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

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Abstract: Cement is one of the most produced materials globally. Population growth and urbanization cause an increased demand for the cement needed for expanding infrastructures. As a result of this circumstance, the cement industry must find the optimum compromise between increasing cement production and reducing the negative environmental impact of that production. Since cement production uses a lot of energy, resources and raw materials, it is essential to assess its environmental impact and determine methods for the sector to move forward in sustainable ways. This paper uses an integrated life cycle assessment (LCA) and a system dynamics (SDs) model to predict the long-term environmental impact and future dynamics of cement production in South Africa. 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) were the major gases emitted. Therefore, the LCA concentrated on the impact of these pollutants on 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. The LCA translates its results into input variables into a system dynamics model to predict the long-term environmental impact of cement production in South Africa. From our projections, the pollutant outputs of cement production in South Africa will each approximately double by the year 2040 with the associated long-term impact of an increase in global warming. These results are an important guide for South Africa's future cement production and environmental impact because it is essential that regulations for cement production are maintained to achieve long-term environmental impact goals. The proposed LCA–SD model methodology used here 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, a number of policy changes are suggested for reducing emissions, such as introducing more eco-blended cement productions, carbon budgets and carbon tax.

Keywords: system dynamics; environmental impact; cement production; global warming; South Africa

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

Academic Editor: Andrés Alastuey Urós

Received: 9 September 2022
Accepted: 26 October 2022
Published: 29 October 2022

1. Introduction

In recent decades, as industries have grown, energy consumption and the 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 process that uses a considerable amount of raw materials (limestone), fuels (thermal energy) and electricity, as well as auxiliaries such as water and air [1–4]. 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 [5]. Globally, cement production accounts for 7% of the total industrial energy use, making it the world's third largest energy user [6]. 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 [7,8]. The cement production of GHGs depends on factors including the fuel used, the emission control system, the technology used, a plant's geographic location and the source of electricity [8]. Raw material emission takes place through the limestone chemical composition that releases CO_2 during the thermal process to convert the compound into lime (CaO), the main component of cement. Our need for cement products, their environmental impact and their energy requirements make it essential to search for ways to reduce their 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 is 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, an increase of 49.3% [9]. South Africa's exported cement is worth USD 95.7 million in 2020, making it the world's 35th largest cement exporter and the 111th most exported product in South Africa [10]. South Africa imported USD 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 [10]. 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 [11] and only produce 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 clinker content within the accepted range of chemical composition, as shown in Table 1 [9].

Table 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 80–94%	Group B 65–79%
CEM III	Gypsum + Slag	Group A 35–64%	Group B 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%), Afrisam 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 [12,13]. 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) [14]. 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 [15–19]. In 2019, global cement production exceeded four billion tons due to higher continuous production growth rates in China and India [17], equivalent to four billion tons of CO_2 released into the atmosphere [20]. 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 [21–32]. Likewise, the need for cement in the construction industry, the demand observed in countries such as China and India [33] and the the demographic profile of Africa, composed of 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. Additionally, cement production is the second largest anthropogenic contributor of GHGs [8,34,35], accounting for about 5% of total GHGs on Earth after steel production, which contributes between 4% and 7% [8,36,37]. 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 significantly contributes to air pollution [38,39]. The cement industry's greenhouse gas (GHG) emissions have been investigated and assessed [23,40,41]. 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 [42,43]. 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 its environmental impact. Replacing coal in cement kilns with various waste or waste-derived fuels [44–46] by 5% or 10% would result in a gross GHG emissions reduction of between 2.33 $MtCO_2e$ and 4.67 $MtCO_2e$ across the sector [47]. The carbon footprint of the industry, as well as its carbon tax liability, would be further reduced depending on the alternative fuel used. Additionally, cement is a highly resource-demanding industry concerning raw materials. Cement production is expected to rise further in the coming years due to the 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 such as municipal waste or tyres can reduce the emissions related to fuel use [48]. 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 its long-term environmental impact in the sector. Carbon Capture and Storage (CCS) is still far from commercial, but 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 [49]. 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 [50]. Additionally, 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 [51,52]. However, the results of the 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 [53,54]. While exploring various policy options for future cement production, it is crucial to consider their environmental implications.

