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Research Article

The Lukala Cement Plant's Life Cycle Analysis: Towards a More Sustainable Production

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Abstract

This paper presents an in-depth Life Cycle Assessment (LCA) of the Lukala Cement Plant, highlighting the environmental impacts associated with cement production. The cement industry, as one of the largest emitters of CO_2, raises major sustainability concerns, particularly due to the deleterious effects on climate and public health. The objectives of this research include not only assessing greenhouse gas emissions but also identifying concrete methods to reduce these impacts. The study reveals that the Lukala Cement Plant emits approximately 579,130 tons of CO_2 per year, mainly from the decarbonation of limestone (67%) and the clinkerization process (33%). These figures far exceed regulatory thresholds, highlighting the urgency of rapid and effective intervention to mitigate these emissions. The LCA identified the most polluting production steps, including extraction, grinding, and clinkerization, paving the way for targeted and strategic improvements. Opportunities for optimization were identified, including the use of less pure limestone, the integration of recycled materials, and the transition to renewable energy sources for the clinkerization process. This research is crucial in the current context of the fight against climate change. As a major contributor to greenhouse gas emissions, the cement industry must imperatively adopt sustainable practices. LCA provides a robust methodology to quantify environmental impacts and identify appropriate solutions. The results of this study can be applied to other cement plants around the world, serving as a model for other carbon-intensive industries. Future research should explore the integration of innovative technologies, such as carbon capture and storage, and the use of alternative materials in cement production. This study highlights the importance of immediate and coordinated action to transform the cement industry into a sustainable sector, ensuring economic profitability while protecting the environment for future generations. Commitment to environmentally responsible production practices is not only desirable but also essential to ensuring a sustainable future.

Introduction

The cement industry is one of the largest consumers of natural resources and a major contributor to greenhouse gas emissions. According to recent statistics, this industry accounts for approximately 8% of global carbon dioxide (CO_2) emissions [1,2]. Each year, more than 4 billion tons of cement are produced worldwide, and the firing of limestone to produce clinker generates a significant amount of CO2, thus exacerbating climate change [1-4]. Faced with this environmental challenge, it is imperative to develop methods to reduce the environmental impact of this industry.

The objective of this study is to explore the environmental impacts of the Lukala cement plant emissions and to answer the following question: do the cement plant emissions have significant effects on the environment? To do this, we assume that the life cycle assessment (LCA) of cement production will highlight the main sources of emissions and identify opportunities for improvement.

LCA is a method that assesses the environmental impacts of a product throughout its life cycle, from the extraction of raw materials to the end of the product's life. By applying this approach to the Lukala cement plant, we can better understand the environmental impacts associated with each production stage. The challenge is to produce sustainable and economically competitive cement while minimizing its environmental impact. To achieve this, it is essential to optimize production by integrating LCA [2,5-11].

This work aims to examine these issues using OpenLCA software, which quantifies the environmental impacts at each production phase [1,2,5-7,8,12,13]. LCA includes several key steps:

- **Flow inventory:** Census of incoming materials and energy, as well as emissions and waste generated;
- **Impact assessment:** analysis of greenhouse gas emissions and pollutants;
- **Modeling:** Use of OpenLCA to model flows and impacts, facilitating decisions towards sustainable practices.

We hope that the application of LCA to the Lukala cement plant will identify significant opportunities to reduce CO_2 emissions and improve the sustainability of production while maintaining the profitability of the company.

Materials and methods

Materials used

The materials used for this work include data from the study as well as the OpenLCA software connected to the free ELCD 3.2 greendeltaV2.18 database, which was used to represent the results of this study. Based on the inventory of flows previously carried out, we reproduced this inventory in the software, followed by modeling [1,2,5].

According to ISO 14040, life cycle assessment is a technique for assessing environmental aspects and potential impacts associated with a product system [1-3,5-7].

Study data: The cement industry causes a lot of environmental damage by emitting more CO_2, mainly from the chemical process of transforming $CaCO_3$:

- The decarbonation of limestone, which produces CO_2 ($CaCO_3 \rightarrow CaO + CO_2$), a reaction producing on average 60% of CO_2 emissions [2,3,5-7];
- The combustion of fossil fuels can reach temperatures of up to 2000 °C. It represents more than 20% of CO_2 emissions [1-3,5-8];
- The electricity supply represents more than 10% of CO_2 emissions [1-3,5-7]. The data that we will present in this section are obtained from the work that was carried out at the Lukala cement plant [1,2,5,6,12].

The maximum amount of information likely to shed light and provide information on our system is collected in the data for the year 2019. This last year was chosen as the reference year for this work. To properly implement the input-output approach, the following assumptions were made:

- Clinker production is done 24 hours a day, 7 days a week;
- At the level of extraction and transport of raw materials, the quantity of fuel consumed depends on the size of the dumpers, their loading, as well as the type of roads they use. Based on an average of about 30 or 40 liters for a distance of 100 km and with a load of 25 tons [1,2,5-7,10];

At the level of estimation of GHG emitted by cement kiln dust, we assume a default factor of $FE_{PFC} = 0{,}04 T_{CO_2}/T_{KK}$ in order to estimate the emissions from the dust sources released considering that there are no available data [1,2,5-7];

The approach used in this present study is from cradle to gate, referring to the emissions from the extraction of raw materials to the finished product at the exit of the plant [1-3,5-8].

