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Environmental life cycle assessment of industrialization process of calcined dredged sediments

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ABSTRACT

This research focus on the life cycle assessment (LCA) of dredged sediments valorization. This tool is part of an environmental management approach, which makes it possible to compare the environmental loads of the different stages of the life cycle of the same product and, by the way to deduce the most polluting step in environmental terms and thus the industrialization process of dredging sediments of dams is optimized by modelling using the GEMIS (Global Emission Model for Integrated Systems) 4.95 software and the classification and characterization method. To propose a model that is the more respectful of the environment, by determining the most environmentally friendly scenario, in order to exploit these dredged sediments after calcination treatment to make them active in the field of the building's construction. The results of this life cycle analysis study of the new industrialization process of dredged sediments show that climate change potential (GHG) is 0,246 ton of CO_2eq/t of sediments, acidification potential is $4{,}55 \times 10^{-4}$ ton of SO_2 eq/t of sediments, the tropospheric ozone precursor potential is $9{,}97 \times 10^{-4}$ ton of TOPP eq/t of sediments and the cumulative energy and exergy demand is 2506,75 in MJ/t of sediments, these values are compared to others carried out in Algeria.

1 Introduction

The dredging is a vital activity for the operation of the Dams. This operation is an important phase in the recovery and preservation of the useful storage volumes of the dams. But, the fate of large quantities of recovered sediment is a major environmental and economic challenge. Several recent research studies [1-7] on the valorization of sediments resulting from the dredging of dams have been conducted in the field of physico-chemical characterization, mechanical and

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durability. They have demonstrated the possibility of using these sediments as a raw material in the field of civil engineering, and especially as a partial substitution for cement. All the results from this research open the possibility to propose a model of industrialization of dredged sediments after an analysis of their life cycle.

Algeria has 72 large dams, with a total capacity of 7692.24 million m³ according to the latest statistics in 2014 [8] (fig.1). Their siltation is approximately 1085,94 million m³. This represents a siltation percentage of 14.12% of their total capacity [8]. According to provisional estimates, this siltation is expected to reach 1,323.52 million m³ by 2020 for the only existing dams, or 17% of the global storage capacity [9].

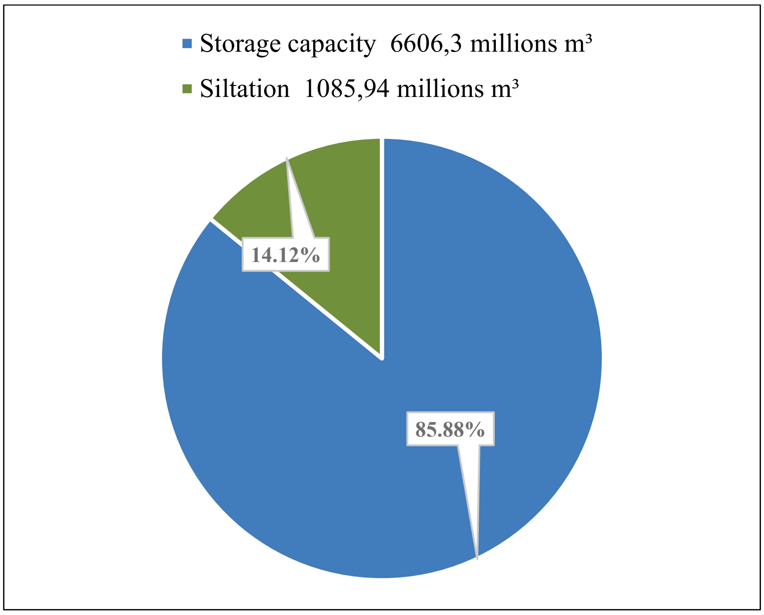

Fig. 1 – Percentage of siltation compared to the total capacity of Algerian dams in 2014 [8].

Figure 2 shows the strong variation in siltation. The dam with a high siltation percentage is Fergoug, wilaya of Mascara followed by Meurad wilaya of Tipaza; Foum El Ghorza wilaya of Biskara etc ....