The system dynamics (SDs) 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 SDs 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 [55]. Forrester developed the SDs model in the mid-20th century based on the feedback control theory to explain the time-variant behaviour of systems [56–59]. 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 [60]. The SDs method assists qualitative and quantitative problem-solving methods, allowing for the use of written and numerical data in conjunction with mental models to better understand 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. The SDs method can also provide time-step simulations to show significant changes in GHG emission trends. The LCA and SDs models can be integrated either by the LCA into SDs or by SDs into LCA method. Combining LCA and SDs 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 of cement production and the long-term environmental impact of 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. The study results will provide suggestions for improving cement sustainability by integrating the SDs 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 [61–63]. 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 [64]. If clay cement is adopted in the cement industry, a profit of between 8% and 10% is expected by 2025 [64]. Turner and Collins [65] estimate that eco-blends can reduce GHG emissions from 13% to 22%, whereas Ishak and Hashim [66] 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 due to its robust coal and steel industries. A total of 40 million tonnes of ash are produced in South Africa each year [67]. 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 eight 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 [67]. 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 [68].

Reducing the clinker content in cement production by 66% could mitigate 0.75 $MtCO_2e$ per year, with a marginal cost of R122/tCO_2e reduction in 2020 [68]. However, the South African waste management act controls how industrial wastes are disposed of 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 the power plants and even the basins where coal is mined [67].

2. Literature Review

2.1. Cement Life Cycle Assessment

LCA is an important method to determine the environmental impacts of cement production as well as to develop and select possible technologies for its production. The environmental impacts of the cement industry are extensively studied using the LCA [21,53,54,69–71], and such studies are crucial to understanding this industry and finding policies to reduce its impact.

Recently, LCA studies were conducted to determine the environmental impact and the best available technology (BAT) to reduce the impacts of cement production [1]. The life cycles of different types of cement production have been studied [51,52]. Valderrama et al. [1] 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. [72] used the LCA method to assess the environmental impact of the French cement industry. Li et al. [73] 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. [74] assessed the environmental impact of ordinary Portland cement production in Naypyitaw, Myanmar, using the LCA method. Morsali [75] examined the impact of the cement production process on ecosystem quality, resource depletion and human health using LCA methodology and SimaPro v7.1 software, Amersfoort, Netherlands, PRé Consultants. Tun et al. [71] applied the LCA method to assess the environmental impact of Myanmar's cement industry, using the LCA software Recipe 2016 v1.1 (Zürich Switzerland) to identify the hotspots of the environmental impacts.

2.2. System Dynamics Model

The system dynamics model is primarily used to explain a complex system's social and corporate behaviour over time. The SDs method is one of the most powerful methods for simulating the behaviour of such interactive systems. Research on the system dynamics method is currently being conducted at many scales, particularly in the industrial sector [76–78]. Recently, some researchers have attempted to use the SDs model to analyse the drivers and potential for reducing urban carbon emissions [79,80] and industrial carbon emissions [81,82]. At the same time, the complete nature of the SDs 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 in GHGs in various fields, such as the energy sector [77,79,83–85], the transport sector [86–89], the cement sector [90,91] and the steel sector [92,93].

Feng et al. [79] 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. [94] used an SDs 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 the IDR with many options for urban policies. Vargas and Halog [95] investigated the advantages of employing fly ash as an alternate clinker material in cement manufacturing using an SDs method. They simulated five different life cycle situations of cement with a fly ash share of 20% and 35% to assess the net CO_2 reductions. Ansari and Seifi [90] 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. [91] used an SDs model to estimate CO_2 emissions in the Indian cement sector.

