmental impact trends from 2000 to 2040 based on the integration method. Study results will provide suggestions for improving cement sustainability by integrating SD and LCA methods.

The cement industry will have to implement all the major mitigation plans to reduce long-term environmental impacts. Various Supplementary Cementitious Materials (SCMs) are available to reduce Portland cement's carbon emission and produce low-carbon substitute eco-blended cement. The SCMs for clinker substitutes such as industrial by-products and waste, i.e., fly ash from the coal industry and slags from the steel industry, are among the most used clinker alternatives [113, 384, 385]. These by-products can be used for the production of eco-blended cement. Using eco-blend cement is estimated to reduce production costs by 2-8 % for fly ash and slag-based blends and 15-25% for clay cement [386]. If clay cement is adopted in the cement industry, a profit of between 8% and 10% is expected by 2025 [386]. Turner and Collins [387] estimate that eco-blends can reduce GHG emissions by 13% to 22%, whereas Ishak and Hashim [225] estimate a 6% to 50% reduction.

South Africa has significant potential to produce eco-blended cement locally using coal and steel as high-level clinker replacements because of its robust coal and steel industries. A total of 40 million tonnes of ash are produced in South Africa each year [388]. Eskom, the South African electricity company, generates 35 million tonnes of ash (10% bottom ash and 90% fly ash), while Sasol, the South African gas distribution company, produces roughly 8 million tonnes of gasification ash annually. Approximately 5% of the fly ash generated in South Africa is utilized effectively, while the remainder is dumped in landfills and ash dams, leading to toxic substances contaminating soils and groundwater [388]. In the short term, clinker content reduction in Portland cement represents more than 50% of the mitigation potential for the cement industry, according to the MPA [389].

Reducing the clinker content in cement production to 66% could mitigate 0.75 $MtCO_2e$ per year, with a marginal cost of R122/tCO_2e reduction in 2020 [389]. But the South Africa waste management act controls how industrial wastes are disposed and the law does not encourage the use of by-products or waste for economic purposes, including the production of eco-blended cement. It is required by government to demonstrate that some of these wastes are categorized as by-products. Therefore, an amendment to the regulations is needed to support the use of eco-blended cement. New policies will also be required regarding the quality of industrial by-products (fly ash and slag) since their characteristics differ based on power plants and even basins where coal is mined [388].

6.2 Literature review

6.2.1 Cement Life Cycle Assessment

LCA is an important method to determine the environmental impacts of cement production and develop and select possible technologies for its production. The environmental impacts of the cement industry are extensively studied using LCA [160, 228, 243, 314, 351, 378], and such studies are crucial to understanding this industry and finding policies to reduce its impact.

Recently, LCA studies were done to determine the environmental impact and the best available technology (BAT) to reduce the impacts of cement production [15]. The life cycles of different types of cement production have been studied [76, 77]. Valderrama et al . [15] used a cradle-to-gate LCA method to study the environmental impacts of just upgraded production lines for possible improvements within the cement plant. Chen et al. [159] used the LCA method to assess the environmental impact of the French cement industry. Li et al. [238] used BATs to investigate China's LCA analysis and compared it with the Japanese cement industry, as Japan is considered a suitable example of improving environmental performance. Thwe et al. [315] assessed the environmental impact of Ordinary Portland Cement production in Naypyitaw, Myanmar, using the LCA method. Morsali [299] examined the impact of the cement production process on ecosystem quality, resource depletion, and human health using LCA methodology and SimaPro software, Amersfoort, Netherlands, PRé Consultants. Tun et al. [314] applied the LCA method to assess the environmental impact of Myanmar's cement industry, using LCA software Recipe 2016 v1.1 (Zürich Switzerland) to identify the hotspots of the environmental impacts.

6.2.2 System Dynamics Model

System dynamics is primarily used to explain a complex system's social and corporate behaviour over time. The SD method is one of the powerful methods for simulating the behaviour of such interactive systems. Research on the system dynamics method is currently being done at many scales, particularly in the industrial sector [390-392]. Recently, some researchers have attempted to use the SD model to analyse the drivers and potential for reducing urban carbon emissions [393, 394] and industrial carbon emissions [395, 396]. At the same time, the complete nature of the SD method and its insistence on causality have led to several applications to study the impact of the implementation of policies and projects related to the reduction of GHG in various fields such as the energy sector [391, 393, 397-399], the transport sector [400-403], cement sector [89, 90] and steel sector [404, 405].

Feng et al. [393] developed an integrated system dynamics model based on the STELLA program framework to model Beijing's energy consumption and CO_2 emission trends from 2005 to 2030. Fong et al. [406] used an SD model to predict the future trends of CO_2 emissions in Malaysia based on various policies in the Iskandar Development Region and provided information for urban planning. Their work presents the projections of future CO_2 emission trends for IDR with many options for urban policies. Vargas and Halog [407] investigated the advantages of employing fly ash as an alternate clinker material in cement manufacturing using an SD method. They simulated five different lifecycle situations of cement with a fly ash share of 20% and 35% to assess the net CO_2 reductions. Ansari and Seifi [89] used a system dynamics model to examine the impact of energy price subsidy reform on energy consumption and CO_2 emissions in the Iranian cement sector. Anand et al. [90] used an SD model to estimate CO_2 emissions in the Indian cement sector.

Jokar and Mokhtar [408] developed a system dynamics model of the Iranian cement industry using Vensim PLE software v7.3.5 Harvard MA, USA, Ventana Systems, Inc. to study the impact of clinker replacement, alternative fuels usage and waste heat recovery on achieving sustainability between 2015–2034. Tang et al. [92] used the SD model to simulate long-term cement production, energy consumption, possible energy demand and CO_2 emission of the cement industry in the Chongqing region, China, by integrating regional differences. Song and Chen [390] developed a simulation model using system dynamics to determine the future emission trends of the cement industry in China. Pan et al. [392] used SD to analyse the Chinese refining industry, emphasizing energy security to determine the appropriate capacity extent of refining to cope with supply risks.

6.2.3 Integration of LCA and SD

There are now studies integrating LCA and SD models in the literature [409]. These models consider the two main stages of LCA, i.e., Life Cycle Inventory (LCI) and Life Cycle impact assessment (LCIA), and focus on introducing the idea of prediction within the methodology [410]. Some recent studies propose incorporating the following factors into the LCI stage. Onat et al. [411] proposed changes in technical structure due to the behaviour of actors and economic costs; Jin and Sutherland [412] proposed incorporating internal dynamics of the system, including feedback; Menten et al. [413] and Stasinopoulos et al. [409] suggested integrating changes in the dynamics of the system due to market changes in another sector. Regarding the LCIA stage, LCA models based on SD can predict the total impact value due to changes [407]. Also, they can predict how environmental impacts will change over time [414]. Recent research has integrated SD and LCA methods into various fields, including transportation [411], manufacturing [415-418], construction [419, 420], agriculture [421, 422] and waste recycling activities [423, 424].

Laurenti et al. [416] discussed the advantages of combining LCA, the Group Model-Building (GMB) method to identify and a causal-loop diagram (CLD) in a literature review. They emphasized the importance of this modelling method when it comes to scenario analysis. Onat et al. [411] developed an integrated and dynamic life cycle sustainability assessment (LCSA) model for sustainable transportation to analyse the environmental, economic, life cycle cost, and social life cycle impact of alternative vehicles in the US.

Thomas et al. [419] simulated dynamic electricity and natural gas demand using Energy Plus and a system dynamic model. They investigated the interactions and feedback between various contributing factors (such as material selection, maintenance, and replacement) and a building's overall energy requirements. The results of the proposed framework suggest that it can be used to determine the optimal period for replacing major building materials, thereby providing options for reducing a building's energy consumption and environmental impact throughout its life cycle. Bixler et al. [420] used a dynamic LCA model to analyse seven different green infrastructure performances for a 30-year life span. Yao et al. [424] used integrated LCA and the SD model to analyse different factors related to mobile phone waste and recycling.

6.3 Materials and Methods

6.3.1 Life Cycle Assessment & System Dynamics methods

LCA datasets are available in complex databases such as Ecoinvent, the European life cycle database (ELCD), and Thinkstep to link businesses and government agencies. The inventory stage is typically the most complex in the LCA stages because gathering the required data is often tricky due to confidentiality and unavailable information in some industries. LCA can be evaluated in such situations by considering the analogous processes and assuming a combined data set using a parameterized model developed in a software application such as SimaPro 9.1.1. Amersfoort, Netherlands, PRé Consultants. Also, a hybrid LCA model calculates the interactions between multiple variables and provides a complete understanding of the system. This research considers the integration of LCA and the System Dynamics method.

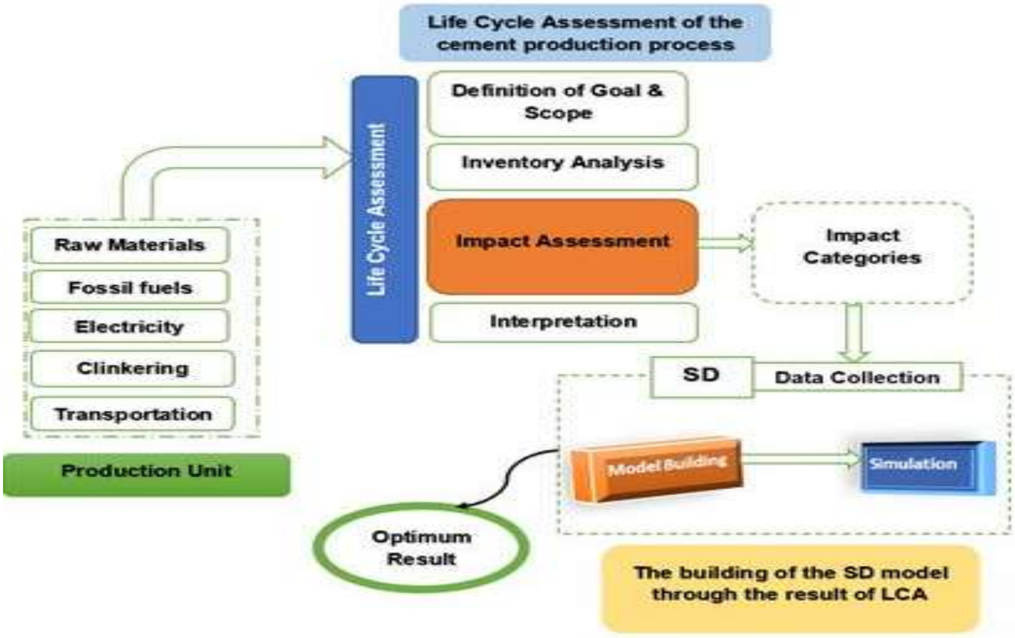

Figure 6-1. The framework of the integrated LCA and SD for Cement production.

Figure 6.1 describes the structure of the proposed methodology for integrating Life Cycle Assessment (LCA) into the System Dynamics Model in this study. In this work, LCA will be used to analyse cement production environmental impact, as shown in Figure 6.1. The LCA results are then integrated into an SD model as input variables to establish their relationship to perform a more comprehensive analysis. Subsequently, SD model simulation is performed using the results of the LCA [191] to predict the long-term environmental impact of cement production. Finally, the results recommend a suitable environmental cement plant.

6.3.2 LCA of the cement production process

The LCA method assesses the environmental impact of a process, product, or service throughout its life cycle. The International Organisation for Standardisation (ISO) has formulated rules for environmental management to establish the principles and guidelines for the LCA methodology [78, 203], with ISO/TS 14071 & 14072 [79, 425], as the latest version. The LCA method has now been extended to Organisational assessments ISO/TS 14071 and ISO/TS 14072 [79], increasing the applications for the approach and increasing its ability to reach a high-level decision- and policymakers. Based on ISO standards [78, 79, 203, 425], the LCA study contains four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 6-1. The integrated life cycle assessment and system dynamics LCA-SD framework of cement production in South Africa involves three main stages, (i) gathering data for key LCA processes, (ii) assessing the impacts of production processes using LCA SimaPro 9.1.1 software, Amersfoort, Netherlands, PRé Consultants and (iii) integrating the results of the LCIA as input variables with SD to predict the possible future dynamic and long-term environmental impact of cement production in South Africa. An integrated LCA-SD methodology is used to assess and predict the environmental impacts of the cement industry. Also, a hybrid LCA-SD model calculates the interactions between multiple variables and provides a complete understanding of the system.

6.3.2.1 System boundary, Goal, and Scope Definition

This study used a cradle-to-gate method and the LCA results were achieved using SimaPro 9.1.1 software with the Ecoinvent database v3.7.1. The system boundary of the cement production process determines the unit processes to be integrated or omitted. The various life cycle stages, unit processes, and flows are necessary when defining the system's boundary, including raw materials, fuel, clinkering and transportation. The environmental impact from packaging, cement use, and cement product end-of-life were omitted due to methodological issues. 1kg of Portland cement was used as a functional unit. The functional unit primarily provides references related to inputs and outputs. Furthermore, the functional unit is an essential factor of any study because it clearly describes the measurement used in the system. The boundary of LCA-based cement production merged into five, including raw material usage, transportation, electricity usage, fuels usage and clinkering stage, simplifying the entire cement production process and making it more appropriate to predict the long-term environmental impact of cement production.

6.3.2.2 Lifecycle Inventory

LCI includes the data collection and calculation procedures used to measure related inputs and outputs of the product system. Inventory analyses record all the needed resources for and all emissions by the particular system under investigation and relate them to a clear functional unit as stated in ISO/TS 14072/14071 [79, 425]. LCA inventory analysis quantifies the inputs and outputs (products and emissions to air, water, and land) from all processing stages through the system boundary. This is an inventory of input/output data related to the system under study. It designs a process where all process stages are mapped and linked from raw material extraction to wastewater treatment. The data collection for each unit process considers inputs (energy, raw materials, auxiliary equipment), emissions (to air, water, and soil), and products, co-products, and waste. This study considers data based on the South African cement production processes. The inventory dataset used for the background system is taken from Ecoinvent, a recognized database company [319, 426, 427].

6.3.2.3 Life Cycle Impact Assessment

LCIA is a tool designed to assess the environmental impacts corresponding to environmental resources as part of an LCI. Several environmental issues are covered by this assessment, including energy, climate change, water pollution, etc., providing a comprehensive analysis of the impact of the product [79, 425]. LCIA presents more information to assess the LCI results of a product system to understand its environmental implication better. Based on the data from an LCI, an impact assessment of a product or process can be executed to calculate environmental effects across the selected system boundaries and impact categories.

In this study, LCIA was conducted using the Recipe 2016 v 1.04 midpoint method. At this stage, the consumption and emissions are converted into environmental effects. Also, the inventory data is categorized into different impact categories and analysed. The impact assessment is divided into classification, characterization, normalization, and valuation as recommended by the Society of Environmental Toxicology and Chemistry (SETAC) [355]. Classification classifies collected data from the inventory into several impact categories. Characterization aggregates inventory data within impact categories using equivalency factors [355]. Primarily, it is a measuring stage that looks at the relative contributions of the various inputs and outputs by category. Characterization factors are measurable analyses of a substance's potential impact per unit emission that are substance specific. They identified each impact category to which a substance or process might contribute [322].

The LCIA normalization stage refers to a procedure for comparing impacts across impact categories and protected areas to prioritize product alternatives or resolve trade-offs [323]. A valuation can be solved in a qualitative or quantitative. For qualitative valuations, expert panels may be used. Examples of quantitative valuation methods include comparing environmental loading or impact profiles [355, 428]. In the ISO report, the impacts are measured and grouped into human health, ecological health, and resource depletion to describe its effects adequately as analysed in a product [428]. The LCIA stage is a multi-step procedure that categorizes all inventory into different impact categories.

6.3.3 System Dynamics

System dynamics is a computer-aided method to analyse and solve complex problems, focusing on policy analysis and design. The SD method is used for various applications, but there is no standard way to model it. According to Ford and Sterman [429], in an SD model, the normal procedure can be summarized in four steps:

Identify Problem:

This includes exploring the problem under investigation and clearly explaining the objectives. This will necessitates identifying the key variables to demonstrate problem behaviour and the simulation possibilities.

Conceptualization of the System:

Identifying and establishing the causal relationships between the key variables and how the problem arose. The two ways to illustrate the interaction of the variable are the Causal-loop diagram (CLD) and the stock-flow diagram (SFD). The CLD develops an early mental model centred on the analyst's impression of the problem's behaviour. It is possible to identify the direction of a relationship between two variables by using a positive (+) or negative (-) sign. SFD is then used to convert the qualitative model to qualitative analysis.

Validation of the Model:

In validation, the objective is to compare whether the model's simulation and actual behaviour reflect the system's historical behaviour.

Evaluation of possible policy:

Following verification of the model's structure and behaviour, the analyst will plan the appropriate policies to improve and intervene in the reality.

As we evaluate the need for cement production in the future, it is crucial to consider their environmental impact when determining what policy options to implement. Using a System Dynamics framework, we can examine the cement industry's environmental impact policy and CO_2 emissions dynamics. This dynamic simulation method uses interactive feedback loops to feed information governing the interactions in a system. As a result, the cement industry may expect intense pressure to cut environmental impact profile as countries seek ways to meet the climate mitigation targets set out in the Paris Agreement. According to the Paris Agreement, countries must reduce GHG emissions and avoid global temperatures increasing by more than 2 °C above preindustrial temperatures [430]. In the Energy Technology Perspectives study [431], the International Energy Agency (IEA) examined the mitigation possibilities for the global cement industry and calculated those emissions required to be reduced to 1.7 Gt to fulfil the 2 °C targets

This work aims to predict the environmental impact of the cement production process and find effective ways to reduce the GHGs produced by cement production. The production stages considered here were used to generate the measurement data for the cement production process. The cement production environmental impacts were projected, and related policies were proposed to design an appropriate model.

6.3.4 System dynamics model development

System Dynamics is a simulation method that has been successfully used in modelling various industrial areas, including carbon mitigation, CO_2 emissions, and energy consumption for decision-making, policy planning, and evaluations [89-91]. By considering the major factors that influence cement production in South Africa, the model below is developed to study and predict the future dynamics of cement production in South Africa.

Assuming a correlation between South Africa's real Gross Domestic Product (G) and cement production (C) we use the following model to fit the data (Figure 6-2).

$$\frac{dC}{dt} = cc(\alpha G), \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6.1)}$$

$$\frac{dG}{dt} = \beta G\left(1 - \frac{G}{MaxG}\right), \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6.2)}$$

where $\frac{dX}{dt}$ symbolizes the rate of change of a variable X with respect to time. In this equation, increasing cement production (C) is correlated to Gross domestic product (G) by a parameter α. G is modelled logistically as in Duffy et al. [432], which assumes that G increases annually over the period but cannot exceed a certain maximum (MaxG). The data for C in South Africa shows a cyclical nonlinearity pattern which is introduced using the function taken from Herdicho et al.[433].

$$cc = \left(1.0 + p0 * cos\left(pi * \frac{t}{12} + q0\right)\right) \ldots\ldots\ldots\ldots\ldots \text{(6.3)}$$

The analysis of this model is used to predict future dynamics of cement production and environmental impact in the cement industry. The meaning of all variables and parameters are given in Tables 6-2 and 6-3 below.

Table 6-2. The Variables

Variables	**Meaning**	**Units**
C(t)	Quantity of cement produced in South Africa per year (t)	Kg
G(t)	Real Gross domestic product of South Africa per year	US dollars

Table 6-3. The Parameters

Parameters	**Meaning**	**Units**
α	Parameter linking GDP and CP	*(US dollars Year)$^{-1}$*
β	Annual growth of G(t)	*Year^{-1}*
MaxG	Maximum value of G(t)	*kg*
$p0, q0$	Fitting parameters	*Dimensionless*

The parameters α, β, MaxG and $p0, q0$ represent linking GDP and CP, the annual growth of G(t), the maximum value of G(t) and fitting parameters to dC and dG, respectively. Long-term projections describe cement production as a function of economic activity per year. To develop such relationships, we collected cement production and trade data from 2007–2017.

LCA does not predict the future, but system dynamics is a scenario prediction method. Then, these scenario predictions help in policy-making decisions and planning. The integrated LCA-SD model present here enables us to form a picture of the cement's environmental impacts going forward and how to avoid these possible impacts by with policies and recommendations. When determining the need for cement production in the next few years, various policy decisions should be considered keeping the environmental impact in mind. Hence, exploring alternative strategies for reducing the environmental impact (GHGs emissions). It also provides a possible methodology that can be used in the future for developing a better understanding of the long-term impacts of various mitigation strategies.

6.4 Data source

The study includes data collected between 2000 and 2017 on cement production and real GDP. Data on cement production were obtained from the South African greenhouse gas inventory report of 2017 [362]. The data on South Africa's real GDP in US dollars were obtained from World Economics [434] and characterization results (impact indicators) at the midpoint of our previous study [191]. It is assumed that cement production is to some extent influenced by real gross domestic product (real GDP).

6.5 Results and Discussion

There is no doubt that population growth, demand for urbanization, and economic development in the country impact cement production. In this study, we use a simple model to relate these factors, fitting the model's parameters using cement production and environmental impact data. It assumes that cement production and environmental impact data depend on real GDP. The production of 1kg of Portland cement prediction using the model simulations are used to predict the impact categories, i.e., the long-term environmental impact of cement production in South Africa by multiplying the total quantity of emissions into the atmosphere at any given time by the quantity of cement produced in South Africa.

6.5.1 Integrating LCA with System Dynamics

The results of the LCA, which address the cement production environmental impact at the midpoint, are combined with the system dynamics in this step. The most sustainable cement production plant in South Africa can then be identified by utilising the SD to predict the long-term cement environmental impact.