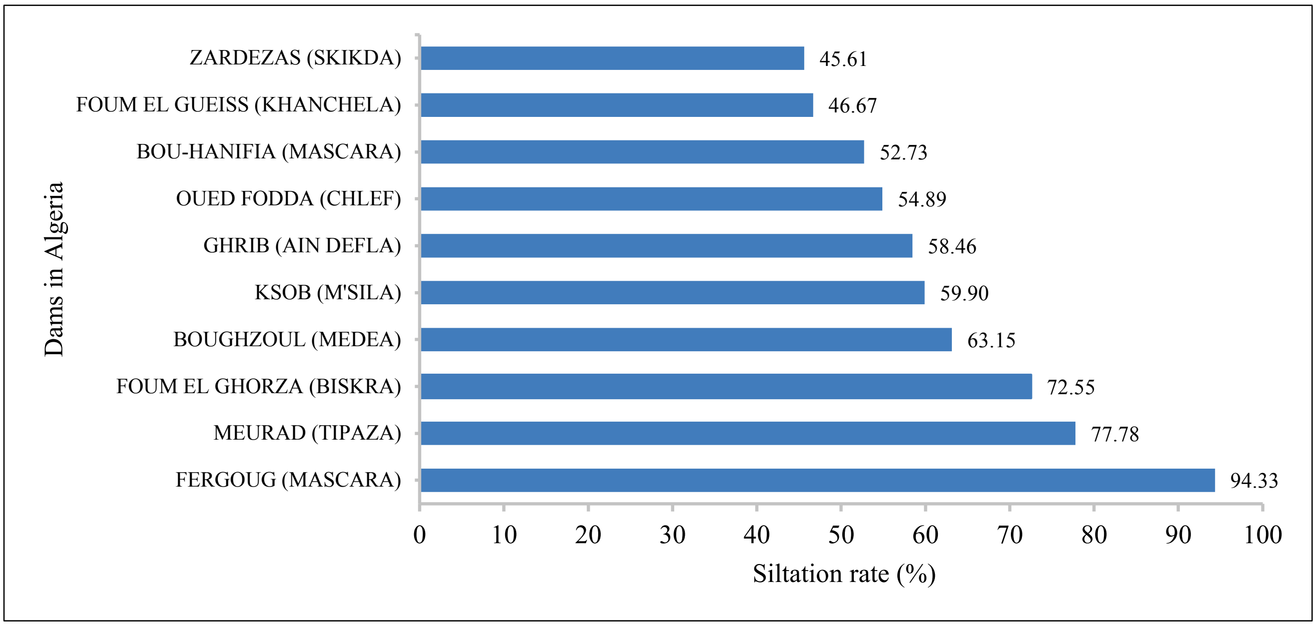

Fig. 2 – The classification of 10 largest dams the most silted in Algeria [8].

Several studies regarding the life cycle assessment (LCA) of dredged sediments have been carried out through the world and especially the studies that deals with environmental assessment of contaminated sediments. Bai et al. [10] have evaluated the methodological framework of the LCA, by treating the stabilization and the valorization of contaminated marine sediment, the article includes two scenarios: the first studies the stages of bioremediation, screening, liming, hydraulic stabilization and crushing before valorization. The second studies the stages of bioremediation and screening before valorization in filling quarries. The results show that the second scenario of bioremediation treatment and screening before valorization in backfilling is potentially less impacting than the first bioremediation scenario, screening, liming, hydraulic stabilization and crushing before valorization. This is due to the liming phase, stabilization and crushing more resource intensive and generating more emissions. Hou et al. [11] have proposed a new hybrid LCA methodology in comparison with the traditional LCA for improving the waterway of the contaminated site at the Olympic Park in London. These results had showed almost all the sediments contained a certain level of petroleum hydrocarbon contaminants, with lubricating range organics (LRO) (over to 1990 mg/kg) and polycyclic aromatic hydrocarbons (PAHs) (over to 72.5 mg/kg) higher than Environment Agency (EA)'s limit for hazardous waste, which represents a long-term risk to the ecosystem and human health. The treatment of sediments has reduced the impacts of contaminants of nearly 30% by washing and 80% at the landfilling. The hybrid LCA had corrected the secondary impact errors of 32% truncation process by the soil washing and 8% of the secondary impact of landfill. Falciglia et al. [12] have compared the techniques of treatments of marine sediments by microwave heating using LCA. The results had showed that this technology is more environmentally sustainable for the decontamination of sediments, with a total harm of 75.74% less than that associated with the electro kinetic decontamination. Beolchini et al. [13] have assessed the effectiveness of lixiviation agents (sulfuric acid, oxalic acid and citric acid) and bioleaching processes (based on different acidophilic bacterial strains) on the mobilization of metals and semi-metals in contaminated port. The LCA has shown that the treatment based on dilute sulfuric acid is less impacting in terms of carbon monoxide emissions compared to other scenarios and on the whole range of impact categories (Global warming potential, photochemical ozone creation potential, acidification potential, resource depletion). The highest environmental potential is the chemical treatment with citric acid mainly due to the consumption of raw materials, as well as the biological treatment mainly due to high energy requirements and long treatment with slurry bioreactors. Sparrevik et al. [14] have applied the LCA to evaluate remediation solutions for contaminated sediments for the Greenland Fjord in Norway. They had studied the environmental footprint of different active and passive alternatives thin film layers recovery compared to natural recovery. The results had showed that the recovery is preferable to the natural recovery vis-a-vis the environmental footprint due to the use of resources and energy during the implementation of a thin layer of recovery.

On the other hand, Abriak et al. [15] have presented a new methodology for the management of dredging operations whose objective is the coupling of qualitative data measures and the complementarities of old methodologies according to a framework of industrial ecology. This methodology had showed that the coupling qualitative measures with sediment data collection may reduce dependence to scientific measures (dredging methodology developed at the port of Dunkerque in France). Manap and Voulvoulis, [16] have assessed the environmental impact of dredging with respect to technological factors and sediments characterization for the environmental management of the developing countries. The study had showed that the concentration on the economic and scientists tests is not well balanced by assessing the concern environmental and socio-economic management of important techniques. The developing countries and developed countries have different approaches for the management of dredged sediments due to their financial situation. Bates et al. [17] have compared the implementation strategy of dredged sediments in the Long Island Sound area of New York according to three scenarios: Upland, Open water, containment island. The main results had showed that the placement of sediments in the offshore generates the lowest impact on 14 impact categories. On the other hand, the sediment placement scenario at the containment island is the most impacting, due to truck transport, which contributes more to climate change and the impacts associated with the construction of containment islands. The sensitivity analysis had showed the efficiency of the type of trailers of transport trucks on the reducing the number of trips due to fuel consumption.

From the results above, it can be seen that most of the previous studies of LCA only evaluate the problem of treatment of contaminated marine sediments and environmental management of dredged sediment waste and emplacement. Very few publications can be found available in the literature that address the issue of environmental assessment and who proposes an industrialization of dredged sediments for a partial or total substitution of cement and to our knowledge. On the other hand, several authors [18-26] have modeled their environmental assessments using GEMIS software (Global Emission Model of Integrated Systems) which is available at our laboratory level.

In this paper, we propose a model of industrialization of dam dredged sediment in Algeria as well as the environmental assessment of this model using GEMIS 4.95 software with the characterization method (Midpoint Characterization) [27].