Jokar and Mokhtar [96] developed a system dynamics model of the Iranian cement industry using the 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 and 2034. Tang et al. [97] used the SDs 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 [76] developed a simulation model using system dynamics to determine the future emission trends of the cement industry in China. Pan et al. [78] used the SDs model to analyse the Chinese refining industry, emphasizing on energy security to determine the appropriate capacity extent of refining to cope with supply risks.

2.3. Integration of LCA and SDs

There are now studies integrating the LCA and SDs models in the literature [98]. 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 [99]. Some recent studies propose incorporating the following factors into the LCI stage. Onat et al. [100] proposed changes in technical structure due to the behaviour of actors and economic costs; Jin and Sutherland [101] proposed incorporating internal dynamics of the system, including feedback; Menten et al. [102] and Stasinopoulos et al. [98] suggested integrating changes in the dynamics of the system due to market changes in another sector. Regarding the LCIA stage, LCA models based on the SDs method can predict the total impact value due to changes [95]. Additionally, they can predict how environmental impacts will change over time [103]. Recent research has integrated the SDs and LCA methods into various fields, including transportation [100], manufacturing [104–107], construction [108,109], agriculture [110,111] and waste recycling activities [112,113].

Laurenti et al. [105] discussed the advantages of combining LCA, the group model-building (GMB) method 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. [100] 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. [108] 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. [109] used a dynamic LCA model to analyse seven different green infrastructure performances for a 30-year life span. Yao et al. [113] used an integrated LCA and the SDs model to analyse different factors related to mobile phone waste and recycling.

3. Materials and Methods

3.1. Life Cycle Assessment and 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. The LCA can be evaluated in such situations by considering the analogous processes and assuming a combined dataset using a parameterized model developed in a software application such as SimaPro 9.1.1. Amersfoort, Netherlands, PRé Consultants. Additionally, 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 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's environmental impact, as shown in Figure 1. The LCA results are then integrated into an SDs model as input variables to establish their relationship and to perform a more comprehensive analysis. Subsequently, SDs model simulation is performed using the results of the LCA [114] to predict the long-term environmental impact of cement production. Finally, the results recommend a suitable environmental cement plant.

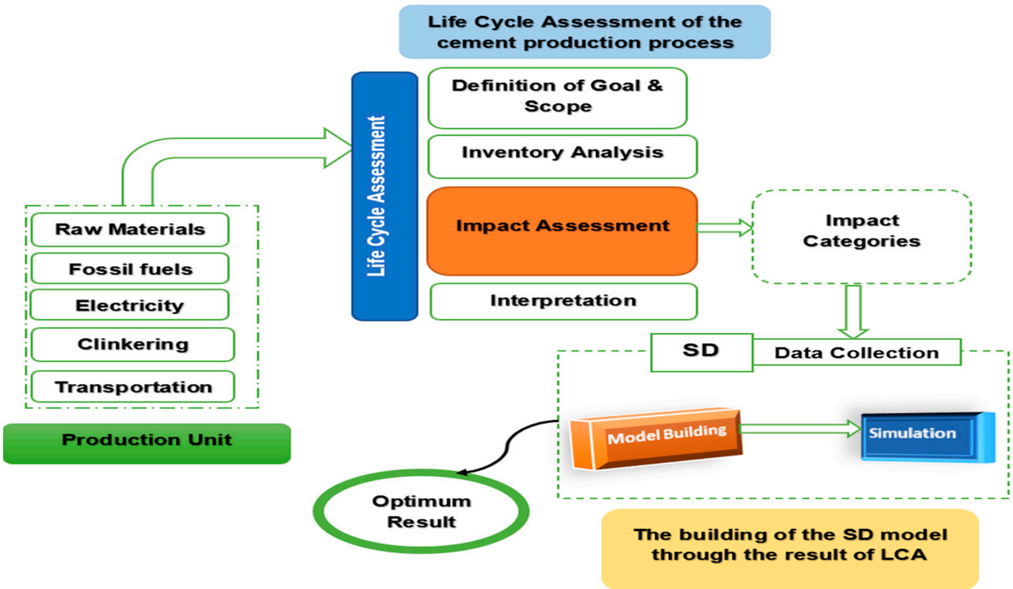

Figure 1. The framework of the integrated LCA and SDs methods for cement production.