6.5.2 Model development

Regarding industrial development, South Africa is among the largest sub-Saharan African countries. South Africa is experiencing rapid population growth due to its industrial potential as an economy-developing country. The increase in CO_2 concentration levels in the atmosphere and the dangers related to global warming have led to increased studies to reduce the environmental impact of the cement industry. The International Energy Agency (IEA) estimates that cement plants worldwide will release 2.34 billion tons of CO_2 into the atmosphere by 2050 [435].

6.5.3 Overview of Cement Production, Real Gross Domestic Product from South Africa from 2000 to 2017

Figure 6.2 illustrates the dynamics of cement production in South Africa from 2000 to 2017. The points in Figure 6.2 represent the actual data and indicate that cement production and Real GDP in South Africa over the period were both nonlinear. Cement productions were 49.3% (4.828×10^9 kg) higher than the (9.80×10^9 kg) in 2000. After an increase of 51.7% in cement production from 2000 to 2009 (1.486×10^{10} kg). The increase in that period was not steady and was attributed to economic growth but declined by 16.8% to (1.2358×10^{10} kg) in 2012. The most notable growth rate was reported between 2005 to 2009 when it increased by 10% over the previous year. The evident decline in cement production between 2009 to 2012 can be attributable to two facts, i.e., (1) The electricity crisis in South Africa and (2) The global recession during that period. According to the South African National Statistics Agency, the country's economy went into recession in 2009, and the GDP declined by 1.8%. The higher interest rates, price increases, and the implementation of the National Credit Act in 2010 caused the cement demand in the residential market and construction industry to decrease. Between 2013 and 2017, cement production increased again by 1.569 × 10^9 kg (12%) due to new producers Sephaku (Dangote cement) and Mamba Cement, a Chinese cement entering the industry.

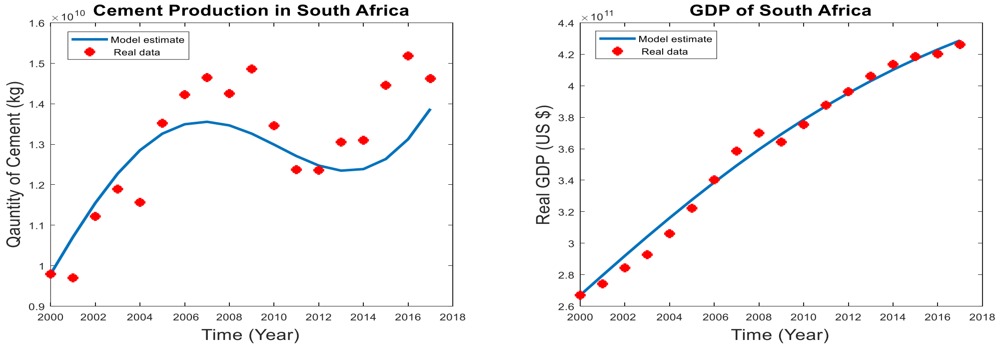

Figure 6-2. Plot showing the model fitting of Cement Production in South Africa and real GDP of South Africa from 2000 to 2017

Since the mid-2000s, the cement market in South Africa has become highly competitive due to the high cost of electricity and a downward trend in cement demand following the post-recession [436]. In South Africa, cement exportation increased dramatically from 6.849 × 10^6 kg to 2.52486 × 10^8 kg between 2000 and 2017 [437, 438]. Cement export from the country was estimated at 2.52486 × 10^8 kg in 2017 and Botswana, Eswatini, Lesotho, Mozambique, and the Dominican Republic are the top destinations for South African cement exports [437]. Cement imports in South Africa remained relatively stable between 2000 and 2005. There was a dramatic increase in cement importation (1.16868 × 10^8 kg) in 2006 and 2007 due to World Cup infrastructure preparations, significant investment in low-cost residential housing, and the Gautrain construction. At the same time, in 2017, South Africa imported 1.8771 × 10^7 kg of cement from Pakistan, United Arab Emirates, Egypt, Turkey, Tunisia, Saudi Arabia, and China [438].

Real gross domestic product (real GDP) is an inflation-adjusted measure of all goods and services produced by an economy over a particular period (expressed in base-year prices). It is also known as constant-price GDP, constant dollar GDP, or inflation-corrected GDP. Real GDP makes it easier to compare GDP between years because it compares the quantity and value of goods and services. According to World Economics figures [434], South Africa's real GDP was valued at $ 430 billion US dollars in 2019 and dropped to $ 400 billion US dollars at the end of 2020 due to the Covid-19 global pandemic.

6.5.4 Model Fitting for Cement Production and Real GDP in the South African Cement Industry from 2000 to 2017

The model fitting toolbox contains proper model selection measures, which makes it possible to identify the most suitable model version based on the data. Accordingly, model fitting is a type of model calibration that provides a pre-established framework for further investigation and model validation. In addition, model fitting is parameter estimation or identifying the parameters that best explain an existing dataset. The model fitting also provides statistical tests for parameters of variations between groups or situations, facilitating statistically sound evaluations [439]. The model fitting provides information about parameter estimates in terms of errors. The results of a well-fitted model are more accurate. Parameters estimates were derived by fitting the model using the South African cement production data (Department of Environment) [362] and World Economics Real Gross Domestic Product data for South Africa [434] from 2000 to 2017. The model was used to fit the cement production and real GDP in US dollars from 2000 to 2017. The lines in Figure 6.2 represent fits to that data using the SD model. The model captures the overall trend in cement production and GDP and is a good fit. The model is simple but captures the dynamics.

6.5.5 Future Prediction of Cement Production in South Africa

Throughout this simulation, the SD model was developed on the assumption that there are no significant changes in government policy and decision-making for the cement industry regarding factors such as population, GDP growth and urbanization. These factors play a significant role in cement production in South Africa. This study analysed data from 2000 to 2040 in two steps using historical data [362]. Firstly, the parameters were calibrated and double-checked so that the simulation matched the real-world situation from 2000 to 2017.

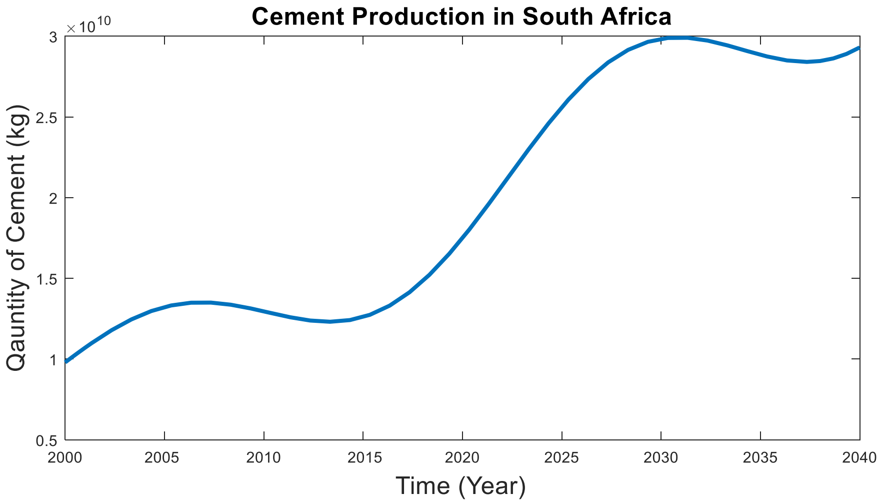

Figure 6-3. Plot showing a possible future dynamic of Cement Production in South Africa.

Secondly, based on the simulation, this work predicted the future of cement production in the South African cement industry from 2018 to 2040 (Figure 6.3). The total cement production will increase from 9.80×10^9 kg in 2000 to 2.93×10^{10} kg in 2040, with a 4.86 % annual growth rate. From the model prediction in Figure 6.3, cement production is nonlinear but gradually increases between 2018 and 2040. According to our projection, the overall cement production will reach 2.93×10^{10} kg by 2040, about 1.93 times higher than the production level in 2018.

A possible explanation for the long-term prediction for cement production staying positive (increase) in the coming decades in South Africa could be due to population growth, economic growth, urbanization, and the emergence of a middle class in the country. Thus, increasing demand for cement will continue till 2040 due to the need for housing and related infrastructure, resulting in an upward cement production trend. This agrees with some literature and reports on the prediction results of cement production [89, 198, 407, 435, 440]. If the current cement production rate is maintained and current mitigation measures are used, a massive amount of CO_2 is expected. Although cement consumption is closely correlated with cement production and the number of new installed capabilities, it is primarily a result of the future increase in the environmental impact. The future cement production will cause cement exportation to increase while cement importation decreases. As cement production increases, energy consumption and CO_2 emissions are also expected to increase significantly in the next few years. The cement industry in South Africa needs to improve its energy and emissions efficiency to maintain its current growth rate. The main improvements include more energy-efficient cooling, milling, conveying, grinding, improved cement kilns and blending technologies that use significant electricity.

6.5.6 Major environmental impact categories of Portland cement

Carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), methane (CH_4) and particulate matter (PM) are the major environmental pollutants emitted from cement plants. The LCA concentrated on the impact assessments of global warming potential (GWP), Ozone formation, Human health, Fine particulate matter formation and Terrestrial acidification based on the released pollutants.

6.5.6.1 Analysis of midpoint approach of five production stages

The five production processes, (1) Clinkering (calcinations and fuel-burning); (2) Raw material usage; (3) Fuel usage; (4) transportation; (5) electricity usage, were assessed according to atmospheric, resource depletion and toxicity and interpreted to determine their environmental impact. Based on the Recipe (H) midpoint method, this study presents the total values for each environmental impact category at the midpoint indicators.

6.5.6.2 Long-term environmental impact of cement production in South African

From Table 6-4 it was discovered that the production of 1kg of Portland cement releases 9.93×10^{-1} kilograms of CO_2 into the atmosphere, which causes Global warming. Therefore, the total quantity of CO_2 emissions emitted into the atmosphere at any given time due to cement production in South Africa can be determined by multiplying $9.93 \times 10^{-1}$with the total quantity of cement produced in South Africa. A similar analysis can be done for other impact categories. The results of these analyses are presented in Figures 6.4-6.7. As cement production increases, the impact categories increase; model simulations show that these increases are nonlinear with increasing growth levels.

Table 6-4. The characterization midpoint method based on1kg Portland cement.

	Impact category	**Unit**	**Portland cement production**
1	Global warming	kg CO2 eq	9.93×10^{-1}
2	Stratospheric ozone depletion	kg CFC11 eq	1.94×10^{-7}
3	Ionizing radiation	kBq Co-60 eq	9.97×10^{-3}

4	Ozone formation, Human health	kg NOx eq	2.10×10^{-3}
5	Fine particulate matter formation	kg PM2.5 eq	7.93×10^{-4}
6	Ozone formation, Terrestrial ecosystems	kg NOx eq	2.12×10^{-3}
7	Terrestrial acidification	kg SO2 eq	2.44×10^{-3}
8	Freshwater eutrophication	kg P eq	3.16×10^{-4}
9	Marine eutrophication	kg N eq	1.93×10^{-5}
10	Terrestrial ecotoxicity	kg 1,4-DB eq	1.04
11	Freshwater ecotoxicity	kg 1,4-DB eq	1.58×10^{-2}
12	Marine ecotoxicity	kg 1,4-DB eq	2.14×10^{-2}
13	Human carcinogenic toxicity	kg 1,4-DB eq	2.44×10^{-2}
14	Human non-carcinogenic toxicity	kg 1,4-DB eq	4.97×10^{-1}
15	Land use	m2a crop eq	7.83×10^{-3}
16	Mineral resource scarcity	kg Cu eq	2.16×10^{-3}
17	Fossil resource scarcity	kg oil eq	1.39×10^{-1}
18	Water consumption	m3	1.36×10^{-3}

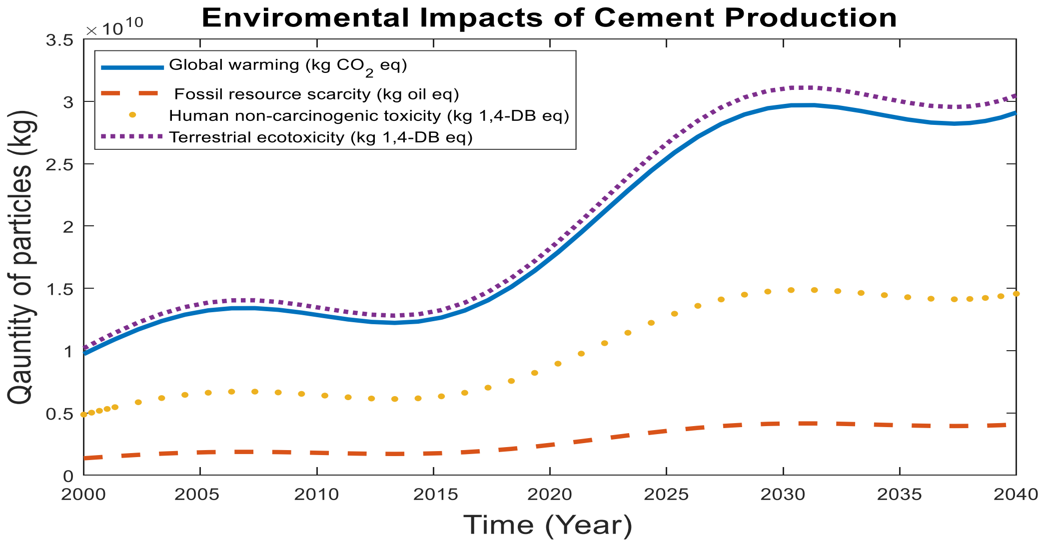

Figure 6-4. Plot showing a possible long-term environmental impact of cement production in South Africa. Global warming, measured in kg CO_2eq, Terrestrial ecotoxicity measured in kg 1,4-DB eq, Fossil resource scarcity measured in kg oil eq and Human non-carcinogenic toxicity measured in kg 1,4-DB eq.

Due to the increase in cement production, the environmental impact of the South African cement industry is expected to increase in the coming decades. CO_2 emissions from the clinkering stage (clinker production), an intermediate step in the cement production process, account for the majority of global warming in cement production. The cement industry contributes about 1% to total GHG emissions in South Africa.

In terms of environmental impacts, Global Warming Potential (GWP) is measured in kg CO_2eq. The global warming impact from cement production will increase from 9.73 × 10^9 kg CO_2 eq in 2000 to 2.91 × 10^{10} kg CO_2 eq in 2040, as shown in Figure 6.4. The GWP is nonlinear, as shown in Figure 6.4 and will slightly increase by 0.75% between 2009 and 2012, then show a consistent increase from 2013 to 2029. The result showed that by the year 2029, the GWP will emit 2.96 × 10^{10} kg CO_2 eq for cement produced in South Africa. The dynamic of the GWP is also going up till 2040. Subsequently, the result will show a slow increase of 0.2% between 2030 and 2035, moving to 2.91 × 10^{10} kg CO_2 eq in 2040 in South Africa, the highest value. The increase is from the rise in cement production due to population and economic growth during this period. The Terrestrial ecotoxicity (TE) measured in kg 1,4-DB eq, has an impact of constant increase from 1.02 × 10^{10} kg 1,4-DB eq in 2000 to 3.05 × $10^{10\ kg}$ 1,4-DB eq in 2040, a clear upward trend with a 240% increase during the prediction phase by 2040 and similar to the global warming impact. In 2030, the TE will increase by 3.11 × 10^{10} kg 1,4-DB eq due to the annual growth rate of cement production. CO_2 and CH_4 (Methane) gases are strongly related to the global warming impact from the cement kiln (calcination reaction and coal burning process) due to the increase in coal's different chemical composition and other fuel consumption in the kiln.

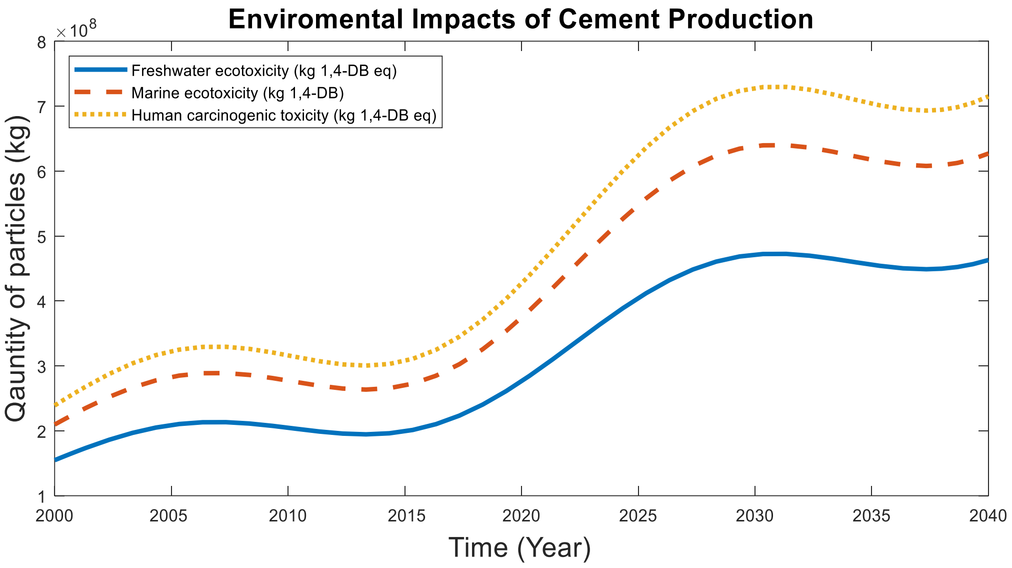

Figure 6-5. Plot showing a possible long-term environmental impact of cement production in South Africa. Freshwater ecotoxicity measured in kg 1,4-DB eq, Marine ecotoxicity measured in kg 1,4-DB eq, Human carcinogenic toxicity measured in kg 1,4-DB eq.

The impact of fossil resource scarcity and Human non-carcinogenic toxicity on the environment will be 4.07 × 10^9 kg 1,4-DB eq and 1.46 × 10^{10} kg oi l eq, respectively, in South Africa by 2040. According to the environmental results, electricity production significantly contributes to the Fossil resource scarcity impact category. The depletion of fossil resources will lead to scarcity. However, more regulation of the growth in overall energy use is still necessary to achieve a long-term reduction goal on cement's environmental impact. Direct emissions from the cement kiln mainly cause global warming and acidification. SO_2 and NO_x are related to Terrestrial acidification impact and cement's clinker content determines their total value. The primary source of SO_2 is coal-based sulphur oxidation in the precalciner kiln process. The clinkering stage was the terrestrial acidification hotspot point; the potential impact will increase from 2.39 × 10^7 kg SO_2 eq in 2000 to 7.15 × 10^7 kg SO_2 eq in 2040.

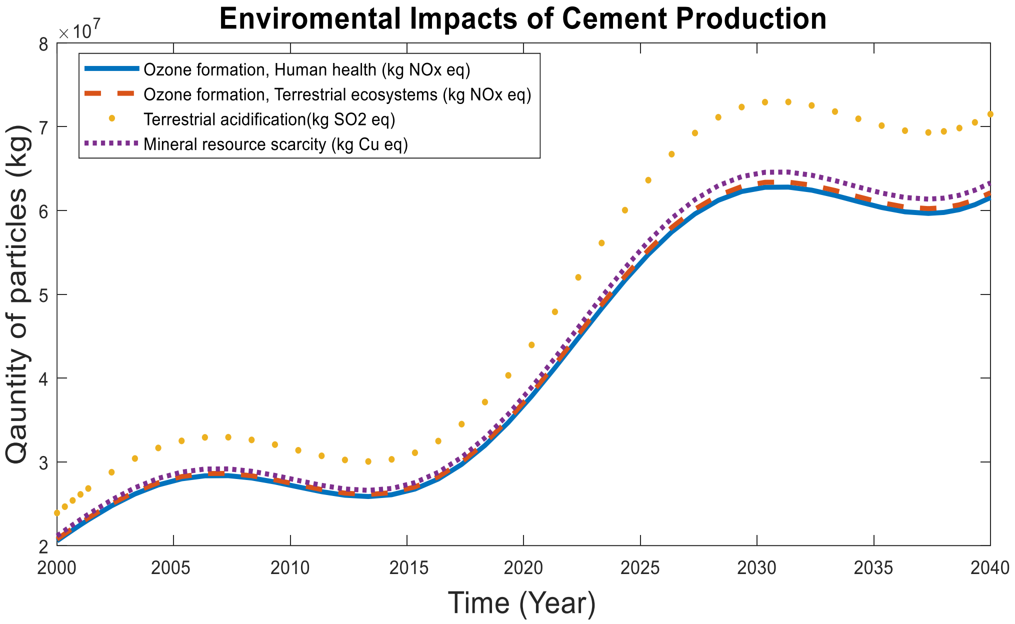

Figure 6-6. Plot showing a possible long-term environmental impact of cement production in South Africa. Ozone formation, Human health measured in kg NOx eq, Ozone formation, Terrestrial ecosystems measured in kg NOx eq, Terrestrial acidification measured in kg SO2 eq, Mineral resource scarcity measured in kg Cu eq.

Acidification is a state in which the environment's acidity degree (pH) is less than 7. The environment's acidity level is caused by some chemical substances absorbed into the water or soil. The Ozone formation, Human health and Terrestrial ecosystems impact category showed a constant increase of 5.8% and 5.9 %, respectively, during the prediction period. It shows clearly by 2040, total Human health and Terrestrial ecosystem impact will have increased by 239% and 243%, respectively. The value of these impact is due to fuel and raw materials for energy production (electricity and fuel refining).