2 Materials and methods

2.1 Methodology of life cycle assessment

The life cycle assessment is a multicriteria and multi steps method. It is based on the notion of sustainable development throughout the entire life cycle of the product or service. A quantification of inputs and outputs (resources consumptions, emissions into the air, water, soil, etc.) is carried out from the extraction of raw material to its treatment at the end of life. Life cycle assessment (LCA) is a decision-making tool that responds to the need to identify priority actions to be undertaken, especially when managers leaders are not ready to invest in environmental issues [28, 29]. Life Cycle Assessment (LCA) is the most comprehensive reference methodology for performing flow inventory, quantify and evaluate the environmental impacts of a product or service according to the series of ISO Standard14040-14044 [28, 29]. The life cycle assessment (LCA) consists of four iterative phases [30]:

(1) The definition of goals and scope of the study.

(2) The inventory analysis.

(3) Evaluation of the impact assessment.

(4) Interpretation of results.

This study was carried out by using GEMIS software version 4.95, this method is the most used and the most consensual [31]. The indicators offer a very small margin of error. This software contains an impact assessment method and a materials database, processes, transport and energy, allowing modeling of the product or service. The database includes a list of products, processes and scenarios. This will allow us to quantify relevant inputs and outputs of a product system. Primary data sources were found in the literature and were adapted to the local conditions in Algeria. These results are compared to others carried out in Algeria [27].

2.2 The life cycle assessment of calcined dredged sediment treatment

The objective of this work is to set up a system to low energy consumption for the treatment of calcined dredged sediments, taking into consideration the environmental impacts throughout the life cycle of this process, and to reduce the emissions of the outflows to the atmosphere (releases in to water, air and soil). Through this study we will expose the different processes, the assumptions and data used in the modeling of the dredged sediments treatment process. This modeling will develop a decision support tool for the optimal choice of disposal of dredged sediments.

2.2.1 Scenario description

Two industrial scenarios are possible for the treatment of sediments, in order to valorize them as raw material in the substitution of cement; the calcined sediment treatment process illustrated in figures 3 and 4 was inspired by the clinker manufacturing process [32]:

Scenario 1: It consists in using sediments after the total settling and the drying in the open air in the discharging areas. Sediment extraction is done by a loader, then transported them by dumper to the treatment station of dredged sediments. The factory installation being at the level of the reject zones (figure 3).

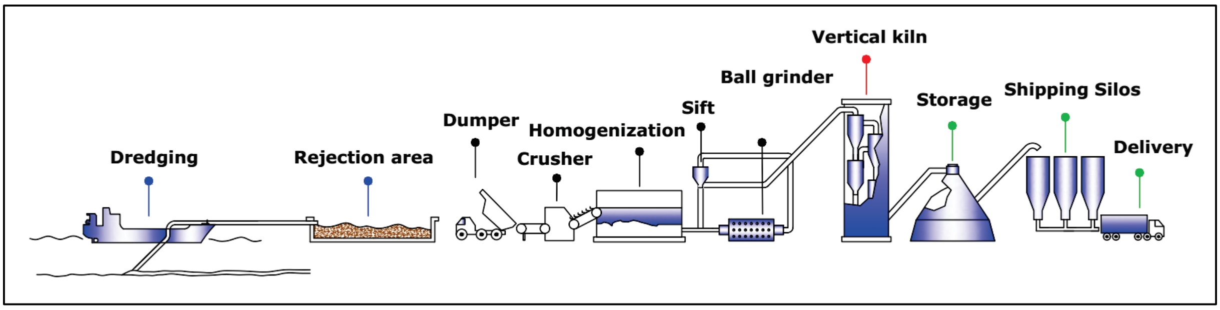

Fig. 3 – Treatment process of the calcined sediment dredged envisaged scenario 1.

Scenario 2: Sediments are exploited after dredging in the release areas or at the level terrestrial lines. A dryer is used for recovering the water and dried sediments, in order to optimize the decantation time in the open air (figure 4).

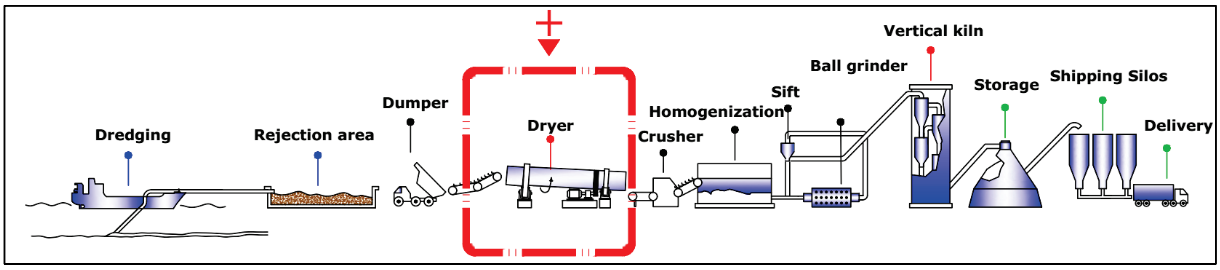

Fig. 4 – Treatment process of calcined sediment dredged envisaged scenario 2.

Several drying processes dredged sediments are compared according to their performances and the desired criteria. A series of processes has been selected to compare them in order to choose the type of process that consumes less energy and has the least impact on the environment (indirect dryers, direct dryers, mixed dryers). We will choose a direct dryer to rotary drum with a capacity of 5 to 100 t/h, allowing to dry the sediments in a paste state. The drying times will be from 10 to 60 min, with a reduced energy consumption of 0.6 to 0.7 kWh/kg of evaporated water [33].