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 Organization for Standardization (ISO) has formulated rules for environmental management to establish the principles and guidelines for the LCA methodology [115,116], with ISO/TS 14071 and 14072 [117,118] as the latest version. The LCA method has now been extended to organizational assessments ISO/TS 14071 and ISO/TS 14072 [117], increasing the applications for the approach and increasing its ability to reach high-level decision- and policymakers. Based on ISO standards [115–118], the LCA study contains four stages: goal and scope definition, inventory analysis, impact assessment and interpretation, as shown in Figure 1. The integrated life cycle assessment and system dynamics LCA–SDs 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 SDs to predict the possible future dynamic and long-term environmental impact of cement production in South Africa. An integrated LCA–SDs methodology is used to assess and predict the environmental impacts of the cement industry. Additionally, a hybrid LCA–SD model calculates the interactions between multiple variables and provides a complete understanding of the system.

3.2.1. System Boundary, Goal and Scope Definition

This study used a cradle-to-gate method and the LCA results were obtained 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 a cement product's end-of-life were omitted due to methodological issues. A total of 1 kg 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 boundaries 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.

3.2.2. Life Cycle Inventory

LCI includes the data collection and calculation procedures used to measure the 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 [117,118]. An 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 wherein 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 [119–121].

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 [117,118]. LCIA presents more information to assess the LCI results of a product system to better understand its environmental implication. 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. Additionally, the inventory data are 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) [122]. Classification classifies collected data from the inventory into several impact categories. Characterization aggregates inventory data within impact categories using equivalency factors [122]. 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 identify each impact category to which a substance or process might contribute [123]. 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 [124]. A valuation can be solved in a qualitative or quantitative manner. For qualitative valuations, expert panels may be used. Examples of quantitative valuation methods include comparing environmental loading or impact profiles [122,125]. 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 [125]. The LCIA stage is a multi-step procedure that categorizes all inventory into different impact categories.

3.3. System Dynamics

System dynamics is a computer-aided method to analyse and solve complex problems, focusing on policy analysis and design. The SDs method is used for various applications, but there is no standard way to model it. According to Ford and Sterman [126], in an SDs model, the normal procedure can be summarized in four steps:

I. Identify Problem:

This includes exploring the problem under investigation and clearly explaining the objectives. Moreover, it is necessary to identify the key variables to demonstrate problem behaviour and the simulation possibilities.

II. 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 into qualitative analysis.

III. 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.

IV. 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 its 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 emission 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 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 [127]. In the Energy Technology Perspectives study [128], 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. We used SDs to explain the variables contributing to the cement environmental impact, such as cement production, population growth, GDP, cement import and export, cement demand, etc.

This work aims to use SDs to predict the future dynamics of the cement production process in South Africa and find effective ways to reduce its GHG emissions. 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.

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 [90,91,129]. 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 2).

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

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

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. [130], who assume 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. [131]:

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

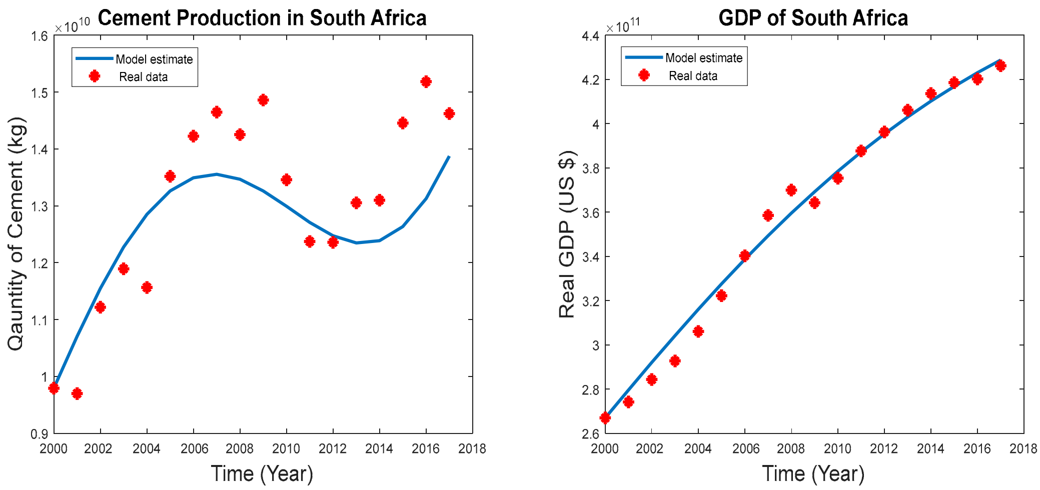

Figure 2. Plot showing the model fitting of cement production in South Africa and real GDP of South Africa from 2000 to 2017.

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 2 and 3 below.

Table 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 3. The parameters.

Parameters	Meaning	Units
α	Parameter linking GDP and CP	(US dollars per 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. Therefore, these scenario predictions help in policy-making decisions and planning. The integrated LCA–SD model presented here enables us to form a picture of the cement's environmental impacts going forward and how to avoid these possible impacts by 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 and thus exploring alternative strategies for reducing the environmental impact (GHG 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.

3.5. 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 [9]. The data on South Africa's real GDP in US dollars were obtained from World Economics [132] and characterization results (impact indicators) at the midpoint of our previous study [114]. It is assumed that cement production is to some extent influenced by real gross domestic product (real GDP).

4. 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 1 kg 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.

4.1. 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 LCA–SD model to predict the long-term environmental impact of cement.

4.2. 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 [133].

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

Figure 2 illustrates the dynamics of cement production in South Africa from 2000 to 2017. The points in Figure 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 (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% (1.2358×10^{10} kg) in 2012. The most notable growth rate was reported between 2005 and 2009, when it increased by 10% over the previous year. The evident decline in cement production between 2009 and 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, such as Sephaku (Dangote cement) and Mamba Cement, a Chinese cement entering the industry.

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 [134]. In South Africa, cement exportation increased dramatically from 6.849×10^6 kg to 2.52486×10^8 kg between 2000 and 2017 [135,136]. 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 [135]. 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 the 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 [136].

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 [132], South Africa's real GDP was valued at USD 430 billion in 2019 and dropped to USD 400 billion at the end of 2020 due to the COVID-19 global pandemic.

4.4. 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 consists of 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 [137]. The model fitting provides information about parameter estimates in terms of errors. The results of a well-fitted model are more accurate. The parameter estimates were derived by fitting the model using the South African cement production data (Department of Environment) [9] and the World Economics Real Gross Domestic Product data for South Africa [132] from 2000 to 2017. The model was used to fit the cement production and real GDP in USD from 2000 to 2017. The lines in Figure 2 represent fits to that data using the SDs 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.

4.5. Future Prediction of Cement Production in South Africa

Throughout this simulation, the SDs 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 [9]. First, the parameters were calibrated and double-checked so that the simulation matched the real-world situation from 2000 to 2017.

Second, based on the simulation, this work predicted the future of cement production in the South African cement industry from 2018 to 2040 (Figure 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 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.