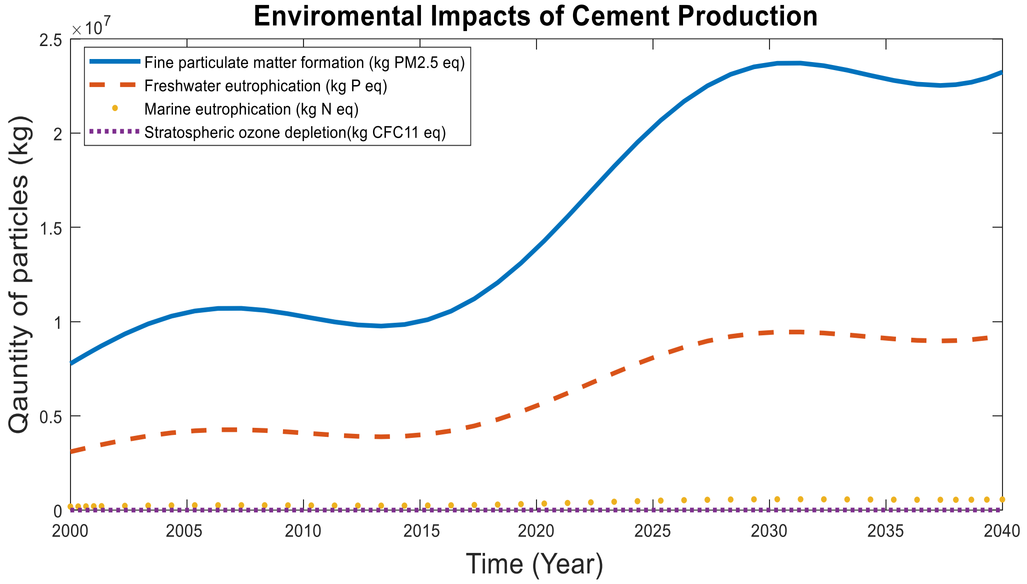

Figure 6-7. Plot showing a possible long-term environmental impact of cement production in South Africa. Fine particulate matter formation measured in kg PM2.5 eq, Freshwater eutrophication measured in kg P eq, Marine eutrophication measured in kg N eq, Stratospheric ozone depletion measured in kg CFC11 eq

Fine Particulate matter ($PM_{2.5}$.) is released during the cement production process, from the extraction to the packaging and loading process. The FPM will increase from 7.77×10^6 kg PM2.5 eq in 2000 to 2.32×10^7 kg PM2.5 eq in 2040 as shown in Figure 6.7, due to the energy consumption (coal and electricity) used in the sector. Similarly, Freshwater eutrophication will increase from 3.09×10^6 kg P eq in 2000 to 9.26×10^6 kg P eq in 2040. Also, NO_x emissions are the main contributor to eutrophication. The main cause of NO_X is rotary Kilns.

Global warming potential has been the cement industry's major focus on environmental impact for years. Therefore, the decisions made by the industry now to address the environmental impact reduction will have effects far beyond 2040. As a result, the cement industry must respond to this problem by adopting these policies. To begin with, companies must gradually reduce CO_2 emissions by: Supplementary Cementitious Materials (SCM) - changing to cement with lower clinker content, i.e.,

i. using composite cement with fly ash from coal or blast furnace slag.
ii. Increase the use of alternative fuels such as bio-based, low-carbon, or waste fuels that reduce CO_2 emissions.
iii. Implementing energy efficiency improvements, i.e., improving equipment and shutting down inefficient plants.

Substituting cement with SCMs reduces the environmental impact of cement production [54, 441]. However, it must be aware that when comparing different SCMs, the substitution level is not directly related to their environmental impact. Different system boundaries, such as cradle-to-grave and cradle-to-gate, can significantly change the relationship between substitution level and environmental impact.

Secondly, the cement industry must significantly increase its research and development (R&D) fund at a much greater level than it does currently to reduce long-term environmental impact. Developing highly novel low-CO_2 strategies, products and low-CO_2 business initiatives must be the main focus of this R&D. Among these initiatives are those capturing CO_2 and sequestering it, co-producing electricity and cement with low CO_2 facilities. The use of nanotechnology in the cement industry can make up for the shortcomings of using SCMs for cement substitutes. Nanotechnology is the application of materials with dimensions smaller than 100 nanometers. Using nanomaterials, such as nano TiO 2, nano SiO2, nano Fe2O3, nano CaCO3, nano Al2O3, nano Zr2O3 and nano-graphene (CNTs and CNFs), which are 10,000 times smaller than a cement particle. These nanomaterials have the potential to reduce cement's environmental impact.

Future cement environmental impact could be decreased if initiatives and technologies are implemented within the cement sector, albeit the cost of implementation is expected to be high. The waste heat recovery from cement kilns could be one of the technologies for future cement plant's environmental impact reduction. In addition to cement environmental impact reduction, renewable energy sources such as biomass can also reduce GHG emissions caused by burning fossil fuels. Limestone calcination and fuel use in the kiln are the primary sources of fossil CO_2 emissions. Using biomass fuel in the kiln leads to zero biogenic emissions as CO_2 is absorbed during biomass growth. Aside from changing from non-renewable to renewable energy (fuels), changing or lowering the content of clinker in cement and employing alternative materials will reduce fossil CO_2 emissions. The above suggestions might be challenging to implement and require advanced technologies, but they can serve as a general framework for future research.

6.6 Conclusions

In this study, we used a system dynamics mathematical model with the LCA methodology to assess the environmental impacts of the South African cement industry. To the best of our knowledge, there is no research of this type regarding long-term projections of environmental impact and future dynamics of cement production (i.e., 2040). While providing predictions of the possible long-term environmental impact and future dynamics of cement production in South Africa, the LCA-SD model is used as proof of concept to demonstrate its innovative worth.

For this analysis, the LCA characterisation result at the midpoint [191] was integrated with a system dynamics model to predict the future long-term environmental impacts of cement production. This study used SimaPro LCA software Amersfoort, Netherlands, PRé Consultants and system dynamics in the form of a mathematical model. Cement plants are located in or near urban centres in many developed and developing countries, including South Africa, affecting public health and the environment. With the increase in cement production, environmental impact is expected to exceed critical levels. The model predicted cement production's environmental impact in South Africa for 492 months between 2000 and 2040. Environmental impact from cement plants affects many interconnected factors, including the population and GDP growth rates, cement production, cement exports, cement imports, clinker use, and the energy consumed. Cement production is expected to increase between 2018 and 2040. A system dynamic model was developed and parameterised using data from 2000 to 2017 and scenarios simulated numerically for a 40 year period, starting in 2000. The predicted cement production is presented in Figure 6.3. The amount of cement production will potentially increase from 1.63×10^{10} kg in 2018 to 3.20×10^{10} kg by 2040. The increase in cement production driven mainly by urbanization, economic activity in South Africa, growth in GDP and industrialization, is predicted to increase environmental impact.

Figures 6.4-6.7 show the simulation results showing the potential long-term environmental impact of cement production in the South African cement plant. The possible long-term impact of global warming will increase from 9.73×10^9 kg CO_2 eq in 2000 to 2.91×10^{10} kg CO_2 eq by 2040, Ozone formation, Human health will increase from 2.06×10^7 kg NOx eq in 2000 to 6.15×10^7 kg NOx eq by 2040, Fine particulate matter formation will increase from 7.77×10^6 kg PM2.5 eq in 2000 to 2.32×10^7 kg PM2.5 eq by 2040 and Terrestrial acidification will increase from 2.39×10^7 kg SO_2 eq in 2000 to 7.15×10^7 kg SO_2 eq by 2040. Figure 6.4-6.7 shows a similar trend. If no new policy is adopted, global warming potential in terms of CO_2 emissions will continue to increase as cement production increases in South Africa from 9.73×10^9 kg CO_2 eq in 2000 to 2.91×10^{10} kg CO_2 eq in 2040. The model can be used to predict and estimate future trends in cement production and long-term environmental impact and CO_2 emissions reductions in the cement industries. All the environmental impact shown in Figure 6.4-4.7 present an increase in effects by the end of 2040. Cement production growth is connected with the country's industrialization, economic activity and infrastructure development. The life cycle assessment of cement production "from cradle to gate" processes help to identify the hotspot of the impact category at the midpoint and predict the long-term environmental impact of cement production in South Africa to meet the needs for sustainable development. By 2040, the model's predicted GWP, TA, HCT and PMF impact categories would increase three times the current levels. The trend observed for all impact categories is similar to cement production. Global warming is caused by CO_2 emissions and is one of the major GHG emissions.

As shown in Figure 6.3, the increasing demand for cement in the future due to infrastructure will negatively impact our environment as cement production increases. With demand for cement in residential, commercial, and industrial constructions, the global warming impact is expected to exceed 3.30×10^{10} kg CO_2 eq in 2040. According to the International Energy Agency (IEA), global cement plants will emit 2.34 billion tons of CO_2 by 2050. As a result, policymakers could create effective international policy instruments that facilitate rapid and cost-effective adoption of the BAT and innovation. However, cement environmental impact can be mitigated by implementing environmental laws through the government agency, supporting the cement industry to use new technology through encouraging policies. In addition to population growth and economic development, cement production is also affected by GDP level and urbanization. Hence, cement environmental impact can be mitigated by controlling population growth.

Additionally, these results indicate that the cement industry will need to develop new technology and cementitious products to achieve more considerable environmental impact reductions by 30% by 2040, when global cement demand is likely to increase substantially, and climate policies might tighten as well. If cutting-edge control methods are utilized, there is the potential to significantly reduce the global warming impact on South Africa's cement sector. The partial substitution of supplementary cementitious materials (SCMs) for Portland cement in finished cement products such as eco-blended cement should be encouraged to improve production technologies. Other measures include using low-environmental impact modes of transportation or moving resources/materials, goods, labour and equipment across shorter distances can reduce transportation impact. Changing the electricity mix by converting fossil fuels (primary energy sources) to renewable energy should be considered at the national level.

Based on our projection, the following mitigation decisions could reduce the long-term environmental impacts of cement production. We suggested reducing the amount of clinker used or increasing the use of clinker substitutes as the most promising cement impact mitigation policy. This can be either low-carbon eco-blended or alternative Portland cement clinkers. Geopolymer cement is another emerging cement technology. Adopt cutting-edge technologies like CCS and alternative types of binders like geopolymers and clay cement will help to reduce cement greenhouse gas emissions. However, geopolymer cement is of less use since does not reduce emissions as much as extended eco-blends and there are not enough clay deposits in South Africa to produce clay cement. Overall, these options provide long-term emission mitigations in cement production but are often not cost-effective. Clinker replacements, fuel switching and energy efficiency are essential and require additional investigation. The SCMs for clinker substitutes include industrial by-products and waste such as fly ash from the coal industry and blast-furnace slags from the steel industry. These by-products can be used for the production of eco-blended cement. The blast furnace slag and fly ash eco-blended cement have the potential to reduce carbon emissions from cement production, have the same performance as traditional Portland cement, and also are cost-effective. Eco-blended cement products reduce the carbon footprint of cement production by substituting high levels of clinker with various SCMs.

Carbon Taxes (Carbon pricing): This includes subsidies for emerging technologies, the removal of fossil fuel subsidies, subsidies for alternative fuels and technology development are proposed policies based on our projection to reduce long-term cement environmental impacts. The carbon budgets and carbon tax policies currently proposed by the Department of Environmental Affairs (DEA) [389] and the National Treasury [442, 443] in South Africa are important in reducing cement production's environmental impact. By introducing a carbon tax, alternative cement with low carbon emissions will become more attractive. Cement producers may reduce carbon tax liability by switching to eco-blended cement replacement clinker with Supplementary Cementitious Materials (SCMs). Implementing carbon pricing legislation will make alternative fuels and SCMs more widely used. Using SCMs in eco-blended cement production has already saved 500 Mt of CO_2 worldwide. Increasing the use of SCMs to produce eco-blended cement can further reduce cement production's environmental impact.

Carbon taxes will induce South African industrial waste producers to invest in waste management and handling to maintain uniformity and raw material quality. A slag-based eco-blend cement, for instance, allows high substitution of clinker, which reduces emissions, but South African regulations limit clinker substitution to 35%. To increase the substitution level of clinker to reduce cement environmental impact, existing policies that limit clinker substitution to 35% in South Africa need to be amended. This will help the cement industry to benefit from lower cement production costs and environmental impact reduction.

Overall, this research demonstrates how scenario prediction models linked to LCA analysis can be used to emphasize requirements for improved cement production systems in South Africa to reduce harmful pollutant emissions.

CHAPTER 7 : Conclusions and Recommendations

7.1 Conclusions

This work combined LCA methods and the SD model to analyse and predict the long-term environmental impact and future dynamics of cement production in South Africa from 2000 to 2040.

Firstly, this work assessed the environmental impact of the cement production process in South Africa to understand these impacts and to identify the hotspot by conducting the LCA using midpoint and endpoint methods. We analysed based on how five production stages contributed to the impact categories at the midpoint and damage categories at the endpoint. These production stages include clinkering, raw material usage, fuel usage, transportation and electricity usage. To effectively mitigate the environmental impact of cement production, it is necessary to measure it correctly, thereby making recommendations for future improvements. This work performed LCA on 1 kg of Portland cement using midpoint and endpoint methods. It explained the results of the different impact categories, i.e., 18 impact indicators at the midpoint and 22 impact indicators at the endpoint method. The midpoint analysis described emissions based on specific substances released along with their subsequent effects into air and water or extracted from the ground.

According to the midpoint characterisation analysis, each kilogram of cement produced, 9.93×10^{-1} kg CO_2 eq (global warming), 1.04 kg 1.4-DCB (terrestrial ecotoxicity), 4.97×10^{-1} kg 1.4-DCB (human non-carcinogenic toxicity), and 1.39×10^{-1} kg oil eq (fossil resource scarcity) respectively were the highest impact values. Chapters 4 and 5 established this study's objectives 1, 2 and 3 by presenting the impacts related to the cement production process and showing that these impacts occur in a South African cement plant, which has been observed in some literature. Analysing the environmental impact of cement production in South Africa using both the midpoint and endpoint method of ReCiPe. The clinkering stage was identified as the environmental impact hotspot. Alternatively, the endpoint analysis showed us how these impacts directly affect us and why we need to be concerned about them. The endpoint analysis showed the damage to human beings, the environment and the economy by quantifying the damage done to our resources. This work used the LCA characterisation result at the midpoint to determine the cement environmental impact and SD to predict the possible long-term environmental impact and future dynamics of cement production in South Africa.

We cannot predict the future without SD coupled with the LCA framework. With the help of the SD, we can easily predict how the environmental impact and the future of cement production in South Africa can change over time. In addition, SD can predict the impact of future scenarios based on changes in key variables affecting particular components. LCA-SD methodology provides a long-term prediction evaluation that can be traced and used as a tool for policymakers. The integrated LCA-SD model described here lets us know the future implications of cement environmental impact in South Africa and identify ways to mitigate them through policies and recommendations. The simulation results show that the possible long-term impact of global warming will increase from 9.73×10^9 kg CO_2 eq in 2000 to 2.91×10^{10} kg CO_2 eq by 2040, Ozone formation, Human health will increase from 2.06×10^7 kg NOx eq in 2000 to 6.15×10^7 kg NOx eq by 2040, Fine particulate matter formation will increase from 7.77×10^6 kg PM2.5 eq in 2000 to 2.32×10^7 kg PM2.5 eq by 2040 and Terrestrial acidification will increase from 2.39×10^7 kg SO_2 eq in 2000 to 7.15×10^7 kg SO_2 eq by 2040. Figure 6.4-6.7 shows a similar trend. By 2040, the model's predicted GWP, TA, HCT and PMF impact categories would increase three times the current levels. The trend observed for all impact categories is similar to cement production. Chapter 6 established objective 4 of this study by showing possible future dynamics of cement production and the long-term environmental impact from 2000 to 2040 and establishing the integrated LCA-SD framework for the cement industry in South Africa.

A significant benefit of integrating SD and LCA models is that it improves understanding and intervention effectiveness. Also, combining SD and LCA models provides the following advantages: (i) An increase in the number of years simulated using endogenous data, preventing overestimation of impacts due to the improvement of technology, (ii) or reducing the environmental impacts due to recycling of materials over time. (iii) preventing inaccuracies in impacts due to unplanned consequences caused by changes in production systems and market dynamics. Combining SD and LCA models provides a possible methodology that can be used to develop a better understanding of the long-term impacts of different mitigation approaches. System dynamics enable policymakers to examine the effects of different policies over time and better consider how system components may affect one another, which can be altered simultaneously and tested via simulation that may have a widespread impact on the system. This work hopes to assist decision-makers and policy planners within the cement industry.

This work presents simulation results that can contribute to understanding the cement long-term environmental impacts of decision-making and formulating cement management policies. The proposed LCA-SD model is feasible and the prediction results of cement production and its long-term environmental impact are more relevant and representative. The integration result is projected to provide more practical benefits, for example, supporting affordable environmental management policies and helping in better decision-making for reducing GHG emissions. This study emphasizes the need for improved cement production systems in South Africa to reduce harmful pollutant emissions through scenario prediction models linked to LCA analysis.

7.2 Recommendations

The following recommendations are made based on this work:

Several policy changes have been suggested based on these results, such as eco-blended cement, carbon budgets and carbon taxes could reduce long-term environmental impacts in the cement industry. Reducing the clinker consumption or increasing the clinker substitutes for cement GHG mitigation. It can be either an eco-blended cement, a cement clinker alternative, or alternative fuels as a promising means of mitigating cement's environmental impact. By implementing these policies, cement production will reduce the negative impacts on human health and the environment caused by using energy sources and raw materials in cement production.

i. The clinker substitution uses supplementary cementitious material such as fly ash from the coal industry and blast-furnace slags from the steel industry (Industrial by-products and waste). It is possible to make eco-blended cement from these Industrial by-products and they have the potential to reduce carbon emissions from the cement plant. Among the recommendations for reducing long-term cement environmental impacts are carbon taxes, which include subsidies for emerging technologies, removing fossil fuel subsidies and subsidies for alternative fuels.

ii. The carbon taxes are proposed to protect the environment from damage caused by cement production and to encourage cement companies to adopt more sustainable business practices. Alternative cement with low carbon emissions will become more attractive by introducing a carbon tax. Switching to eco-blended cement as a clinker replacement with SCMs can reduce cement producers' carbon tax liability. The adoption of carbon pricing will increase the use of alternative fuels and SCMs. Implementing carbon taxes will encourage industrial waste manufacturers in South Africa to invest in waste management and handling.

For instance, slag-based eco-blend cement reduces emissions by substituting cement clinker, but South African policies do not allow clinker substitution with slag-based above 35%. The existing policies that limit clinker substitution below 35% must be revised to increase clinker substitution levels in cement production to reduce the environmental impact. By doing this, the cement industry will benefit from low cement production costs and reduce environmental impact. Despite this, there is still room for further research.

7.3 Further Research

Further research could include a comparative analysis of the LCA to get an environmental gauge on sustainable resource sources relative to Portland cement to determine those sustainable resources from environmental impact and economic perspectives. In addition, further research could focus on identifying which GHG emission mitigation policies are best suited to the environment, as recommended in this work. Ideally, the best fit must have high GHG emission reduction potential, be cost-effective and have practical applicability while using existing equipment. Further research on the LCA-SD model is required to simulate other life-cycle scenarios that include developing new or multiple upgrading processes and experimenting with new raw materials as SCM substitutes for clinker since more than 50% of CO_2 is generated by limestone decarbonisation.

Reference

[1] S. Cohen, D. Demeritt, J. Robinson, and D. Rothman, "Climate change and sustainable development: towards dialogue," *Global environmental change,* vol. 8, no. 4, pp. 341-371, 1998.

[2] N. Rosenberg, "The role of electricity in industrial development," *The Energy Journal,* vol. 19, no. 2, 1998.

[3] M. Mirzaei and M. Bekri, "Energy consumption and CO2 emissions in Iran, 2025," *Environmental Research,* vol. 154, pp. 345-351, 2017/04/01/ 2017, doi: https://doi.org/10.1016/j.envres.2017.01.023.

[4] C. Luo and D. Wu, "Environment and economic risk: An analysis of carbon emission market and portfolio management," *Environmental Research,* vol. 149, pp. 297-301, 2016/08/01/ 2016, doi: https://doi.org/10.1016/j.envres.2016.02.007.

[5] K. E. Trenberth *et al.*, "Observations: surface and atmospheric climate change," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*: Cambridge University Press, 2007.

[6] E. Ekinci, Y. Kazancoglu, and S. K. Mangla, "Using system dynamics to assess the environmental management of cement industry in streaming data context," *Science of The Total Environment,* vol. 715, p. 136948, 2020/05/01/ 2020, doi: https://doi.org/10.1016/j.scitotenv.2020.136948.

[7] F. Ma, A. Sha, P. Yang, and Y. Huang, "The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China," (in eng), *International journal of environmental research and public health,* vol. 13, no. 7, p. 632, 2016, doi: 10.3390/ijerph13070632.

[8] I. Z. Bribián, A. V. Capilla, and A. A. Usón, "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential," *Building and environment,* vol. 46, no. 5, pp. 1133-1140, 2011.

[9] E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, "Global strategies and potentials to curb CO2 emissions in cement industry," *Journal of cleaner production,* vol. 51, pp. 142-161, 2013.