Figure 5 shows the growing consumption energy as a function of the moisture content of wet state of dredged sediments. It’s clear that to optimize energy consumption it is necessary to use sediments in the dry state. For the following of the research a sensitivity analysis will be proposed to compare the moisture content from 0% to that of 90% for scenario 2.

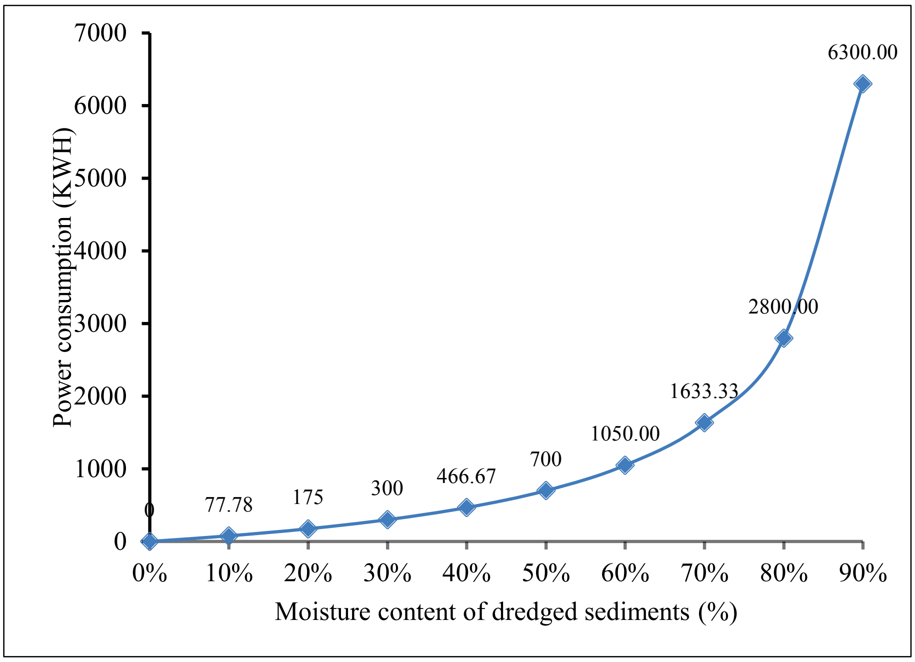

Fig. 5 – Relationship between dredged sediment moisture content in evaporated water and Algerian energy consumption [33].

2.2.2 System definition and goal

System function: The analysis will focus on the three stages of production: The dredged sediments extraction stage, the processing stage and finally the storage stage using the cradle approach at the exit of the factory. It will be a question of modelling the various stages of production in order to treat a ton of calcined dredged sediments ready to be substituted in the cement.

Functional unit: Treatment of one (1) ton of calcined dredged sediment that will be used in the partial substitution of cement (for fineness greater than 3000 cm²/g).

System boundaries: The dredging stage is excluded from the analysis of the process of treatment of dredged sediments. This step is made by the national agency of dams and transfers in Algeria [8]. Sediment is exploited after dredging in the disposal areas.