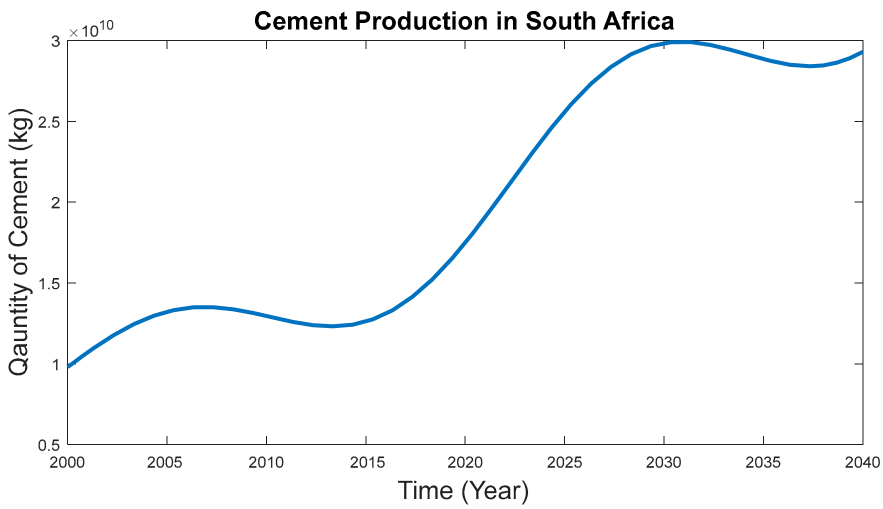

Figure 3. Plot showing a possible future dynamic of cement production in South Africa.

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 the population growth, economic growth, urbanization and the emergence of a middle class in the country. Thus, the increasing demand for cement will continue until 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 [25,90,95,133,138]. If the current cement production rate is maintained and the current mitigation measures are used, a significant 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.

4.6. 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.

4.6.1. Analysis of Midpoint Approach of Five Production Stages

The five production processes, namely (1) clinkering (calcinations and fuel-burning); (2) raw material usage; (3) fuel usage; (4) transportation and (5) electricity usage, were assessed according to atmospheric impact, 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.

4.6.2. Long-Term Environmental Impact of Cement Production in South Africa

From Table 4, it was discovered that the production of 1 kg of Portland cement releases 9.93×10^{-1} kg 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 9.93×10^{-1} by the total quantity of cement produced in South Africa. A similar analysis can be conducted for other impact categories. The results of these analyses are presented in Figures 4–7. As cement production increases, the impact categories increase; model simulations show that these increases are nonlinear with increasing growth levels.

Table 4. The characterization midpoint method based on 1 kg 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 $PM_{2.5}$ 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}

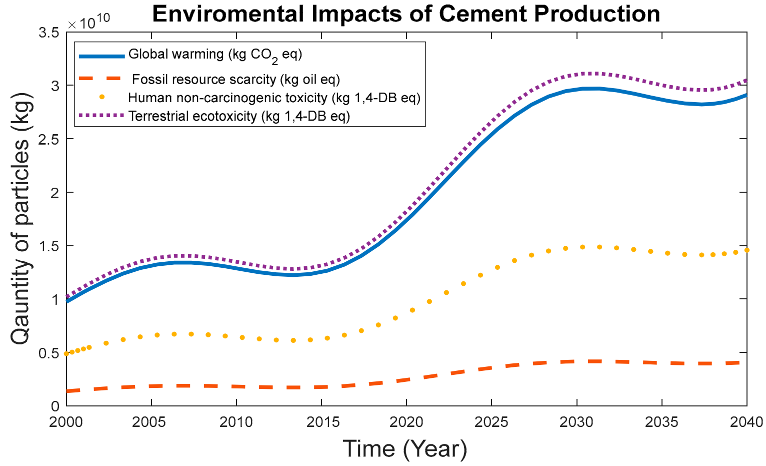

Figure 4. Plot showing a possible long-term environmental impact of cement production in South Africa. Global warming, measured in kg CO_2 eq, terrestrial ecotoxicity measured in kg 1,4-DB eq, fossil resource scarcity measured in kg oil eq and human non-carcinogenic toxicity measured in kg 1,4-DB eq.