[10] C.-Y. Zhang, B. Yu, J.-M. Chen, and Y.-M. Wei, "Green transition pathways for cement industry in China," *Resources, Conservation and Recycling,* vol. 166, p. 105355, 2021/03/01/ 2021, doi: https://doi.org/10.1016/j.resconrec.2020.105355.

[11] W. Shen *et al.*, "Cement industry of China: Driving force, environment impact and sustainable development," *Renewable and Sustainable Energy Reviews,* vol. 75, pp. 618-628, 2017/08/01/ 2017, doi: https://doi.org/10.1016/j.rser.2016.11.033.

[12] M. Ntuli, M. Dioha, D. Ewim, and A. Eloka-Eboka, "Review of energy modelling, energy efficiency models improvement and carbon dioxide emissions mitigation

options for the cement industry in South Africa," *Materials Today: Proceedings,* vol. 65, pp. 2260-2268, 2022.

[13] M. Milkoreit, "The Paris agreement on climate change—made in USA?," *Perspectives on Politics,* vol. 17, no. 4, pp. 1019-1037, 2019.

[14] S. Africa, "South Africa signs Paris Agreement on Climate Change in New York," Department of Forestry, Fisheries and the Environment, Pretoria, South Africa, 2016. [Online]. Available: https://www.dffe.gov.za/mediarelease/southafricasignsparisagreementonclimate

[15] C. Valderrama, R. Granados, J. L. Cortina, C. M. Gasol, M. Guillem, and A. Josa, "Implementation of best available techniques in cement manufacturing: a life-cycle assessment study," *Journal of Cleaner Production,* vol. 25, pp. 60-67, 2012.

[16] J.-L. Galvez-Martos and H. Schoenberger, "An analysis of the use of life cycle assessment for waste co-incineration in cement kilns," *Resources, Conservation and Recycling,* vol. 86, pp. 118-131, 2014.

[17] N. Madlool, R. Saidur, N. Rahim, and M. Kamalisarvestani, "An overview of energy savings measures for cement industries," *Renewable and Sustainable Energy Reviews,* vol. 19, pp. 18-29, 2013.

[18] S. Bhattacharya and J. Saha, "High level automation to achieve improved productivity, energy efficiency and consistent cement quality," in *2015 IEEE-IAS/PCA Cement Industry Conference (IAS/PCA CIC),* 2015: IEEE, pp. 1-7.

[19] N. Madlool, R. Saidur, M. Hossain, and N. Rahim, "A critical review on energy use and savings in the cement industries," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 4, pp. 2042-2060, 2011.

[20] M. S. Imbabi, C. Carrigan, and S. McKenna, "Trends and developments in green cement and concrete technology," *International Journal of Sustainable Built Environment,* vol. 1, no. 2, pp. 194-216, 12// 2012, doi: http://dx.doi.org/10.1016/j.ijsbe.2013.05.001.

[21] F. Soltanzadeh, M. Emam-Jomeh, A. Edalat-Behbahani, and Z. Soltan-Zadeh, "Development and characterization of blended cements containing seashell powder," *Construction and Building Materials,* vol. 161, pp. 292-304, 2018.

[22] A. Gonzalez-Corominas, M. Etxeberria, and C.-s. Poon, "Influence of the quality of recycled aggregates on the mechanical and durability properties of high performance concrete," *Waste and biomass valorization,* vol. 8, no. 5, pp. 1421-1432, 2017.

[23] D. L. Summerbell, C. Y. Barlow, and J. M. Cullen, "Potential reduction of carbon emissions by performance improvement: A cement industry case study," *Journal of Cleaner Production,* vol. 135, pp. 1327-1339, 2016.

[24] L. Zhang and W. E. Mabee, "Comparative study on the life-cycle greenhouse gas emissions of the utilization of potential low carbon fuels for the cement industry," *Journal of Cleaner Production,* vol. 122, pp. 102-112, 2016.

[25] S. A. Ishak, H. Hashim, and T. S. Ting, "Eco innovation strategies for promoting cleaner cement manufacturing," *Journal of Cleaner Production*, vol. 136, pp. 133-149, 2016.

[26] G. Tesema and E. Worrell, "Energy efficiency improvement potentials for the cement industry in Ethiopia," *Energy*, vol. 93, Part 2, pp. 2042-2052, 12/15/ 2015, doi: http://dx.doi.org/10.1016/j.energy.2015.10.057.

[27] K. Karstensen, C. Engelsen, S. Ng, P. Saha, and M. Malmedal, "Cement manufacturing and air quality," *vol*, vol. 73, pp. 683-705, 2016.

[28] J. G. Olivier, J. A. Peters, and G. Janssens-Maenhout, "Trends in global CO2 emissions. 2012 report," 2012.

[29] Rubenstein, "Emissions from the Cement Industry," Columbia Climate School climate earth and society, 2012. Accessed: February 2022. [Online]. Available: https://news.climate.columbia.edu/2012/05/09/emissions-from-the-cement-industry/

[30] D.-Y. Oh, T. Noguchi, R. Kitagaki, and W.-J. Park, "CO2 emission reduction by reuse of building material waste in the Japanese cement industry," *Renewable and sustainable energy reviews*, vol. 38, pp. 796-810, 2014.

[31] Cembureau, "The European Cement Association (Cembureau) 2017 Activity Report," ed. Brussels, Belgium: The European Cement Association Brussels, Belgium, 2017, pp. pp. 1–42.

[32] Cembureau, "The European Cement Association (Cembureau) 2020 Activity report," ed. Brussels, Belgium: Brussels, 2020, pp. 1-52.

[33] M. Garside, "Major countries in worldwide cement production 2015–2019," *Statista International*, 2020.

[34] IRCResearch, "Uncertain times (world consumption production capacity) " in *International Cement Review (IRC)*, ed, 2022.

[35] J. Hussain, A. Khan, and K. Zhou, "The impact of natural resource depletion on energy use and CO2 emission in Belt & Road Initiative countries: a cross-country analysis," *Energy*, vol. 199, p. 117409, 2020.

[36] IPCC, "IPCC 2013: Summary for policymakers," *Climate change. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed.; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.*

, pp. 1–203, 2013.

[37] IPCC, "Climate change 2014: mitigation of climate change," *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed.; Edenhofer, O.R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al., Eds.*, pp. 1–1523., 2014.

[38] IEA, "Reducing CO2 emissions while producing enough cement to meet demand is a global challenge, especially since demand growth is expected to resume.," 2019. Accessed: March 2020. [Online]. Available: https://www.iea.org/fuels-and-technologies/cement

[39] P. Sarker, "A constitutive model for fly ash-based geopolymer concrete," *Archit Civil Eng Environ,* vol. 1, no. 4, pp. 113-20, 2008.

[40] DOE, "Energy Balances," Department of Energy South Africa, Pretoria, 2016. [Online]. Available: http://www.energy.gov.za/files/media/Energy_Balances.html.

[41] DOE, "Energy information management," in "Digest of South African Energy Statistics. Pretoria, South Africa Process Design and Publications," Department of Energy South Afriva Process Design and Publications, 2009. Accessed: September 2021. [Online]. Available: http://www.energy.gov.za/files/media/explained/2009%20Digest%20PDF%20version.pdf

[42] USAID, "Greenhouse Gas Emissions in South Africa," 2016. Accessed: September 2021. [Online]. Available: https://www.climatelinks.org/sites/default/files/asset/document/GHG%20Emissions%20Fact%20Sheet%20South%20Africa%20-%207-5-16%20USAIDSAcomm_rev08-26-16_Clean.pdf

[43] S. Hedden and S. Hedden, "Gridlocked: A long-term look at South Africa's electricity sector," *Institute for Security Studies Papers,* vol. 2015, no. 15, p. 24, 2015.

[44] B. B. Ateba, J. J. Prinsloo, and R. Gawlik, "The significance of electricity supply sustainability to industrial growth in South Africa," *Energy Reports,* vol. 5, pp. 1324-1338, 2019.

[45] H. Trollip, A. Butler, J. Burton, T. Caetano, and C. Godinho, "Energy Security in South Africa," 2014.

[46] N. Beg *et al.*, "Linkages between climate change and sustainable development," *Climate policy,* vol. 2, no. 2-3, pp. 129-144, 2002.

[47] N. Brown, Hasson, R, "South Africa's cement industry is setting firmly. Quarterly Strategy Note, Electus Fund Managers.," 2016. Accessed: 2 May 2022. [Online]. Available: https://docplayer.net/amp/47668773-Quarterly-strategy-note-october-south-africa-s-cement-industry-is-setting-firmly-by-mish-al-emeran.html

[48] G. Du Toit, E. P. Kearsley, J. M. Mc Donald, R. A. Kruger, and E. M. van der Merwe, "Chemical and mechanical activation of hybrid fly ash cement," *Advances in Cement Research,* vol. 30, no. 9, pp. 399-412, 2018.

[49] O. E. Ige, "Energy efficiency in the South African cement finishing plant: drivers, barriers and improvement," 2018.

[50] F. Senzani and A. Mulaba-Bafubiandi, "Site determination for artisanal rock carbonate processing using qualitative multifactor analysis–case studies: Malawi and South

Africa," *Transactions of the Royal Society of South Africa*, vol. 74, no. 1, pp. 55-66, 2019.

[51] ICR, "The Global Cement Report," in *Global CementmConsumption Forecasts 2016-18*, ed. ICR Research: Cement review, 2017.

[52] Reinhardt Arp, Tjaša Bole-Rentel, and N. Jakuja, "Greenhouse Gas Emissions Reduction Options for the South African Cement Sector," in "WWF Technical Report. ," WWF Technical Report. , Emerging Climate Smart Business Opportunities. Technical Report. WWF, 2018. Accessed: 2 May 2022. [Online]. Available: http://awsassets.wwf.org.za/downloads/wwf_2018_ghg_reduction_options_for_sa_cement_sector.pdf

[53] Lafarge, "LAfargeholcim Annual Report," in "Lafarge Annual Report," 2016. Accessed: May 6 2022. [Online]. Available: https://www.lafarge.co.za/sites/zarevamp/files/atoms/files/03022017-finance-lafargeholcim_annual_report_2016-en_1_0.pdf

[54] S. Pradhan, B. Tiwari, S. Kumar, and S. V. Barai, "Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix," *Journal of Cleaner Production*, vol. 228, pp. 679-691, 2019.

[55] P. Pretoria Portland Cement, "Annual Report 2018.," in "Pretoria Portland Cement," 2018. Accessed: May 2 2022. [Online]. Available: https://www.sharedata.co.za/data/000567/pdfs/PPC_fin_mar18.pdf

[56] P. Pretoria Portland Cement, "Integrated report 2021," Pretoria Portland Cement Limited, 2021. Accessed: May 2 2022. [Online]. Available: https://thevault.exchange/?get_group_doc=189/1627394227-PPCintegratedreport2021.pdf

[57] AfriSam, "Our History," in "AfriSam ", 2022. Accessed: May 6 2022. [Online]. Available: https://www.afrisam.co.za/our-history/

[58] AfriSAm. "Afrisam takes the lead with pre-blended Readymix deliveries to the site." https://www.afrisam.co.za/media/113192/afrisam_takes_the_lead_with_preblended_readymix_deliveries_to_site_08_2013.pdf (accessed May 6 2022).

[59] V. W. Llewellyn, L.-v. Wyk, Ed. *The Green Bulding Handbook* (The Essential Guide). South Africa, 2017, p. 119.

[60] Lafarge, "Lafarge Lichtenburg Plant Brochure," in "Lafarge ", 2010. Accessed: May 4 2022. [Online]. Available: http://www.lafarge.co.za/Lichtenburg_Plant_Brochure.pdf

[61] Lafarge, "Choose the right cement," in "Lafarge Report," 2008. Accessed: May 6 2022. [Online]. Available: https://www.lafarge.co.za/sites/southafrica/files/documents/Choose_the_right_cement_brochure_2.pdf

[62] Lafarge, "Lafarge Lichtenburg Cement Works," in "Lafarge ", 2010. Accessed: May 6 2022. [Online]. Available: https://silo.tips/download/lafarge-lichtenburg-cement-works

[63] Sephaku, " Exploration, Development, Income, Growth Roadshow Presentation

" Sephaku Holdings Ltd 2013. Accessed: 10 May 2022. [Online]. Available: https://thevault.exchange/?get_group_doc=381/1473846623-Sephaku_Roadshow_Aug_Sep.pdf

[64] P. Fourie, "Certainty in cement-building success: SARMA-cover story," *IMIESA*, vol. 38, no. 11, pp. 28-29, 2013. [Online]. Available: https://journals.co.za/doi/epdf/10.10520/EJC144255.

[65] A. Akinyoade and C. Uche, "Dangote cement: The challenges of Pan-African expansion," in *Entrepreneurship in Africa*: Brill, 2017, pp. 279-306.

[66] NPC, "Natal Portland Cement Company History," 2013. Accessed: May 12 2022. [Online]. Available: http://www.npc.co.za/PDF-Downloads/About/Company-History.aspx

[67] M. Scott, "Commission refers a case of collusion against Natal Portland Cement Cimpor," *The Competition Commission of South Africa*, vol. 2, 2015.

[68] A. Josa, A. Aguado, A. Heino, E. Byars, and A. Cardim, "Comparative analysis of available life cycle inventories of cement in the EU," *Cement and Concrete Research*, vol. 34, no. 8, pp. 1313-1320, 2004.

[69] H. O. Njoku, O. R. Bafuwa, C. A. Mgbemene, and O. Ekechukwu, "Benchmarking energy utilization in cement manufacturing processes in Nigeria and estimation of savings opportunities," *Clean Technologies and Environmental Policy*, vol. 19, no. 6, pp. 1639-1653, 2017.

[70] M. A. Shah, "A Review on Cement Waste Heat Recovery," *IJSRD-Int J Scientific Res Dev*, vol. 3, no. 05, 2015.

[71] E. Worrell, "Cement and Energy A2 - Cleveland, Cutler J," in *Encyclopedia of Energy*. New York: Elsevier, 2004, pp. 307-315.

[72] D. Olsen, "Opportunities for energy efficiency and demand response in the California cement industry," 2011.

[73] A. Jankovic, W. Valery, and E. Davis, "Cement grinding optimisation," *Minerals Engineering*, vol. 17, no. 11-12, pp. 1075-1081, 2004.

[74] W. A. Pelser, J. C. Vosloo, and M. J. Mathews, "Analysis of energy consumption and cost distribution on a South African cement plant," in *2017 International Conference on the Industrial and Commercial Use of Energy (ICUE)*, 2017: IEEE, pp. 1-6.

[75] M. Ristimäki, A. Säynäjoki, J. Heinonen, and S. Junnila, "Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design," *Energy*, vol. 63, pp. 168-179, 2013.

[76] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, and R. Marshall, "Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and

key performance indicators to assess development within the cement industry," *Journal of Cleaner Production*, vol. 98, pp. 272-281, 2015.

[77] S. Boughrara, H. Aksas, and K. Louhab, "Comparative study of wet and dry process of cement manufacturing using Life Cycle Assessment approach," 2014.

[78] ISO, "14040: International Organisation for Standardisation. Environmental Management: Life Cycle Assessment; Principles and Framework," in "International Organisation for Standardisation," ISO, 2006. Accessed: 12 June 2022. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

[79] ISO/TS, "Environmental management — Life cycle assessment — Requirements and guidelines for Organisational life cycle assessment. ISO/TS,14072:2014. ," in "International Organisation for Standardisation," ISO, Geneva, Switzerland, 2014. Accessed: Feburary 23 2023. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:ts:14072:ed-1:v1:en

[80] H. Matthews, C. Hendrickson, and D. Matthews, "Life Cycle Assessment: Quantitative Approaches for Decisions That Matter. Pittsburgh," in *PA, USA: Carnegie Mellon University*, ed: PA, USA: Carnegie Mellon University, 2015.

[81] G. Finnveden *et al.*, "Recent developments in life cycle assessment," *Journal of environmental management*, vol. 91, no. 1, pp. 1-21, 2009.

[82] A. Manuilova, J. Suebsiri, and M. Wilson, "Should life cycle assessment be part of the environmental impact assessment? Case study: EIA of CO2 capture and storage in Canada," *Energy procedia*, vol. 1, no. 1, pp. 4511-4518, 2009.

[83] J. B. Guinee *et al.*, "Life cycle assessment: past, present, and future," ed: ACS Publications, 2011.

[84] R. Sinha, M. Lennartsson, and B. Frostell, "Environmental footprint assessment of building structures: A comparative study," *Building and Environment*, vol. 104, pp. 162-171, 2016.

[85] I. T. Herrmann and A. Moltesen, "Does it matter which Life Cycle Assessment (LCA) tool you choose?–a comparative assessment of SimaPro and GaBi," *Journal of Cleaner Production*, vol. 86, pp. 163-169, 2015.

[86] J. W. Forrester, "Industrial dynamics—a response to Ansoff and Slevin," *Management Science*, vol. 14, no. 9, pp. 601-618, 1968.

[87] J. W. Forrester, *Industrial dynamics*. [Cambridge, Mass.: M.I.T. Press (in English), 1961.

[88] B. K. Bala, F. M. Arshad, and K. M. Noh, "System dynamics," *Springer Texts in Business and Economics*, 2017.

[89] N. Ansari and A. Seifi, "A system dynamics model for analyzing energy consumption and CO2 emission in Iranian cement industry under various production and export scenarios," *Energy Policy*, vol. 58, pp. 75-89, 2013, doi: 10.1016/j.enpol.2013.02.042.

[90] S. Anand, P. Vrat, and R. Dahiya, "Application of a system dynamics approach for assessment and mitigation of CO2 emissions from the cement industry," *Journal of environmental management,* vol. 79, no. 4, pp. 383-398, 2006.

[91] A. Kunche and B. Mielczarek, "Application of System Dynamic Modelling for Evaluation of Carbon Mitigation Strategies in Cement Industries: A Comparative Overview of the Current State of the Art," *Energies,* vol. 14, no. 5, 2021, doi: 10.3390/en14051464.

[92] M. Tang, S. Wang, C. Dai, and Y. Liu, "Exploring CO2 mitigation pathway of local industries using a regional-based system dynamics model," *International Journal of Information Management,* vol. 52, p. 102079, 2020/06/01/ 2020, doi: https://doi.org/10.1016/j.ijinfomgt.2020.102079.

[93] M. Georgiopoulou and G. Lyberatos, "Life cycle assessment of the use of alternative fuels in cement kilns: A case study," *Journal of environmental management,* vol. 216, pp. 224-234, 2018.

[94] R. Muigai, M. Alexander, and P. Moyo, "Cradle-to-gate environmental impacts of the concrete industry in South Africa," *Journal of the South African Institution of Civil Engineering,* vol. 55, no. 2, pp. 02-07, 2013.

[95] J. H. Potgieter, "An Overview of Cement production: How" green" and sustainable is the industry?," *Environmental Management and Sustainable Development,* vol. 1, no. 2, pp. 14-37, 2012.

[96] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "Carbon dioxide emissions from the global cement industry," *Annual review of energy and the environment,* vol. 26, no. 1, pp. 303-329, 2001.

[97] C. C. IPCC, "Mitigation of climate change," *Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change,* p. 1454, 2014.

[98] IEA, "Capturing the Multiple Benefits of Energy Efficiency," 2014. Accessed: June 12 2022. [Online]. Available: http://www.iea.org/publications/freepublications/publication/Captur_the_MultiplBenef_ofEnergyEficiency.pdf

[99] T. Gao, L. Shen, M. Shen, L. Liu, and F. Chen, "Analysis of material flow and consumption in cement production process," *Journal of Cleaner Production,* vol. 112, pp. 553-565, 2016.

[100] M. Schneider, M. Romer, M. Tschudin, and H. Bolio, "Sustainable cement production—present and future," *Cement and Concrete Research,* vol. 41, no. 7, pp. 642-650, 7// 2011, doi: http://dx.doi.org/10.1016/j.cemconres.2011.03.019.

[101] S. Supino, O. Malandrino, M. Testa, and D. Sica, "Sustainability in the EU cement industry: the Italian and German experiences," *Journal of Cleaner Production,* vol. 112, pp. 430-442, 2016.

[102] J. A. Swanepoel, E. H. Mathews, J. Vosloo, and L. Liebenberg, "Integrated energy optimisation for the cement industry: A case study perspective," *Energy Conversion and Management,* vol. 78, pp. 765-775, 2// 2014, doi: http://dx.doi.org/10.1016/j.enconman.2013.11.033.

[103] E. Woolley, Y. Luo, and A. Simeone, "Industrial waste heat recovery: A systematic approach," *Sustainable Energy Technologies and Assessments,* vol. 29, pp. 50-59, 2018.

[104] E. Worrell, L. Bernstein, J. Roy, L. Price, and J. Harnisch, "Industrial energy efficiency and climate change mitigation," *Energy efficiency,* vol. 2, no. 2, p. 109, 2009.

[105] E. Abdelaziz, R. Saidur, and S. Mekhilef, "A review on energy saving strategies in industrial sector," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 1, pp. 150-168, 2011.

[106] M. Uwasu, K. Hara, and H. Yabar, "World cement production and environmental implications," *Environmental Development,* vol. 10, pp. 36-47, 2014.

[107] R. Kajaste and M. Hurme, "Cement industry greenhouse gas emissions–management options and abatement cost," *Journal of Cleaner Production,* vol. 112, pp. 4041-4052, 2016.

[108] A. Hasanbeigi, H. Lu, C. Williams, and L. Price, "International Best Practices for Pre-Processing and Co-Processing Municipal Solid Waste and Sewage Sludge in the Cement Industry," Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (United …, 2012.