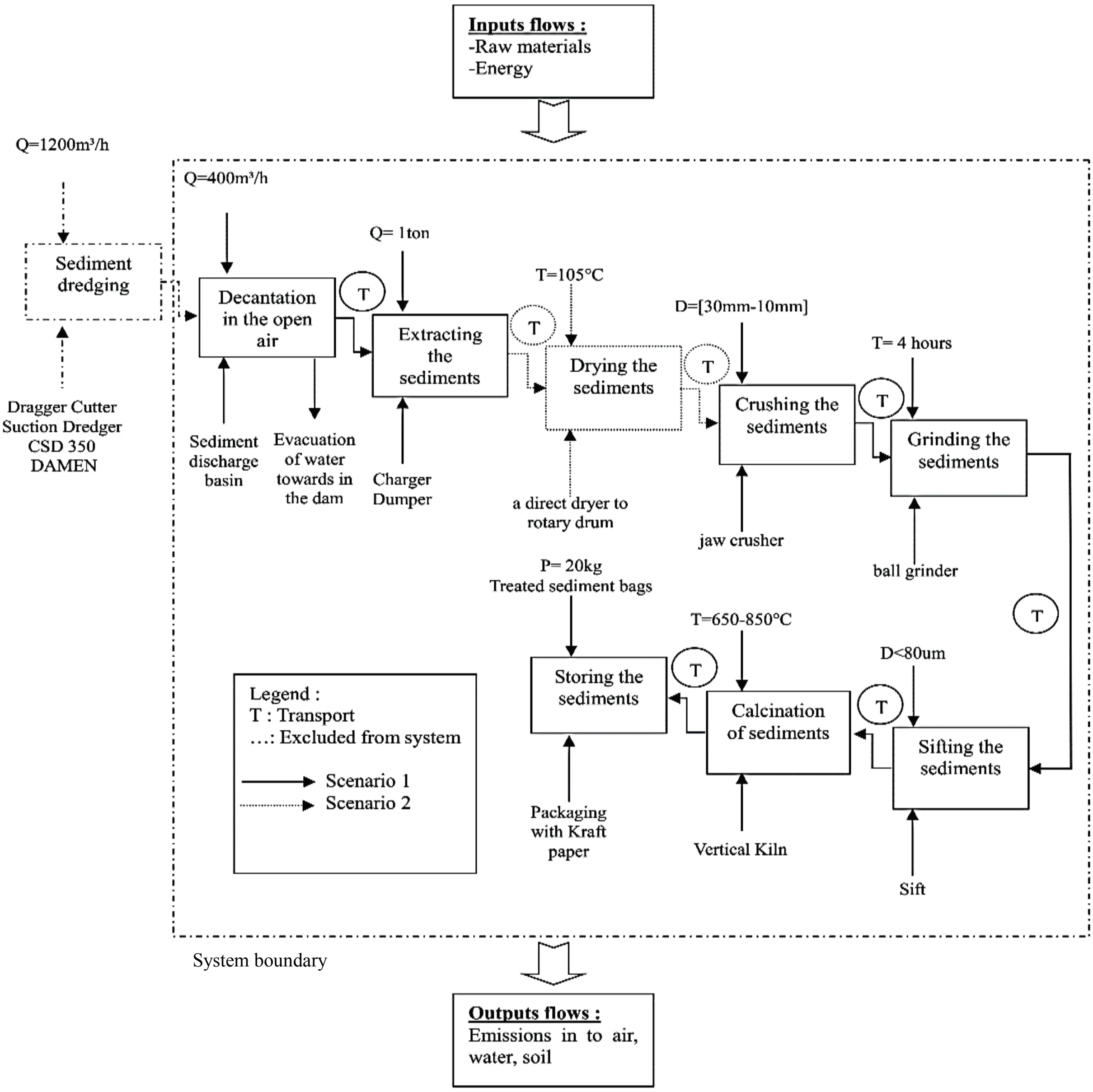

Fig. 6 – Principle of definition of the system boundary.

Figure 6 represents the principle of definition of the system border using the approach (from the cradle to gate).

2.2.3 Inventory and data quality of life cycle assessment (LCI)

The study carried in this research is a prospective study to the proposal of a new process for the treatment of calcined dredged sediments. Until now all sediment treatment processes are in the research laboratory scale in Algeria and abroad. Table 1 illustrates the inventory of the calcined dredged sediment treatment process describing the different processes used to obtain a finished product substituable for cement and estimate of the quantities of energy required for sediment treatment at each stage.

Table 1 - Inventory of the treatment process of the calcined sediments dredged.

The different phases	Process	Consumption	Unit	Scenario 1	Scenario 2	Ref
Extraction phase	Extraction	Diesel fuel	MJ/t	76,9	76,9	[34]
Treatment phase	Dryer	Electricity	KWh/t	-	Sensitivity analysis	[33]
Treatment phase	Crusher	Electricity	KWh	0,57	0,57	Estimated
Treatment phase	Grinder	Electricity	KWh	10,90	10,90	Estimated
Treatment phase	Sift	Electricity	KWh	5,45	5,45	Estimated
Treatment phase	Vertical calcination	Natural gas	MJ/t	1894,7	1894,7	[34]
Storage phase	Storage in a bag	Kraft paper	Kg	3	3	Estimated

This table will allow us to quantify relevant inputs and outputs of the treatment of one (1) ton of calcined dredged sediment that will be used in the partial substitution of cement system, primary data sources were found in the literature and were adapted to the local conditions in Algeria (data for electricity and heat generated by natural gas).

Table 2 represents the quantitative of the mineralogical composition of a (01) ton of sediment dredging from the Chorfa dam (Algeria), this mineralogical composition of dredged sediments is based on a qualitative analysis.

Table 2 - The mineralogical quantitative of the sediment dredging of the Chorfa dam.

Minerals	Composition	Classification	Sediments (%)
Quartz	SiO_2	Silicon oxide	43,50 (%)
Kaolinite	$(KH_3O)(AL,Mg,Fe)(Si,Al)_4O_{10}(OH)_2,H_2O$	Phyllosilicate	33,60 (%)
Calcite	$Ca(CO_3)_2$	Anhydrous carbonate	16,10 (%)
Dolomite	$CaMg(CO_3)$	Anhydrous carbonate	6,80 (%)

Table 3 represents the emissions of the gas in the air during the transportation of sediments by the gears.

Table 3 - Inventory of air emissions from the gear of sediment transport. Hugrel and Joumard, 2006 [34].

Emission of gas in the air	Quantity (Kg/t)
CO_2	5,599
CO	0,016
COGNM	0,007
NOx	0,071
CH_4	0
Particles PM10	0,004
N_2O	0,001
H_2O	0

Table 4 shows the emissions of gas into the air over a period of 2 hours in the Fireplace using the benchmarking method. This process has been inspired by a study made by the central laboratory of bridges and roadways in Nantes (France) on the environmental assessment of a metakaolin manufacturing process (flash calcination) [34].

Table 4 - Inventory of air emissions from the treatment process of the calcined sediments dredged: Argeco-LCPC Convention, April 2010 [34].

Emission of gas in the air	Quantity (Kg/t)
CO_2	89,9
CO	0,206
COGNM	0,190
NOx	0,15
CH_4	0,007
Particles PM10	Not measured
N_2O	Not measured
H_2O	Sensitivity analysis

All the information which relate to the treatment of calcined sediments dredged have been estimated using the approach (from the cradle to gate). This approach has been chosen mainly by lack of accurate data of the calcined dredged sediments treatment process. The exploitation of the GEMIS 4.95 database has allowed us to adapt the databases (electricity production and natural gas production) to the real Algerian conditions.

2.2.4 Methods of calculating impact indicators

GEMIS 4.95 software performs simulation the analysis of environmental impacts with weighted characterization method: which quantifies the overall effects of substances emitted or consumed. Inventory results with similar effects are grouped into impact categories called intermediate categories, which is associated an intermediate Indicator (midpoint indicator) to compare the flows of substances contributing to the category concerned. In order to carry out the impact assessment, the reflection will be based on 4 indicators: (The climate change potential (greenhouse effect), the acidification potential, The tropospheric ozone precursor potential and the cumulative energy and exergy demand: The cumulative energy demand (CED) in megajoules (MJ) [27].