The qualitative and quantitative balance of the different input flows, in particular raw materials (limestone and clay), fuels, and energy (mainly fossil), in the cement production circuit is presented here. In this work, limestone and clay are considered the basic raw materials entering into the composition of Portland cement, as illustrated in Tables 1 and 2.

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Table 1: Consumption rate of raw materials.

Raw materials	Flow rate [tonnes/hour]	Flow rate [tonnes/year]	Rate/clinker [%]
Limestone	350 [11]	3066000	76-80 [4]
Clay	28,19 [11]	246944,4	16-17 [4]
Coal mass	9,5 [11]	83220	-
PCI	5900 Kcal/kg [11]	-	-

Note that PCI denotes the lower calorific value.

Table 2: Composition of raw materials [20,21].

Raw materials (composition)	
$CaCO_3$	76%
$MgCO_3$	1,6%
AL_2O_3	3,4%
H_2O	0,6%
SiO_3	12,8%
Fe_2O_3	1,8%
SO_3	0,76%
Na_2SO_4	0,76%
Fe_2S	0,76%
$CaSO_4$	0,76%
K_2SO_4	0,76%

Regarding energy, this study only considered the fossil fuels required for the extraction, transportation, and manufacturing phases of the product, as shown in Table 3.

The qualitative and quantitative balance of outgoing flows, emissions, and potential impacts of the Portland cement production process is calculated from extraction, through the transport phase, to the manufacture of finished and semi-finished products, as illustrated in Table 4.

In cement plants, we observe considerable air pollution due to dust emissions at almost all levels of the production line:

- At the quarry, dust comes from mining, loading, and dumping into the crusher, as well as during conveyor belt transport to the storage hall [1-8];
- At the raw grinding workshop, it frequently occurs at the conveyor belts, the crusher dryer, the ball mill, and during discharge into the homogenization silos [1-8];
- At the firing workshop, the clinkerization operation is accompanied by dust and combustion gas emissions [1-8];
- At the cement workshop, this occurs during dumping into the silo and during bagging (bagging).

Regarding air pollution by dust emissions, mention should be made of emissions during the filling of bags and loading of trucks with bulk or bagged cement.

Methods

Methods used to assess the environmental impacts of cement production at the Lukala cement plant. We will use both mathematical and graphical approaches.

Table 3: Energy rates required for the three phases.

Fossil fuels				
Extraction (quarry)		Transport (quarry-factory)		Manufacturing (factory)
Limestone	Clay	Limestone (d = 950 m)[16]	Clay (d = 400 m) [16]	Clinker
560 liters/day	45,104 liters/day	0,38 liters	0,16 liters	9.5 tonnes/hour [11]

Table 4: Daily and annual production rates of raw flour, clinker, and cement of CILU [11].

Raw flour	Clinker (semi-finished product)	Cement production (finished product)
2880 tonnes/day	1815.264 tonnes/days	2880 tonnes/day
1051200 tonnes/year	662571.36 tonnes/year	1051200 tonnes/year

In the case of the Lukala Cement Plant, we used OpenLCA software to perform the LCA as follows:

- **Data collection:** Using 2019 production data to establish an inventory of material and energy flows;
- **Modeling:** Creating a model in OpenLCA to represent the production processes, from raw material extraction to cement production;
- **Impact analysis:** Applying impact assessment methods to quantify environmental impacts, including CO_2 emissions and other pollutants;
- **Recommendations:** Identifying opportunities for improvement, such as integrating recycled materials and optimizing combustion and clinkerization processes.

This LCA methodology provides a comprehensive view of the environmental impacts of the Lukala Cement Plant and contributes to more sustainable production practices [2,5-8].

Mathematical modeling

Mathematical modeling allows us to quantify greenhouse gas emissions generated during cement production. The steps required for our study are as follows:

- **Production Inventory:** Census of materials and energies used in the production process and identify the inputs and outputs of each production stage;
- **Emissions Calculation:** Greenhouse Gas (GHG) emissions [1-3,5-9,12,14]: For the extraction of raw materials, we use the following formula:

$$E_E = \sum_{i=1}^{n} Q_{CCi} \times FE_{CCi} \quad (1)$$

Where :

- E_E: Emissions from extraction (tonnes/day);

Q_{CCi}: Amount of fuel consumed (litres);

FE_{CCi}: Fuel emission factor (kg CO_2/litre);

Transport of Materials: Emissions due to the transport of materials are calculated by multiplying the distance travelled by the same formula [1-3,5-7]:

$$E_T = d \times \sum_{i=1}^{n} Q_{CCi} \times FE_{CCi} \quad (2)$$

Where d is the distance between the quarry and the workshop (km);

- **Clinker production:** CO_2 emissions linked to the decarbonation of limestone are calculated as follows [2,7,8,15,16]:

$$E_{CO_2} = FE_{kk} \times Q_{kk} \quad (3)$$

Where :

- FE_{kk}**:** Emission factor for clinker (tonnes CO_2/tonnes clinker);
- Q_{kk}**:** Quantity of clinker produced (tons);
- **Combustion emissions:** Energy consumption is calculated to estimate CO_2 emissions during clinkerization [2,3,6-8]:

$$C_E = C_f \times PCI\ C_E \quad (4)$$

Where:

- C_E**:** Energy consumption (GJ);
- C_f**:** Fuel consumption (tonnes);
- **PCI:** Lower calorific value of the fuel (GJ/t).
- **Dust emissions:** Emissions due to dust generated during the process are calculated as follows [1-3,5-9]:

$$Emission_{PFC} = FE_{PFC} \times Q_{PFC} \quad (5)$$

Where:

$Emission_{PFC}$**:** Carbon dioxide (CO_2) emissions from dust produced by the cement kiln (Tons of CO_2);

FE_{PFC}**:** Emission factor for cement kiln dust, which indicates the amount of CO_2 emitted per tonne of dust (tonnes CO_2/ tonne PFC);

Q_{PFC}**:** Amount of cement kiln dust produced during the manufacturing process (Tonnes of dust).