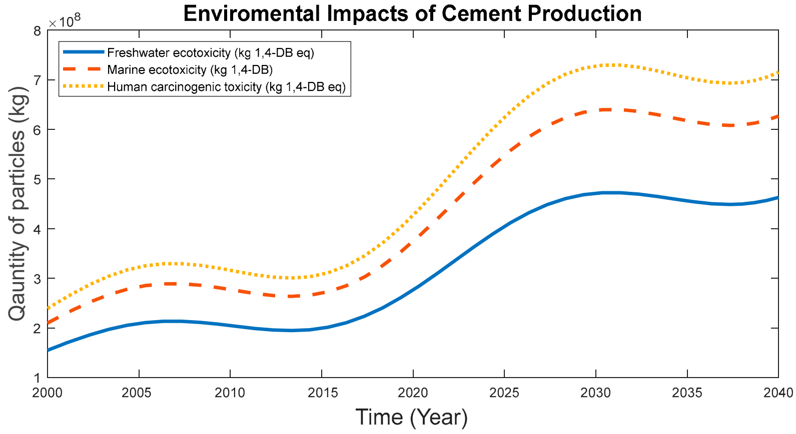

Figure 5. Plot showing a possible long-term environmental impact of cement production in South Africa. Freshwater ecotoxicity measured in kg 1,4-DB eq, marine ecotoxicity measured in kg 1,4-DB eq and human carcinogenic toxicity measured in kg 1,4-DB eq.

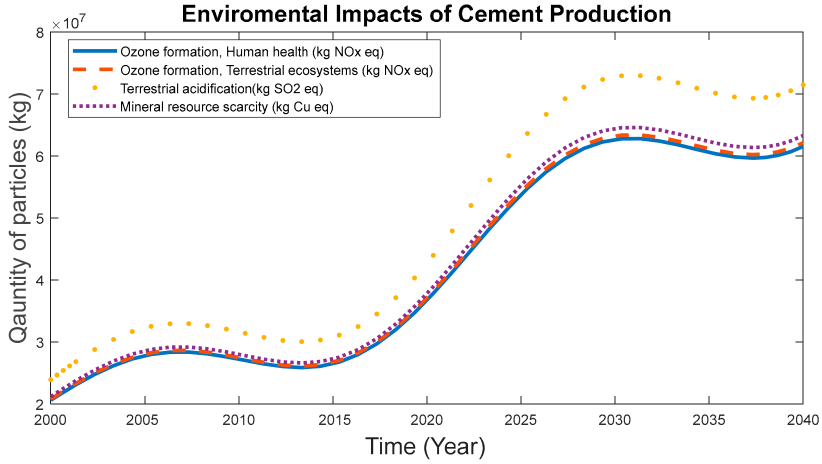

Figure 6. Plot showing a possible long-term environmental impact of cement production in South Africa. Ozone formation, human health measured in kg NOx eq, ozone formation, terrestrial ecosystems measured in kg NOx eq, terrestrial acidification measured in kg SO2 eq and mineral resource scarcity measured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