3 Results and discussion

Figure 7 represents the emitted flows of the 4 environmental impact indicators for the treatment of one (1) ton of calcined dredged sediment that will be used in the partial substitution of cement for the scenario N 1, after modelling:

3.1 The climate change potential (greenhouse effect)

This potential is 0,246 ton of CO_2 eq/UF. The percentages of the main greenhouse gases generated by the treatment of one (01) ton of calcined dredged sediment are: 97,28% of CO_2, 2,21% of CH_4 and 0,50% of N_2O. The quantity of CO_2 emitted is 0,239 ton of CO_2 eq/UF of production throughout the life cycle of the sediments due to the combustion of the gas during the calcination phase with 46,36%, the emissions of gas from the chimney measured during the decarbonation and the transformation of kaolin into metakaolin of the process is 37,53% and the diesel consumption is 7,02%. The quantity of CH_4 produced throughout the life cycle of the sediments production is $5{,}45\times10^{-3}$ ton of CO_2 eq/UF. Its production is mainly caused by the processing of natural gas with about 52,37%. The extraction of natural gas with 32,36% and lastly the emissions of gases from the chimney by 3,85%. The quantity of N_2O produced is $1{,}23\times10^{-3}$ ton of CO_2 eq/UF. Its production is mainly caused by the burning of gas with about 48,33%, followed by emissions of gases from the gear of sediment transport in the order of 21,44%, diesel consumption of 14,87% and the electricity consumption by 6,62%. In this section, the treatment of one (1) ton of calcined dredged sediment that will be used in the partial substitution of cement requires less of the energy in order to be actived, when this type of treatment of calcined dredged sediment is compared with cement, it allows a strong reduction of the global warming potential. From 850 kg of equivalent CO_2 per ton for cement [35], the dredged sediment emits only 246 kg of equivalent CO_2 per ton, which represents a saving of 71,05%.

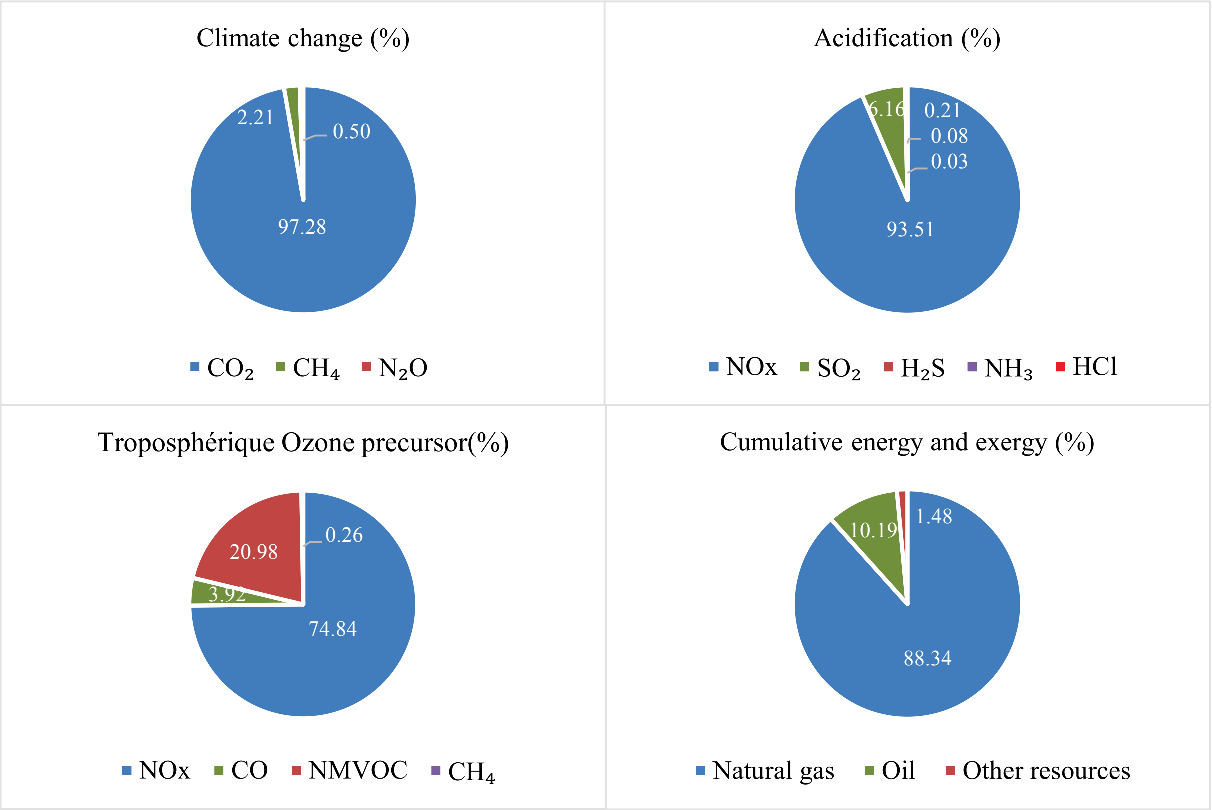

Fig. 7 – Emission flows of the 4 environmental impact indicators by GEMIS 4.95.

3.2 Acidification potential

This potential is 4,55×10^{-4} ton of SO_2 eq/UF and the main gases in terms of emissions are: NO_x, SO_2 and H_2S with a percentage of 93,51%, 6,15% and 0,20% respectively. The contributor to NO_x emissions is 4,26×10^{-4} ton of SO_2 eq/UF for the treatment of one (01) ton of calcined dredged sediments which are divided into 35,80% of diesel consumption, the chimney emissions with 24,51% and the combustion of the gas during the calcination phase with18,42%. The SO_2 emissions are 2,80×10^{-5} ton of SO_2 eq/FU. The sources emission of gases are the consumption of diesel with 56,70%, the Kraft paper in the storage phase with 7,24% and the gases emissions of the heavy oil with 5,36%. The H2S emissions are 9,42×10^{-7} ton SO_2 eq/UF. The sources of gases emissions are the kraft paper in the storage phase with 99,96%.