Graphical modeling

Graphical modeling in OpenLCA allows us to visually illustrate the material and energy flows throughout the production process [1-3,5-9,12-14]. It works by making the following setup and assumptions:

- Software configuration by creating the database after installing OpenLCA, the first step is to create a new localized database, named "CILU" in this case. This facilitates data sharing and transfer;
- **Databases used:** inventory database where there is the import of life cycle inventory datasets, containing input and output flows of various product systems, including materials, energy, and emissions;
- **System modeling:** creating product systems in OpenLCA, which can contain one or more processes. Impacts can be calculated for these systems;
- **Impact assessment methods:** LCIA, impact assessment methods relate production processes to potential environmental impacts, quantifying the consequences of emissions;
- **Specific parameters analyzed:** projects, using projects to compare the impacts of different product systems;
- **Processes:** Includes unit and system processes, transforming inputs into outputs;
- **Flows:** Identification of elementary, product, and loss flows, defined by reference flow properties;
- **General assumptions:** Continuous Production We have clinker production, which is done 24 hours a day, 7 days a week;
- **Extraction and transport assumptions:** fuel consumption, where the amount of fuel consumed depends on the size of the dumpers, their loading, and the types of roads used;
- **Emission assumptions:** Dust Emissions: Use of a default factor to estimate CO_2 emissions from cement kiln dust;
- **Study duration assumptions:** Base Year: 2019 data is used as the base year for the analysis;
- **Assessment approach assumptions:** Cradle-to-Gate Approach to analyze emissions from raw material extraction to finished product.

Results

The results indicate that the Lukala cement plant is a significant contributor to CO_2 emissions, particularly during extraction and manufacturing. The analyses show that changes in the production process could reduce these emissions. A

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discussion of the implications of these results for the industry, as well as recommendations for sustainable improvements, is also included.

Mathematical modeling

The calculation of greenhouse gases emitted by extraction is carried out separately for the two quarries, limestone and clay, and the result is presented in Table 5 as follows:

The calculation of greenhouse gases emitted by transport is carried out separately for the two quarries by multiplying by the distance between each quarry and the crushing plant. The result is presented in Table 6 as follows:

Considering the total mass of limestone in the mass of raw flour, we obtain the result in Table 7:

Since the Lukala cement plant uses coal as a fuel for a total mass of 228 tons, we obtain the result in Table 8:

Regarding the greenhouse gas emission from cement kiln dust, the result below was obtained based on some assumptions in Table 9.

By grouping these results in the same Table 10, we estimate CO_2 emissions on an annual basis.

Table 5: CO_2 emitted by the extraction of raw materials.

Career	Emission CO_2 [tonne de CO_2]
Limestone	1,50136
Clay	0,12092382
Total	1,622283824

Table 6: CO_2 emitted by the transport of raw materials.

Career	Emission CO_2 [tonne de CO_2]
Limestone in the crushing workshop	0,967841
Clay in the crushing workshop	0,171584
Total	1,139425

Table 7: CO_2 emitted by the decarbonation of the total limestone content.

Full title	Emission factor [tonne CO_2/tonne$_{kk}$]	Emission CO_2 [tonne de CO_2]
$CaMg_2(CO_3)$	0,47826087	1068,424187

Table 8: CO_2 emitted by the combustion of cementization.

Fuel	Emission CO_2 [tonne de CO_2]
Coal	518,35184277184

Table 9: CO_2 emitted by cement kiln dust (PFC).

Emission factor FE_{PFC} [T_{co2}/T_{kk}]	Emission CO_2 [tonne de CO_2]
0,04	24,52

Table 10: CO_2 emissions during the year 2019 from all phases of the cement production process.

Process	Emissions CO_2 [tonne/year]	Percentage of Total
Extraction of raw materials	592,13	0,10%
Transport of raw materials	415,89	0,07%
Decarbonation of limestone	389974,82	67,3%
Combustion for clinkerization	189198,42	32,6¨%
Cement Kiln Dust	8949,8	1,54%

With total emissions of 579,130.06 metric tons of CO_2 per year, the company largely exceeds Directive 2003/87/EC, which sets a threshold of 25,000 metric tons of CO_2 per year [1-3,5-7,17,18]. An action plan is needed, particularly targeting the processes with the highest emissions: decarbonation and clinkerization.

The decarbonation process consists of transforming limestone into lime (CaO) and carbon dioxide (CO_2). This process emits a large amount of CO_2 due to the large amount of limestone involved in the reaction.

To achieve this transformation of limestone into carbon dioxide, it is necessary to generate combustion in the kiln, which requires a large amount of fuel. This is why this process emits a significant amount of CO_2.

The inventory of materials and energy at the input, with the aim of identifying the quantity of CO_2 emitted at the output of each process, is summarized in the following Table 11.