[109] W. Chen, J. Hong, and C. Xu, "Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement," *Journal of Cleaner Production,* vol. 103, pp. 61-69, 2015.

[110] Z. Liu *et al.*, "Reduced carbon emission estimates from fossil fuel combustion and cement production in China," *Nature,* vol. 524, no. 7565, pp. 335-338, 2015.

[111] G. Habert, C. Billard, P. Rossi, C. Chen, and N. Roussel, "Cement production technology improvement compared to factor 4 objectives," *Cement and Concrete Research,* vol. 40, no. 5, pp. 820-826, 2010.

[112] E. Benhelal, G. Zahedi, and H. Hashim, "A novel design for green and economical cement manufacturing," *Journal of Cleaner Production,* vol. 22, no. 1, pp. 60-66, 2012.

[113] E. Gartner, "Industrially interesting approaches to “low-CO2” cements," *Cement and Concrete research,* vol. 34, no. 9, pp. 1489-1498, 2004.

[114] C.-Y. Zhang, R. Han, B. Yu, and Y.-M. Wei, "Accounting process-related CO2 emissions from global cement production under Shared Socioeconomic Pathways," *Journal of cleaner production,* vol. 184, pp. 451-465, 2018.

[115] N. Mahasenan, S. Smith, and K. Humphreys, "The cement industry and global climate change: current and potential future cement industry CO2 emissions," in *Greenhouse Gas Control Technologies-6th International Conference*, 2003: Elsevier, pp. 995-1000.

[116] P. Duxson and J. L. Provis, "Designing precursors for geopolymer cements," *Journal of the American Ceramic Society*, vol. 91, no. 12, pp. 3864-3869, 2008.

[117] A. Atmaca and M. Kanoglu, "Reducing energy consumption of a raw mill in cement industry," *Energy*, vol. 42, no. 1, pp. 261-269, 2012.

[118] Z. Utlu, Z. Sogut, A. Hepbasli, and Z. Oktay, "Energy and exergy analyses of a raw mill in a cement production," *Applied Thermal Engineering*, vol. 26, no. 17-18, pp. 2479-2489, 2006.

[119] T. Engin and V. Ari, "Energy auditing and recovery for dry type cement rotary kiln systems—A case study," *Energy conversion and management*, vol. 46, no. 4, pp. 551-562, 2005.

[120] G. Kabir, A. Abubakar, and U. El-Nafaty, "Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant," *Energy*, vol. 35, no. 3, pp. 1237-1243, 2010.

[121] A. Atmaca and R. Yumrutaş, "Thermodynamic and exergoeconomic analysis of a cement plant: Part I–Methodology," *Energy conversion and management*, vol. 79, pp. 790-798, 2014.

[122] S. Karellas, A.-D. Leontaritis, G. Panousis, E. Bellos, and E. Kakaras, "Energetic and exergetic analysis of waste heat recovery systems in the cement industry," *Energy*, vol. 58, pp. 147-156, 2013.

[123] R. Riccardi, G. Oggioni, and R. Toninelli, "Efficiency analysis of world cement industry in presence of undesirable output: application of data envelopment analysis and directional distance function," *Energy Policy*, vol. 44, pp. 140-152, 2012.

[124] A. Hasanbeigi, C. Menke, and A. Therdyothin, "The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry," *Energy policy*, vol. 38, no. 1, pp. 392-405, 2010.

[125] L. Szabó, I. Hidalgo, J. C. Ciscar, and A. Soria, "CO2 emission trading within the European Union and Annex B countries: the cement industry case," *Energy Policy*, vol. 34, no. 1, pp. 72-87, 1// 2006, doi: http://dx.doi.org/10.1016/j.enpol.2004.06.003.

[126] A. Hasanbeigi, L. Price, H. Lu, and W. Lan, "Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: A case study of 16 cement plants," *Energy*, vol. 35, no. 8, pp. 3461-3473, 2010.

[127] J.-H. Xu, T. Fleiter, W. Eichhammer, and Y. Fan, "Energy consumption and CO2 emissions in China's cement industry: A perspective from LMDI decomposition analysis," *Energy policy*, vol. 50, pp. 821-832, 2012.

[128] G. Oggioni, R. Riccardi, and R. Toninelli, "Eco-efficiency of the world cement industry: A data envelopment analysis," *Energy Policy*, vol. 39, no. 5, pp. 2842-2854, 2011/05/01/ 2011, doi: https://doi.org/10.1016/j.enpol.2011.02.057.

[129] S. K. Mandal, "Do undesirable output and environmental regulation matter in energy efficiency analysis? Evidence from Indian Cement Industry," *Energy Policy*, vol. 38,

no. 10, pp. 6076-6083, 2010/10/01/ 2010, doi: https://doi.org/10.1016/j.enpol.2010.05.063.

[130] H. Mikulčić *et al.*, "The application of CFD modelling to support the reduction of CO2 emissions in cement industry," *Energy,* vol. 45, no. 1, pp. 464-473, 2012/09/01/ 2012, doi: https://doi.org/10.1016/j.energy.2012.04.030.

[131] J. Ke, N. Zheng, D. Fridley, L. Price, and N. Zhou, "Potential energy savings and CO2 emissions reduction of China's cement industry," *Energy Policy,* vol. 45, pp. 739-751, 2012/06/01/ 2012, doi: https://doi.org/10.1016/j.enpol.2012.03.036.

[132] J. A. Moya, N. Pardo, and A. Mercier, "The potential for improvements in energy efficiency and CO2 emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria," *Journal of Cleaner Production,* vol. 19, no. 11, pp. 1207-1215, 2011/07/01/ 2011, doi: https://doi.org/10.1016/j.jclepro.2011.03.003.

[133] J. Sathaye, L. Price, S. Can, and D. Fridley, "Assessment of energy use and energy savings potential in selected industrial sectors in India," *Lawrence Berkeley National Library, Berkeley,* 2005.

[134] E. W. Ottermann, "Energy management challenges and opportunities in the South African cement industry," in *2011 Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy*, 2011: IEEE, pp. 34-39.

[135] C. Ohanyere and M. Alexander, "The South African cement industry: A review of its energy efficiency and environmental performance since 1980," *University of Cape Town, Cape Town,* 2012.

[136] A. Telukdarie and M. Munsamy, "The impact of cement sustainability initiative on the South African cement industry's performance," 2018.

[137] X. Qin, T. Mohan, M. El-Halwagi, G. Cornforth, and B. A. McCarl, "Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment," *Clean Technologies and Environmental Policy,* vol. 8, no. 4, pp. 233-249, 2006.

[138] D. García-Gusano, H. Cabal, and Y. Lechón, "Long-term behaviour of CO2 emissions from cement production in Spain: scenario analysis using an energy optimisation model," *Journal of Cleaner Production,* vol. 99, pp. 101-111, 2015.

[139] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, "Sustainable development and climate change initiatives," *Cement and concrete research,* vol. 38, no. 2, pp. 115-127, 2008.

[140] T. Herzog, "World greenhouse gas emissions in 2005," *World Resources Institute,* vol. 7, p. 2009, 2009.

[141] DNT, "Carbon Tax Policy Paper: Reducing greenhouse gas emissions and facilitating the transition to a green economy,," Department of National Treasury, , Pretoria South Africa, 2013. Accessed: February 2022. [Online]. Available: http://www.treasury.gov.za/public%20comments/Carbon%20Tax%20Policy%20Paper%202013.pdf

[142] S. Mwakasonda, "IPCC guidelines: setting up SA system; SA GHG emission profile," *University of Cape Town*, 2012.

[143] T. Gao, L. Shen, M. Shen, F. Chen, L. Liu, and L. Gao, "Analysis on differences of carbon dioxide emission from cement production and their major determinants," *Journal of Cleaner Production*, vol. 103, pp. 160-170, 2015.

[144] M. Realff, P. Lemieux, S. Lucero, J. Mulholland, and P. Smith, "Characterization of transient puff emissions from the burning of carpet waste charges in a rotary kiln combustor," in *Conference Record Cement Industry Technical Conference, 2005.*, 2005: IEEE, pp. 212-228.

[145] M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. Van Der Linden, and C. E. Hanson, "IPCC, 2007: climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change," *Cambridge Uni-versity Press, Cambridge, UK*, 2007.

[146] J. B. Smith *et al.*, "Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC)"reasons for concern"," *Proceedings of the national Academy of Sciences*, vol. 106, no. 11, pp. 4133-4137, 2009.

[147] X. F. Zhang, S. Y. Zhang, Z. Y. Hu, G. Yu, C. H. Pei, and R. N. Sa, "Identification of connection units with high GHG emissions for low-carbon product structure design," *Journal of Cleaner Production*, vol. 27, pp. 118-125, 2012.

[148] IEA-GHG, "CO 2 Capture in the Cement Industry. International Energy Agency Greenhouse Gas R&D Programme, Technical Study," Report, 2008.

[149] IEA&WBCSD, "Cement Technology Roadmap 2009–Carbon emissions reductions up to 2050," *World Business Council on Sustainable Development (WBCSD), International Energy Agency (IEA). https://www. iea. org/publications/freepublications/publication/Cement. pdf*, 2009.

[150] GHG-IEA, "CO2 capture in the cement industry," in "Report," 2008, vol. 3.

[151] IEA, "Energy technology transitions for industry," Paris, France., 2009. Accessed: 15 January 2022. [Online]. Available: https://www.iea.org/publications/freepublications/publication/industry2009.pdf

[152] CSI and ECRA, "Development of State of the Art–Techniques in Cement Manufacturing. Trying to Look Ahead," ed: CSI and ECRA Dusseldorf, Germany and Geneva, Switzerland, 2009.

[153] E. Commission and BAT, "Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)," ed: Joint Research Centre, Institute for Prospective Technological Studies …, 2013.

[154] L. Beltran and T. Arnesh, "Uses of Alternative Fuels as Best Practices to Reduce CO2 Emissions from the South African Cement Industry," presented at the International

Conference on Industrial Engineering and Operations Management, Pretoria/Johannesburg, South Africa, 2018.

[155] M. Ali, R. Saidur, and M. Hossain, "A review on emission analysis in cement industries," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 5, pp. 2252-2261, 2011.

[156] IEA-ETSAP, "Technology Systems Analysis Programme Technology Brief I03 Cement Production," ed, 2010.

[157] D. N. Huntzinger and T. D. Eatmon, "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies," *Journal of Cleaner Production,* vol. 17, no. 7, pp. 668-675, 2009.

[158] A. Josa, A. Aguado, A. Cardim, and E. Byars, "Comparative analysis of the life cycle impact assessment of available cement inventories in the EU," *Cement and concrete research,* vol. 37, no. 5, pp. 781-788, 2007.

[159] C. Chen, G. Habert, Y. Bouzidi, and A. Jullien, "Environmental impact of cement production: detail of the different processes and cement plant variability evaluation," *Journal of Cleaner Production,* vol. 18, no. 5, pp. 478-485, 2010.

[160] D. A. Salas, A. D. Ramirez, C. R. Rodríguez, D. M. Petroche, A. J. Boero, and J. Duque-Rivera, "Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review," *Journal of Cleaner Production,* vol. 113, pp. 114-122, 2016/02/01/ 2016, doi: https://doi.org/10.1016/j.jclepro.2015.11.078.

[161] A. A. Usón, A. M. López-Sabirón, G. Ferreira, and E. L. Sastresa, "Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options," *Renewable and Sustainable Energy Reviews,* vol. 23, pp. 242-260, 2013.

[162] D. García-Gusano, D. Garraín, I. Herrera, H. Cabal, and Y. Lechón, "Life Cycle Assessment of applying CO2 post-combustion capture to the Spanish cement production," *Journal of Cleaner Production,* vol. 104, pp. 328-338, 2015.

[163] S. P. Holt and N. D. Berge, "Life-cycle assessment of using liquid hazardous waste as an alternative energy source during Portland cement manufacturing: A United States case study," *Journal of Cleaner Production,* vol. 195, pp. 1057-1068, 2018.

[164] L. Barcelo, J. Kline, G. Walenta, and E. Gartner, "Cement and carbon emissions," *Materials and structures,* vol. 47, no. 6, pp. 1055-1065, 2014.

[165] A.-M. Cormos and C.-C. Cormos, "Reducing the carbon footprint of cement industry by post-combustion CO2 capture: Techno-economic and environmental assessment of a CCS project in Romania," *Chemical Engineering Research and Design,* vol. 123, pp. 230-239, 2017.

[166] ECRA, "Technical Report TR-ECRA-119/2012 – ECRA C.C.S. Project – Report on I.I.I. Phase " European Cement Research Academy, Germany, 2012. Accessed: 01 November 2022. [Online]. Available: https://ecra-

online.org/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_III.pdf

[167] M. Ormazabal, C. Jaca, and R. Puga-Leal. *Analysis and comparison of life cycle assessment and carbon footprint software, Advances in Intelligent Systems and Computing*, vol. 281, pp. 1521-1530, 2014.

[168] R. Speck, S. Selke, R. Auras, and J. Fitzsimmons, "Choice of life cycle assessment software can impact packaging system decisions," *Packaging Technology and Science*, vol. 28, no. 7, pp. 579-588, 2015.

[169] R. Speck, S. Selke, R. Auras, and J. Fitzsimmons, "Life cycle assessment software: Selection can impact results," *Journal of Industrial Ecology*, vol. 20, no. 1, pp. 18-28, 2016.

[170] D. Silva, A. O. Nunes, A. da Silva Moris, C. Moro, and T. O. R. Piekarski, "How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto," in *Proceedings of the VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, Medellin, Colombia*, 2017, pp. 10-15.

[171] A. Ciroth, "ICT for environment in life cycle applications openLCA—A new open source software for life cycle assessment," *The international journal of life cycle assessment*, vol. 12, no. 4, pp. 209-210, 2007.

[172] A. Ciroth, C. Di Noi, T. Lohse, and M. Srocka, "OpenLCA 1.9 Comprehensive User Manual," ed: GreenDelta, 2019.

[173] K. K. Ramagiri, R. Chintha, R. K. Bandlamudi, P. Kara De Maeijer, and A. Kar, "Cradle-to-gate life cycle and economic assessment of sustainable concrete mixes—alkali-activated concrete (AAC) and bacterial concrete (BC)," *Infrastructures*, vol. 6, no. 7, p. 104, 2021.

[174] T. Anasstasia, E. Lestianingrum, R. Cahyono, and M. Azis, "Life Cycle Assessment of Refuse Derived Fuel (RDF) for Municipal Solid Waste (MSW) Management: Case Study Area Around Cement Industry, Cirebon, Indonesia," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 778, no. 1: IOP Publishing, p. 012146.

[175] R. Chairani, A. R. Adinda, D. Fillipi, M. Jatmoko, and I. Suryawan, "Environmental Impact Analysis in The Cement Industry with Life Cycle Assessment Approach," 2021.

[176] N. B. R. Monteiro, J. M. M. Neto, and E. A. da Silva, "Environmental assessment in concrete industries," *Journal of Cleaner Production*, vol. 327, p. 129516, 2021.

[177] OPENLCA, "openLCA – the Life Cycle and Sustainability Modeling Suite." Accessed: October 2021. [Online]. Available: https://www.openlca.org/openlca/

[178] R. Dandautiya and A. P. Singh, "Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment," *Waste Management*, vol. 99, pp. 90-101, 2019.

[179] R. Dandautiya and A. P. Singh, "Life-Cycle Assessment of Production of Concrete Using Copper Tailings and Fly Ash as a Partial Replacement of Cement," in *Advances in Sustainable Construction Materials*: Springer, 2020, pp. 75-85.

[180] P.-C. Chiang and S.-Y. Pan, "System Analysis," in *Carbon Dioxide Mineralization and Utilization*: Springer, 2017, pp. 187-217.

[181] PE-international, "PE-international GaBi " PE-international Germany., 2012. Accessed: October 2021. [Online]. Available: http:www.gabi-software.com

[182] R. Meshram and S. Kumar, "Comparative life cycle assessment (LCA) of geopolymer cement manufacturing with Portland cement in Indian context," *International Journal of Environmental Science and Technology,* vol. 19, no. 6, pp. 4791-4802, 2022.

[183] S. C. Galusnyak, L. Petrescu, and C.-C. Cormos, "Environmental impact assessment of post-combustion CO2 capture technologies applied to cement production plants," *Journal of Environmental Management,* vol. 320, p. 115908, 2022.

[184] J. An, R. S. Middleton, and Y. Li, "Environmental performance analysis of cement production with CO2 capture and storage technology in a life-cycle perspective," *Sustainability,* vol. 11, no. 9, p. 2626, 2019.

[185] M. Goedkoop, A. De Schryver, M. Oele, S. Durksz, and D. de Roest, "Introduction to LCA with SimaPro 7," *PRé Consultants, The Netherlands,* 2008.

[186] L. A. Calderón, L. Iglesias, A. Laca, M. Herrero, and M. Díaz, "The utility of Life Cycle Assessment in the ready meal food industry," *Resources, conservation and recycling,* vol. 54, no. 12, pp. 1196-1207, 2010.

[187] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, and A. Ventura, "LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete," *Resources, Conservation and Recycling,* vol. 54, no. 12, pp. 1231-1240, 2010.

[188] M. Pizzol, P. Christensen, J. Schmidt, and M. Thomsen, "Impacts of "metals" on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA)," *Journal of Cleaner Production,* vol. 19, no. 6-7, pp. 646-656, 2011.

[189] C. Scacchi, S. González-García, S. Caserini, and L. Rigamonti, "Greenhouse gases emissions and energy use of wheat grain-based bioethanol fuel blends," *Science of the total environment,* vol. 408, no. 21, pp. 5010-5018, 2010.

[190] F. Colangelo, T. G. Navarro, I. Farina, and A. Petrillo, "Comparative LCA of concrete with recycled aggregates: A circular economy mindset in Europe," *The International Journal of Life Cycle Assessment,* vol. 25, no. 9, pp. 1790-1804, 2020.

[191] O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, "Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method," *Energies,* vol. 15, no. 7, p. 2708, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/7/2708.

[192] B. D. Olagunju and O. A. Olanrewaju, "Life Cycle Assessment of Ordinary Portland Cement (OPC) Using both Problem Oriented (Midpoint) Approach and Damage Oriented Approach (Endpoint)," in *Product Life Cycle-Opportunities for Digital and Sustainable Transformation*: Intech Open London, 2021.

[193] A. Al-Ghandoor, I. Al-Hinti, J. Jaber, and S. Sawalha, "Electricity consumption and associated GHG emissions of the Jordanian industrial sector: empirical analysis and future projection," *Energy Policy,* vol. 36, no. 1, pp. 258-267, 2008.

[194] N. A. Madlool, R. Saidur, M. S. Hossain, and N. A. Rahim, "A critical review on energy use and savings in the cement industries," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 4, pp. 2042-2060, 2011.

[195] IEA, "Technology Roadmap, Springer Reference," International Energy Agency, Paris, 2018. Accessed: August 2020. [Online]. Available: https://doi.org/10.1007/SpringerReference_7300

[196] IPCC, "Climate change 2007: impacts, adaptation and vulnerability," *Working Group II, IPCC 4th Assessment Report, http://www. ipcc. ch*, 2007.

[197] H. Mikulčić, J. J. Klemeš, M. Vujanović, K. Urbaniec, and N. Duić, "Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process," *Journal of cleaner production,* vol. 136, pp. 119-132, 2016.

[198] A. Hasanbeigi, L. Price, and E. Lin, "Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 8, pp. 6220-6238, 2012/10/01/ 2012, doi: https://doi.org/10.1016/j.rser.2012.07.019.

[199] DEA, *2nd South Africa environment outlook: A report on the state of the environment executive summary*. Pretoria: Department of Environmental Affairs, 2012.

[200] J. M. Allwood *et al.*, *Sustainable materials: with both eyes open*. Citeseer, 2012.

[201] IEA, "Technology Roadmap - Low-Carbon Transition in the Cement Industry," 2018. Accessed: 5 January 2023. [Online]. Available: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

[202] F. N. Stafford, A. C. Dias, L. Arroja, J. A. Labrincha, and D. Hotza, "Life cycle assessment of the production of Portland cement: a Southern Europe case study," *Journal of cleaner production,* vol. 126, pp. 159-165, 2016.

[203] ISO, "14044: International Organisation for Standardisation. Environmental Management: Environmental management: life cycle assessment; requirements and guidelines," in "International Organisation for Standardisation," ISO Geneva, Switzerland, 2006. Accessed: 12 June 2022. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

[204] K. Abeliotis, A. Kalogeropoulos, and K. Lasaridi, "Life cycle assessment of the MBT plant in Ano Liossia, Athens, Greece," *Waste Management*, vol. 32, no. 1, pp. 213-219, 2012.

[205] O. E. Ige, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, "A review of the effectiveness of Life Cycle Assessment for gauging environmental impacts from cement production," *Journal of Cleaner Production*, p. 129213, 2021/10/02/ 2021, doi: https://doi.org/10.1016/j.jclepro.2021.129213.

[206] IEA, "Tracking Industry, IEA, Paris," 2019. Accessed: March 2020. [Online]. Available: https://www.iea.org/reports/tracking-industry/cement

[207] M. Cetin, "Landscape engineering, protecting soil, and runoff storm water," in *Advances in landscape architecture-Environmental Sciences*: Intech-Open Science-Open Minds, 2013, ch. 27, pp. 697-722.

[208] M. Cetin, "Using recycling materials for sustainable landscape planning," in *Environment and ecology at the beginning of 21st century*. Sofia: ST. Kliment Ohridski University Press, 2015, ch. 55, pp. 783-788.