3.3 The tropospheric ozone precursor potential

This potential is 9,97×10^{-4} ton of TOPP eq/UF and the main gases in terms of emissions are: NO_x, COVNM and CO with a percentage of 74,84%, 20,97% and 3,92% respectively. The contributor to NOx emissions is 7,46×10^{-4} ton of TOPP eq/UF for the treatment of one (01) ton of calcined dredged sediments consisting by the diesel consumption of the order of 35,80%, the emissions of gases in the chimney in the order of 24,51% and the combustion of the gas during the calcination phase with 18,42%. The COVNM emissions are 2,09×10^{-4} ton of TOPP eq/UF. The sources of emissions gases are the evacuation of gases by the chimney of 90,80%, the emissions from the gear of sediment transport with 3,35%, the combustion of natural gas with 2,42% and the gases emissions of the heavy oil with 1,15%.

3.4 The cumulative energy and exergy demand

The cumulative energy expenditure is 2506,75 in MJ/UF with 2500,40 in MJ/UF of non-renewable resources and 4,39 MJ/UF of renewable resources and other resources with 1,96 MJ/UF. The treatment of one (01) ton of calcined dredged sediments consumes mainly 2214,37 MJ/UF of natural gas, 255,38 MJ/UF of oil and other resources with 37MJ/UF.

Figure 8 shows the processing phases of calcined dredged sediments for each environmental impact indicator.

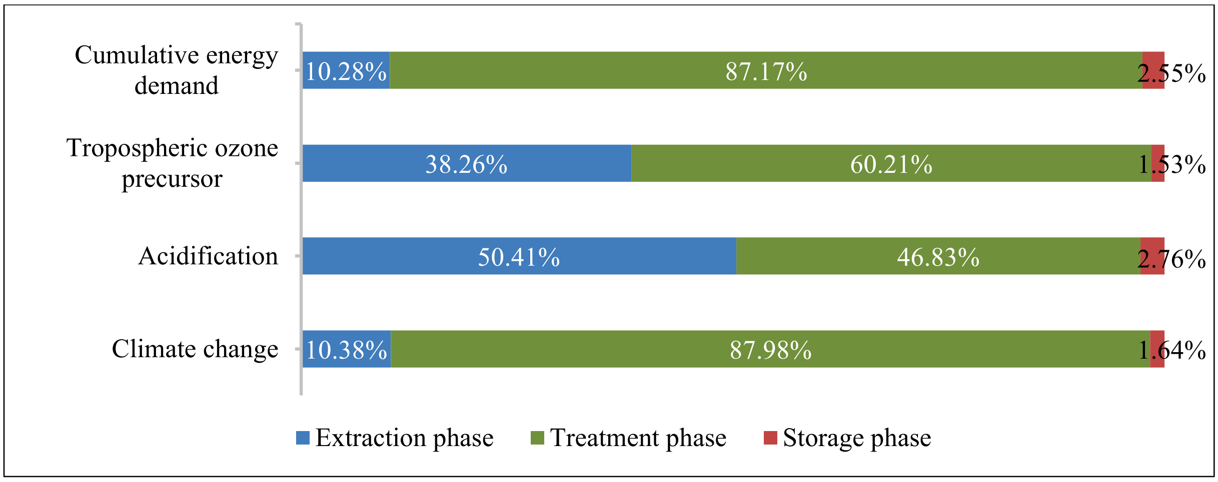

Fig. 8 – The treatments for each impact indicator for the treatment of dredged sediments by GEMIS 4.95.

The results allow us to notice that the treatment phase due mainly to the flash calcination sub-phase is the most impacting phase for the indicators of climate change, tropospheric Ozone precursor and cumulative energy demand, the extraction phase due mainly to diesel consumption with 73,60% and the air emissions from gear of sediment transport with 23,85% are the most impacting sub-phases for the acidification indicator. It is followed by the extraction phase and finally by the storage phase of the dredged sediments.

3.5 Sensitivity analysis

The results of drying the dredged sediments as a function of the shows the results of drying with a moisture content ranging from 0% to 90% of dredged sediments are summarized in table 5 and figure 9.

Table 5 - Sensitivity analysis to compare the moisture content from 0% to 90% for scenario 2.

Process		**Environmental Impact Indicator Greenhouse gas (GES)**		**Dry process (Sour El Ghozlane Cement)**	**Dry process (Sour El Ghozlane Cement)**	**Wet process (Sour El Ghozlane Cement)**
		Unit	**Sensitivity analysis**	**Aksas et al. [35]**	**Boughrara et al. [36]**	**Aksas et al. [35]**
Scénario 1 :	In the dry state (0%)	TCO2 eq/UF	0,246	0,651	0,882	0,850
Scénario 2 :	In the wet state (10%)		0,258			
	In the wet state (20%)		0,267			
	In the wet state (30%)		0,296			
	In the wet state (40%)		0,334			
	In the wet state (50%)		0,387			
	In the wet state (60%)		0,467			
	In the wet state (70%)		0,600			
	In the wet state (80%)		0,865			
	In the wet state (90%)		1,662			