This inventory is established on the basis of the inputs (materials and energy flows) required to produce flour, clinker, and cement. The quantities of substances emitted are then calculated using factors that quantify these emissions per unit of input. Studies on greenhouse gas emissions in cement plants show that decarbonation contributes on average to 60% of greenhouse gas emissions [1-3,5-9,12,14]. Thus, as shown in Table 12, the decarbonation process represents 67.21% of the greenhouse gas emissions of the Lukala cement plant.

Figure 1 illustrates the different phases of the cement production process at the Lukala cement plant. It provides a clear view of the key steps, inputs, and outputs, as well as losses at each level of the process.

This figure illustrates the entire cement production process at the Lukala Cement Plant, detailing the quantities of materials at each stage as well as the associated losses. It helps identify potential areas for improvement, which are essential to optimize production and reduce environmental impact, in line with sustainable development goals.

Table 11: Summary of the inventory of the Lukala cement plant.

Input	Output
Extraction	
Energy : 14522,496 litres Matter : 9076,56 tonnes	1,6223 tonne de CO_2
Transport	
Energy : 12,96 litres Matter : 9076,56 tonnes	1,1394 tonne de CO_2
Decarbonation	
2234 tonnes	1068,42 tonnes de CO_2
Combustion	
228 tonnes	518,35 tonnes de CO_2

Table 12: Contribution to the environmental impacts of the CILU cement manufacturing process.

N°	Impact category	Unité/UF	Calcium carbonate	Hard coal	Glass container
1	Terrestrial ecotoxicity	6.63678E4 kg 1.4-DCB	86 %	10 %	4 %
2	Water consumption	-492.22240 m^3	-88 %	------	2 %
3	Soil acidification	324.52136 kg SO_2 eq	66 %	18 %	6 %
4	Ozone layer depletion	0.03152 kg CFC 11 eq	57 %	40 %	2 %
5	Ozone formation, terrestrial ecosystems	404.15626 kg NO_x eq	39 %	69 %	2 %
6	Ozone formation, human health	398.02712 kg NO_x eq	39 %	69 %	2 %
7 8	Shortage of mineral resources	2.69296 kg Cu eq	56 %	12 %	22 %
9	Marine eutrophication	0.45894 kg N eq	36 %	38 %	16 %
10	Marine ecotoxicity	78.59942 kg 1.4-DCB	68 %	38 %	4 %
11	End-use	0.000000 m^2 a crop eq			
12	Ionizing radiation	682.18236 kg Bq CO-60 eq	38 %	38 %	22 %
13	Non-carcinogenic toxicity	4184.35184 kg 1.4-DCB	70 %	15 %	15 %
14	Carcinogenic toxicity	30.81008 kg 1.4-DCB	73 %	17 %	10 %
15	Global warming	1.81982E5 kg CO_2 eq	50 %	42 %	8 %
16	Eutrophication of freshwater	0.03960 kg P eq	20 %	18 %	62 %
17	Ecotoxicity in freshwater	20.25981 kg 1.4-DCB	66 %	32 %	2 %
18	Fossil fuel shortage	1.71550E5 kg oil eq	19 %	80 %	1 %
19	Formation of fine particles	101.386 kg PM2.5 eq	16 %	77 %	7 %

Graphical modeling

OpenLCA software offers the possibility to export the results found in Excel from the software. The inventory of materials and energies at the input, in order to identify the quantity of category of the impacts of the contribution of the cement manufacturing process in the following Table 12:

After exporting the results to Excel, we represent the results in Figure 2.

In this contribution diagram, we have:

- **On the abscissa:** All the impact categories calculated by the ReCiPe method;
- **On the ordinate:** The percentages that correspond to the contribution of each element necessary for the production of cement.

Discussion

The above-mentioned results are in line with the assessment requirements reported by several researchers: According to the study of [2], life cycle assessment (LCA) in Mexico has evolved considerably since the 2000s, moving from a focus on waste management to an application in energy systems, carbon and water footprints, and construction. Companies such as CEMEX and PEMEX have integrated LCA to optimize their processes and reduce their environmental impact. However, the development of LCA is hampered by a