[209] M. U. Hossain, C. S. Poon, I. M. Lo, and J. C. Cheng, "Comparative LCA on using waste materials in the cement industry: A Hong Kong case study," *Resources, Conservation and Recycling*, vol. 120, pp. 199-208, 2017.

[210] T. A. Napp, A. Gambhir, T. P. Hills, N. Florin, and P. S. Fennell, "A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 616-640, 2014.

[211] E. Worrell, K. Kermeli, and C. Galitsky, *Energy efficiency improvement and cost saving opportunities for cement making an ENERGY STAR® guide for energy and plant managers*. EPA-United States Environmental Protection Agency, 2013.

[212] F. Zeman, "Oxygen combustion in cement production," *Energy Procedia*, vol. 1, no. 1, pp. 187-194, 2009.

[213] I. O. f. Standardisation, *Environmental management: Life cycle assessment; requirements and guidelines*. ISO Geneva, 2006.

[214] A. Rahman, M. Rasul, M. M. K. Khan, and S. Sharma, "Impact of alternative fuels on the cement manufacturing plant performance: an overview," *Procedia Engineering*, vol. 56, pp. 393-400, 2013.

[215] Y. Wang, Q. Zhu, and Y. Geng, "Trajectory and driving factors for GHG emissions in the Chinese cement industry," *Journal of Cleaner Production*, vol. 53, pp. 252-260, 2013.

[216] C. Cembureau, "Sustainable cement production: Co-Processing of alternative fuels and raw materials in the European Cement Industry," *Europe*, vol. 2, pp. 1-6, 2009.

[217] E. Frauenhofer, "Oeko Institut (2009)“Methodology for the free allocation of emission allowances in the EU ETS post 2012. "Sector report for the cement industry”," ed, 2009.

[218] I. G. E. Outlook, "International Energy Agency (IEA)," in *Outlook, IEA Global*, ed: Paris, 2018.

[219] F. Rodrigues and I. Joekes, "Cement industry: sustainability, challenges and perspectives," *Environmental Chemistry Letters*, vol. 9, no. 2, pp. 151-166, 2011.

[220] C. Le Quéré *et al.*, "Global carbon budget 2018," *Earth System Science Data,* vol. 10, no. 4, pp. 2141-2194, 2018.

[221] Y. Lei, Q. Zhang, C. Nielsen, and K. He, "An inventory of primary air pollutants and CO2 emissions from cement production in China, 1990–2020," *Atmospheric Environment,* vol. 45, no. 1, pp. 147-154, 2011.

[222] M. Al-Dadi, H. Hassan, T. Sharshar, H. Arida, and H. Badran, "Environmental impact of some cement manufacturing plants in Saudi Arabia," *Journal of Radioanalytical and Nuclear Chemistry,* vol. 302, no. 3, pp. 1103-1117, 2014.

[223] A. Kendall, S. E. Kesler, and G. A. Keoleian, "Geologic vs. geographic constraints on cement resources," *Resources Policy,* vol. 33, no. 3, pp. 160-167, 2008.

[224] W. R. Morrow III, A. Hasanbeigi, J. Sathaye, and T. Xu, "Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries," *Journal of Cleaner Production*, vol. 65, pp. 131-141, 2014.

[225] S. A. Ishak and H. Hashim, "Low carbon measures for cement plant–a review," *Journal of Cleaner Production,* vol. 103, pp. 260-274, 2015.

[226] D. Leeson, N. Mac Dowell, N. Shah, C. Petit, and P. Fennell, "A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources," *International Journal of Greenhouse Gas Control,* vol. 61, pp. 71-84, 2017.

[227] E. Gartner and T. Sui, "Alternative cement clinkers," *cement and concrete research,* vol. 114, pp. 27-39, 2018.

[228] D. García-Gusano, I. Herrera, D. Garraín, Y. Lechón, and H. Cabal, "Life cycle assessment of the Spanish cement industry: implementation of environmental-friendly solutions," *Clean Technologies and Environmental Policy,* vol. 17, no. 1, pp. 59-73, 2015.

[229] M. E. Boesch and S. Hellweg, "Identifying improvement potentials in cement production with life cycle assessment," *Environmental science & technology,* vol. 44, no. 23, pp. 9143-9149, 2010.

[230] C. Valderrama, R. Granados, J. L. Cortina, C. M. Gasol, M. Guillem, and A. Josa, "Comparative LCA of sewage sludge valorisation as both fuel and raw material substitute in clinker production," *Journal of Cleaner Production,* vol. 51, pp. 205-213, 2013.

[231] T. Hanein, J.-L. Galvez-Martos, and M. N. Bannerman, "Carbon footprint of calcium sulfoaluminate clinker production," *Journal of Cleaner Production,* vol. 172, pp. 2278-2287, 2018.

[232] W. S. Ismaeel, "Midpoint and endpoint impact categories in Green building rating systems," *Journal of Cleaner Production,* vol. 182, pp. 783-793, 2018.

[233] P. Van den Heede and N. De Belie, "Environmental impact and life cycle assessment (LCA) of traditional and ‘green’concretes: literature review and theoretical calculations," *Cement and Concrete Composites,* vol. 34, no. 4, pp. 431-442, 2012.

[234] M. I. García Herrero *et al.*, "Towards a sustainable agri-food system by an energetic and environmental efficiency assessment," 2018.

[235] V. Paramesh, V. Arunachalam, A. Nikkhah, B. Das, and S. Ghnimi, "Optimization of energy consumption and environmental impacts of arecanut production through coupled data envelopment analysis and life cycle assessment," *Journal of cleaner production,* vol. 203, pp. 674-684, 2018.

[236] V. Filimonau, *Life cycle assessment (LCA) and life cycle analysis in tourism* (Springer). Berlin/Heidelberg, Germany: Springer, 2016.

[237] C. Li, Z. Nie, S. Cui, X. Gong, Z. Wang, and X. Meng, "The life cycle inventory study of cement manufacture in China," *Journal of Cleaner Production,* vol. 72, pp. 204-211, 2014.

[238] C. Li, S. Cui, Z. Nie, X. Gong, Z. Wang, and N. Itsubo, "The LCA of Portland cement production in China," *The International Journal of Life Cycle Assessment,* vol. 20, no. 1, pp. 117-127, 2015.

[239] S. Çankaya and B. Pekey, "Identifying environmental impacts of cement production with life cycle assessment: literature review," *J. Int. Sci. Publ,* vol. 9, 2015.

[240] EPA, "Life Cycle Assessment: Principles and Practice, EPA/600/R-06/060. US Environmental Protection Agency, Office of Research & Development. Cincinnati, Ohio," 2006.

[241] M. E. Boesch, A. Koehler, and S. Hellweg, "Model for cradle-to-gate life cycle assessment of clinker production," *Environmental science & technology,* vol. 43, no. 19, pp. 7578-7583, 2009.

[242] M. Marceau, M. A. Nisbet, and M. G. Van Geem, "Life cycle inventory of portland cement manufacture," Portland Cement Association Skokie, IL, 2006.

[243] S. Çankaya and B. Pekey, "A comparative life cycle assessment for sustainable cement production in Turkey," *Journal of environmental management,* vol. 249, p. 109362, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301479719310710?via%3Dihub.

[244] A. A. Usón, G. Ferreira, A. M. López-Sabirón, E. L. Sastresa, and A. S. De Guinoa, "Characterisation and environmental analysis of sewage sludge as secondary fuel for cement manufacturing," *Chemical Engineering Transactions,* vol. 29, pp. 457-462, 2012.

[245] M. A. Nisbet, M. G. VanGeem, J. Gajda, and M. Marceau, "Environmental life cycle inventory of portland cement concrete," *PCA R&D Serial,* no. 2137a, 2000.

[246] M. Nisbet, M. Marceau, M. VanGeem, and J. Gajda, "Environmental life cycle inventory of Portland cement concrete and asphalt concrete pavements," *Portland Cement Association PCA R&D Serial,* vol. 2489, 2001.

[247] A. Matanza, G. Vargas, I. Leon, M. Pousse, N. Salmon, and C. Marieta, "Life cycle analysis of standard and high-performance cements based on carbon nanotubes composites for construction applications," *World SB,* vol. 4, pp. 28-30, 2014.

[248] J. Hong and X. Li, "Environmental assessment of sewage sludge as secondary raw material in cement production–a case study in China," *Waste Management,* vol. 31, no. 6, pp. 1364-1371, 2011.

[249] F. Puertas *et al.*, "Ceramic wastes as alternative raw materials for Portland cement clinker production," *Cement and Concrete Composites,* vol. 30, no. 9, pp. 798-805, 2008.

[250] E. B. Petavratrzi, J "Industrial sector study on the utilisation of alternative materials in the manufacture of cement," 2007. Accessed: August 2020.

[251] E. PCA, "US and Canadian Portland Cement Industry: Plant Information Summary, in," *Portland Cement Association [PCA]-Economic Research Department, Skokie, IL,* 2008.

[252] C. Galitsky *et al.*, "Guidebook for using the tool BEST cement: benchmarking and energy savings tool for the cement industry," Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2008.

[253] E. Worrell and C. Galitsky, "Energy efficiency improvement and cost saving opportunities for cement making—An Energy Star® guide for energy and plant managers: Berkeley, California, Ernest Orlando Lawrence Berkeley National Laboratory.," ed, 2008.

[254] I. Bureau, "Draft reference document on best available techniques in the cement, lime and magnesium oxide manufacturing industries," *European IPPC Bureau,* 2009.

[255] H. G. Van Oss, "Background facts and issues concerning cement and cement data," *US Geological Survey Open-File Report,* vol. 1152, p. 88, 2005.

[256] M. F. Bhatty JI, Kosmatka SH, "Innovations in Portland Cement Manufacturing," *PCA, Illinois, USA,* 2004.

[257] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: A critical review," *Cement and Concrete Composites,* vol. 51, pp. 38-48, 2014/08/01/ 2014, doi: https://doi.org/10.1016/j.cemconcomp.2014.03.005.

[258] J. Moya, N. Pardo, and A. Mercier, "Energy Efficiency and CO2 Emissions: Prospective Scenarios," 2010.

[259] R. Hischier *et al.*, "Implementation of life cycle impact assessment methods. Ecoinvent report no. 3, v2. 2," *Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland,* 2010.

[260] M. Goedkoop, S. Effting, and M. Collignon, *The eco-indicator 99: a damage oriented method for life-cycle impact assessment: manual for designers*. PRé Consultants, 2000.

[261] C. Strazza, A. Del Borghi, M. Gallo, and M. Del Borghi, "Resource productivity enhancement as means for promoting cleaner production: analysis of co-incineration in cement plants through a life cycle approach," *Journal of cleaner production,* vol. 19, no. 14, pp. 1615-1621, 2011.

[262] C. Knoeri, E. Sanyé-Mengual, and H.-J. Althaus, "Comparative LCA of recycled and conventional concrete for structural applications," *The international journal of life cycle assessment,* vol. 18, no. 5, pp. 909-918, 2013.

[263] M. Valipour, M. Yekkalar, M. Shekarchi, and S. Panahi, "Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments," *Journal of Cleaner Production,* vol. 65, pp. 418-423, 2014.

[264] WBCSD, "The Cement Sustainability Initiative (CSI) Recycling Concrete Excutive Summary," ed: World Business Council for Sustainable Development Geneva, Switzerland, 2009.

[265] W. IEA, "Cement Technology Roadmap 2009–Carbon emissions reductions up to 2050," *Paris, France,* pp. 1-2, 2021.

[266] S. Miccoli, F. Finucci, and R. Murro, "Criteria and procedures for regional environmental regeneration: A European strategic project," in *Applied Mechanics and Materials,* Switzerland 2014, vol. 675, Switzerland Trans Tech Publ, pp. 401-405.

[267] M. Nadal, M. Schuhmacher, and J. L. Domingo, "Cost–benefit analysis of using sewage sludge as alternative fuel in a cement plant: a case study," *Environmental Science and Pollution Research,* vol. 16, no. 3, pp. 322-328, 2009.

[268] Z. Cao *et al.*, "Toward a better practice for estimating the CO2 emission factors of cement production: An experience from China," *Journal of Cleaner Production,* vol. 139, pp. 527-539, 2016.

[269] IEA, "Cement," in "IEA report," 2020. Accessed: 15 January 2022. [Online]. Available: https://www.iea.org/reports/cement

[270] F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, and A. G. De Magalhaes, *Eco-efficient construction and building materials: life cycle assessment (LCA), eco-labelling and case studies*. woodhead Publishing, 2014.

[271] O. E. Ige, F. L. Inambao, O. A. Olanrewaju, K. J. Duffy, and O. C. Collins, M. J. Acosta, Ed. *Drivers and barriers to industrial energy efficiency: A case study of South Africa's cement finishing mill plant* (ADVANCES IN ENERGY RESEARCH). USA: Nova Science Publishers, 2020, p. 45.

[272] J. Wang, Y. Dai, and L. Gao, "Exergy analyses and parametric optimizations for different cogeneration power plants in cement industry," *Applied Energy,* vol. 86, no. 6, pp. 941-948, 2009.

[273] M. Singhi and R. Bhargava, "Sustainable Indian cement industry," in *Workshop on International comparison of Industrial Energy efficiency*, 2010, pp. 27-28.

[274] R. T. Lidbetter, "Demand Side Management opportunities for a typical South African cement plant," North-West University, 2010.

[275] A. Kumar, "Global warming, climate change and greenhouse gas mitigation," in *Biofuels: Greenhouse Gas Mitigation and Global Warming*: Springer, 2018, pp. 1-16.

[276] R. E. O'Connor, R. J. Bord, B. Yarnal, and N. Wiefek, "Who wants to reduce greenhouse gas emissions?," *Social Science Quarterly*, vol. 83, no. 1, pp. 1-17, 2002.

[277] D. Dodman, "Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories," *Environment and urbanization*, vol. 21, no. 1, pp. 185-201, 2009.

[278] I. Statistics, "Key world energy statistics. paris. International energy agency," *International energy agency (IEA) report*, 2014.

[279] I. Arto, I. Capellán-Pérez, R. Lago, G. Bueno, and R. Bermejo, "The energy requirements of a developed world," *Energy for Sustainable Development*, vol. 33, pp. 1-13, 2016.

[280] S. Anand, P. Vrat, and R. Dahiya, "Application of a system dynamics approach for assessment and mitigation of CO 2 emissions from the cement industry," *Journal of environmental management*, vol. 79, no. 4, pp. 383-398, 2006.

[281] F. V. Bekun, F. Emir, and S. A. Sarkodie, "Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa," *Science of the Total Environment*, vol. 655, pp. 759-765, 2019.

[282] D. S. Africa, "GHG Inventory for South Africa 2000-2010," in *Educational Forum*, 2014.

[283] DEA, "GHG National Inventory Report For South Africa 2000-2010," Department of Environmental Affairs (DEA) Pretoria, South Africa, 2014. Accessed: 09 January 2022. [Online]. Available: http://www.saaqis.org.za

[284] M. Mann and P. Spath, "A life cycle assessment of biomass cofiring in a coal-fired power plant," *Clean Products and Processes*, vol. 3, no. 2, pp. 81-91, 2001.

[285] M. Whitaker, G. A. Heath, P. O’Donoughue, and M. Vorum, "Life cycle greenhouse gas emissions of coal-fired electricity generation: Systematic review and harmonization," *Journal of Industrial Ecology*, vol. 16, pp. S53-S72, 2012.

[286] R. Inglesi and A. Pouris, "Forecasting electricity demand in South Africa: A critique of Eskom's projections," *South African Journal of Science*, vol. 106, no. 1, pp. 50-53, 2010.

[287] C. Gross, "Electricity Generation Options considered by Eskom," in *Presentation at the Energy Planning Colloquium*, 2012, vol. 30, Eskom Holdings SOC Limited, 2012.

[288] K. Humphreys and M. Mahasenan, "Towards a sustainable cement industry. Substudy 8: climate change," 2002. [Online]. Available: www.wbcsdcement.org.

[289] A. Karagiannidis, *Waste to Energy: Opportunities and Challenges for Developing and Transition Economies.* Springer, 2012.

[290] B. M. Scalet, "Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide (CLM BREF)," 2013.

[291] J. W. Phair, "Green chemistry for sustainable cement production and use," *Green chemistry,* vol. 8, no. 9, pp. 763-780, 2006.

[292] JRC, *Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*. TP 270 – 21027 Ispra (VA) Italy: European Union, 2010.

[293] E. Amrina and A. L. Vilsi, "Key performance indicators for sustainable manufacturing evaluation in cement industry," *Procedia Cirp,* vol. 26, no. 1, pp. 19-23, 2015.

[294] X. Wang, H. K. Chan, and D. Li, "A case study of an integrated fuzzy methodology for green product development," *European Journal of Operational Research,* vol. 241, no. 1, pp. 212-223, 2015.

[295] G. A. Blengini, M. Busto, M. Fantoni, and D. Fino, "Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA," *Waste management,* vol. 32, no. 5, pp. 1000-1008, 2012.

[296] M. Mazari, S. F. Aval, S. M. Satani, D. Corona, and J. Garrido, "Developing Guidelines for Assessing the Effectiveness of Intelligent Compaction Technology," 2021.

[297] S. Satani, S. Aval, J. Garrido, and M. Mazari, *Preliminary evaluation of using intelligent compaction for life cycle assessment and life cycle cost analysis of pavement structures* (Pavement, Roadway, and Bridge Life Cycle Assessment 2020). London: Taylor & Franscis Group, 2020, pp. 460-468.

[298] F. N. Stafford, F. Raupp-Pereira, J. A. Labrincha, and D. Hotza, "Life cycle assessment of the production of cement: A Brazilian case study," *Journal of Cleaner Production,* vol. 137, pp. 1293-1299, Nov 2016, doi: 10.1016/j.jclepro.2016.07.050.

[299] S. Morsali, "Emissions from portland cement production using life cycle assessment inventory and method," *Environ Energy Econ,* vol. 1, no. 1, pp. 1-8, 2016.

[300] F. Dabbaghi, A. Sadeghi-Nik, N. A. Libre, and S. Nasrollahpour, "Characterizing fiber reinforced concrete incorporating zeolite and metakaolin as natural pozzolans," in *Structures,* 2021, vol. 34: Elsevier, pp. 2617-2627.

[301] M. A. Mousavi *et al.*, "Strength optimization of cementitious composites reinforced by carbon nanotubes and Titania nanoparticles," *Construction and Building Materials,* vol. 303, p. 124510, 2021.

[302] M. Mazari, S. F. Aval, and T. Rodriguez-Nikl, "Evaluating the Use of Recycled and Sustainable Materials in Self-Consolidating Concrete for Underground Infrastructure

Applications," United States. Dept. of Transportation. Office of the Assistant Secretary for Research and Technology, Washington, DC, 2020.

[303] A. Bahari, A. Sadeghi-Nik, E. Cerro-Prada, A. Sadeghi-Nik, M. Roodbari, and Y. Zhuge, "One-step random-walk process of nanoparticles in cement-based materials," *Journal of Central South University,* vol. 28, no. 6, pp. 1679-1691, 2021.

[304] A. Bahari *et al.*, "Experimental studies on rheological, mechanical, and microstructure properties of self-compacting concrete containing perovskite nanomaterial," *Structural Concrete,* 2021.

[305] M. Askarian, S. Fakhretaha Aval, and A. Joshaghani, "A comprehensive experimental study on the performance of pumice powder in self-compacting concrete (SCC)," *Journal of Sustainable Cement-Based Materials,* vol. 7, no. 6, pp. 340-356, 2018.

[306] M. Y. Vahabi, B. Tahmouresi, H. Mosavi, and S. F. Aval, "Effect of pre-coating lightweight aggregates on the self-compacting concrete," *Structural Concrete,* 2021.

[307] M. Tüfekçi, A. Demirbaş, and H. Genc, "Evaluation of steel furnace slags as cement additives," *Cement and Concrete Research,* vol. 27, no. 11, pp. 1713-1717, 1997.

[308] X. Xu and Y. Tian, "Application of Electric Arc Furnace Dust in Cement Production," *IRON AND STEEL-BEIJING-,* vol. 33, pp. 61-64, 1998.

[309] R. G. Hilton, "Use of stabilized EAFD as a raw material in the production of a portland cement clinker," ed: Google Patents, 1998.

[310] İ. Yüksel, "A review of steel slag usage in construction industry for sustainable development," *Environment, Development and Sustainability,* vol. 19, no. 2, pp. 369-384, 2017.

[311] X. Zhang, S. Zhao, Z. Liu, and F. Wang, "Utilization of steel slag in ultra-high performance concrete with enhanced eco-friendliness," *Construction and Building Materials,* vol. 214, pp. 28-36, 2019.

[312] A. Hasanbeigi and C. Springer, "California’s Cement Industry: Failing the Climate Challenge," *Global E ciency Intelligence. San Francisco, CA,* 2019.

[313] A. Sagastume Gutiérrez, J. J. Cabello Eras, C. A. Gaviria, J. Van Caneghem, and C. Vandecasteele, "Improved selection of the functional unit in environmental impact assessment of cement," *Journal of Cleaner Production,* vol. 168, pp. 463-473, 2017/12/01/ 2017, doi: https://doi.org/10.1016/j.jclepro.2017.09.007.

[314] T. Z. Tun, S. Bonnet, and S. H. Gheewala, "Life cycle assessment of Portland cement production in Myanmar," *The International Journal of Life Cycle Assessment,* vol. 25, no. 11, pp. 2106-2121, 2020.