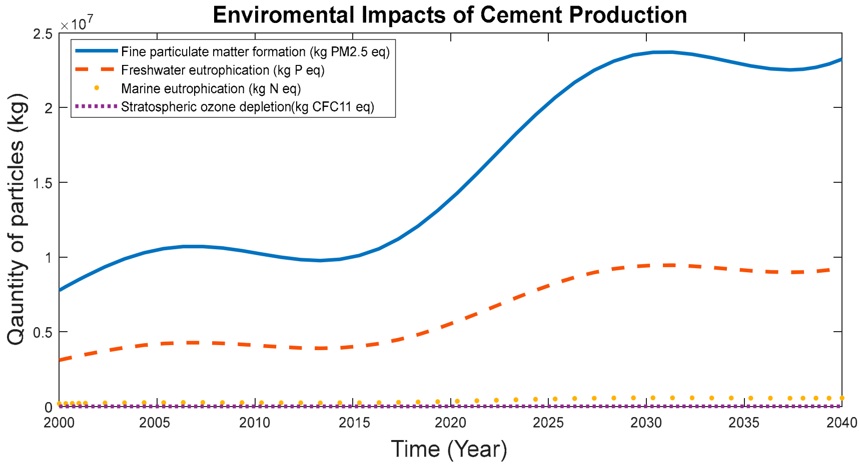

Figure 7. Plot showing a possible long-term environmental impact of cement production in South Africa. Fine particulate matter formation measured in kg $PM_{2.5}$ eq, freshwater eutrophication measured in kg P eq, marine eutrophication measured in kg N eq and stratospheric ozone depletion measured in kg CFC11 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 caused by cement production. The cement industry contributes about 1% of the 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 4. The GWP is nonlinear, as shown in Figure 4, and will slightly increase by 0.75% between 2009 and 2012, then show a consistent increase from 2013 to 2029. The result shows that by the year 2029, the GWP will correspond to emissions of 2.96×10^{10} kg CO_2 eq for cement produced in South Africa. The dynamic of the GWP is also increasing until 2040. Subsequently, the result shows 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 compositions and other fuel consumptions in the kiln.

The impact of fossil resource scarcity and human non-carcinogenic toxicity on the environment will be of 4.07×10^9 kg 1,4-DB eq and 1.46×10^{10} kg oil 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 the cement's clinker content determines their total value. The primary source of SO_2 is coal-based sulphur oxidation in the pre-calciner 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.

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 clearly shows that by 2040, total human health and terrestrial ecosystem impact will have increased by 239% and 243%, respectively. The value of these impacts is due to fuel and raw materials for energy production (electricity and fuel refining).

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 $PM_{2.5}$ eq in 2000 to 2.32×10^7 kg $PM_{2.5}$ eq in 2040 as shown in Figure 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. Additionally, 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 (SCMs)—switching to cement with lower clinker content, i.e., using composite cement with fly ash from coal or blast furnace slag;

Increase the use of alternative fuels such as bio-based, low-carbon or waste fuels that reduce CO_2 emissions;

Implementing energy-efficiency improvements, i.e., improving equipment and shutting down inefficient plants.

Substituting cement with SCMs reduces the environmental impact of cement production [139,140]. However, it must be taken into consideration 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.

Second, the cement industry must significantly increase its research and development (R&D) fund at a much greater level than it does currently to reduce its 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 SiO_2, nano $Fe2O_3$, nano $CaCO_3$, nano $Al2O_3$, nano $Zr2O_3$ and nano-graphene (CNTs and CNFs), which are 10,000 times smaller than a cement particle, has the potential to reduce cement's environmental impact.

The 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.

5. 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 impacts 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 [114] was integrated with a system dynamics model to predict the future long-term environmental impacts of cement production. This study used the SimaPro 9.1.1 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 the 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 dynamics 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 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 4–7 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 $PM_{2.5}$ eq in 2000 to 2.32×10^7 kg $PM_{2.5}$ 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. Figures 4–7 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 impacts and CO_2 emission reductions in the cement industries. All the environmental impacts shown in Figures 4–7 present an increase in effects by the end of 2040. Cement production growth is connected to 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 by 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 which are one of the major GHG emissions.

As shown in Figure 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 the rapid and cost-effective adoption of the best available technologies (BATs) 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 of 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 which can reduce transportation impact. Changing the electricity mix by converting fossil fuels (primary energy sources) into 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. Adopting cutting-edge technologies such as CCS and alternative types of binders such as geopolymers and clay cement will help to reduce cement greenhouse gas emissions. However, geopolymer cement is of less use since it 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 are also 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, which are proposed policies based on our projection to reduce the long-term environmental impacts of cement. The carbon budgets and carbon tax policies currently proposed by the Department of Environmental Affairs (DEAs) [68] and the National Treasury [141,142] 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 for the high substitution of clinker, which reduces emissions, but South African regulations limit clinker substitution to 35%. In order to increase the substitution level of clinker to reduce cement's 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 the requirements for improved cement production systems in South Africa to reduce harmful pollutant emissions.

Author Contributions: Methodology, K.J.D. and O.E.I.; software, O.E.I., K.J.D. and O.C.C.; validation, O.E.I., K.J.D. and O.C.C.; writing—original draft preparation, O.E.I.; writing—review and editing O.A.O., K.J.D. and O.C.C.; supervision, O.A.O., K.J.D. and O.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The National Research Foundation of South Africa (Grant Number 131604).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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