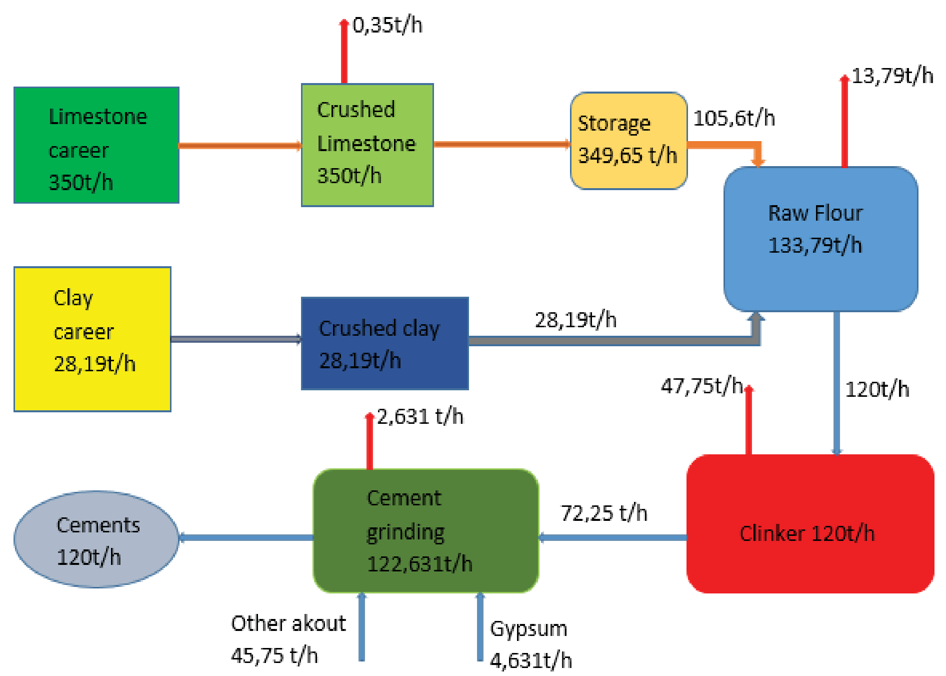

Figure 1: Life Cycle Assessment of the Lukala Cement Plant

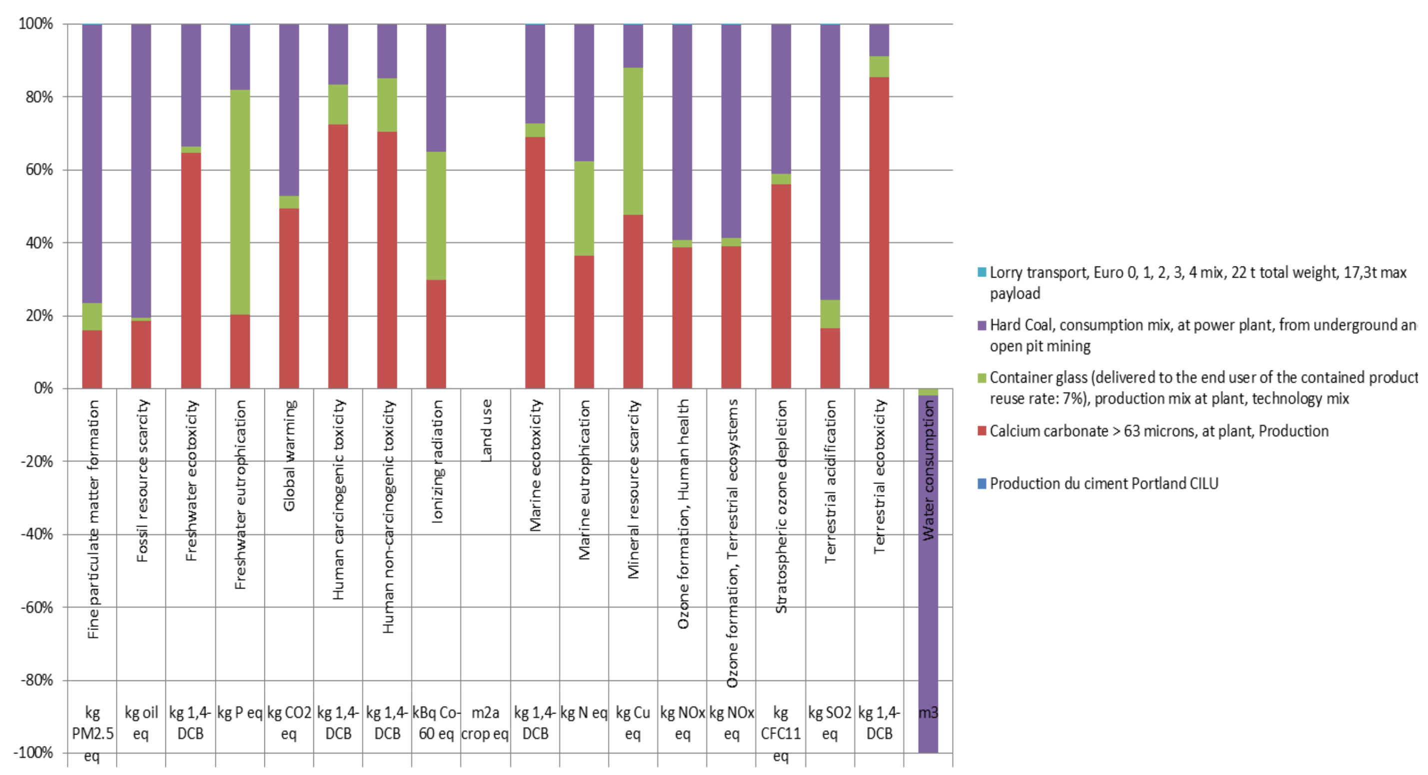

Figure 2: Contribution diagram of the CILU cement manufacturing process in Excel.

lack of collaboration between stakeholders and the absence of a national database. Enhanced training of practitioners is needed to ensure the quality of studies and promote a collaborative approach between government, industry, and academia.

The study of [5] shows that life cycle assessment (LCA) is emerging as a fundamental tool to assess the environmental impacts of products throughout their life cycle. Current practices highlight diversified assessment methods anchored in clearly defined impact categories, such as climate change and ecotoxicity. However, challenges persist, including data uncertainty and the need to adapt methods to local contexts. To enhance the effectiveness of LCA, it is crucial to improve the standardization of methods and to create reliable databases. These efforts will increase the comparability of studies and support informed decision-making on sustainability.

The study [6] highlights that life cycle assessment (LCA) is an essential tool for assessing the environmental impacts of products and services, from resource extraction to disposal. It identifies several significant impact categories: climate change, ecotoxicity, acidification, and eutrophication, which structure the assessment and highlight critical steps. Assessment tools, such as CML and ReCiPe, offer integrative approaches for a comprehensive analysis. ISO 14040 and 14044 standards ensure the rigor and comparability of studies. Despite this, challenges remain, including data uncertainty and the need to adapt methods. To improve reliability, it is essential to standardize methods and create accessible databases.