[315] E. Thwe, D. Khatiwada, and A. Gasparatos, "Life cycle assessment of a cement plant in Naypyitaw, Myanmar," *Cleaner Environmental Systems,* vol. 2, p. 100007, 2021.

[316] A. Rosyid, R. Boedisantoso, and A. Iswara, "Environmental impact studied using life cycle assessment on cement industry," in *IOP Conference Series: Earth and*

Environmental Science, 2020, vol. 506, no. 1, Philadelphia, PA 19106 USA: IOP Publishing, 2020, p. 012024.

[317] PRé Sustainability, "SimaPro," *Software To Measure And Improve The Impact Of Your Product Life Cycle,[online], available: pre-sustainability.* , 2017.

[318] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008," *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*, vol. 1, pp. 1-126, 2009. [Online]. Available: https://web.universiteitleiden.nl/cml/ssp/publications/recipe_characterisation.pdf.

[319] E. Moreno Ruiz *et al.*, "Cement production: Documentation of changes implemented in ecoinvent database v3. 7 & v3. 7.1. documentation Cement production, Portland - ZA," ecoinvent Association, Allocation, cut-off ed. Identifying Improvement Potentials in Cement Production with Life Cycle Assessment 2010, 2019.," 2020.

[320] L. C. Dreyer, A. L. Niemann, and M. Z. Hauschild, "Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99," *The international journal of life cycle assessment*, vol. 8, no. 4, pp. 191-200, 2003.

[321] A. Azapagic and R. Clift, "The application of life cycle assessment to process optimisation," *Computers & Chemical Engineering*, vol. 23, no. 10, pp. 1509-1526, 1999.

[322] M. A. J. Huijbregts *et al.*, "Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES–LCA," *Chemosphere*, vol. 41, no. 4, pp. 541-573, 2000/08/01/ 2000, doi: https://doi.org/10.1016/S0045-6535(00)00030-8.

[323] D. W. Pennington *et al.*, "Life cycle assessment Part 2: Current impact assessment practice," *Environment International*, vol. 30, no. 5, pp. 721-739, 2004/07/01/ 2004, doi: https://doi.org/10.1016/j.envint.2003.12.009.

[324] G. Finnveden *et al.*, *Normalization, grouping and weighting in life cycle impact assessment* (Life Cycle Impact Assessment: Striving Towards Best Practice. Society of Environmental Toxicology and Chemistry (SETAC)). Pensacola, FL: SETAC Press, 2002.

[325] B. Pré Consultants, "SimaPro," in "https://network. simapro. com/esuservices," 2016. Accessed: 13 August 2022. [Online]. Available: https://network. simapro. com/esuservices

[326] J. Zhang, G. Liu, B. Chen, D. Song, J. Qi, and X. Liu, "Analysis of CO2 emission for the cement manufacturing with alternative raw materials: a LCA-based framework," *Energy Procedia*, vol. 61, pp. 2541-2545, 2014.

[327] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, and R. Marshall, "Improving the CO2 performance of cement, part II: framework for assessing CO2 improvement measures in the cement industry," *Journal of Cleaner Production*, vol. 98, pp. 282-291, 2015.

[328] K. Vatopoulos and E. Tzimas, "Assessment of CO2 capture technologies in cement manufacturing process," *Journal of cleaner production,* vol. 32, pp. 251-261, 2012.

[329] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, and R. Marshall, "Improving the CO2 performance of cement, part III: the relevance of industrial symbiosis and how to measure its impact," *Journal of Cleaner Production,* vol. 98, pp. 145-155, 2015.

[330] L. P. Güereca, N. Torres, and C. R. Juárez-López, "The co-processing of municipal waste in a cement kiln in Mexico. A life-cycle assessment approach," *Journal of Cleaner Production,* vol. 107, pp. 741-748, 2015.

[331] D. Hu, Z. Guo, Z. Wang, and Q. Xiao, "Metabolism analysis and eco-environmental impact assessment of two typical cement production systems in Chinese enterprises," *Ecological Informatics,* vol. 26, pp. 70-77, 2015.

[332] J. Zhang, J. C. Cheng, and I. M. Lo, "Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong," *The international journal of life cycle assessment,* vol. 19, no. 4, pp. 745-757, 2014.

[333] M. A. Huijbregts *et al.*, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *The International Journal of Life Cycle Assessment,* vol. 22, no. 2, pp. 138-147, 2017.

[334] B. Neuffer and M. Laney, *Alternative control techniques document update: NOX emissions from new cement kilns*. US Environmental Protection Agency, Office of Air Quality Planning and …, 2007.

[335] WBCSD, "Guidelines for co-processing fuels and raw materials in cement manufacturing," in *Cement Sustainability Initiative (CSI),* ed: World Business Council for Sustainable Development Geneva, 2014.

[336] T. Z. Tun, S. Bonnet, and S. H. Gheewala, "Emission reduction pathways for a sustainable cement industry in Myanmar," *Sustainable Production and Consumption,* vol. 27, pp. 449-461, 2021/07/01/ 2021, doi: https://doi.org/10.1016/j.spc.2021.01.016.

[337] N. Chatziaras, C. Psomopoulos, and N. Themelis, "Use of alternative fuels in cement industry," in *Proceedings of the 12th International Conference on Protection and Restoration of the Environment*, 2014, vol. 1: ISBN, pp. 521-529.

[338] E. Gençer, S. Torkamani, I. Miller, T. W. Wu, and F. O'Sullivan, "Sustainable energy system analysis modeling environment: Analyzing life cycle emissions of the energy transition," *Applied Energy,* vol. 277, p. 115550, 2020.

[339] R. L. Reaño, V. A. N. de Padua, and A. B. Halog, "Energy Efficiency and Life Cycle Assessment with System Dynamics of Electricity Production from Rice Straw Using a Combined Gasification and Internal Combustion Engine," *Energies,* vol. 14, no. 16, p. 4942, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/16/4942.

[340] IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector," 2021. Accessed: February 2022. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[341] IEA, " World Energy Outlook 2020-Summary," in "International Energy Agency," IEA: Paris, France,, 2020. Accessed: 02 February 2022. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2020

[342] S. Miccoli, F. Finucci, and R. Murro, "Assessing project quality: A multidimensional approach," in *Advanced Materials Research*, 2014, vol. 1030: Trans Tech Publ, pp. 2519-2522.

[343] T. R. Anderson, E. Hawkins, and P. D. Jones, "CO2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models," *Endeavour*, vol. 40, no. 3, pp. 178-187, 2016.

[344] S. Nta and A. Olorunnisola, "Experimental production and evaluation of cement-bonded composite pipes for water conveyance," *International Journal of Composite Materials*, vol. 6, no. 1, pp. 9-14, 2016.

[345] WBCSD, "GNR Project Reporting CO2," in "Cement Sustainability Initiative," 2015. Accessed: 02 November 2022. [Online]. Available: https://www.wbcsdcement.org/GNR-2016/index.html

[346] J. Green, "Global demand for cement to reach 5.2 billion t," worldcement., 2015. Accessed: 18 August 2022. [Online]. Available: https://www.worldcement.com/europe-cis/27082015/global-demand-cement-billion-tons-449/

[347] M. C. Caillahua and F. J. Moura, "Technical feasibility for use of FGD gypsum as an additive setting time retarder for Portland cement," *Journal of materials research and technology*, vol. 7, no. 2, pp. 190-197, 2018.

[348] L. Moretti and S. Caro, "Critical analysis of the life cycle assessment of the Italian cement industry," *Journal of Cleaner Production*, vol. 152, pp. 198-210, 2017.

[349] N. Madlool, "Assessment of waste preheater gas and dust bypass systems: Al-Muthanna cement plant case study," *Case Studies in Thermal Engineering*, vol. 8, pp. 330-336, 2016.

[350] Y.-L. Lü, J. Geng, and G.-Z. He, "Industrial transformation and green production to reduce environmental emissions: Taking cement industry as a case," *Advances in Climate Change Research*, vol. 6, no. 3-4, pp. 202-209, 2015.

[351] A. A. M. Ali, A. M. Negm, M. F. Bady, M. G. Ibrahim, and M. Suzuki, "Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: a comparative study between Egyptian and Swiss plants," *Clean Technologies and Environmental Policy*, vol. 18, no. 4, pp. 1053-1068, 2016.

[352] A. Somoza-Tornos, O. J. Guerra, A. M. Crow, W. A. Smith, and B.-M. Hodge, "Process modeling, techno-economic assessment, and life cycle assessment of the electrochemical reduction of CO2: a review," *iScience*, vol. 24, no. 7, p. 102813, 2021/07/23/ 2021, doi: https://doi.org/10.1016/j.isci.2021.102813.

[353] S. Marinković, "Life cycle assessment (LCA) aspects of concrete," in *Eco-efficient concrete*: Elsevier, 2013, pp. 45-80.

[354] A. Martínez-Rocamora, J. Solís-Guzmán, and M. Marrero, "LCA databases focused on construction materials: A review," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 565-573, 2016.

[355] K. Andersson, T. Ohlsson, and P. Olsson, "Life cycle assessment (LCA) of food products and production systems," *Trends in Food Science & Technology*, vol. 5, no. 5, pp. 134-138, 1994.

[356] E. M. Nigri, S. D. F. Rocha, and E. Romeiro Filho, "Portland cement: an application of life cycle assessment," *Product: Management and Development*, vol. 8, no. 2, pp. 167-172, 2010.

[357] M. L. Mittal, C. Sharma, and R. Singh, "Decadal emission estimates of carbon dioxide, sulfur dioxide, and nitric oxide emissions from coal burning in electric power generation plants in India," *Environmental monitoring and assessment*, vol. 186, no. 10, pp. 6857-6866, 2014.

[358] D. Song, J. Yang, B. Chen, T. Hayat, and A. Alsaedi, "Life-cycle environmental impact analysis of a typical cement production chain," *Applied Energy*, vol. 164, pp. 916-923, 2016.

[359] O. E. Ige, K. J. Duffy, O. A. Olanrewaju, and O. C. Collins, "An Integrated System Dynamics Model and Life Cycle Assessment for Cement Production in South Africa," *Atmosphere*, vol. 13, no. 11, p. 1788, 2022. [Online]. Available: https://www.mdpi.com/2073-4433/13/11/1788.

[360] WBCSD, "Cement technology roadmap shows how the path to achieve CO2 reductions up to 24% by 2050," World Business Council for Sustainable Development (WBCSD), Paris and Geneva, 2018. Accessed: 23 June 2022. [Online]. Available: https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/News/Cement-technology-roadmap-shows-how-the-path-to-achieve-CO2-reductions-up-to-24-by-2050

[361] R. Maddalena, J. J. Roberts, and A. Hamilton, "Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements," *Journal of cleaner production*, vol. 186, pp. 933-942, 2018.

[362] SouthAfricaGHGinventory, " Draft 7th National GHG Inventory Report South Africa 2000 - 2017," in " " Department of environment, forestry and fisheries, Pretoria, 2020. Accessed: March 2022. [Online]. Available: https://cer.org.za/wp-content/uploads/2020/09/Draft-7th-National-Greenhouse-Gas-Inventory-Report-for-the-Republic-of-South-Africa-for-public-comment.pdf

[363] OEC, "South Africa Cement Import and Export ", 2020. Accessed: 17 June 2022. [Online]. Available: https://oec.world/en/profile/bilateral-product/cement/reporter/zaf#:~:text=The%20fastest%20growing%20export%20markets,of%20Cement%20in%20the%20world.

[364] R. Muigai, M. G. Alexander, and P. Moyo, "Cradle-to-gate environmental impacts of the concrete industry in South Africa," *Journal of the South African Institution of Civil*

Engineering, vol. 55, pp. 02-07, 2013. [Online]. Available: http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-20192013000200001&nrm=iso.

[365] S. A. Abdul-Wahab, G. A. Al-Rawas, S. Ali, and H. Al-Dhamri, "Assessment of greenhouse CO2 emissions associated with the cement manufacturing process," *Environmental Forensics*, vol. 17, no. 4, pp. 338-354, 2016/10/01 2016, doi: 10.1080/15275922.2016.1177752.

[366] Cembureau, "The role of cement in the 2050 low carbon economy," ed: The European Cement Association Brussels, Belgium, 2013.

[367] IEA, "CO2 emissions from fuel combustion: Overview," *Paris: IEA Publications*, 2017.

[368] B. J. Mathew, M. Sudhakar, and C. Natarajan, "Strength, economic and sustainability characteristics of coal ash–GGBS based geopolymer concrete," *International Journal of Computational Engineering Research*, vol. 3, no. 1, pp. 207-212, 2013.

[369] J. David, M. Flower, and J. G. Sanjayan, "Green house gas emissions due to concrete manufacture," *The International Journal of Life Cycle Assessment*, vol. 12, no. 5, p. 282, 2007.

[370] E. Worrell, K. Kermeli, and C. Galitsky, "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making an ENERGY STAR® Guide for Energy and Plant Managers," ed: EPA-United States Environmental Protection Agency, 2013.

[371] C. A. Hendriks, E. Worrell, D. De Jager, K. Blok, and P. Riemer, "Emission reduction of greenhouse gases from the cement industry," in *Proceedings of the fourth international conference on greenhouse gas control technologies*, 1998: IEA GHG R&D Programme Interlaken, Austria, pp. 939-944.

[372] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry," 2016.

[373] D. Brown, R. Sadiq, and K. Hewage, "An overview of air emission intensities and environmental performance of grey cement manufacturing in Canada," *Clean Technologies and Environmental Policy*, vol. 16, no. 6, pp. 1119-1131, 2014.

[374] J. Liu, S. Zhang, and F. Wagner, "Exploring the driving forces of energy consumption and environmental pollution in China's cement industry at the provincial level," *Journal of Cleaner Production*, vol. 184, pp. 274-285, 2018.

[375] M. P. Chinyama, "Alternative fuels in cement manufacturing," *Alternative fuel*, pp. 263-284, 2011. [Online]. Available: https://www.intechopen.com/chapters/17593.

[376] A. Rahman, M. Rasul, M. M. K. Khan, and S. Sharma, "Recent development on the uses of alternative fuels in cement manufacturing process," *Fuel*, vol. 145, pp. 84-99, 2015.

[377] W. W. Fund, "Cement sector: Life Cycle Optimisation Service," in "Emerging climate-smart business opportunities," World Wide Fund for Nature South Africa,

Johannesburg, South Africa, 2018. Accessed: 1 October 2022. [Online]. Available: https://wwfafrica.awsassets.panda.org/downloads/wwf_2018_cement_sector_life_cycle_optimisation_service.pdf?25461/Cement-Sector-Life-Cycle-Optimisation-Service

[378] A. Ali, A. Negm, M. Bady, and M. Ibrahim, "Effect of Fuel Type on the life cycle of Egyptian cement industry: environmental impact assessment approach," in *The Asian Conference on Sustainability, Energy & the Environment*, 2014, vol. 4.

[379] P. Koelling and M. J. Schwandt, "Health systems: A dynamic system-benefits from system dynamics," in *Proceedings of the Winter Simulation Conference, 2005.*, 2005: IEEE, p. 7 pp.

[380] G. S. Brown and D. P. Campbell, *Principles of servomechanisms: dynamics and synthesis of closed-loop control systems*. J. Wiley, 1948.

[381] R. H. Macmillan, *An introduction to the theory of control in mechanical engineering* (Cambridge University Press). Cambridge University Press, 2016.

[382] R. G. Schaefer, *Introduction to servomechanisms* (University of Wyoming

). University of Wyoming, 1950.

[383] X. Dong, C. Li, J. Li, W. Huang, J. Wang, and R. Liao, "Application of a system dynamics approach for assessment of the impact of regulations on cleaner production in the electroplating industry in China," *Journal of Cleaner Production*, vol. 20, no. 1, pp. 72-81, 2012.

[384] E. Gartner and H. Hirao, "A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete," *Cement and Concrete research*, vol. 78, pp. 126-142, 2015.

[385] K. L. Scrivener, "Options for the future of cement," *Indian Concr. J*, vol. 88, no. 7, pp. 11-21, 2014.

[386] Y. C. Díaz *et al.*, "Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies," *Development Engineering*, vol. 2, pp. 82-91, 2017.

[387] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete," *Construction and building materials*, vol. 43, pp. 125-130, 2013.

[388] J. Shekhovtsova, "Using South African fly ash as a component of alkali-activated binder," 2015.

[389] DEA, "South Africa’s Greenhouse Gas (GHG) Mitigation Potential Analysis," Department of Environmental Affairs Pretoria, South Africa, 2014. Accessed: October 01 2022. [Online]. Available: https://www.dffe.gov.za/sites/default/files/docs/appendixA_approachandmethodology.pdf

[390] D. Song and B. Chen, "A life cycle modeling framework for greenhouse gas emissions of cement industry," *Energy Procedia*, vol. 61, pp. 2649-2653, 2014.

[391] N. Ansari and A. Seifi, "A system dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry," *Energy*, vol. 43, no. 1, pp. 334-343, 2012/07/01/ 2012, doi: https://doi.org/10.1016/j.energy.2012.04.020.

[392] L. Pan, P. Liu, and Z. Li, "A system dynamic analysis of China's oil supply chain: Over-capacity and energy security issues," *Applied Energy*, vol. 188, pp. 508-520, 2017/02/15/ 2017, doi: https://doi.org/10.1016/j.apenergy.2016.12.036.

[393] Y. Y. Feng, S. Q. Chen, and L. X. Zhang, "System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China," *Ecological Modelling*, vol. 252, pp. 44-52, 2013/03/10/ 2013, doi: https://doi.org/10.1016/j.ecolmodel.2012.09.008.

[394] S. Gu, B. Fu, T. Thriveni, T. Fujita, and J. W. Ahn, "Coupled LMDI and system dynamics model for estimating urban CO2 emission mitigation potential in Shanghai, China," *Journal of Cleaner Production*, vol. 240, p. 118034, 2019.

[395] N. C. Onat, G. Egilmez, and O. Tatari, "Towards greening the U.S. residential building stock: A system dynamics approach," *Building and Environment*, vol. 78, pp. 68-80, 2014/08/01/ 2014, doi: https://doi.org/10.1016/j.buildenv.2014.03.030.

[396] L. Proaño, A. T. Sarmiento, M. Figueredo, and M. Cobo, "Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: A system dynamics approach," *Journal of Cleaner Production*, vol. 263, 2020, doi: 10.1016/j.jclepro.2020.121457.

[397] A. K. Saysel and M. Hekimoğlu, "Exploring the options for carbon dioxide mitigation in Turkish electric power industry: System dynamics approach," *Energy Policy*, vol. 60, pp. 675-686, 2013.

[398] A. Robalino-López, A. Mena-Nieto, and J. E. García-Ramos, "System dynamics modeling for renewable energy and CO2 emissions: A case study of Ecuador," *Energy for Sustainable Development*, vol. 20, pp. 11-20, 2014.

[399] W. Sun, J. Wang, and Y. Ren, "Research on CO2 emissions from China's electric power industry based on system dynamics model," *International Journal of Industrial and Systems Engineering*, vol. 22, no. 4, pp. 423-439, 2016.

[400] A. Procter *et al.*, "The effectiveness of Light Rail transit in achieving regional CO 2 emissions targets is linked to building energy use: insights from system dynamics modeling," *Clean Technologies and Environmental Policy*, vol. 19, no. 5, pp. 1459-1474, 2017.

[401] J. Han and Y. Hayashi, "A system dynamics model of CO2 mitigation in China's inter-city passenger transport," *Transportation Research Part D: Transport and Environment*, vol. 13, no. 5, pp. 298-305, 2008.

[402] J. Han, K. Bhandari, and Y. Hayashi, "Evaluating Policies for CO2 Mitigation in India's Passenger Transport," *International Journal of Urban Sciences*, vol. 12, no. 1, pp. 28-39, 2008/06/01 2008, doi: 10.1080/12265934.2008.9693625.

[403] A. Barisa and M. Rosa, "A system dynamics model for CO2 emission mitigation policy design in road transport sector," *Energy Procedia,* vol. 147, pp. 419-427, 2018.

[404] K.-S. Kim, Y.-J. Cho, and S.-J. Jeong, "Simulation of CO2 emission reduction potential of the iron and steel industry using a system dynamics model," *International journal of precision engineering and manufacturing,* vol. 15, no. 2, pp. 361-373, 2014.

[405] L. Wen, L. Bai, and E. Zhang, "System dynamic modeling and scenario simulation on Beijing industrial carbon emissions," *Environmental Engineering Research,* vol. 21, no. 4, pp. 355-364, 2016.

[406] W.-K. Fong, H. Matsumoto, and Y.-F. Lun, "Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities," *Building and Environment*, vol. 44, no. 7, pp. 1528-1537, 2009/07/01/ 2009, doi: https://doi.org/10.1016/j.buildenv.2008.07.010.

[407] J. Vargas and A. Halog, "Effective carbon emission reductions from using upgraded fly ash in the cement industry," *Journal of Cleaner Production,* vol. 103, pp. 948-959, 2015.

[408] Z. Jokar and A. Mokhtar, "Policy making in the cement industry for CO2 mitigation on the pathway of sustainable development- A system dynamics approach," *Journal of Cleaner Production,* vol. 201, pp. 142-155, 2018/11/10/ 2018, doi: https://doi.org/10.1016/j.jclepro.2018.07.286.

[409] S. McAvoy, T. Grant, C. Smith, and P. Bontinck, "Combining Life Cycle Assessment and System Dynamics to improve impact assessment: A systematic review," *Journal of Cleaner Production,* vol. 315, p. 128060, 2021/09/15/ 2021, doi: https://doi.org/10.1016/j.jclepro.2021.128060.