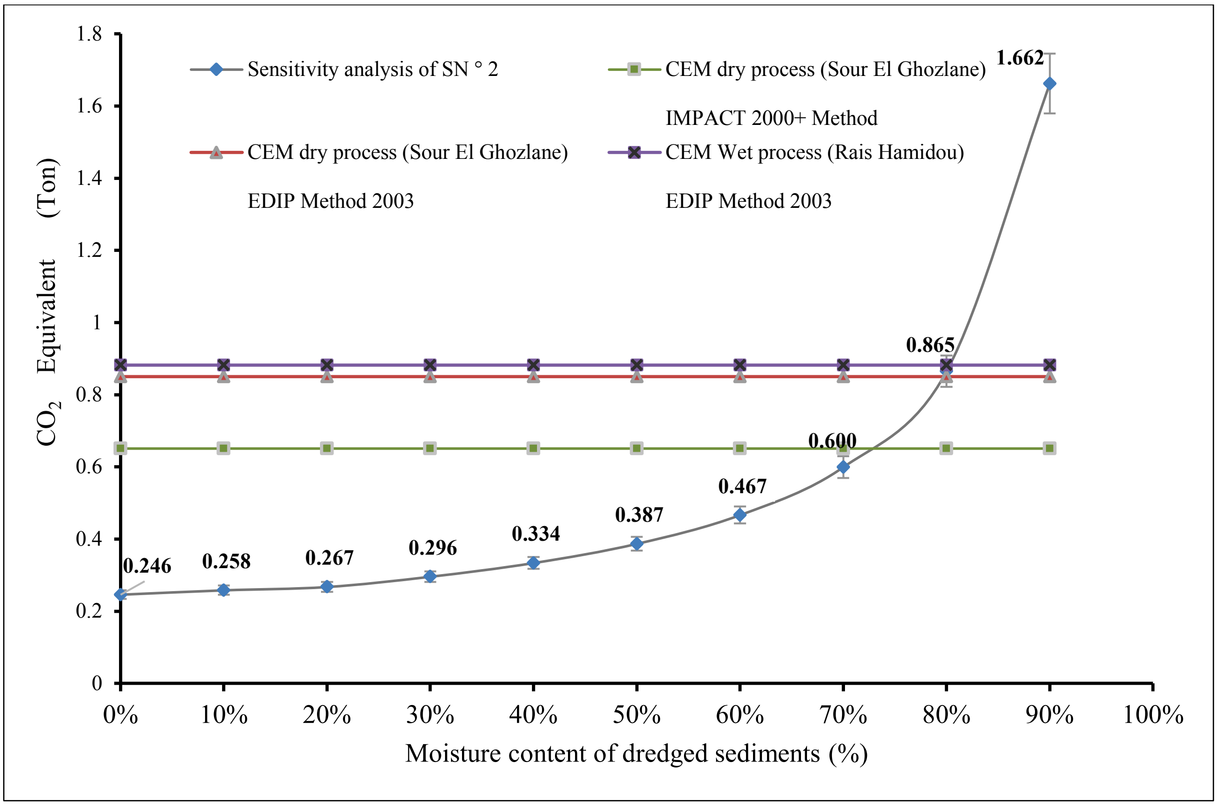

Fig. 9 – Sensitivity analysis to compare the moisture content from 0% to 90% for scenario 2.

The predominant indicator is climate change, we realized our sensitivity analysis on this impact. We note that the evolution of the drying rate of dredged sediments is strongly correlated with emissions in tons of CO_2 equivalent. We also note that the drying of sediments with a humidity less than 70% is less impacting by referring to two recent studies carried out in Algeria:

The first is conducted by Boughrara et al. [36], who studied the use of the life cycle assessment of the Portland production cement plant at Sour El Ghozlane in east of Algeria using the dry process. They observed that the emissions generated on the climate change effect are the order of 882Kg eq CO_2 for the production of one (01) ton of cement. The second is realized by Aksas et al. [35], who compared the environmental impacts of two types of Portland cement in Algeria. The first using the dry process in a rural area (Cement Plant of sour El Ghozlane) in east of Algeria and the second wet process in an urban area (Cement Plant of Rais Hamidou) in Algiers. They observed that the wet process emits 850kg CO_2 while the dry process emits 651kg eq CO_2. When these treatments of calcined dredged sediments are compared with both portland production cement plant in Algeria, it allows a strong reduction of the global warming potential varying between 651 to 850 kg of equivalent CO_2 per ton for cement [35, 36], the dredged sediment emits only 246 kg of equivalent CO_2 per ton, which represents a saving between 62,05% to 71,05%.

4 Conclusion

The interest of the valorization of dam sediment recovery responds to the elimination of areas of rejection which pose a significant problem to the National Agency for Dams and Transfers (ANBT) [8] managers for in the reduction of CO_2 emissions into the atmosphere. The scenarios studied have focused on the development of a new process for producing calcined dredged sediments in Algeria according to two scenarios. Scenario 1 consisted of using sediments in the dry state. This operation requires a drying time in the open air more important. the scenario 2 has been realizing on the sediments in the wet state. The drying time is more reduced. The choice will focus on the scenario 1, the environmental impacts have been lower, hence a clear improvement on environmental indicators.

The results of the life cycle assessment of the dredged sediments production process highlight the possibility of developing an environmentally friendly process and the best solution is cement substitution by mineral additions with calcined dredged sediments in order to minimize CO_2 emissions. The calcination stage is the most impacting on the environment. There is reason to consider a more detailed research on a new process, with an optimization of energy consumption. The calcination phase can be envisaged with a more judicious choice of a flash kiln that consumes less energy. The best way to exploit dredged sediments is in the dry state. The installation of a dredged sediments processing plant may be envisaged. The exploitation after a complete drying, will optimize the environmental impacts. Our future research will focus on the assessment of the environmental impact for the development of a new cement containing calcined dredged sediments in Algeria. Future research could focus on more refined sensitivity analyzes and on uncertainty analyzes with adoption of the Monte Carlo method and the design of an environmental display to promote the results of the industrialization of calcined dredged sediment.

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