The study [7] on the environmental analysis of an Algerian cement plant highlights the importance of reducing environmental impacts in a competitive industrial context. By combining Life Cycle Analysis (LCA) and Failure Mode, Effects, and Environmental Criticality Analysis (FMECA-E), the integrated approach makes it possible to identify and quantify major impacts, such as dust emissions and resource consumption. This methodology helps to prioritize the necessary actions and guide managers' decisions to improve sustainability. Recommendations include the adoption of an environmental management system compliant with ISO 14000 standards and training staff on best practices, essential for sustainable management of cement plant activities.

According to [3], a study on the dramatic growth of CO_2 emissions in the global cement industry, drawn from new installations in emerging countries, used the Global Cement Emission Database (GCED) and China Cement Emission Database (CCED), as well as the Monta Carla analysis. The results show:

- **Increased emissions:** CO_2 emissions from the cement industry increased from 0.86 Gt in 1990 to 2.46 Gt in 2019, an increase of 186%;
- **Regional disparities:** Emerging countries, particularly

in Asia, the Middle East, and Africa, have experienced the highest growth in emissions, with the Middle East and Africa region increasing by 4.5% per year between 1990 and 2019.

- **Infrastructure characteristics:** Much of the cement production facilities in these regions are recent, with around 50% of the clinker capacity in operation being less than 10 years old;
- **Future emissions commitment:** Emerging countries accounted for 90.1% of the global CO_2 commitment in 2019, posing significant challenges for future decarbonization;
- **Technologies and energy efficiency:** The study highlights the need to adopt low-carbon technologies, such as carbon capture and storage, to mitigate future emissions;
- **Policy impact:** The results suggest that emission reduction policies need to be implemented in emerging countries, given their increasing role in global cement-related CO_2 emissions.

Finally, according to [19], a study on environmental sustainability in the cement industry presents an integrated approach for green and cost-effective cement production, with several key results regarding CO_2 emissions reduction in the cement industry in China:

- **Emissions inventory:** The study provides an updated inventory of CO_2 emissions for the cement industry in China, with a breakdown of emissions by source (fossil fuels, processes, electricity);
- **G-LEAP model:** The G-LEAP model was developed to project future CO_2 emissions, integrating cement demand and technology application;
- **Potential emission reduction:** CO_2 emissions could be reduced by 63% - 73% by 2060 through the application of abatement technologies. Near-term measures mainly rely on energy efficiency improvements and the use of alternative fuels, contributing to 9% - 12% and 17% - 22% of cumulative reductions, respectively;
- **Specific technologies:** Alternative cements could reduce emissions by 30% – 39%, and carbon capture and storage (CCS) is expected to be deployed by 2030, contributing to around 28% – 44% of cumulative reductions;
- **Residual emissions:** Despite the measures taken, around 300-400 million metric tons of CO_2 will remain to be neutralized by 2060, requiring further technological innovations;
- **Production scenarios:** Projections indicate that per capita cement consumption will reach a plateau before 2030, followed by a decline, leading to a decline in total cement production of around 35% by 2060.

The model indicates that the plant releases excessive quantities of greenhouse gases, with production in 2019 far exceeding regulatory thresholds [1-3,5-7,18,19]: 579,130 tons of CO_2 equivalent emitted per year by the Lukala cement plant. The decarbonation (67% of impacts) and clinkerization (33% of impacts) processes are particularly emitting. Decarbonation releases the CO_2 contained in the limestone used in large quantities.

Areas for improvement include the use of less pure limestone or partial substitutes, as well as the integration of recycled materials in the cement formulation. In addition, clinkerization carried out using coal emits a large quantity of CO2; a switch to gas or renewable energies could significantly reduce this impact.

The installation of desulfurization filters is also recommended to limit SO_2 emissions. The life cycle assessment (LCA) identified the most polluting production steps in the cement manufacturing process at the Lukala cement plant. As shown in Figure 1, the quarry extracts 350 t/h of limestone, resulting in a loss of 0.35 t/h during the extraction of raw materials.

This loss can lead to significant environmental impacts, including soil degradation and surface water pollution. The clay quarry, for its part, supplies 28.19 t/h of clay with no losses noted. After extraction, the limestone is crushed, which produces 349.65 t/h of limestone for storage. At the same time, the clay is also crushed and integrated directly into the process, with an input of 28.19 t/h. The combination of these raw materials then produces 133.79 t/h of raw meal, resulting in a loss of 13.79 t/h, which can lead to a waste of resources and an increased carbon footprint.

An eco-design solution would be to optimize the grinding process to minimize these losses. At this stage, 122.631 t/h of materials are ground to generate cement while integrating other additions, such as 45.75 t/h of other materials and 4.631 t/h of gypsum. This results in a loss of 2.631 t/h during the grinding of the cement, which can generate dust and CO_2 emissions, impacting air quality. Implementing dust collection systems and optimizing the grinding processes could reduce these losses.

Finally, the process results in the production of 120 t/h of clinker, which is the key product in cement manufacturing, generating a loss of 47.75 t/h. This step is particularly polluting due to the greenhouse gas emissions generated by the combustion of fossil fuels and the decarbonation of limestone. Eco-design could also include the use of alternative, less carbon-intensive clinker or the addition of cement based on recycled materials.