[410] P. Karka, S. Papadokonstantakis, and A. Kokossis, "Predictive LCA-a systems approach to integrate LCA decisions ahead of design," in *Computer Aided Chemical Engineering*, vol. 46: Elsevier, 2019, pp. 97-102.

[411] N. C. Onat, M. Kucukvar, O. Tatari, and G. Egilmez, "Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles," *The International Journal of Life Cycle Assessment,* vol. 21, no. 7, pp. 1009-1034, 2016.

[412] E. Jin and J. W. Sutherland, "An integrated sustainability model for a bioenergy system: Forest residues for electricity generation," *Biomass and Bioenergy,* vol. 119, pp. 10-21, 2018.

[413] F. Menten, S. Tchung-Ming, D. Lorne, and F. Bouvart, "Lessons from the use of a long-term energy model for consequential life cycle assessment: the BTL case," *Renewable and Sustainable Energy Reviews,* vol. 43, pp. 942-960, 2015.

[414] D. Arbault, M. Rivière, B. Rugani, E. Benetto, and L. Tiruta-Barna, "Integrated earth system dynamic modeling for life cycle impact assessment of ecosystem services," *Science of the total environment,* vol. 472, pp. 262-272, 2014.

[415] P. Stasinopoulos, P. Compston, B. Newell, and H. M. Jones, "A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites," *The international journal of life cycle assessment,* vol. 17, no. 2, pp. 199-207, 2012.

[416] R. Laurenti, D. Lazarevic, S. Poulikidou, V. Montrucchio, L. Bistagnino, and B. Frostell, "Group Model-Building to identify potential sources of environmental impacts outside the scope of LCA studies," *Journal of Cleaner Production,* vol. 72, pp. 96-109, 2014.

[417] J. Sim and V. Prabhu, "The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States," *Journal of Cleaner Production,* vol. 170, pp. 1231-1243, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.jclepro.2017.09.203.

[418] J. T. Pinto and A. Diemer, "Supply chain integration strategies and circularity in the European steel industry," *Resources, Conservation and Recycling,* vol. 153, p. 104517, 2020.

[419] A. Thomas, C. C. Menassa, and V. R. Kamat, "System dynamics framework to study the effect of material performance on a building's lifecycle energy requirements," *Journal of Computing in Civil Engineering,* vol. 30, no. 6, p. 04016034, 2016.

[420] T. S. Bixler, J. Houle, T. Ballestero, and W. Mo, "A dynamic life cycle assessment of green infrastructures," *Science of The Total Environment,* vol. 692, pp. 1146-1154, 2019/11/20/ 2019, doi: https://doi.org/10.1016/j.scitotenv.2019.07.345.

[421] I. El Gafy, N. Grigg, and W. Reagan, "Dynamic behaviour of the water–food–energy Nexus: focus on crop production and consumption," *Irrigation and Drainage,* vol. 66, no. 1, pp. 19-33, 2017.

[422] Y. Zhai *et al.*, "Grain self-sufficiency versus environmental stress: An integration of system dynamics and life cycle assessment," *Renewable and Sustainable Energy Reviews,* vol. 159, p. 112153, 2022/05/01/ 2022, doi: https://doi.org/10.1016/j.rser.2022.112153.

[423] T. Ekvall, G. Assefa, A. Björklund, O. Eriksson, and G. Finnveden, "What life-cycle assessment does and does not do in assessments of waste management," *Waste management,* vol. 27, no. 8, pp. 989-996, 2007.

[424] L. Yao, T. Liu, X. Chen, M. Mahdi, and J. Ni, "An integrated method of life-cycle assessment and system dynamics for waste mobile phone management and recycling in China," *Journal of Cleaner Production,* vol. 187, pp. 852-862, 2018/06/20/ 2018, doi: https://doi.org/10.1016/j.jclepro.2018.03.195.

[425] ISO/TS, "Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006. ISO/TS,14071:2014. ," in "International Organisation for Standardisation," International Organisation for Standardisation Geneva, Switzerland,

2014. Accessed: Feburary 23 2023. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:ts:14071:ed-1:v1:en

[426] E. Moreno Ruiz *et al.*, "Documentation of changes implemented in ecoinvent database v3. 7 & v3. 7.1. ecoinvent Association," *Zürich, Switzerland*, 2020.

[427] R. Frischknecht *et al.*, "The ecoinvent database: Overview and methodological framework (7 pp)," *The international journal of life cycle assessment*, vol. 10, no. 1, pp. 3-9, 2005.

[428] I. S. Arvanitoyannis, "ISO 14040: life cycle assessment (LCA)–principles and guidelines," *Waste management for the food industries*, pp. 97-132, 2008.

[429] D. N. Ford and J. D. Sterman, "Dynamic modeling of product development processes," *System Dynamics Review: The Journal of the System Dynamics Society*, vol. 14, no. 1, pp. 31-68, 1998.

[430] J. Rockström, O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H. J. Schellnhuber, "A roadmap for rapid decarbonization," *Science*, vol. 355, no. 6331, pp. 1269-1271, 2017.

[431] IEA, "Energy Technology Perspectives ", 2014. Accessed: October 1 2022. [Online]. Available: https://www.iea.org/reports/energy-technology-perspectives-2014

[432] K. J. Duffy, O. C. Collins, and T. Simelane, "SYSTEM DYNAMICS MODEL LINKING DEMAND, EMPLOYMENT MOVEMENT BETWEEN SECTORS AND THE ECONOMY FOR THE SOUTH AFRICAN CONSTRUCTION SECTOR," *Theoretical and Empirical Researches in Urban Management*, vol. 17, no. 2, pp. 5-15, 2022.

[433] F. F. Herdicho, W. Chukwu, and H. Tasman, "An optimal control of malaria transmission model with mosquito seasonal factor," *Results in Physics*, vol. 25, p. 104238, 2021.

[434] W. Economics, "South Africa Real Gross Domestic Product," World Economics, 2020. Accessed: 25 August 2020. [Online]. Available: http://dev.worldeconomics.com/GrossDomesticProduct/Real-GDP/South%20Africa.aspx

[435] I. E. Agency, "Cement Technology Roadmap Plots Path to Cutting CO2 Emissions 24% by 2050—News. IEA," in *Iea*, 2018, pp. 1-3.

[436] I. Pricing, *Review of Regulated Retail Tariffs and Charges for Electricity 2010-2013: Electricity-Final Report*. Independent Pricing and Regulatory Tribunal, 2010.

[437] WITS, "South Africa Cement; Portland, Exports " in "The World Bank," World Integrated Trade Solution (WITS), 2017. Accessed: April 01 2022. [Online]. Available: https://wits.worldbank.org/trade/comtrade/en/country/ZAF/year/2017/tradeflow/Exports/partner/ALL/product/252321

[438] WITS, "South Africa Cement; Portland, Import.

," in "The World Bank," World Integrated Trade Solution (WITS). 2017. Accessed: April 01 2022. [Online]. Available: https://wits.worldbank.org/trade/comtrade/en/country/ZAF/year/2017/tradeflow/Imports/partner/ALL/product/252321

[439] E. Erdfelder, M. Castela, M. Michalkiewicz, and D. W. Heck, "The advantages of model fitting compared to model simulation in research on preference construction," (in eng), *Front Psychol*, vol. 6, p. 140, 2015, doi: 10.3389/fpsyg.2015.00140.

[440] M. Taylor, C. Tam, and D. Gielen, "Energy efficiency and CO2 emissions from the global cement industry," *Korea*, vol. 50, no. 2.2, p. 61.7, 2006.

[441] S. S. Berriel *et al.*, "Assessing the environmental and economic potential of Limestone Calcined Clay Cement in Cuba," *Journal of cleaner Production*, vol. 124, pp. 361-369, 2016.

[442] S. A. NT, "Carbon Tax Policy Paper," Republic of South Africa. National Treasury, Pretoria South Africa, 2013. Accessed: October 01 2022. [Online]. Available: http://www.treasury.gov.za/public%20comments/carbon%20tax%20policy%20paper%202013.pdf

[443] S. A. NT, "Draft Carbon Tax Bill," Republic of South Africa National Treasury, Pretoria South Africa, 2015. Accessed: October 01 2022. [Online]. Available: http://www.treasury.gov.za/public%20comments/carbontaxbill2015/carbon%20tax%20bill%20final%20for%20release%20for%20comment.pdf

APPENDIX A

Ecoinvent 3.6 dataset documentation cement production, Portland - ZA

Detailed information for exchanges (Dataset Values)

Reference Product	Annual prod. vol.	Amount	**Detailed information on dataset values**
Cement, Portland	3.48E+9 kg	1Kg	Values were calculated based on primary data collection in South Africa. The data were collected from 5 cement companies representing 90% of the cement market. Annual production capacity of 90% of cement mills in South Africa in 2008. Source: C&CI; (2008). Cement and Concrete Institute South Africa, "Cement and Concrete Review (annual)". Carbon Disclosure Project (2012). Available at: http://www.nbi.org.za/Publications/Fastfacts/Pages/default.aspx **Source:** Concrete Institute 2009
Inputs from Technosphere			
Product	**Amount**		
Cement factory	5.36E-11 unit		Literature Value. Adopted from the "cement production, Portland, GLO 2009" dataset. **Activity link:** market for cement factory - GLO **Source:** Kellenberger D. 2007
Clinker	0.902 kg		Values were calculated based on primary data collection in South Africa. The data were collected from 5 cement companies representing 90% of the cement market. **Activity link:** market for clinker - ZA **Source:** Gary Theodosiou 2010
Electricity, medium voltage	0.0376 kWh		Literature Value. Adopted from the "cement production, Portland, GLO 2009" dataset. **Activity link:** market for electricity, medium voltage - ZA **Source:** Boesch, M.E. 2010

Ethylene glycol	0.00019 kg	Ancillary product for grinding. Adopted from the "cement production, Portland, GLO 2009" dataset. **Activity link:** market for ethylene glycol – GLO **Source:** Kellenberger D. 2007
Gypsum, mineral	0.0475 kg	Values were calculated based on primary data collection in South Africa. The data were collected from 5 cement companies representing 90% of the cement market**.** Value represents demand of products, electricity etc. for input/output group c. **Activity link:** market for gypsum, mineral – ZA **Source:** Gary Theodosiou 2010
Limestone, crushed, for mill	0.05 kg	Values were calculated based on primary data collection in South Africa. The data were collected from 5 cement companies representing 90% of the cement market**.** **Activity link:** market for limestone, crushed, for mill – RoW **Source:** Gary Theodosiou 2010
Steel, low-alloyed	5.25E-05 kg	Literature value:Adopted from the "cement production, Portland, CH 2010" dataset **.** **Activity link:** market for steel, low-alloyed – GLO **Source:** Kellenberger D. 2007
Emissions to air	**Amount**	
Heat, waste	0.135 MJ	Literature value. Adopted from the "cement production, Portland, GLO 2009" dataset. Value represents others emitted to air for input/output group p. **Source:** Boesch, M.E. 2010

Source information

First author: Kellenberger D.
Additional author(s): Althaus H.-J., Jungbluth N., Künniger T.
Title: Life Cycle Inventories of Building Products
Year: 2007
Volume number: 7

First author: Concrete Institute
Title: Cement and Concrete Institute South Africa
Year: 2009

First author: Gary Theodosiou
Title: Cement and Concrete Institute Concrete Industry Greenhouse Gas Emissions
Year: 2010

First author: Boesch, M.E.
Additional author(s): Hellweg, S.
Title: Identifying Improvement Potentials in Cement Production with Life Cycle Assessment
Year: 2010
Journal: Environmental Science & Technology
Volume number: 44
Issue number: 23

First author: Muigai, R.
Additional author(s): Pradhan, A.
Title: Life Cycle Inventories of Cement, Concrete and Related Industries - South Africa
Year: 2017

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Review	Marion Sié, Sié

APPENDIX B

Characterisation results of each production stages at midpoint method

		Atmospheric impacts			
Impact category	Raw material consumption	Clinker production	Electricity usage	Fuel consumption	Fuel consumption
Global warming	8,60E-03	7,58E-01	1,82E-01	2,15E-02	2,00E-02
Ozone depletion	4,36E-09	0,00E+00	1,28E-07	5,77E-08	3,52E-09
Terrestrial ecosystems	1,83E-04	8,98E-04	7,15E-04	1,10E-04	2,06E-04
Human health	1,86E-04	8,92E-04	7,08E-04	1,01E-04	1,98E-04
Particulate matter formation	1,77E-05	1,39E-04	5,17E-04	3,80E-05	3,45E-05
Ionizing radiation	9,25E-03	0,00E+00	2,38E-04	4,70E-04	0,00E+00
		Resource depletion impacts			
	Raw material consumption	Clinker production	Electricity usage	Fuel consumption	Fuel consumption
Terrestrial acidification	1,75E-04	4,12E-04	1,67E-03	9,79E-05	9,06E-05
Freshwater eutrophication	7,09E-06	0,00E+00	0,00E+00	3,09E-04	0,00E+00
Marine eutrophication	6,57E-07	0,00E+00	0,00E+00	1,86E-05	0,00E+00
Mineral resource scarcity	2,16E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Fossil resource scarcity	1,09E-03	0,00E+00	0,00E+00	1,38E-01	0,00E+00
Land use	7,42E+02	0,00E+00	1,67E-05	3,08E-03	2,39E-03
Water consumption	9,77E-04	-3,72E-05	3,27E-04	8,31E-05	4,45E-07
		Toxicity impacts.			
	Raw material consumption	Clinker production	Electricity usage	Fuel consumption	Fuel consumption
Terrestrial ecotoxicity	3,27E-01	7,39E-02	1,06E-01	1,97E-02	1,86E-02
Marine ecotoxicity	8,57E-03	2,48E-05	4,41E-05	1,24E-02	3,49E-04
Freshwater ecotoxicity	6,72E-03	0,00E+00	0,00E+00	8,92E-03	5,42E-05
Human carcinogenic toxicity	1,39E-03	1,06E-04	1,99E-04	2,12E-02	1,02E-05
Human non-carcinogenic toxicity	2,10E+02	6,10E-03	6,10E-03	3,82E-01	6,83E-03

APPENDIX C

Percentage (%) of each production stage contribution at midpoint method

		Atmospheric impacts			
Impact category	Clinkering	Raw Material Usage	Fuel Usage	Transportation	Electricity Usage
Global warming	76	0	3	2	18
Ozone depletion	0	30	2	2	66
Terrestrial ecosystems	43	9	5	10	34
Human health	43	8	5	10	34
Particulate matter formation	18	8	5	4	66
Ionizing radiation	0	93	5	0	2
		Resource depletion impacts			
	Clinkering	Raw Material Usage	Fuel Usage	Transportation	Electricity Usage
Terrestrial acidification	17	7	4	4	68
Freshwater eutrophication	0	2	98	0	0
Marine eutrophication	0	3	97	0	0
Mineral resource scarcity	0	100	0	0	0
Fossil resource scarcity	0	1	99	0	0
Land use	0	29	40	31	0
Water consumption	0	72	4	0	24
		Toxicity impacts.			
	Clinkering	Raw Material Usage	Fuel Usage	Transportation	Electricity Usage
Terrestrial ecotoxicity	7	31	2	49	10
Marine ecotoxicity	0	41	57	2	0
Freshwater ecotoxicity	0	43	57	0	0
Human carcinogenic toxicity	0	5	88	0	6
Human non-carcinogenic toxicity	1	18	78	1	1

APPENDIX D

LCIA results for selected impact categories (Damage Result)

Impact Category	uint	Raw Material	Clinkering	Fuel Usage	Transportation	Electricity Usage
Human health	DALY	2,05E-07	7,93E-07	7,55E-08	4,38E-08	4,97E-07
Ecosystems	species.yr	1,43E-10	2,33E-09	2,67E-10	1,29E-10	9,61E-10
Resources	USD2013	6,24E-04	0,00E+00	1,62E-02	0,00E+00	0,00E+00

Percentage (%) of each production stage contribution at endpoint method

Material Usage	Clinkering	Fuel Usage	Transportation	Electricity Usage
0,8	77,3	2,1	1,9	18,0
0,8	77,3	2,1	1,9	18,0
0,8	77,3	2,1	1,9	18,0
25,7	0,0	5,9	1,7	66,7
97,6	0,0	0,1	0,0	2,4
8,4	42,5	5,0	9,6	34,5
7,4	17,5	4,6	4,6	65,8
8,5	42,4	5,1	9,6	34,3
6,8	16,8	3,8	3,6	68,8
3,5	0,0	96,5	0,0	0,0
3,5	0,0	96,5	0,0	0,0
31,6	7,1	1,8	49,6	10,0
92,6	0,0	7,0	0,4	0,0
39,9	0,1	58,0	1,6	0,2
10,9	0,4	87,0	0,0	1,6
17,0	1,2	78,7	1,8	1,2
29,3	0,0	39,8	30,6	0,2
100,0	0,0	0,0	0,0	0,0
0,9	0,0	99,0	0,0	0,0
60,5	0,4	1,1	0,1	38,0
77,0	2,4	5,8	0,0	14,8
83,5	4,4	10,2	0,0	10,5

APPENDIX E

The input parameter values used for model validation

Years	Cement production (Kg)	Real GDP (USD $)
2000	9 794 000 000	267 001 436 052
2001	9 700 000 000	274 210 460 320
2002	11 218 000 000	284 357 295 800
2003	11 893 000 000	292 743 217 487
2004	11 565 000 000	306 076 361 734
2005	13 519 000 000	322 228 184 699
2006	14 225 000 000	340 285 199 108
2007	14 647 000 000	358 526 105 165
2008	14 252 000 000	369 966 840 760
2009	14 860 000 000	364 276 420 244
2010	13 458 000 000	375 349 442 837
2011	12 373 000 000	387 676 549 661
2012	12 358 000 000	396 257 207 214
2013	13 053 000 000	406 104 993 310
2014	13 099 000 000	413 605 718 439
2015	14 456 000 000	418 543 065 568
2016	15 182 000 000	420 213 420 422
2017	14 622 000 000	426 157 392 310

APPENDIX F

Long-term environmental impact of cement production in South African from 2000-2040

Year	2000	2005	2010	2015	2020	2025	2030	2035	2040
Global warming	9,72E+09	1,34E+10	1,34E+10	1,44E+10	1,79E+10	2,5889E+10	2,9688E+10	2,8538E+10	2,91E+10
Stratospheric ozone depletion	1,90E+03	2,63E+03	2,62E+03	2,81E+03	3,50E+03	5,07E+03	5,82E+03	5,59E+03	5,70E+03
Ionizing radiation	9,77E+07	1,35E+08	1,34E+08	1,44E+08	1,80E+08	2,60E+08	2,98E+08	286648602	2,92E+08
Ozone formation, Human health	2,06E+07	2,84E+07	2,83E+07	3,04E+07	3,78E+07	5,48E+07	6,28E+07	6,04E+07	6,15E+07
Fine particulate matter formation	7,77E+06	1,07E+07	1,07E+07	1,15E+07	1,43E+07	2,07E+07	2,37E+07	2,28E+07	2,32E+07
Ozone formation, Terrestrial ecosystems	2,07E+07	2,86E+07	2,85E+07	3,06E+07	3,81E+07	5,52E+07	6,33E+07	6,08E+07	6,20E+07
Terrestrial acidification	2,39E+07	3,30E+07	3,29E+07	3,53E+07	4,40E+07	6,37E+07	7,30E+07	7,02E+07	7,16E+07
Freshwater eutrophication	3,10E+06	4,28E+06	4,26E+06	4,58E+06	5,70E+06	8,25E+06	9,46E+06	9,10E+06	9,27E+06
Marine eutrophication	1,89E+05	2,62E+05	2,60E+05	2,80E+05	3,48E+05	5,04E+05	5,78E+05	5,56E+05	5,67E+05
Terrestrial ecotoxicity	1,02E+10	1,41E+10	1,40E+10	1,51E+10	1,88E+10	2,72E+10	3,11E+10	2,99E+10	3,05E+10
Freshwater ecotoxicity	1,55E+08	2,13E+08	2,13E+08	2,28E+08	2,84E+08	4,12E+08	4,72E+08	4,54E+08	4,63E+08
Marine ecotoxicity	2,10E+08	2,89E+08	2,88E+08	3,09E+08	3,85E+08	5,58E+08	6,40E+08	6,15E+08	6,27E+08
Human carcinogenic toxicity	2,39E+08	3,30E+08	3,28E+08	3,53E+08	4,39E+08	6,36E+08	7,29E+08	7,01E+08	7,15E+08
Human non-carcinogenic toxicity	4,83E+09	6,67E+09	6,64E+09	7,14E+09	8,89E+09	1,29E+10	1,48E+10	1,42E+10	1,45E+10
Land use	7,67E+07	1,06E+08	1,05E+08	1,13E+08	1,41E+08	2,04E+08	2,34E+08	2,25E+08	2,29E+08
Mineral resource scarcity	2,12E+07	2,92E+07	2,91E+07	3,12E+07	3,89E+07	5,63E+07	6,46E+07	6,21E+07	6,33E+07
Fossil resource scarcity	1,36E+09	1,88E+09	1,87E+09	2,01E+09	2,50E+09	3,62E+09	4,15E+09	3,99E+09	4,07E+09
Water consumption	1,33E+07	1,83E+07	1,82E+07	1,96E+07	2,44E+07	3,53E+07	4,05E+07	3,90E+07	3,97E+07