Based on the color distribution in Figure 2, we can deduce the significant environmental impacts of the different chemical elements in the CILU plant:

- **Fine particle formation:** Impact: 101,386 kg PM2.5 equivalent, main contributor: Hard coal (77%) and consequences: The formation of fine particles can lead to respiratory problems and have adverse impacts on human and animal health;
- **Fossil resource shortage:** Impact: 171,550 kg oil equivalent, main contributor: Hard coal (80%) and consequences: The depletion of fossil resources compromises the sustainability of energy supplies for future generations;
- **Freshwater ecotoxicity:** Impact: 20.25981 kg 1.4-DCB equivalent, contributors: calcium carbonate (66%), hard coal (32%), and consequences: This toxicity can harm aquatic fauna and drinking water quality.
- **Freshwater eutrophication:** Impact: 0.03960 kg P equivalent, contributors: calcium carbonate (20%), container glass (62%), and consequences: Eutrophication can cause algal blooms, reducing water quality and threatening aquatic life.
- **Global warming:** Impact: 181.982 kg CO2 equivalent, contributors: calcium carbonate (50%), hard coal (42%), and consequences: These emissions contribute to climate change, with impacts on ecosystems and societies;
- **Carcinogenic toxicity:** impact: 30.81008 kg 1.4-DCB equivalent, main contributor: calcium carbonate (73%) and consequences: This toxicity increases the risk of cancer in exposed humans and animals;
- **Non-carcinogenic toxicity:** Impact: 4184.35184 kg equivalent 1.4-DCB, main contributor: calcium carbonate (70%) and consequences: This form of toxicity can also affect the health of ecosystems and human populations;
- **Ionizing radiation:** Impact: 682.18236 kg equivalent Bq CO-60, balanced contributions: calcium carbonate, hard coal, and container glass, and consequences: Exposure to ionizing radiation can increase the risks of diseases and genetic mutations;
- **Marine ecotoxicity:** Impact: 78.59942 kg equivalent 1.4-DCB, main contributor: calcium carbonate (68%) and consequences: This toxicity has a major impact on marine ecosystems, threatening biodiversity;
- **Marine eutrophication:** Impact: 0.45894 kg N equivalent, contributors: calcium carbonate (36%), hard coal (38%), and consequences: May cause dead zones in the oceans, threatening marine life;
- **Mineral resource shortage**: Impact: 2.69296 kg Cu equivalent, main contributor: calcium carbonate (56%), and consequences: Impacts the availability of mineral resources for future generations;
- **Ozone formation (human health):** Impact: 398.02712 kg NO_x equivalent, main contributor: Hard coal (69%) and consequences: Affects human health, causing respiratory problems;
- **Ozone formation (terrestrial ecosystems):** Impact: 404.15626 kg NO_x equivalent, main contributor: Hard coal (69%) and consequences: Impacts the health of plants and terrestrial ecosystems;
- **Ozone depletion:** Impact: 0.03152 kg CFC 11 equivalent, main contributor: Calcium carbonate (57%) and consequences: Ozone depletion increases exposure to UV radiation;
- **Soil acidification:** Impact: 324.52136 kg SO_2 equivalent, main contributor: Hard coal (66%) and consequences: Acidification affects soil fertility and biodiversity;
- **Terrestrial ecotoxicity:** Impact: 66.63678 kg 1.4-DCB equivalent, main contributor: calcium carbonate (86%) and consequences: Affects the health of terrestrial species and biodiversity;
- **Water consumption:** Impact: -492.22240 m^3, the main contributor is hard coal (-88%) and consequences: Excessive water consumption can lead to shortages and affect aquatic ecosystems.

The Life Cycle Assessment (LCA) conducted on the Lukala plant has some limitations:

- **Simplified modeling:** The mathematical and graphical models used in OpenLCA can simplify complex processes, which can lead to an underestimation of some environmental impacts;
- **Baseline data:** The data used for comparisons may not be fully representative of local conditions, which limits the accuracy of the results;
- **Interpretation of results:** The interpretation of the results may vary depending on the modeling assumptions, which could influence the conclusions drawn on the sustainability of the plant;

- **Regional considerations:** The results are based on a specific case (Lukala) without taking into account the variations that could exist in other plants, making the recommendations less generalizable;

- **Lack of future scenario analysis:** The study does not sufficiently take into account potential developments in technologies and regulations that could influence long-term environmental performance.

To improve future work on LCA and environmental assessment in the cement industry, here are some recommendations:

- **Deepening modeling:** Use more detailed models that take into account the complex interactions between the different stages of the production process in order to obtain a more accurate assessment of impacts.

- **Expanding baseline data:** Integrate data from several similar facilities for better representativeness and more relevant comparisons.

- **Alternative scenarios:** Develop future scenarios based on technological evolution and environmental policies to anticipate the impacts of innovations on emissions.

- **Multi-criteria analysis:** Incorporate multi-criteria analysis methods to assess not only environmental impacts but also economic and social aspects of the cement industry.

- **Collaboration with other plants:** Establish partnerships with other facilities to share data and best practices, which could enrich the analysis and recommendations.

- **Sustainability awareness:** Promote awareness initiatives to train staff on sustainable practices and environmental impact management.

- **Continuous monitoring:** Establish a system for regular monitoring of environmental performance to assess the effectiveness of implemented measures and adjust strategies accordingly.

By implementing these recommendations, future studies will be able to provide more robust results and more effective solutions to reduce the environmental footprint of the cement industry.

Conclusion

The study on the environmental impact of the cement industry, in particular at the Lukala cement plant, highlights crucial issues in terms of sustainability and greenhouse gas emissions. The Life Cycle Assessment (LCA) reveals several salient points:

- **High CO_2 emissions:** The Lukala cement plant emits approximately 579,130 tons of CO_2 per year, mainly due to decarbonation (67%) and clinkerization (33%). These figures largely exceed the regulatory thresholds, which underlines the urgency to act.

- **Identification of polluting stages:** The LCA made it possible to target the most polluting production stages, in particular extraction, grinding, and clinkerization. This paves the way for targeted and effective improvements.

- **Opportunities for improvement:** Opportunities for optimization include the use of less pure limestones, the integration of recycled materials, and the transition to renewable energy sources for clinkerization, which could significantly reduce CO_2 emissions.

This research is of paramount importance in the context of the fight against climate change. As one of the main contributors to greenhouse gas emissions, the cement industry must imperatively adopt sustainable practices. LCA provides a robust methodology to quantify environmental impacts and identify solutions. The results of this study can be applied not only to the Lukala cement plant but also to other cement plants around the world. The methodological approach can serve as a model for other carbon-intensive industries seeking to improve their sustainability. Future research could explore the integration of innovative technologies, such as carbon capture and storage, as well as the use of alternative materials or advanced production processes. Finally, this study highlights the need for immediate and coordinated action to transform the cement industry into a more sustainable sector while ensuring the economic profitability of operations. The transition to more responsible practices is not only desirable but essential for environmental sustainability and the health of future generations.

References

1. de Bortoli A, Agez M. Environmentally-extended input-output analyses efficiently sketch large-scale environmental transition plans: illustration by Canada's road industry. J Clean Prod. 2023;388:136039.

2. Güereca L, Sosa R, Gilbert H, Reynaga N. Life cycle assessment in Mexico: overview of development and implementation. Int J Life Cycle Assess. 2015;1-7.

3. Chen C, Xu R, Dan Tong D, Qin X, Cheng J, Liu B, Zheng L, Yan Q, Qiang Zhang. A striking growth of CO2 emissions from the global cement industry driven by new facilities in emerging countries. Environ Res. 2022;17:044007:1-13.

4. Bouhidél M. Application of life cycle analysis for sustainable development: Case of Algerian cement plants. Master's thesis, El-Hadj Lakhdar Batna University, Algeria; 2009:1-128.

5. Pennington DW, Potting J, Finnveden G, Lindeijer E, Jolliet O, Rydberg T, Rebitzer G. Life cycle assessment part 2: current impact assessment practice. Environ Int. 2004 Jul;30(5):721-39. doi: 10.1016/j.envint.2003.12.009. PMID: 15051247.

6. Habibi A, Tavakoli H, Esmaeili A, Golzary A. Comparative life cycle assessment (LCA) of concrete mixtures: a critical review. Eur J Environ Civil Eng. 2022;1-19.

7. Boubaker L, Gondran N, Djebabra M. Towards a combination of LCA / FMEA-E for the environmental analysis of an Algerian cement plant. Waste Sci Technol. 2008;24-28.

8. Cabeza L, Rincón V, Vilariño G, Pérez A, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev. 2014;9:394-416.

9. Amran M, Makul N, Fediuk R, Huei Lee Y, Ivanovich Vatin N, Yong Lee K, Mohammed K. Global carbon recoverability experiences from the cement industry. Case Stud Constr Mater. 2022;17.

10. Dandautiya R, Singh AP. Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment. Waste Manag. 2019 Nov;99:90-101. doi: 10.1016/j.wasman.2019.08.036. Epub 2019 Aug 29. PMID: 31473485.

11. Mavungu T. Design of a digital-technical tool dedicated to the study and exergoenergetic analysis of cement installations. Bachelor's thesis, Kongo University; 2018.

12. Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T. Life cycle assessment: past, present, and future. Environ Sci Technol. 2011 Jan 1;45(1):90-6. doi: 10.1021/es101316v. Epub 2010 Sep 2. PMID: 20812726.

13. Lopes Silva DA, Nunes AO, da Silva Moris VA, Piekarski CM, Rodrigue TO. How important is the LCA software tool you choose? Comparative results from GaBi, openLCA, SimaPro and Umberto. In: VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica; 2017; 1-6.

14. Azapagic A. Life cycle analysis and its application to process selection, design and optimization. Chem Eng J. 1999;73:1–21. Available from: https://doi.org/10.1016/S1385-8947(99)00042-XR.

15. Finkbeiner M, Inaba A, Tan R, Christiansen K, Kluppel H-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assess. 2006;11(2):80–85.

16. García-Segura T, Yepes V, Alcala J. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int J Life Cycle Assess. 2014;19(1):3–12.

17. Izumi Y, Iizuka A, Ho H-J. Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry. J Clean Prod. 2021;312:127618.

18. Regulation (EU) No 601/2012. Commission Regulation of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council. Off J Eur Union. 2012;181-204.

19. Poudyal L, Adhikari K. Environmental sustainability in the cement industry: an integrated approach for green and economical cement production. Resour Environ Sustain. 2021;4:100024.

20. Mungyeko B-JR. Thermal study and optimization of the performance of the cement rotary kiln of the Kimpese National Cement plant. Bachelor's thesis, Kongo University; 2010.

21. Mungyeko B-JR, Wanlongo-Ndiwulu G, Pongo-Pongo C. Analysis of parameters affecting energy consumption in a cement rotary kiln and possible energy optimization solutions. In: French Thermal Congress; 2015;1-8.

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